RESPONSES TO REVIEWERS

**Reviewer 1**

**Comment:** This manuscript documents the formation of wintertime haline stratification in the Gulf of Finland due to freshwater transport and discusses its implications for early plankton bloom dynamics. The authors combined water column temperature, salinity and fluorescence data from two along-Gulf transects in winters 2011–2012 and 2014, cross Gulf measurements of surface T-S collected with a Ferrybox system and 10 years of GETM-modelled mixed-layer depths. Altogether this is a powerful dataset that allowed to a thorough documentation and description of an interesting phenomenon, which has implications for (usually disregarded) winter primary production in the area. Overall, my view on the manuscript is quite positive and I would be happy to see it published. Still there are several formal issues that need to be addressed before publication. I also feel that the description of some aspects of the dynamics of the system could be described in more depth. I develop this further below but, for example, the general seasonal wind patterns in the area, and how they relate to expected advection patterns are poorly discussed in my view. The authors have nice model simulations and a set of references to better describe the advection dynamics of the system in response to changing winds. I would suggest to develop this aspect a bit more. I feel that if the authors could condensate this information together with their own conclusions in a schematic figure that would help a lot and make the manuscript more shinny and visual.
**Reply:** Thank you for your review and helpful comments! We have addressed all of the points you have highlighted. We have added new schematic figure (12).
**Action:** As we explain below, the seasonal wind pattern and its role is now dealt in the paper. We added thematic figure (last one), which explains the UML distributions in the case of westerly wind and easterly wind dominance. We have addressed all the detailed comments below.

**Comment:** Line 179. Be careful with the positioning of parenthesis for references.
**Reply:** We fixed it.
**Action:** Done

**Comment:** Wind pattern.  The wind pattern (Fig. 6) is strikingly similar for the three years shown here, with strong westerly winds until January and weaker more variable winds after that. Is this the typical seasonal pattern in the region? I think this is a very important point for your message that is not very well developed in the manuscript. You focus more on interannual variation and the links to NAO, but what are the expected seasonal variations of wind forcing during the studied period. Is this transition from strong westerlies to weak variable winds over winter a persistent pattern? Then this is very important for the onset of wintertime stratification. Could you develop this a bit more please?
**Reply:** Yes, we agree. This is a very good point you made. Thank you! Yes, it is part of the annual cycle of wind. The cycle is not as persistent as it looks from the three selected years, but it exists. There is a period from October/November to January when there are more westerly storms and after that, when atmospheric high pressure systems sustain, it calms down. The timing and magnitude vary from year to year though.

**Action:** We have added a new figure showing the annual cycle of along gulf wind stress, we have added sentences about it to the 3.2 (results), discussion, conclusions, and abstract.

**Comment:** Figure 7 and lines 212-227 I like Figure 7, it is quite illustrative, but the only really new information displayed in this figure is the mixed-layer depth. Consequently, some of the information provided in lines 212-227 becomes somewhat repetitive. As the paper has a long number of display items I would suggest to show the MLD already in Figure 6.
**Reply:** Yes, we agree with the comment.
**Action:** We removed the text in 212-227 and added MLD to the figures 5 and 6. We made three minor changes in the previous two sections, just to mention the upper mixed layer depth there. Otherwise, we think the section was repetitive, as you noted.

**Comment:** Figure 8. Could you highlight in the caption the location of the starting point of the transects (x = 0 km)?
**Reply:** Yes, that is a good idea.
**Action:** We added, "the starting point of the transect (x = 0 km) is in the Bay of Tallinn at 59.500° N and 24.752° E."

**Comment:** Line 237 "Spreading from the east to west". This information is not really contained in the Figure. In my view it is a bit confusing to include it in the middle of this sentence which is, otherwise, a pure description of the information that is being displayed.
**Reply:** Yes, we agree.
**Action:** We removed "Spreading from the east to west", but added next sentence to explain the freshwater origin: "Since the main sources of freshwater are in the east, water must have flown westward along the northern coast."

**Comment:** Line 245 Which year are you talking about? Also I am curious about the fact that the onset of haline and, more importantly, thermal stratification seems to have taken place early than in the previous years. Is this related to variability in wind forcing?
**Reply:** We talked about 2014 and 2016. We added an explaining sentence. The earlier onset in 2016 is related to the wind forcing. One can see it in figure 4c. The westerlies eased off earlier in 2016 than two other years. We added a sentence about it to the manuscript.
**Action:** we changed **"**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)."

**Comment:** Figure 11 The x-labels are placed in a strange way in this figure. Do the ticks correspond to the 1st of January of each year? Why is the label to the right of the tick? The color scale for MLD in panel b) is reversed with respect to Figure 10. This confused me.
**Reply:** We agree and fixed the issues.
**Action:** We solved the problem with ticks and we put the color scale the same way as in the previous figure.

**Comment:** Lines 280-294. I think this part is very interesting but needs to be improved. From Figure 11 it is a bit hard to compare the timing of stratification on-set in the different years. I would try to rethink this figure a bit and find a better way to make your point. Also the winter NAO index is an important element here. I would add this information to the figure somehow.

**Reply:** Thank you for this recommendation.
**Action:** We added another subplot, where one can see detailed time-series of UML in different years. We also added the Dec-Feb mean NAO index to the second subplot.

**Comment:** Line 305. In my view "vertical movements of the pycnocline" due to upwelling, internal waves, etc, are transient and have a mostly reversible effect on buoyancy fluxes unless part of their energy is irreversibly lost to turbulent mixing. I would avoid mentioning them or explain better what you mean.
**Reply:** We agree.
**Action:** We removed "vertical movements of the pycnocline".

**Comment:** Lines 326-328. "The western border of the phenomenon is around 23◦E, i.e. at the entrance area to the gulf between Hiiumaa Island and the Finnish coast. Vertical mixing dominates over lateral buoyancy fluxes, and shallow stratification is not a common feature in the Baltic Proper." I find this quite sharp boundary intriguing. Could you add some reference for this or develop a bit more this subject? Why is this change in regime, is the Baltic proper much more wind exposed so that haline stratification is completely eroded? Or is it that some dynamical process precludes the advection of freshwater out of the Gulf?
**Reply:** Yes, this can be mentioned here. We think the feature can occur in the Gulf of Finland because of the two factors: the high riverine input and elongated shape. The phenomenon vanishes in the area, where the extension of the gulf (at the entrance of the gulf) gets wider. Likewise, it is simply far from the main freshwater sources.
**Action:** We added the following text to the manuscript: "The absence of the phenomenon in the Baltic Proper can be explained by the long distance from rivers, due to its larger size and topography. 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, narrow shape of the gulf accounts contributes to the formation of stratification as well as high freshwater input."

**Comment:** Lines 343–345. This sentence needs a reference.
**Reply:** We agree.
**Action:** We added Smetacek and Passow (1990) and Fennel (1990).

**Comment:** Figure 12. I don't like this figure very much. There is very few data available for interpolation. Why don't you use a scatter plot of biomass (with a color/size code) superimposed to a salinity contour plot? This would maybe make your point stronger.
**Reply:** We agree, this figure can be better designed.
**Action:** We have changed the figure according to your recommendation.

**Comment:** Color scale. In the contour figures you use a highly non linear colormap which strengthens low values a lot. I feel that sometimes the use of such a colorscale can be misleading, as it attracts the attention of the reader to this very low values, and sometimes this is not the most relevant aspect. I would suggest that the authors re-think a bit this choice for certain figures.
**Reply:** We agree.
**Action:** We have changed the color scales of figs. 5, 6, 11, 12 (according to the first submission numbering).

**Reviewer 2.**

**Comment:** In fairness to the authors, the editorial staff should not have requested reviews for a manuscript in such a rough state. I think it could warrant publication at some point, but as it is, the manuscript is not even ready for submission. Overall, the manuscript reports observational and model results but it fails to put these results into context and it fails to provide any motivation for the study. The science appears to be sound, but it's not clear why it was done. The manuscript requires extensive editing for grammar and style. There are too many minor grammatical errors for me to keep track of. Tell the reader early on why your work matters and how it fits into a larger context. I am sure it is important, but as it is written now, the manuscript fails to convey that importance. I recommend reading Mensh and Kording (2017) Ten simple rules for structuring papers. C1 -PLOS Computational Biology 10.1371/journal.pcbi.1005619
**Reply:** Thank you for your comments and recommendation.
**Action:** We wrote about the motivation at lines 28-36 and 75-83. To provide for a reader the importance of the paper in a larger context, we added a section to the beginning of the manuscript. The results chapter was shortened to keep it more condensed, introductive sentences were added to each section, to make it easier to read. We arranged extensive editing for grammar and style.

**Comment:** Given that the manuscript lacks a clear motivation, it is difficult to evaluate it using the journals review criteria, which are listed here: https://www.oceanscience.net/peer_review/review_criteria.html. The authors may also wish to use these criteria when revising their manuscript.
**Reply:** We have added a section to the very beginning of the introduction to indicate what is the overall motivation of the study. Details about motivation (why stratification is important for the physics, biogeochemistry and biology) were given at lines 28-36 (previous submission).
**Action:** We added a section to the beginning of the section. We checked the criteria before revising the manuscript.

**Comment:** + 'Phenomena' is typically the plural form of phenomenon (https://www.merriamwebster. com/dictionary/phenomenon) So the title should read ': : : phenomena and their consequences : : :' or 'Winter stratification and its consequences'
**Reply:** Thank you for the note.
**Action:** We changed it to "phenomenon".

**Comment:** + Introduction- the first paragraph of the introduction should state the main goal or problem that the manuscript aims to address. As it is written now, the first paragraph is full of many details about the seasonal cycle of stratification in the Baltic Sea but we are left guessing as to the importance of these details. Please tell the reader the main point or what particular issue your manuscript addresses in the first few sentences and then move on to specific information that the reader needs to understand what has been done, and what is new.
**Reply:** Yes, this paragraph can be added in the beginning.
**Action:** We added: "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.“

**Comment:** + The motivation for this manuscript is not stated until line 75 - “Details about the formation of the haline stratification in the larger areas of the Baltic Sea during wintertime is mainly unknown.” This is the new topic that you address. Please make that clear in the first paragraph and then tell us about what is known. When it’s the other way around, we’re left wondering why you are telling us all this information and where it is going.
**Reply:** Yes, it can be mentioned earlier.
**Action:** Please see our previous response.

**Comment:** + The OSTIA product is not technically remote sensing data. It is gap-filled remote sensing data that also uses in situ observations. The most recent citation for OSTIA is Good et al. (2020) The Current Configuration of the OSTIA System for Operational Production of Foundation Sea Surface Temperature and Ice Concentration Analyses. Remote Sensing. 12:720 doi:10.3390/rs12040720
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**Reply:** Thank you for the information.
**Action:** We removed “remote sensing” from the text in several places and added the reference.

**Comment:** + Regarding the OSTIA data- from the text it’s not clear if you used daily OSTIA fields or mean SST for the entire period from 2010-2019. Can you please clarify?
**Reply:** We use daily OSTIA fields. We clarified this in the data and methods part.
**Action:** It reads now “OSTIA (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.“

**Comment:** + Section 1.2- why use nautical miles? The journal requires the use of metric units. https://www.ocean-science.net/for_authors/manuscript_preparation.html
**Reply:** Metric units for the GETM run are and were also written in the text. We used nautical miles as those are also commonly used in the modelling community – the original grid is planned in nautical miles (either 1 n.m. or 2 n.m., in our case 0.5 n.m.) and it makes sense to indicate this. See e.g. https://os.copernicus.org/articles/15/1691/2019/ or https://os.copernicus.org/articles/15/1399/2019/
**Action:** We added metric units also for the COPERNICUS reanalysis product.

**Comment:** + What are your open boundary conditions? Relaxation? How is riverine input treated in the model? How did you spin up the model?
**Reply:** Thank you for the remark, we have made adjustments in the model description. The boundary conditions for different parameters differ in the model. Observed sea surface height is set to the boundary with Flather (1994) radiation scheme, while the temperature and salinity are relaxed to climatological profiles (Janssen et al. 1999 along the open boundary. There is also a sponge layer with 3-points for the latter.

Riverine water has a constant salinity 0.5 g/kg due to numerical reasons. We are pretty sure that the model can handle also lower values, but at least in the used experiment, it was 0.5. As the temperatures for different rivers are not known/hard to prescribe, the model uses target cell value. Riverine water enters as a change in the sea surface height – the volume of entered water within one model iteration divided by target cell area will give the additional change in the SSH.

We use re-analysis product from Copernicus Marine Service as the initial temperature and salinity. By definition, it is supposed to be the best available possibility to get 3D field of T/S as it "interpolates" observations using the state-of-the-art method. In reality, one can always argue whether it is the "best" way. Nevertheless, we assume that the re-analysis product has all correct salinities and temperatures for different basins and is already baroclinically balanced. Our simulations start from the motionless state but as the Baltic Sea is shallow and wind-driven circulation prevails, the model will quickly adjust to forcing. Lips et al (2016) showed that the volume-averaged kinetic energy reaches correct values within 5-days. In summary, we do not think further spin-up is necessary for the simulations.

**Action:** We have considerably modified the section 1.2.

**Comment:** + Results- since the response of the water column was very similar in each winddriven event, perhaps describe the general behavior first - strong winds, well-mixed water column, low chl-a.
**Reply:** We considered this but realized that it is better if this comes after we have described the observations. Strong westerlies- well mixed water column relation is given in the introduction and the possibility of the formation of the shallow halocline is also mentioned there.
**Action:** No particulate action here, but we think with other changes (complementing introduction, and introducing each section in the results chapter) help a reader to follow the results.

**Comment:** + Line 219 - "Since freshwater originates from the east: : :" Is this statement supported by data or is it speculation? If it's speculation, please move speculative arguments to the Discussion.
**Reply:** We expected here a reader noted from the introduction that the riverine water enters the gulf mainly from the eastern part of the gulf. Anyhow according to the other reviewer comment we realized this section is repeating the previous section, so we decide to remove it.
**Action:** We removed this section.

**Comment:** + Instead of describing what was observed in each dataset, use all the data to describe the stratification phenomena of interest. You are using widely accepted methods so there is no need to justify their use. Communicate your point clearly and succinctly
**Reply:** We describe the phenomenon in the order of subtopics. In the first two sections, we describe the stratification phenomenon along the gulf, its vertical structure and impact on Chl *a*. Next, we describe the surface characteristics (measured by the ferrybox two times a day), which give us a more detailed understanding of the temporal developments of haline stratification formation. In 3.2 we make statistics of the process based on the model and historical CTD data to put our results to a broader context. We added introducing sentences before sections and renamed chapter 3.1. to make it easier

**Action:** We renamed the 3.1 title and added introducing sentences to each section to make it easier to follow for a reader. Likewise, we have shortened 3.1 considerably. We also removed figure 7 after comment from another reviewer.

**Comment:** + Line 295 - this also appears to be speculative and should be moved to the discussion
**Reply:** We change the first sentence of this section to make it less speculative. There is a strong correlation between ice coverage and the NAO index in winter according to literature. But we agree, since the section includes references to previous studies, it rather belongs to the discussion.
**Action:** We moved the section to the discussion.

**Comment:** + Figure 2 is not necessary. Simply state the rˆ2, p value, and n in the manuscript
**Reply:** We agree.
**Action:** We removed the figure and added a sentence about it to the manuscript.

**Comment:** + Figure 5 contains too many subplots. It's cluttered and difficult to take in
**Reply:** We agree, this figure needed improvement.
**Action:** We remade figure 5. We hope it looks better now.

**Comment:** + Figure 9 also contains too many subplots. Perhaps create an animation?

**Reply:** We agree, this figure needed improvement. We believe it is better to keep it in figure format though.

**Action:** We modified the figure. The axis labels were removed (except in one plot) and the plots are now more zoomed in to the area of interest. We believe after these changes the figure is much easier to read.

Manuscript with track changes

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

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

Department of Marine ~~s~~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 system, with a~~. The~~ shallow mixed layer being ~~is~~ one of the preconditions for ~~the~~ enhanced primary production in the ocean. In the Baltic Sea, t~~T~~he general understanding is that the upper mixed layer (UML) is well ~~deeper~~ below ~~than~~ the euphotic zone ~~in the Baltic Sea~~ ~~during~~in winter.  In this ~~work~~study, we demonstrate that ~~the~~ wintertime UML stratification is ~~a~~ common ~~phenomenon~~ in the ~~UML in of the~~ Gulf of Finland. Shallow haline stratification forms at ~~the~~ a depth comparable to the euphotic zone ~~depth forms~~ in late January–early February. Stratification is in~~e~~voked by ~~the~~ a positive buoyancy flux created by the westward advection of riverine water along the northern coast of the gulf after the relaxation of westerly winds. ~~-~~Fresher water and haline stratification ~~appeared~~ occurs approximately one month later in the southern part of the gulf. The onset of restratification is likely ~~may~~ ~~can~~ associated with the annual cycle of westerly winds, which ease off in late January~~–~~–early February. Winter restratification ~~The phenomenona~~ can occur in the whole gulf and in the absence of ~~also without~~ ice, ~~.~~ t~~T~~hus, it ~~the winter restratification~~ is a regular seasonal feature in the area. ~~The~~I~~i~~nterannual~~-annual~~ variations in the wintertime UML correspond with variations in ~~can be related to~~ the North Atlantic Oscillation.~~-~~ Chlorophyll *a* ~~Chl *a*~~ concentration~~ and phytoplankton biomass~~s in winter can be comparable to mid~~-~~ summer; t~~. T~~he limiting factor for phytoplankton bloom in winter is likely insufficient solar radiation.

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~~**1.**~~

## ~~2.~~1. Introduction

~~The~~U~~ u~~pper layer stratification is an important characteristic in the dynamics of the pelagic ecosystem. However, to our knowledge, ~~The dedicated study dealing with the~~ the formation of ~~the~~ wintertime haline stratification in the upper layer of the whole Gulf of Finland ~~to our knowledge is missing in the literature~~has not been investigated; ~~. Th~~the present study focuses~~d~~ on the formation of wintertime haline stratification caused by freshwater ~~the~~ inflow ~~of freshwater a~~and wind forced circulation~~ in the Gulf of Finland~~, and the ~~. The~~ observed haline stratification explains~~ed~~ early phytoplankton dynamics.

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The Baltic Sea is ~~a~~ shallow and ~~,~~brackish, ~~-~~ has ~~sea with~~ limited water exchange with the North Sea and is characterized by ~~. The sea has~~ strong seasonality and gradients of oceanographic parameters (e.g. Leppäranta and Myrberg, 2009). The u~~U~~pper 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 Białogrodzka, 2015; Tronin, 2017) and thermal stratification strengthens until August. The

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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 ~~in stratification~~ has substantial implications for ~~on~~ physical, biogeochemical and biological processes in the sea.~~ First~~ C~~, c~~haracteristics of the pycnocline (e.g. strength) determine vertical fluxes between the surface and sub-thermocline layer. Moreover, the vertical structure of currents is strongly linked to pycnoclines (Suhhova et al., 2018). The annual cycle in stratification, together with solar radiation, mainly determines ~~the~~ seasonality in primary production and nutrient consumption. Vertical mixing from the deeper layers, and low production in winter, allows ~~the~~ nutrients to accumulate ~~ion of nutrients~~ in the upper layer (e.g. Lilover and Stips, 2008; Nehring and Matthäus, 1991). The ~~In spring, when the~~ water column becomes stable in spring and~~,~~ the mixed layer ~~depth~~ is shallower than the euphotic zone, so that ~~, and~~ the spring bloom is triggered when solar radiation is sufficiently strong ~~enough, spring bloom is evoked~~ (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 m~~. Mean river~~ean runoff of ~~to the gulf is~~ 3700 m$^3$ s$^{-1}$ (Johansson, 2018). Since ~~the~~ river discharge is concentrated in ~~to~~ the east, and the gulf is connected to the Baltic Proper in the west, there is a mean longitudinal salinity gradient in the upper layer from virtually 0 g kg$^{-1}$ ~~in~~ at the easternmost end to 6 g kg$^{-1}$ in the west~~ exists~~ ~~in the upper layer of the gulf~~ (Alenius et al., 1998). Also, mean salinity in the upper layer is lower on the northern coast than the southern d~~D~~ue 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), ~~mean salinity in the upper layer is lower along the northern coast of the gulf compared to the southern coast~~ (e.g. Kikas and Lips, 2016). Free water ~~Gulf has a free water~~ exchange between the gulf and ~~with~~ the Baltic Proper means that there is a ~~. Thus,~~ quasi-permanent halocline and saltier deep layer ~~also exist~~ in the gulf. This lateral and vertical structure can be strongly modified by wind forcing; w~~. W~~esterly winds drive accumulation of ~~e~~ saltier upper layer water, deepen the UML~~upper mixed layer~~ ~~depth in the gulf~~ (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, e~~E~~asterly winds ~~, in turn,~~ encourage westward transport of riverine water and strengthen 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 extent of the ice-coverage has high inter-annual variability~~. The brackish nature~~water~~ of ~~the~~ Baltic Sea water means that the ~~has~~ maximum density temperature $T_{md}$ (2.2–3.3 °C) is higher than the freezing temperature (from –0.4 to –0.1 °C), unlike ~~in~~ most of the world ocean. Thus, when the temperature of the surface layer is below $T_{md}$, warming ~~of the surface layer below $T_{md}$~~ increases water density and causes convection and vertical mixing, while c~~. C~~ooling ~~at < $T_{md}$ s~~stabilizes the water column. Water~~The~~ temperature typically ~~passes~~ exceeds the $T_{md}$ in ~~the~~ northern and eastern parts of the Baltic Sea during ~~the cooling period~~winter (Karlson et al., 2016; Liblik et al., 2013), but ~~while~~ it is not always the case in ~~the~~ offshore areas in the southern Baltic Sea (e.g. Stepanova et al., 2015). Lateral haline buoyancy flux can compensate the thermal convection and stabilization of the shallow upper layer in spring and can occur at temperatures already below $T_{md}$

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(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 ~~impact~~ on density is relatively small compared to the impact of salinity. Thus, ~~the~~ onset of the seasonal pycnocline is not necessarily initiated by ~~the~~ thermal buoyancy but could be related to ~~the~~ haline buoyancy~~ instead~~. Temperature below $T_{md}$ in the cold intermediate layer after establishment of the seasonal pycnocline provides d~~Straightforward~~ irect evidence of the latter~~ is~~ ~~the temperature below $T_{md}$ in the cold intermediate layer after the establishment of the seasonal pycnocline~~ (Chubarenko et al., 2017; Eilola, 1997; Liblik and Lips, 2017). Haline stratification creates favourable conditions for spring phytoplankton bloom (Kahru and Nõmmann, 1990; Lips et al., 2014); w~~W~~ithout haline stratification, warming would cause mixing until $T_{md}$ is reached. ~~. The haline stratification creates favourable conditions for spring phytoplankton bloom (Kahru and Nõmmann, 1990; Lips et al., 2014).~~

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

The Gulf of Finland has favorable preconditions for ~~the~~ haline stratification in the upper layer in winter. The g~~G~~ulf receives large amounts of fresh water, and it is at least partly covered by ice during winter~~s~~. The present ~~work~~study hypothesizes that haline stratification occurs at a depth comparable to the euphotic zone ~~depth occurs~~ in the Gulf of Finland, and ~~-~~potentially in the northeastern Baltic Proper, during wintertime. This ~~It~~ means that the general understanding 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~~ify~~ this hypothesis, we analyzed data from research vessel measurement campaigns, ~~the research vessel gathered and~~ autonomously acquired Ferrybox data and historical sources, along with ~~and across the Gulf of Finland. Likewise, model simulat~~model simulation ~~ion~~ data.~~ were examined.~~

~~Details about the formation of the haline stratification in the larger areas of the Baltic Sea during wintertime is mainly unknown. The Gulf of Finland has favourable preconditions for that process in winter. Gulf receives large amounts of freshwater, and it is at least partly covered by ice during winters. The present work hypothesizes that haline stratification depth comparable to the euphotic zone depth occurs in the Gulf of Finland and potentially in the northeastern Baltic Proper during wintertime. It means that the general understanding 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 testify this hypothesis, we analyzed the research vessel gathered and autonomously acquired data along and across the Gulf of Finland. Likewise, model simulation data were examined.~~

## 2. Data and methods

### In ~~-~~situ and remote sensing data

We arranged t~~T~~wo measurement campaigns ~~we arranged~~ in winters 2011/12 and 2013/14 abord RV *Salme* to investigate estuarine circulation reversals in the Gulf of Finland (Fig. 1); six along the gulf surveys were conducted in each winter, with full details of survey and data processing in ~~to investigate estuarine circulation reversals in the Gulf of Finland (~~Liblik et al. (~~,~~ 2013) and ~~;~~ Lips et al. (~~,~~ 2017). ~~Details of the along the gulf surveys and data processing are well described in the referenced papers. Six surveys onboard the RV Salme were~~ was ~~conducted in both winters.~~ In the present study, ~~is work,~~ we ~~present~~ utilized temperature, ~~and~~ salinity and chlorophyll *a* (Chl *a*~~-~~) data from ~~the~~ cruises in 2011 (~~on~~ 21 December ~~2011~~), 2012 (24–25 January, 7–8 February, 29 February, 15–16 March) and ~~2012 and~~ 2014 (9–10 January, 3–4 February, ~~and~~ 4–5 March). ~~2014. The~~V~~v~~ertical profiles of temperature, salinity~~,~~ and ~~chlorophyll *a* (~~Chl *a*~~)~~ fluorescence were recorded using an Ocean Seven 320plus CTD probe (Idronaut S.r.l.) equipped with a Seapoint Chl *a* fluorometer. The ~~The quality of the~~ salinity data was calibrated against ~~the~~ 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 ~~the~~ 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 calibration device were smaller than the initial accuracy (0.001 °C) of the Ocean Seven 320plus temperature sensor.

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~~Chlorophyll *a* (~~Chl *a*~~)~~ fluorescence data was compared and calibrated against water samples o~~i~~n the selected cruises ~~(Fig 2)~~. The linear regression between Chl *a* fluorescence sensor values and Chl *a* acquired from water samples was~~ere~~: 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 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 ~~the~~ water samples from a selection of stations in ~~in~~ winter 2014~~, and the samples were not collected in all stations~~ (Fig. 1). ~~The~~ S~~s~~ub-samples (100 ml) were preserved and analyzed following ~~according to the~~ HELCOM recommendations and EVS-EN 15972:2011 standard. P~~The p~~hytoplankton carbon (C) content was calculated using the C: biovolume factors method of ~~according to~~ Menden-Deuer and Lessard (2000) and ~~for~~ for photosynthetic naked ciliate Mesodinium rubrum a~~a~~ccording to the method of Putt and Stoecker (1989).

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~~The~~ W~~w~~ind data were ~~measured~~ recorded at Tallinnamadal and Kalbå~~a~~dagrund l~~L~~ighthouses (Fig. 1) at ~~the~~ heights of 36 m and 32 m above ~~the~~ sea level and ~~recorded with~~ 1-h and 3-h intervals, respectively. A height correction coefficient of 0.91 (neutral atmospheric stratification) was applied to convert ~~The~~ wind speed measurements ~~was multiplied by a height correction coefficient of 0.91 (neutral atmospheric stratification) to reduce the recorded wind speed to that of the height of~~ to 10 m height equivalent (Launiainen and Saarinen, 1984). Wind measurements from ~~d at the~~ Tallinnamadal for ~~in~~ winters 2011/12, 2013/14 and 2015/16 were used in the ~~analyses with~~ oceanographic data analysis. The Kalbådagrund dataset ~~from~~for the period ~~Kalbåadagrund~~ 1981–~~-~~2015 was used to ~~de~~illustrate ~~scribe~~ the annual cycle of the along-gulf component of wind stress.

~~Tallinn–Helsinki~~ Ferrybox measurements of temperature and salinity between Tallinn–Helsinki ~~from~~ for January–~~-~~March 2012, 2014 and 2016 were also used in the study. ~~are presented in the paper. The~~ Details of the ~~information about the~~ Ferrybox system and data processing methods are given in ~~detail in~~ Kikas and Lips (2016). A~~The a~~nalyses have shown that a ~~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). ~~After removal the offset t~~The standard deviation of the difference in ~~between~~ 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 ~~of the Ferrybox~~ is 0.04 °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 ~~describe~~ determine past~~the~~ stratification conditions ~~in the past~~. Quality assurance and data processing ~~of this data~~ were in accordance with the HELCOM Monitoring Manual (Anon, 2017).

~~Remotely sensed~~ OSTIA (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 M~~m~~arine E~~e~~nvironment M~~m~~onitoring S~~s~~ervice ~~products~~. ~~Mean~~ The mean difference between ~~of~~ the ~~remotely sensed~~OSTIA SST product and in ~~-~~situ measurements is 0.01–~~-~~0.03 °C and the standard deviation is ~~-~~0.4–~~-~~0.5 °C (Worsfold et al., n.d.). ~~The~~ D~~d~~aily mean SST along the thalweg in the Gulf of Finland (Thalweg GoF in Fig. 1) and in the Gotland Deep (box in Fig. 1) w~~ere~~as calculated to determine if and when ~~the~~ SST was ~~declined~~above or ~~-~~below ~~and rose above~~ $T_{md}$. Saliniti~~y~~es of 6 g kg$^{-1}$ and 7 g kg$^{-1}$ were used in ~~the~~ $T_{md}$ estimation for the Gulf of Finland and Gotland Deep, 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**).

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Density is given as a potential density anomaly ($\sigma_0$) to a reference pressure of 0 dbar (Association for the Physical Sciences of the Sea, 2010). The ~~upper mixed layer (~~UML~~)~~ depth was defined as the minimum depth where $\rho_z \geq \rho_3 + 0.15$ kg m$^{-3}$ was satisfied. The density at 3 m depth is $\rho_3$~~,~~ and $\rho_z$ is the density at ~~a certain~~ depth $z$.

## Model~~l~~ing

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

~~The~~V ~~v~~ertical mixing in the ~~In~~ GETM ~~the vertical mixing parameters are~~is calculated using a General Ocean Turbulence Model (GOTM, ~~(~~Umlauf and Burchard (~~,~~2005)). For ~~In this model,~~ the current study, the ~~the~~

eddy diffusivity and eddy viscosity parameters ~~are~~ were found ~~by a~~wusing ~~ith~~ a two-equation k-ε model coupled with an algebraic second-moment closure (Burchard et al., 2001; Canuto et al., 2001).

~~The~~ A horizontal ~~resolution of the GETM grid~~grid spacing of 0.5 nautical miles (approximately 926 m) was established for the ~~for the~~ setup domain of the whole Baltic Sea (Fig. 1)~~ is 0.5 nautical miles (approximately 926 m)~~, ~~over the whole Baltic Sea (Fig. 1); there are~~with 60 vertically adaptive layers~~ in the vertical direction~~. Parameters controlling the vertical resolution of the model during ~~the~~ simulations ~~are~~were taken from ~~chosen the same as in~~ 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 ~~xxxxx~~1 April 2020), ~~and adapted for the Gulf of Finland based on the~~with additional data for the Gulf of Finland from ~~by~~ Andrejev et al. (2010). ~~The~~ S~~atmospheric forcing~~surface boundary conditions (~~the~~ wind stress and surface heat flux components) w~~as~~ere calculated using bulk formulae from ~~the wind, solar radiation, air temperature, total cloudiness and relative humidity~~ data generated by the operational forecast model HIRLAM (High-Resolution Limited Area Model). HIRLAM ~~-~~is ~~version maintained~~used and maintained by the Estonian Weather Service and has ~~with the~~ a spatial resolution of 11 km and ~~the~~ a daily forecast interval of 1 h ~~with~~for a total forecast length of 54 h (Männik and Merilain, 2007). ~~The wind velocity components at the 10 m level along with other HIRLAM~~All ~~the~~ meteorological parameters were interpolated to the model grid~~s~~. ~~The~~ M~~m~~odel simulation ~~runs~~ ~~were~~was performed from 1 April 2010 to 31 December 2019.

~~The model domain has an open boundary in the Danish straits~~Open boundary conditions ~~are~~were used in the Danish Straits. ~~The~~I~~i~~nflow- and outflow from the model is barotropically controlled using ~~the~~ sea surface height measurements from ~~the~~ Gothenburg station and, more specifically, ~~(~~Flather~~,~~ (1994) ~~Flather (1994)~~ radiation. In terms of ~~As for the~~ 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)~~Martinsen and Engedahl (1987)~~. ~~For the boundary conditions, the sea surface height measurements from the Gothenburg station and the climatological temperature and salinity profiles along the open boundary were utilized.~~ The simulation used freshwater input from the 54 largest Baltic Sea rivers,~~,~~ together with their interannual variability as reported in ~~the~~ HELCOM (Johansson, 2018)~~ was~~is ~~used~~ ~~in the~~ ~~model~~~~simulation~~. The riverine input ~~is~~is treated as a rise in the sea surface height and each ~~all the~~ river~~s~~ has~~ve~~ a prescribed constant salinity of 0.5 g/kg that is diluted in the corresponding grid cell. ~~The~~R~~ r~~iver water temperature is assumed to be the same as that ~~in~~ in the target cell.

The initial thermohaline field was ~~generated by~~taken from the Copernicus~~OPERNICUS~~ reanalysis of the Baltic Sea for the period 1989–2014. As ~~T~~the product provides~~d~~ ~~the~~ a horizontal resolution of 3 nautical miles (approximately 5.56 km), and ~~the~~ 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. ~~The~~M~~ m~~odel simulations started from a motionless state, ~~-~~that is ~~i.e.~~ with initial sea surface height and current velocity~~ies~~ set to zero. Previous studies (e.g. ~~(~~Lips et al., 2016)~~Krauss and Brügge, 1991; Lips et al, 2016)~~ have shown that wind-driven circulation in the Baltic Sea adjusts to forcing within 5 ~~-~~days.

Model ~~For the model~~ validation used available Ferrybox data (2011–2016) along the ~~transect from~~ ~~T~~Tallinn to Helsinki transect (see Fig. 1 for location)~~ were used~~. The model captures the observed variability of ~~the~~ temperature and salinity reasonably well (Fig. 3). Standard deviations of ~~the~~ simulated temperature and salinity for the overall (1 November~~.11.~~ 2011–1 June ~~.06.~~ 2016) and wintertime (December to ~~–~~March 2011–2016) periods

**Formatted:** Hyperlink, Font: (Default) Times New are close to observations. The standard deviation of simulated salinity is smaller than the observed for ~~in~~ winter 2016 (January–March) and larger for ~~in~~ 2012, while for ~~in~~ 2014 it is close to the observed~~observations~~. The ~~simulated~~ variability of ~~the~~ temperature is captured well~~-~~ ~~— the~~ standard deviations from the simulations are at least 0.8 of the observed for all ~~the~~ time ~~-~~periods, although the ~~. The~~ model slightly overestimated ~~the~~ temperature variability for the winter of 2012.

~~For salin~~T~~ity, t~~he overall correlation coefficient for salinity is 0.62, while it is over 0.74 ~~both~~ for both the whole wintertime period and single years as well. There is a ~~A~~ higher correlation for temperature (as expected); o~~is for temperature. O~~verall correlation, which includes ~~as the~~ seasonal variability~~, is included,~~ is 0.99, and ~~while~~ for ~~the~~ wintertime it is 0.95. Very high correlation (>0.94) for ~~the~~ temperature is also shown for ~~single~~ individual winters.

~~The~~ Root mean ~~root-~~squared differences between model and observed values are slightly larger for ~~the~~ salinity but do not exceed the observed variability. In general, the model captures ~~the~~ wintertime changes in the surface layers of the Gulf of Finland well. More details about ~~the~~ model setup and validation in the Baltic Proper ~~is~~ are given in ~~(~~Zhurbas et al. (~~,~~ 2018).

## ~~3.~~ 3. Results

### 3.1. O~~The o~~nset of stratification and its link to wind forcing~~Wind forcing, hydrography and Chlorophyll *a* patterns~~

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 together with wind data ~~in~~for winters 2011/12 and 2013/14. Prior to the survey of 21 December 2011, there was a s

~~S~~trong westerly wind with a ~~,~~ maximum along ~~-~~gulf wind stress ~~was~~ of 1.3 N m$^{-2}$~~, prevailed before the survey on 21 December 2011~~ (Fig. 3~~4~~a). ~~The~~ C~~c~~umulative wind stress increased by 6 N m$^{-02}$ d from 1 November to 21 December, resulting in a ~~by 6 N m$^{-2}$ d. As a result,~~ warm (>5 C°, Fig. 4~~5~~a), relatively salty (>6.3 g kg$^{-1}$, Fig. 4~~5~~b) and well-mixed water column ~~was observed~~ in the gulf (Fig. 4~~5~~c). ~~Very low~~ Chl *a* concentrations were very low, ~~, around~~ below 1 mg m$^{-3}$~~, was seen in the section~~ (Fig. 4~~5~~d). Prior to the survey on 24–25 January 2012, w~~W~~eaker easterly winds had prevailed since mid ~~-~~January ~~before the survey on 24–25 January 2012~~ (Fig. 3~~4~~a). Lower temperature (3–4 C°, Fig. 4~~5~~e) in the upper 20 m coincided with slightly fresher water on 24–25 January 2012 (Fig. 4~~5~~f). A s~~S~~alinity minimum (down to 5.8 g kg$^{-1}$) caused stratification in the upper layer (Fig. 4~~5~~g) at ~~the~~ a distance of 80– ~~to~~ 110 km in the section; this location was also characterized by ~~, and~~ slightly higher Chl *a* concentration (up to 1.5 mg m$^{-3}$) ~~was seen there~~ (Fig. 4~~5~~h). Variable and relatively weak winds prevailed in late January and early February (Fig. 3~~4~~a). On 7–8 February 2012, t~~The t~~emperature of the upper layer was below ~~was lower than~~ $T_{md}$ (2.7 °C) ~~in the upper layer on 7–8 February~~ (Fig. 4~~5~~i), ~~. The cold water in the upper layer coincided with lower~~ salinity was low (4.8–6.0 g kg$^{-1}$, Fig. 4~~5~~j) and there was a ~~rema~~mark~~ed~~able stratification and shallow UML ~~was observed~~ (Fig. 4~~5~~k). Higher Chl *a* concentration, occasionally >2 mg m$^{-3}$, ~~-~~was seen in the fresher and colder water along the section (Fig. 4~~5~~l). Lateral Chl *a* ~~shape~~ extent was closely linked to the salinity (density) structure, with h~~. H~~igher Chl *a* concentration associated with ~~was connected to the~~ lower salinity and vice versa.

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~~lower Chl *a* concentration to the higher salinities.~~ Westerly winds prevailed in the ~~during the~~ period before the next survey at the end of February (Fig. 3~~4~~a), resulting in ~~. This resulted in~~ well ~~-~~mixed conditions and relatively high salinity (6.0–6.7 g $kg^{-1}$) in the western part of the section on 29 February (Fig. 4~~5~~m–n). Lower salinity, stronger stratification and slightly higher Chl *a* in the upper layer were observed in the central part of the section (Fig. 4~~5~~n–p). The e~~E~~astern part of the section was not visited on 29 February due to ice conditions ~~on 29 February~~. 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. 4~~5~~r~~q~~–t~~s~~). Chl *a* c~~C~~oncentrations in the upper layer were within the ~~of Chl *a* within the~~ range ~~of~~ 2–4 mg $m^{-3}$ ~~were found in the upper layer~~ (Fig. 4~~5~~u~~t~~).

Similar ~~developments~~ trends in ~~in the~~ wind forcing and spatiotemporal patterns ~~in~~ 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 ~~the~~ cumulative wind stress of 10 N $m^{-2}$ d from ~~increased since~~ 1 November 2013 ~~by 10 N $m^{-2}$ d~~ (Fig. 3~~4~~b). The 9–10 January 2014 survey shows a w~~W~~ell-mixed water column and low Chl *a* ~~were observed on 9–10 January 2014~~ (5~~6~~a–d). Fresher and colder water, but only slightly higher Chl *a*, ~~-~~was found in the upper layer on 3–4 February (Fig. 5~~6~~e–h). By 4–5 March, the area of ~~Spreading of~~ fresher water had expanded (salinity <6 g $kg^{-1}$) and the ~~stronger stratification~~ ~~shallow upper mixed layer~~UML extended over ~~were observed in~~ most of the section ~~on 4–5 March~~ (Fig. 5~~6~~j, k). The cold and fresher upper layer showed h~~H~~igher Chl *a*, ~~was found in the cold and fresher upper layer,~~ especially in the eastern part of the section (Fig. 5~~6~~i, j, l).

~~To illustrate wintertime re-stratification phenomena and formation of the shallow upper mixed layer along the gulf, we show longitudinal upper mixed layer depth, surface layer salinity, the density difference between 40 m depth and the surface layer, and surface layer Chl *a* in winters 2011/12 and 2013/2014. Very thick mixed layer (70–90 m), high surface salinity (6.3–6.5 g $kg^{-1}$), small along gulf gradient of the surface salinity, small density difference (<0.1 kg $m^{-3}$) and low Chl *a* concentration was observed on 21 December 2011 (Fig. 7). Similar characteristics were observed in most of the section on 24 January 2012. An exception was the region at a distance from 80 to 110 km, where surface salinity within the range 5.8–6.3 g $kg^{-1}$ was observed. Interestingly, saltier water was found further in the east again. Since freshwater originates from the east, the fresher water must have been first flown to west along the northern coast and later advected to the central part of the gulf likely as a filament. Upper mixed layer depth < 20 m, density difference up to 0.5 g $kg^{-1}$ and Chl *a* concentration up to 1.5 mg $m^{-3}$ were observed in this area. Mixed layer depth <20 m and density difference >0.5 g kg $m^{-3}$ occurred in most of the sections on 7–8 February, 29 February and 15–16 March 2012. Similar developments were seen in winter 2013/14. Thick mixed layer, high salinity, small density difference and low Chl *a* were observed on 9–10 January 2014. Occasionally lower salinity, smaller upper mixed layer thickness, stronger stratification and elevated Chl *a* concentration were found on 3–4 February, and well-developed stratification and Chl *a* concentration mostly in the range 2–3.5 mg $m^{-3}$ registered on 4–5 March 2014.~~

Thus, ~~we observed~~ haline stratification and elevated Chl *a* concentration was observed in both winters (2011/12 and 2013/14) from the ~~since the~~ beginning of February. ~~in~~ A s~~both winters (2011/12 and 2013/14). S~~hallow UML~~mixed layer~~ ~~depth~~ (<20 m) was ~~not observed~~absent after prevailing westerly winds and ~~in the case~~ when SST~~sea surface temperature~~ was >$T_{md}$. Stratification formed as fresher water occupied the upper layer.

To ~~describe~~examine ~~the~~ temporal ~~developments~~trends in ~~of the~~ haline stratification in more detail, ~~Next,~~ we ~~next~~ ~~describe~~ analyzed across the gulf changes ~~of~~ in temperature and salinity using measurements acquired by the Ferrybox system ~~at~~ along the Tallinn–Helsinki transect for ~~in~~ January–March 2012, 2014 and 2016 (Fig. 6~~8~~). Generally, ~~General~~ temporal ~~temporal~~ changes ~~of~~ in salinity and temperature along the transect were ~~in these years were~~ quite similar for each of the study years, ~~-~~as was wind forcing (Fig. 3~~4~~). Strong westerly winds dominated until early or mid January~~-January~~, and ~~.~~a~~ A~~fter ~~the~~ relaxation of ~~the~~wind forcing, fresher water ~~appeared~~was recorded in ~~to~~ the transect.

Based on ~~According to the~~ observations at the longitudinal sections (Figs. 4~~5~~ and 5~~6~~), the highest ~~we assume s~~sea surface salinity at which stratification and relatively shallow UML can form was assumed as ~~of~~ 6 g kg$^{-1}$ ~~as the highest salinity, where stratification and relatively shallow UMLupper mixed layer could form~~. Similar~~ly~~ to the along-gulf observations (Fig. 4~~5~~a, b), salty and warm water occupied the transect at the beginning of January ~~in~~ 2012 (Fig. 6~~8~~a, b). The northern part of the transect was covered in f~~F~~resher water (< 6 g kg$^{-1}$) ~~spreading from the east to west covered the northern part of the transect~~ by the end of January, ~~while~~ although salinity slightly increased in the southern part of the section at this ~~e same~~ time. Since the main sources of freshwater are in the east, ~~the~~ 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 ~~the~~ sea surface salinity was observed in 2014 and 2016 (Fig. 6~~8~~c–f). Fresher water first appeared in the northern part in the first half of January in ~~early or mid-January~~both ~~in~~ 2014 and 2016. The onset of haline stratification ~~took a place~~occurred slightly earlier in 2016 due to ~~. This is associated with the~~ wind forcing – the ~~,~~westerlies had eased off ~~already~~by ~~at~~ 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 ~~the~~ mid ~~-~~February 2014. A pulse of s~~S~~trong westerly wind occurred ~~impulse occurred~~ at the end of January–beginning of February ~~in~~ 2016 (Fig. 3~~4~~c). We suggest that the lighter,~~,~~ less saline water that originates in the ~~from the~~ east flowed westwards ~~alo~~along the northern coast ~~to the west~~ and was later transported to~~ward~~ the southern coast in the central and western part of the gulf. The l~~L~~atter is likely related to the ~~the~~ Ekman transport induced by the westerly ~~winds~~ wind impulse ~~early February in both years~~ (Fig. 3~~4~~). Thus, stratification related to the spreading of fresher water forms about one month earlier in the northern part of the gulf than in the ~~than in the~~ southern part~~ of the gulf~~.

### 3.2. S~~The occurrence s~~patiotemporal patterns of ~~the~~ restratification~~-stratification phenomen~~on~~a~~

Here, ~~Next,~~ we ~~describe~~examine ~~The~~ the spatiotemporal pattern of the restratification~~-stratification~~ process using ~~can be described by~~ model simulation data and ~~statistics of~~ statistics of historical observations. ~~Monthly mean simulated UML depth and occurrence of the UML depth <20 m are presented in Fig. 9.~~

As noted from the in ~~-~~situ observations, ~~the~~ haline stratification forms after the relaxation of ~~the~~ westerly winds. The annual cycle of the along-gulf component of wind stress shows higher monthly mean values (>0.04 N m$^{-2}$) and higher variability from October~~–~~–January (Fig. 7); this ~~. It~~ means that ~~the~~ strong westerly winds ~~from westerly directions~~ are more frequent and storminess is higher in these months. ~~Generally~~As a consequence, ~~the occurrence of~~ UML depth <20 m was infrequent and ~~as very low and~~ mean UML depth varied between ~~within~~

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~~the range~~ 40–60 m in the western and central gulf in November, December and January 2010–2019 (Fig. 8~~9a–f~~). As an exception, the probability of ~~the~~ UML depth <20 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~~ occurrence of UML depth <20 m increased to 50–60% (Fig. ~~9~~8~~g and h~~), although ~~. Still,~~ in the southern and western parts of the gulf, ~~the~~ mean UML depth was 30–40 m ~~in February~~. The~~se~~ statistics from ~~based on~~ model simulation data ~~well~~ agree well with our observations of westward advection of fresher water from the northern coast (Fig. 6~~8~~). ~~The~~ M~~m~~ean UML depth was 20 m or lower in the central part of the gulf in March, ~~-~~and ~~while the UML was~~ thicker at the gulf entrance (Fig. 8) ~~area of the gulf in March~~ ; ~~(Fig.~~ 8~~9i). T~~the occurrence of ~~the~~ UML depth <20 m was >60% in the central part, around 50% at the gulf entrance ~~area of the gulf~~ and much lower to the ~~ess in the~~ west of ~~from the~~ longitude 22° E (Fig. 8~~9j~~). A similar pattern is shown in ~~revealed in~~ the mean occurrence of the density difference between 40 m depth ~~-~~and the sea surface of >0.5 kg $m^{-3}$, based on in-situ measurements for the period ~~in~~ 1904–2020 (Fig. 9~~10~~): ~~. The~~ occurrence was 40–75% in the central part of the gulf, 30–50% in the ~~western part~~entrance of the gulf and <5% further to ~~in~~ the west. Thus, ~~the~~ wintertime upper layer stratification extends ~~ed~~ to 23°E in the western gulf.

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Model simulation data (2010–2019) were used t~~T~~o ~~describe~~ examine the development of UML depth from October to March along ~~the~~ a transect from the northern Baltic Proper to the central Gulf of Finland and in ~~in~~ the Gotland Deep ~~model simulation data (2010–2019) were used~~. The time series of m~~The m~~ean UML depth for ~~the~~ transects in the gulf (Thalweg GoF, Fig. 1) and Gotland Deep (box, Fig. 1) show that ~~was calculated.~~ t~~T~~he maximum ~~of the~~ mean UML depth in the gulf mostly occurred in December, ~~and~~ well before SST decreased to $T_{md}$ (Fig. 10~~1~~a). The onset of restratification~~-stratification~~ occurred at temperatures below $T_{md}$ (Fig. 10~~1~~b~~a~~). ~~The~~ T~~t~~emperature dropped below $T_{md}$ later and ~~raised~~ rose above~~over~~ $T_{md}$ earlier in the Gotland Deep compared to the gulf. In five winters out of ten SST did not fall below $T_{md}$ in the Gotland Deep (Fig. 10~~1~~b~~a~~). However, whether the temperature was below $T_{md}$ or not, restratification~~-stratification~~ phenomenon~~a~~ were absent from the ~~in the~~ upper layer ~~did not occur~~ in the Gotland Deep in January–March; this ~~. It~~ means that buoyancy, created by slight thermal stratification at <$T_{md}$~~-~~, is overshadowed by vertical mixing in the Gotland Deep. 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. 6~~8~~) creates a shallow mixed layer (Fig. 10~~1~~a-c).

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~~-annual~~ variability (Fig. 10~~1~~c~~b~~). The deepest UML occurred in the gulf in winters 2011/12 and 2013/14, i.e. precisely the years~~,~~ when measurements along the thalweg also showed deep UML in the gulf (Figs. 4~~5~~ and 5~~6~~). The estuarine circulation reversal caused by strong westerly winds gave rise to a deep UML, while ~~the~~ restratification~~-stratification~~ occurred after ~~the~~ prevailing ~~of~~ easterly winds (Figs. 3~~4~~–5~~6~~). The frequency of westerly (easterly) winds over the Gulf of Finland in winter is positively (negatively) correlated to the ~~North Atlantic Oscillation (~~NAO~~)~~ index (Jaagus and Kull, 2011). The strong reversal event and deep UML in winter 2011/12 were accompanied by an anomalously positive NAO index (Liblik et al., 2013). The mean December to February NAO index ~~(Jones et al., 1997)~~ in 2011/12 was 2.18 ~~(Jones et al., 1997)~~. Likewise, the mean NAO index in the other three winters (2013/14, 2014/15, 2015/2016)~~,~~ when ~~the~~ mean UML depth in the gulf reached 60 m or deeper~~r (Fig. 11a)~~ ~~had~~ was ~~mean NAO index~~ > 2 in December–February (Fig. 10b). Winters 2010/11 and 2012/13, which stand out in the time ~~-~~series with early onset restratification~~-stratification~~ ~~onset already~~ in early January, ~~(Fig. 11a)~~ had

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the lowest December–February averaged NAO indices~~exes~~ during the period 2010–2019: –1.06 and 0.47, respectively (Fig. 10 a and -b). Thus, large scale atmospheric forcing alters the restratification~~-stratification phenomena~~. Low NAO index ~~conditions~~ and easterly winds support restratification~~-stratification~~ while high NAO index and westerly winds have the opposite effect.

~~It has to be noted that besides the frequency of easterly winds, also ice coverage tends to be larger in the case of low NAO (Jaagus, 2006). The landfast ice zone is expected to prevent vertical mixing and therefore supports lateral advection of riverine fresher water (Granskog et al., 2005). During the onset of re-stratification in late January 2012, the gulf was virtually ice-free. In both winters at the end of January, only the eastern part of the gulf and the adjacent part of the northern shore of the gulf were covered with ice. Thus, winter stratification phenomena occurred even if most of the gulf was not covered by ice.~~

## 4~~.~~2. Discussion

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Positive net buoyancy flux is required for the onset of stratification in the upper layer. ~~The P~~Processes causing ~~accounting for the~~ negative buoyancy fluxes ~~areis~~include vertical mixing caused by wind stirring, current shear and~~,~~ convection ~~and vertical movements of the pycnocline~~. Positive buoyancy fluxes result ~~are resulting~~ from ~~the~~ advection (arrival) of ~~the~~ lighter water ~~in~~ 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 ~~coming~~ from the cooling of ~~the~~ 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 °C) and freezing temperature (–0.3 °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 °C) and vary salinity by 0.09 g kg$^{-1}$. Our data show that ~~The ch~~changes in ~~the~~ sea surface salinity in winter are of the order of ~~were approximately~~ 1–2 g kg$^{-1}$ ~~during winters~~ (Fig. 6~~8~~), so ~~. Therefore,~~ the effect of salinity change to the density and buoyancy flux ~~was~~ is about 10–20-fold higher than ~~compared to~~ the effect of temperature change in the gulf. We can conclude that fresher water advection from the east ~~was~~ is the primary source of buoyancy for the development of the stratification. ~~This tra~~F~~nsport~~ reshwater transport is controlled by wind forcing; e~~. E~~asterly winds support advection of ~~the~~ fresher water ~~advection~~ to the west while westerly winds impede it (Liblik and Lips, 2012; Pavelson et al., 1997). To exemplify the processes, two cases from the Gulf of Finland are illustrated ~~The example of the processes prevailing in the case of strong westerly wind and the weak and variable wind in the Gulf of Finland~~ in ~~is displayed in~~ Fig. 11.~~-~~ When westerlies dominate, ~~Blockage of~~ riverine water transport to the west is blocked, ~~strong~~ vertical mixing~~,~~ is strong and the ~~a deep~~ UML is deep ~~occurs, when westerlies dominate~~ (Fig. 11a), while easterly or weak winds are associated with westwards advection of ~~the~~ fresher water ~~towards the west~~ along the northern coast, formation of haline stratification ~~formation~~ and phytoplankton growth ~~occur when easterly or weak winds prevail~~ (Fig. 11b).

The role of the wind forcing in stratification depends on preexisting conditions. ~~In~~ W~~one hand, w~~esterly winds generally deepen the mixed layer depth due to transport of the surface layer water from the northern Baltic Proper to the gulf (Liblik and Lips, 2017). However, ~~On the other hand,~~ if ~~the~~ fresher water is already present along the north coast, westerly winds spread it ~~spreads~~ to the south ~~by westerly winds~~ and create~~s~~ stratification there (Figs. 3~~4~~ and 6~~8~~), ~~and~~ as noted in summer also by Pavelson et al. (1997).

Wintertime stratification phenomen~~a~~on 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 Lepparanta, 2015). However, ~~All~~ these studies were concerned with stratification ~~dealt with the phenomena~~on under the ice, whereas in our ~~. In the current~~ study ~~, on the example~~ of the Gulf of Finland, we have shown ~~ed~~ that wintertime stratification may ~~could~~ also occur ~~in~~ at the basin-scale (along-gulf extent 400 km) and in the absence of ~~without~~ considerable ice coverage. During the onset of restratification ~~-stratification~~ in late January 2012, the Gulf of Finland was virtually ice-free. In both winters (2011/12 and 2013/14) ~~at the end of January~~, only the eastern part of the Gulf of Finland and the adjacent ~~part of the~~ northern shore of the gulf were ice covered ~~with ice~~at the end of January; t~~. T~~hus, winter stratification phenomenon occurred even ~~if~~when most of the Gulf of Finland was not covered by ice. It should be ~~has to be~~ noted that, ~~besides~~along with ~~-~~the frequency of easterly winds, ~~also ice coverage is larger in the case of~~ low NAO index is also associated with increased ice coverage (Jaagus, 2006). The landfast ice zone would be ~~is~~ expected to prevent vertical mixing and therefore supports lateral advection of riverine fresher water (Granskog et al., 2005).

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The western border of the stratification phenomenon is around 23° E, i.e. at the entrance to the gulf~~entrance area to the gulf~~ between Hiiumaa Island and the Finnish coast. This ~~. It~~ means ~~Vertical~~ vertical mixing dominates over ~~the~~ lateral buoyancy fluxes in the Baltic Proper~~,~~ and shallow stratification is not a common feature. ~~in the Baltic Proper. The~~ T~~abs~~he absence~~ence~~ of the phenomenon in the Baltic Proper can be explained by the long distance from ~~the~~ rivers, due to its larger size and ~~and due to the t~~topography. ~~The~~R~~r~~iverine 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 ~~One can note that the~~ wintertime stratification phenomenon vanishes at the wider entrance area to ~~in the area, where the extension of~~ the Gulf of Finland, it is ~~. gets wider. Thus,~~ likely that the ~~the~~ elongated~~, and~~ narrow shape of the gulf accounts contributes to ~~to~~ the formation of ~~the~~ stratification as well as ~~besides~~ high freshwater input. In the northern part of the Gulf of Finland, o~~- The o~~ccurrence of the shallow (<20 m) halocline reached over 50% in ~~the northern part of the Gulf of Finland in~~ February, and in the southern part it reached over 50% in Ma~~of the gulf in Ma~~rch. The high synoptic-scale and interannual variability of ~~the~~ UML~~upper mixed layer~~ depth can be related to the wind regime and NAO index (Janssen et al., 2004), respectively. High NAO index is associated with h~~-H~~igh wind stress, low ice cover, strong upwelling/downwelling (Janssen et al., 2004) and extreme estuarine circulation reversal events ~~occur in the case of high NAO index~~ (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 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, l~~L~~ow NAO index ~~instead~~ supports the consumption of riverine nutrients in the Gulf of Finland while the vertical mixing of nutrients from the deeper layer is modest.

~~Gulf of FinlandGulf of Finland Gulf of Finland~~

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We observed ~~the~~ Chl *a* concentration ~~in the range 1.5~~ up to 3.0 and 4.5 mg m$^{-3}$ ~~in~~ from February to the~~the~~ first half of March, respectively in 2012 and 2014, i.e. occasionally comparable with the mean values in summer in the Gulf of Finland (Kononen et al., 1998; Suikkanen et al., 2007). The higher Chl *a* concentration coincided with ~~the~~ a cold and fresher upper layer and stronger stratification. The distribution of phytoplankton biomass concentration (Fig. 12) generally follows Chl *a* structure (Fig. ~~6~~5) in winter 2014. The observed winter biomass concentrations were much ~~smaller~~ lower compared to summer values in the Gulf of Finland (Kononen et al., 1998, 1999). This discrepancy is probably related to the ~~fact that~~ biomass/ Chl *a* ratio being ~~is~~ higher in summer, as shown for instance in the southern Baltic (Lyngsgaard et al., 2017). The ~~main~~ dominan~~t~~t~~ing~~ species in the phytoplankton community in more elevated biomass patches in February ~~were~~ was the photosynthetic ciliate *Mesodinium rubrum*, which is often the dominant primary producer ~~also~~ in ~~during~~ 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 ~~f~~were equally abundant ~~ormed~~ as ~~equal share with~~ the photosynthetic ciliate.

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Spring bloom ~~evokes~~ is instigated when ~~the~~ phytoplankton growth ~~of the phytoplankton~~ exceeds losses in the upper layer due to grazing or vertical mixing downwards (Smetacek and Passow, 1990). Necessary conditions for ~~the~~ 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~~Upper mixed layer~~ depth was 10–20 m in most of the Gulf of Finland ~~gulf~~ in early March 2012 and 2014. Euphotic layer depth, estimated according to Luhtala and Tolvanen (2013) from our Secchi depth measurements, was 15–19 m in both winters, i.e. comparable with the UML depth. Also, there were ~~enough~~ sufficient nutrients available in the upper layer in ~~2014~~ 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). The onset of spring bloom typically occurs in April in the Gulf of Finland ~~gulf~~ (Groetsch et al., 2016; Lips et al., 2014; Lips and Lips, 2017).

## 4~~.~~3. Conclusions

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Using in situ measurements and model simulation, w~~W~~e have demonstrated wintertime occurrence of ~~by in-situ measurements and model simulationsnumerical modelling that~~ haline stratification at ~~the~~ a depth comparable to that of the ~~e~~ euphotic zone ~~depth occureds~~ in in the Gulf of Finland ~~during wintertime~~, 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 ~~to west~~ 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 easing of ~~the~~ westerly winds; ~~has eased off. The~~ relaxation of westerly winds is a part of the annual cycle ~~in~~of the local wind regime and thus the mid winter~~-winter~~ restratification is a regular seasonal feature in the area. Fresher water and haline stratification ~~appeared~~ occurred approximately one month later along the southern coast of the gulf. Earlier observations of a local stratification phenomenon in the Baltic Sea in winter ~~have been registered in ice-coverage conditions~~were under conditions of ~~. Ou~~ice coverage. Our observations show~~ed~~ that haline stratification ~~could~~ can occur in the whole G~~g~~ulf of Finland and in the absence of ~~without~~ ice cover ~~as well~~. Therefore, we can assume that wintertime stratification is a common phenomenon in the Gulf of Finland and~~. I~~its western boundary is at the entrance area to the gulf, between Hiiumaa Island and the Finnish coast.

Elevated Chl *a* and phytoplankton biomass was~~ere~~ registered in the UML~~mixed layer~~ well ~~above the halocline~~ in the Gulf of Finland before the spring bloom. The limiting factor for phytoplankton growth in winter ~~was~~ is likely insufficient light radiation. The exact role of wintertime stratification in the nutrient cycle and phytoplankton dynamics in the Gulf of Finland needs further investigation~~s~~.

*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 ~~of~~ 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 ~~f~~phytoplankton biomass measurements.

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

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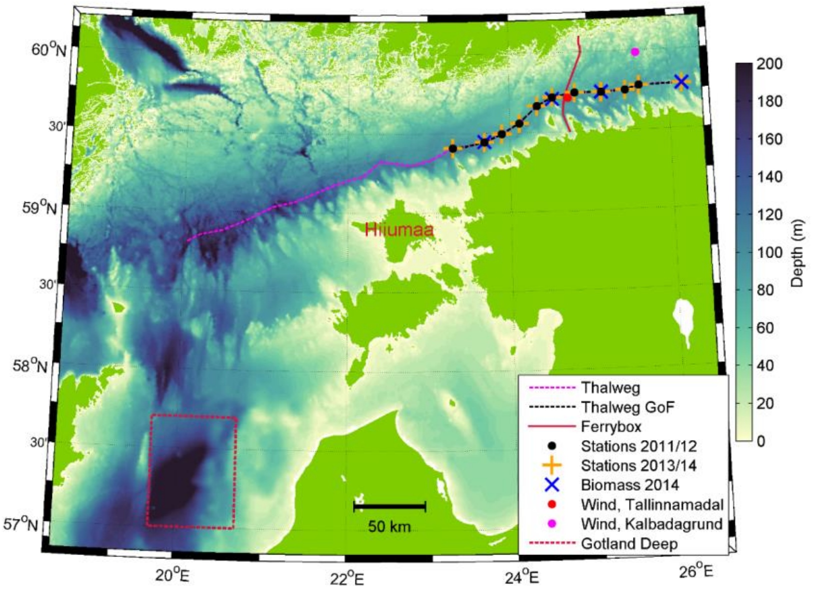

**Fig. 1. Bathymetric map of the Baltic Proper and the Gulf of Finland. Thalweg from the Central Gulf of Finland, CTD stations visited in 2011/12 and 2013/14, phytoplankton biomass sampling stations, Tallinn–Helsinki Ferrybox line, Tallinnamadal and Kalbådagrund wind measurements locations and Gotland Deep area are shown.**

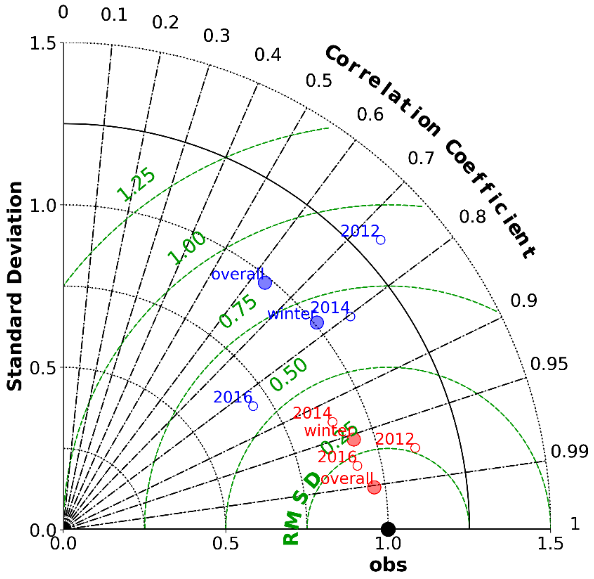

Fig. 2~~3~~. Taylor diagram of simulated and measured temperature (red) and salinity (blue) along the Ferrybox transect from Tallinn to Helsinki. Overall – all ~~the ~~available observations from 1.11. 2011 to 1.06. 2016 (filled circles); ~~,~~winter – all ~~the ~~available observations from December to the end of March, ~~in~~ 2011–~~—~~2016 (filled circles)~~,~~ and winter observations from January–March in 2012, 2014 and 2016 (open circles).

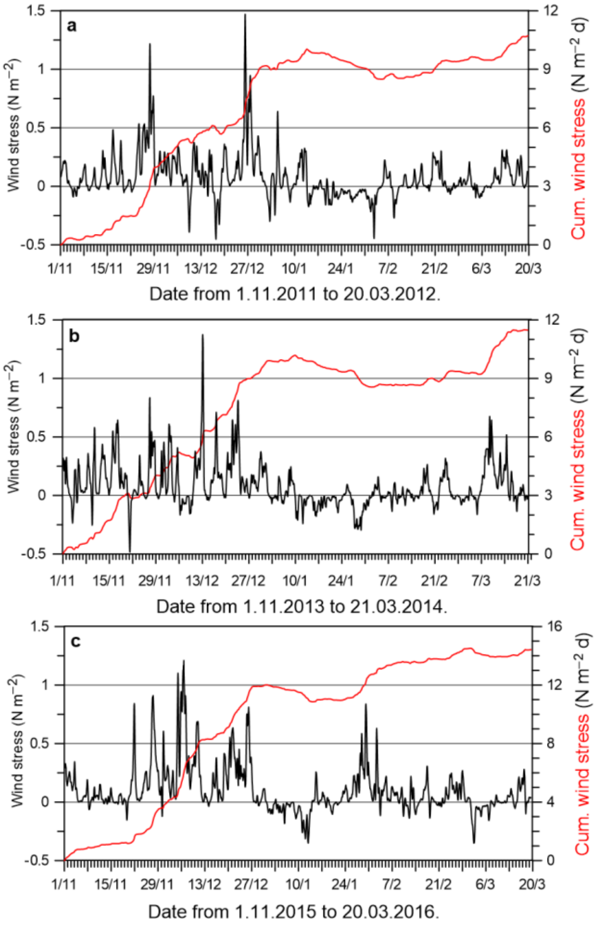

**Fig. 34. Time ~~-~~series of an along-gulf component of wind stress (black curve, positive eastward) and cumulative along-gulf wind stress (red curve), based on wind data measured at Tallinnamadal Lighthouse in the Gulf of Finland. ~~from~~ (a) 1 November 2011 to 20 March 2012; (b) ~~(a), from~~ 1 November 2013 to 21 March 2014; ~~(b) and~~ (c) ~~from~~ 1 November 2011 to 20 March 2016 ~~measured at Tallinnamadal Lighthouse in the Gulf of Finland~~.**

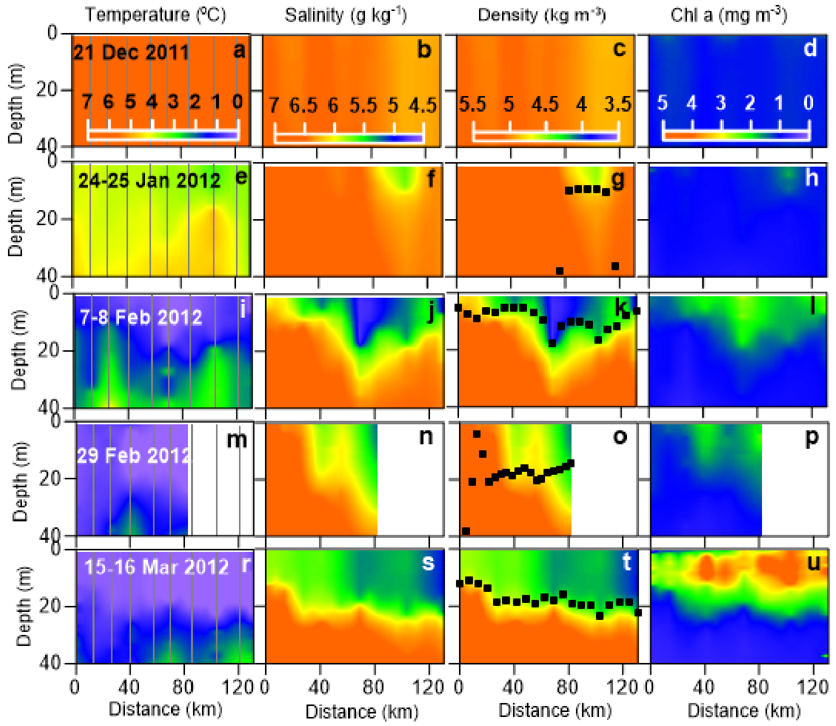

Fig. 4~~5~~. Vertical sections of temperature, salinity, density anomaly~~,~~ and Chl *a* along a west to east profile in the Gulf of Finland (black dots in Fig. 1) in winter 2911/12.~~, on 21 December 2011, 24–25 January 2012, 7–8 February, 29 February and 15–16~~ March 2012 ~~March along the Gulf of Finland (black dots in Fig. 1) from west to east~~. Vertical g~~G~~ra~~e~~y ~~vertical~~ lines ~~show~~ mark the location of CTD-casts. Black dots on density anomaly panels ~~show~~mark the depth of the upper mixed layer ~~depth (m)~~.

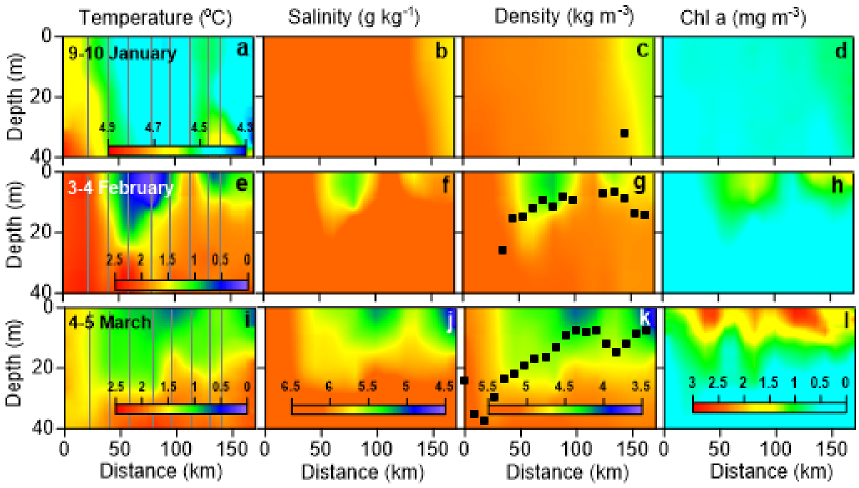

Fig. 5~~6~~. Vertical sections of temperature, salinity, density anomaly and Chl *a* along a west to east profile in the Gulf of Finland (orange crosses in Fig. 1) in winter 2013/14. ~~, on 9–10 January, 3–4 February, and 4–5 March 2014~~. ~~along the Gulf of Finland (orange crosses in Fig1) from west to east~~~~.~~ Vertical gray ~~Grey vertical~~ lines ~~show~~ mark the location of CTD-casts. Black dots on density anomaly panels ~~show~~mark the depth of the upper mixed layer ~~depth~~.

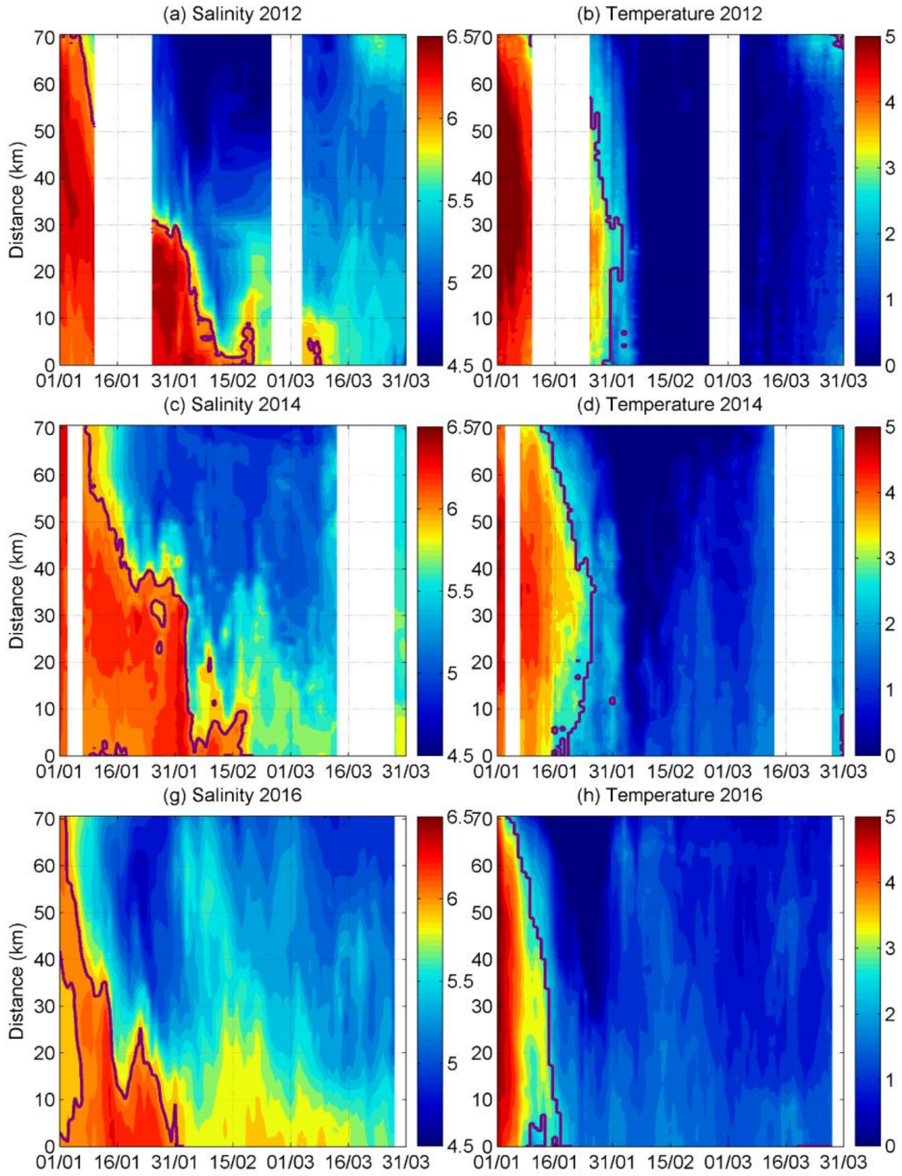

**Fig. 6~~8~~. Salinity (g kg$^{-1}$) and temperature (°C) ~~in~~ of the upper layer along ~~the~~ a transect from Tallinn to Helsinki (red line in Fig. 1) in January–March 2012, 2014 and 2016. The i~~I~~soline 6 g kg$^{-1}$ is ~~shown~~ marked on the salinity plots and the maximum density temperature T$_{md}$ on the temperature plots. The starting point of the transect (x = 0 km) is in the Bay of Tallinn at 59.500° N and 24.752° E.**

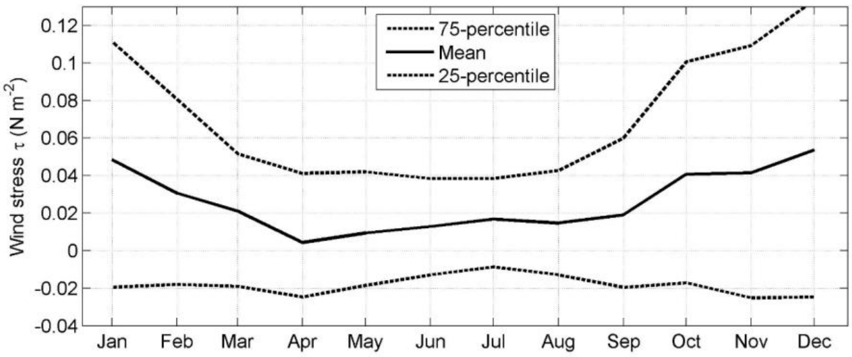

Fig. 7. Annual cycle of an along-gulf component of wind stress. Mean (solid black curve, positive eastward), 75- and 25-percentiles (dashed lines) are ~~given~~ based on data from 1981-2015, measured at Kalbå~~a~~dagrund Lighthouse~~, data in the~~ Gulf of Finland~~ in 1981-2015~~.

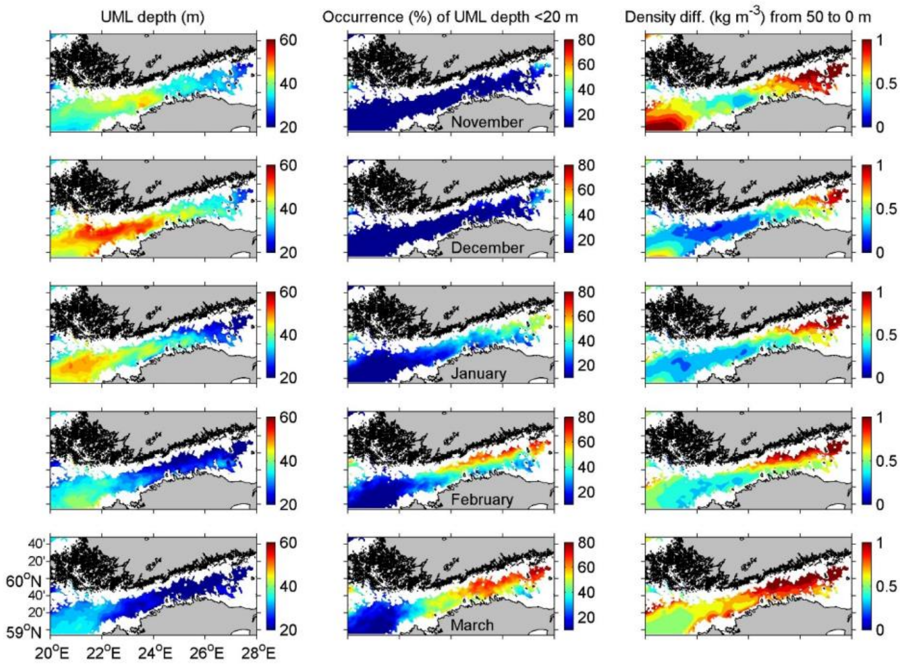

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Fig. 8~~9~~. Mean simulated upper mixed layer (UML) depth,~~ and~~ percent occurrence of ~~the~~ UML depth <20 m~~,~~ and density difference between 50 ~~m~~ and 0 m depth from November ~~(uppermost panel)~~ to March, ~~(lowermost panel) from~~ 2010 to 2019.

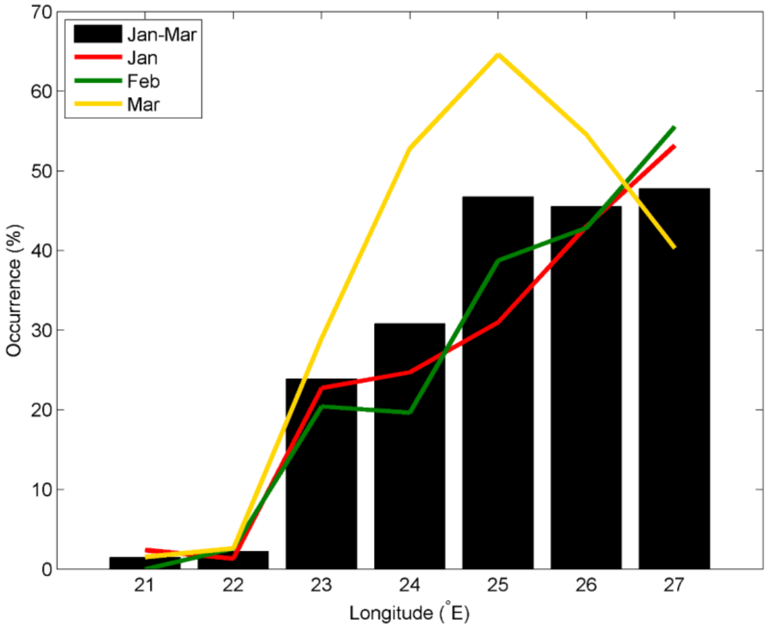

Fig. 9~~10~~. ~~The~~ O~~o~~ccurrence of ~~the~~ >0.5 kg m$^{-3}$ density difference ~~>0.5 kg m$^{-3}$~~ between 40 m depth and the sea surface in the Gulf of Finland from January to March ~~in~~ 1904–2020. A ~~In~~ total of 2560 temperature-salinity data pairs for the ~~in the~~ surface layer and ~~at~~ 40 m depth ~~were~~ are included.

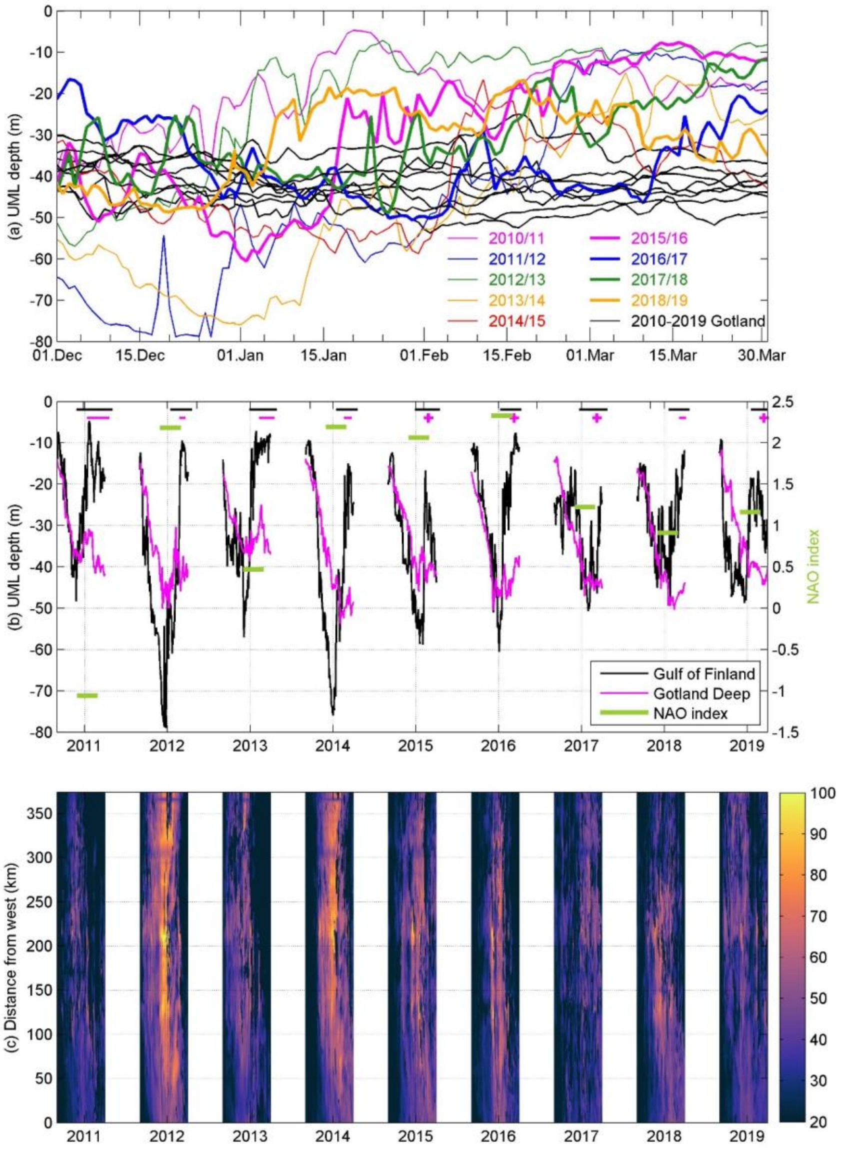

**Fig. 10~~11~~. (a-b~~a~~) Time series of m~~the m~~ean upper mixed layer depth ~~time series~~ in the Gulf of Finland and Gotland Deep based on model simulation data. The areal mean in (a) ~~the plots a~~ is calculated for the transect in the Gulf of Finland (Thalweg GoF, Fig. 1) and the box in the Gotland Deep (Fig. 1). In ~~with~~ (b), green horizontal lines mark the mean December–February~~-February~~ NAO index (from (Jones et al., ~~,~~ 1997); black and pink ~~from autumn 2010 to spring 2019.~~ horizontal lines mark where the OSTIA SST is below $T_{md}$ and**

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**pink crosses indicate where the minimum winter temperature did not fall below $T_{md}$ in the Gotland Deep. ~~Black lines at subplot a represent time-series in the Gotland Deep and colored lines show time-series in the Gulf of Finland in respective years.~~ ~~and~~ (c~~b~~) Depth of the u~~upper~~ ~~U~~pper mixed layer ~~depth~~ along ~~the~~ the transect from the northern Baltic Proper to the c~~C~~entral Gulf of Finland (~~see~~ Thalweg in Fig. 1) for ~~. Only periods from~~ October to March, 2011 to 2019 ~~are shown~~. ~~Horizontal lines in the upper panel show the periods when remotely sensed~~OSTIA ~~SST was below $T_{md}$, and crosses indicate the day of minimum temperature in winters when the temperature below $T_{md}$ was not observed in the Gotland Deep.~~ ~~The areal mean in the plots a is calculated for the transect in the Gulf of Finland (Thalweg GoF, Fig. 1) and the box in the Gotland Deep (Fig. 1).~~**

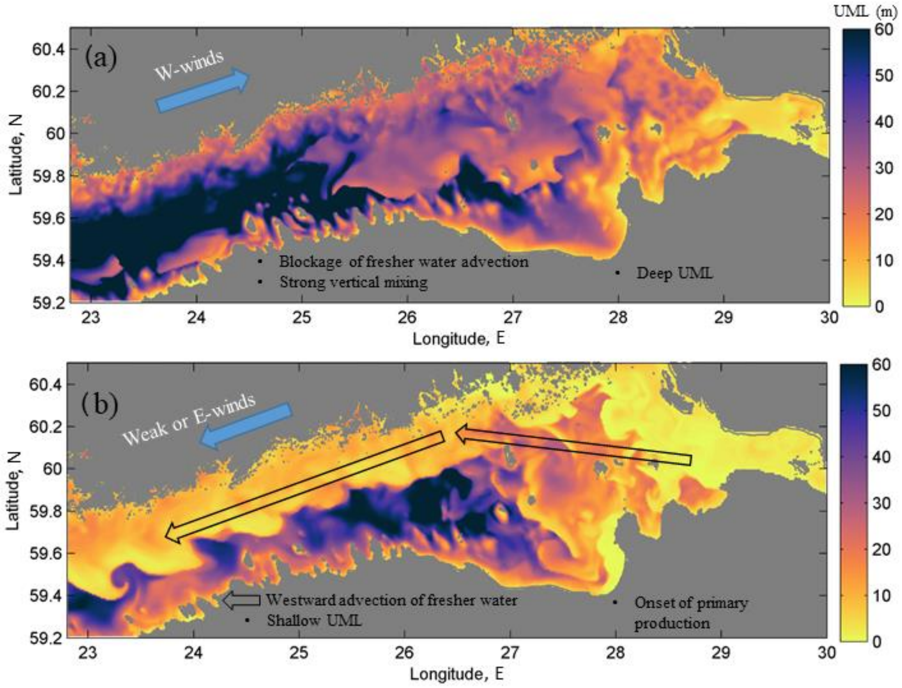

**Fig. 11. Upper mixed layer depth (m) based on model simulation data in the Gulf of Finland on (a) 29 December 2011 and (b) 8 February 2012. Strong westerly winds dominated before the 29 December survey while variable and weaker wind occurred before the 8 February survey.**

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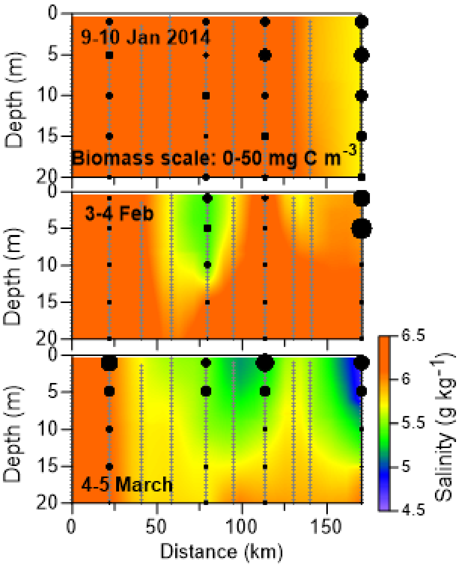

**Fig. 12. Vertical distributions of salinity (color scale) and phytoplankton biomass (black dots) along the Gulf of Finland in winter 2014. Phytoplankton biomass (mg C m$^{-3}$) scale is shown in the upper panel. Biomass sampling ~~The~~ locations ~~of biomass sampling~~ are shown in Fig. 1 (blue crosses).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

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