REPORT OCEANOGRAPHY No. 77, 2024

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Front:
Photo: Ilja Enger-Tsizikov. “Offshore Windmill farm. Windmills isolated at sea on a beautiful bright day, Netherlands. Green energy Flevoland global warming renewable energy with windmills”

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Department of Research and Development, SMHI

Summary

For two future scenarios on the expansion of offshore wind power in the Baltic Sea and the North Sea, SMHI has investigated how the hydrography, i.e. temperatures, salinities, currents and stratification, may be affected. Effects were induced by wind stress reductions on the sea surface and by the increased friction and turbulence in the water from wind turbine foundations.

The results show that an expansion of wind power in the Baltic Sea in general will cause a shallowed halocline, and increased deep water salinities and temperatures, due to decreasing winds behind the wind farms that lead to decreasing vertical mixing in the Baltic Sea. However, the magnitude of changes shows a strong sensitivity to assumptions about the wind stress reduction at the sea surface, and the size of wind power expansion.

The wind farm scenarios are prepared in collaboration with the Swedish Agency for Marine and Water Management (SwAM) and are based on marine plans from Sweden's neighbouring countries as well as new proposals for suitable wind power areas that SwAM will present to the government in 2024. In one scenario, Scenario 1, it is assumed that there will be offshore wind in all proposed areas, while in the second scenario, Scenario 2, it is assumed that only 50% of areas will be developed. Both scenarios represent large offshore wind power developments that will probably not be realized in reality. The scenarios have been investigated by running an ocean model for the Baltic Sea and the North Sea with and without wind power for the period 1985 – 2016 to evaluate how different the sea would have looked if the wind power had been built in 1985 according to the scenarios.

There is still lack of knowledge about how wind farms affect the wind at the sea surface, so this work is based on studies of existing wind farms in the North Sea, where studies show a reduction of the wind by around 8% and an area that extends about 30 km behind the wind farm under stable atmospheric conditions. When the atmosphere is unstable, which it often is in winter, the reduction is less. In order to get an estimate of the largest and smallest possible impact of wind power on the sea, we have therefore, for both scenarios, assumed that the reduction of wind only exists in summer and no reduction during winter (minimum possible impact), or that the reduction exists all year round (upper limit of impact).

The magnitude of expected changes is very dependent on the assumptions on the wind wakes, and the response is much smaller for the minimum possible impact than for the upper limit impact. The real response for these scenarios probably lays somewhere in between these estimates.

For the scenario with less wind farms in Swedish waters (Scenario 2), the influences on salinity, temperature, and halocline are reduced relative to Scenario 1 in a manner that may be expected from the difference in total wind farm areas in the Baltic Sea in the two scenarios.

The model results also show that the wind power foundations (modelled as bottom mounted) cause a salinity decrease in the Baltic Sea deep water, probably due to increased friction and mixing in the entrance region to the Baltic Sea. This effect is much smaller than the wind wake effect when it is active during the whole year.

The Baltic Sea surface salinity, surface temperature, and currents show much smaller and less robust changes than the salinity and temperature changes in the deepwater.

Sammanfattning

SMHI har för två framtidsscenarier för utbyggnad av havsbaserad vindkraft i Östersjön och Nordsjön undersökt hur hydrografin, det vill säga temperaturer, salthalter, strömmar och skiktning, kan påverkas av minskad vindpåverkan på havsytan och av ökad friktion och turbulens i vattnet från vindkraftsfundament.

Resultaten visar att en omfattande utbyggnad av vindkraften i Östersjön kommer att orsaka en grundare haloklin, samt ökade salthalter och temperaturer i djupvattnet på grund av minskande vindar bakom vindkraftsparkerna som leder till minskad vertikal blandning i Östersjön. Förändringarnas storlek visar dock på en stark känslighet för antaganden om hur vindkraften påverkar vinden vid havsytan samt storleken på vindkraftsutbyggnaden.

Vindkraftsscenarierna har tagits fram i samarbete med Havs- och Vattenmyndigheten (HaV) och bygger på havsplaner från Sveriges grannländer samt nya förslag på lämpliga vindkraftsområden som HaV ska presentera för regeringen 2024. I ett scenario, Scenario 1, antas det finnas havsbaserad vindkraft i alla föreslagna områden, medan det i det andra scenariot, Scenario 2, antas att endast 50 % av dessa områden kommer att utvecklas. Både scenarierna representerar stora utbyggnader av havsbaserad vindkraft, som förmodligen aldrig kommer att realiseras. Scenarierna har undersökts genom att köra en havsmodell för Östersjön och Nordsjön med och utan vindkraft för perioden 1985 – 2016 för att utvärdera hur annorlunda havet skulle ha sett ut om vindkraften hade byggts 1985 enligt scenarierna.

Det saknas fortfarande kunskap om hur vindkraftsparker påverkar vinden vid havsytan, så detta arbete baseras på studier av befintliga vindkraftsparker i Nordsjön, där studier visar en minskning av vinden med cirka 8 % och en yta som sträcker sig cirka 30 km bakom vindkraftsparken under stabila atmosfäriska förhållanden. När atmosfären är instabil, vilket den ofta är på vintern, är minskningen mindre. För att få en uppskattning av största och minsta möjliga påverkan av vindkraft på havet har vi därför, för båda scenarierna, antagit att minskningen av vind endast finns på sommaren och helt uteslutit påverkan under vintern (minsta möjliga påverkan), eller att minskningen existerar hela året runt (övre påverkansgräns).

Storleken på förväntade förändringarna är mycket beroende av antagandena om vindvaken, och responsen är mycket mindre för den minst möjliga påverkan än för den övre påverkansgränsen. Det verkliga svaret för dessa scenarier ligger förmodligen någonstans mellan dessa uppskattningar.

För scenariot med färre vindkraftsparker i svenska vatten (Scenario 2) reduceras påverkan relativt Scenario 1 på ett sätt som kan förväntas utifrån skillnaden i totala ytan av vindparksområden i Östersjön i de två scenarierna.

Modellresultaten visar även att vindkraftsfundamenten (modellerade bottenfasta) orsakar en minskning av salthalten i Östersjöns djupvatten, troligen på grund av ökad friktion och blandning i mynningsområdet av Östersjön. Denna effekt är mycket mindre än vindvakseffekten när den är aktiv hela året.

Östersjöns ytsalthalt, yttemperatur och strömmar visar mycket mindre förändringar än förändringarna i salthalt och temperatur i dess djupvatten.

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1 Background

Around the world, offshore wind power is being planned and built in order to convert from fossil-fuel-based to sustainable energy systems. In Sweden, the Swedish Agency for Marine and Water Management (SwAM) have the mission to present new marine spatial plans that include suitable areas for 120 TWh/year offshore wind energy in Swedish waters. Other countries around the Baltic Sea and the North Sea also have plans for offshore wind power. Relatively large wind farms have already been built in the North Sea, and both in the North Sea and the Baltic Sea, many wind farms are being planned and are currently in different phases of permit examination (e.g. https://map.4coffshore.com/offshorewind/).

Hydrographic effects are not always considered in environmental impact assessments of offshore wind, and if they are, cumulative impacts of multiple future farms are not considered. Broström (2008) suggested that the wind wake behind wind farms may influence the ocean circulation. Recent investigations of present and future wind farms in the southern North Sea show that the wind wakes behind wind farms as well as the friction and turbulence induced by wind power plant foundations in the water do change ocean salinities, temperatures, currents, stratification, mixing, and primary production in areas much larger than covered by the individual wind farms (Christiansen et al. 2022, 2023, Daewel et al. 2022).

2 Aim

The aim with this study is to determine whether future scenarios for offshore wind power in the Baltic Sea and North Sea have the potential to cause hydrographic changes, e.g. on currents, salinity, temperature and stratification, in Swedish waters, and discuss whether such changes may be important for marine ecosystems.

3 Methodology

The effects of reduced wind stress on the ocean surface in the lee of wind farms as well as the extra friction and mixing in the water mass caused by power plant foundations were implemented in the Nemo-Nordic ocean model that covers the Baltic Sea and large parts of the North Sea (Hordoir et al. 2019) with a lateral resolution of 3.7 km and vertical resolution 3 m at the surface. The model has been updated from Nemo version 3.6 in Hordoir et al. (2019) to version 4.2 and tuned to better represent inflows to the Baltic Sea. The model was used to investigate changes on various physical parameters in the ocean for two different scenarios of future offshore wind power, as described in further detail below.

3.1 Definition of scenarios

3.1.1 Choice of future wind farm areas

Scenarios were chosen in discussion between representatives from SwAM and SMHI in order to represent an expected maximum scenario (Scenario 1) for future wind power locations and a more realistic scenario (Scenario 2). For both scenarios, polygons for existing and planned wind farms in the surrounding countries were taken from EmodNet (https://emodnet.ec.europa.eu/). For Swedish waters, wind power areas considered in Scenario 1 correspond to the areas accounted in the drafts of marine spatial plans (in Mars 2024) and Scenario 2 corresponds to a randomly selected reduction of those areas, chosen after discussions with SwAM representatives, Fig. 1. Scenario 1 represents about 345 TWh/year in Swedish waters and Scenario 2 represents 131 TWh/year, the latter being more realistic in light of the goal of 120 TWh/year by the Swedish government.

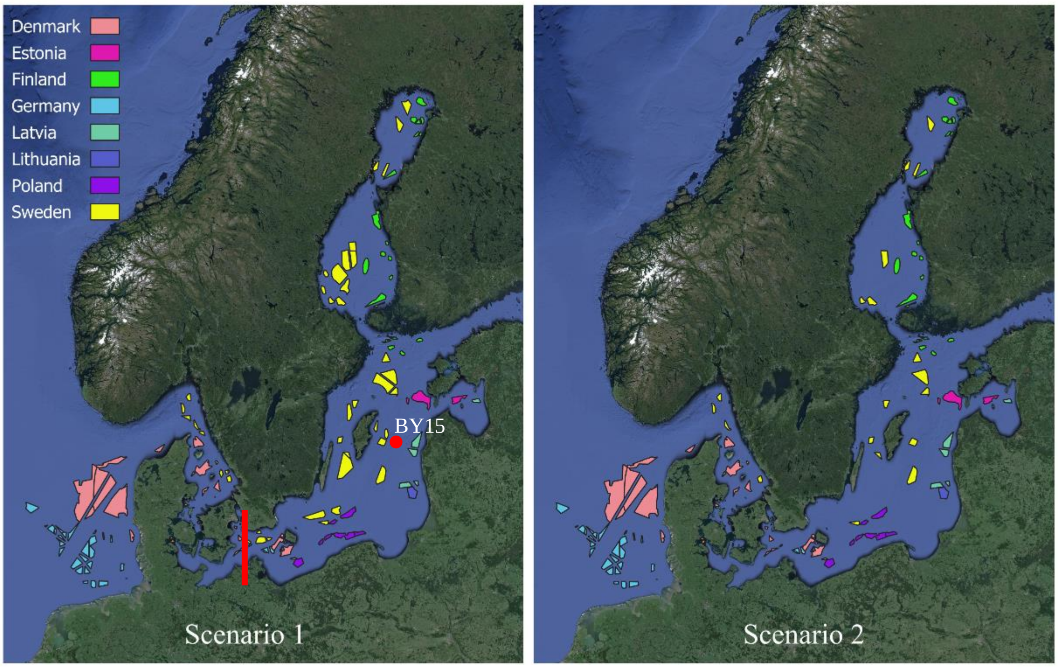

Figure 1: Wind power areas for the two scenarios. The station BY15 is shown as a red dot, and the 13°E meridian is shown as a red line, in the left-hand side panel.

3.1.2 Assumptions about future power plant density and foundation diameter

The parameterizations of drag and mixing from the wind power foundations require input on the foundation diameter and pile density, which depend on the foundation type (Table *1*).

Table 1. Assumed diameter and number of piles per turbine. Source: https://www.iberdrola.com/sustainability/offshore-wind-turbines-foundations

Foundation Type	Pile diameter (m)	Number of Piles per turbine
Jacket (6 legs/2 turbines)	3.6	3
Gravity	15	1
Monopile	5	1
Jacket (3 legs)	3.6	3

For most of the existing wind farms, the foundation type and density information were available in the HELCOM holistic assessment (HOLAS 3). The missing information was obtained by consultation of the specific windfarm parks descriptions available in the corresponding webpages. A summary of the main assumptions can be found in Table *A1*, in Appendix section 8.

Future wind farms were assumed as having gravity foundation, which corresponds to a 15m diameter and a density of 0.5 pile per km^2, agreed after discussions with SwAM.

As some of the planned wind farm structures are located in deeper areas, they will probably be installed in floating structures rather than piles. In the present implementation, this type of structures is not accounted since it would require additional model development. They are therefore assumed to be installed with gravity foundation, which will give an overestimate of the mixing and friction from the foundations.

3.2 Wind wake effect – assumptions and implementation

The wind wake effect is implemented in the same way as Christiansen et al. (2022), i.e. assuming a wind speed reduction downstream of the wind farm with a maximum reduction of 8% that decreases exponentially downstream with an e-folding scale of 30 km, and a transverse decay scale of a third of the wind farm width, Fig. 2.

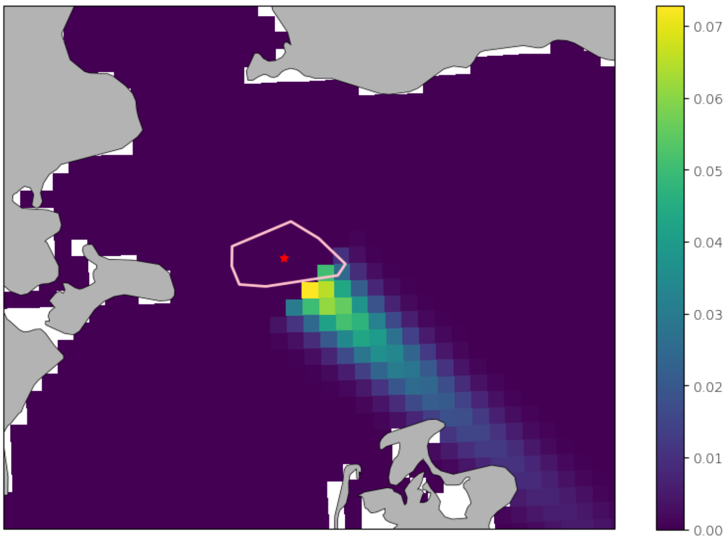

Figure 2: Example of relative wind speed reduction downstream of the Kriegers Flak wind farm for wind direction 315 °. The boxes indicate the resolution of the model.

This is a rather coarse description of the wind wake effect, based on observations in the atmosphere downstream of other windfarms. There is ongoing research on this topic, and the wind wake has been implemented and studied in high-resolution meteorological models. For example, the assumed wake shape and strength is mainly valid when the atmosphere is stable, as it usually is during summer, while it will overestimate the wake effect during large parts of the other seasons. The results are also based on present day wind power plants which are much smaller than future wind power plants. Future wind power plants will be taller and placed further apart, which will impact the wind wake at sea level. The details of the wind wake are, however, beyond the scope of the present study, where the main aim is to investigate the order of magnitude of the effect and whether there may be a potential effect from future wind wakes.

In order to tackle the problem of atmospheric stability we perform two experiments for each wind farm scenario, one where we assume that the wind wake is present during the whole year ("whole"), and one where the wind wake is only present during the summer months ("summer"), June, July, and August. The "whole" experiment will provide an overestimate of the wake effect, whereas the "summer" experiment will most likely provide an underestimate. The truth will probably be somewhere between those two experiments.

The resolution of the model (3.7 km) is rather coarse for describing wind speed reduction (Fig. 2) and the local flow features around the downstream wake. However, tests with a higher resolution (750 m) model show very similar results (not shown) as those from the coarse resolution model when investigating the wake downstream of the Kriegers Flak wind farms. In order to be able to, from a computer resource perspective, obtain long-term runs (32 years) of a rather large area, we chose to use the coarse resolution model, which means that there may be a slight underestimation of the wind wake effect, especially for the smaller wind farms.

3.3 Implementation of drag and turbulence from foundations

The friction and mixing from wind power foundations are implemented with the method presented in Rennau et al. (2012), using a parameter choice for weak mixing and a drag coefficient $C_d = 0.63$, which we assess as being most relevant for the Reynolds and Froude numbers present in the investigated area. The input needed for that parameterization is the diameter of the foundation and the number of foundations per area within the perimeter of the wind farm, Section 3.1.2.

3.4 Evaluation of robustness of change in results

When running a dynamic ocean model, small changes to initial conditions may cause rather large changes to the physical fields, since small changes to eddy positions may cause rather large changes in areas with large gradients. This may partly be due to model precision and partly to physical processes in a chaotic system. In atmosphere modeling it is well known that it is difficult to perform accurate forecasts further ahead than some days due to these effects. In the following we will call this variability for “background variability”.

When comparing a run with wind farms to a run without, part of the difference will therefore be due to the wind farms, and part of it will be due to the background variability. In order to evaluate the changes in the wind farm runs in relation to the background variability, we perform 10 slightly perturbed reference runs without wind farms. The only difference between these runs is that the initial salinity is changed slightly in two points in Kattegat in order to induce different realizations of the ocean conditions under the given forcing. In the following, we will define wind farm effects as robust if the differences from the mean of the reference runs is larger than two standard deviation of the reference runs. Assuming a normal distribution, this means that we are more than 95% sure that a change is caused by wind farms.

3.5 Model runs

The model runs are for the period 1985 to 2016 with forcing at the lateral boundaries, at the surface, and from land according to the physical forcing described in Ruvalcaba-Baroni et al. (2024), Table 2. 10 reference runs without wind farms were performed to assess the background variability. Two runs for each wind farm scenario were performed, one with wind wake only during summer, and one with wind wake during the whole year. Finally, a run without the influence of drag and mixing from the foundations was performed, to evaluate the importance of the foundations relative to the wind wake. This was done for a case, Scenario1_summer, where the wind wake effect is assumed to be small and the foundation effects relatively larger. The number and selection of runs were balanced against computer resources for these very demanding analyses.

Table 2: Summary of model runs

Run	Period	Scenario	Wind wake	Foundations
10 perturbation runs	1985-2016	10 reference runs with perturbed initial conditions	None	None
Scenario1_summer	1985-2016	Scenario 1	During summer (June, July, August)	Yes
Scenario1_whole	1985-2016	Scenario 1	Whole year	Yes
Scenario2_summer	1985-2016	Scenario 2	During summer	Yes
Scenario2_whole	1985-2016	Scenario 2	Whole year	Yes
Scenario1_summer_ Nofoundations	1985-2016	Scenario 1	During summer (June, July, August)	None

4 Results

4.1 Impacts on salinity, temperature, and stratification

4.1.1 Changes in mean salinity and temperature in the Baltic Sea due to offshore wind farms

The changes in mean salinity (volume average) in the Baltic Sea, east of longitude 13° E (around Trelleborg, see Fig. 1) due to wind farms are shown as function of time in Fig. 3. It is seen that both wind farm scenarios do show a continuously increasing mean salinity when the wind wake is active during the whole year. The maximum change is about 1% of the mean salinity of the Baltic Sea (≅ 8 g/kg). When the wind wake is only active during the summer, there is also small increases but not robust in comparison to the range of the background variability. The salinity increase without foundations is somewhat larger than the corresponding run with foundations, indicating that the foundations tend to decrease the salinity.

The mean temperatures do also change, but with a much stronger seasonal signal than salinity. The seasonal difference in mean temperature in the Baltic Sea is shown in Fig. 4. For the runs with wind wake during the whole year there is an increase in winter and spring temperatures but not summer temperatures. This corresponds to a decreased difference in heat content between summer and winter when wind farms are present. When the wind wake is present only during the summer, there is a slight decrease of summer temperatures but no change in winter temperatures.

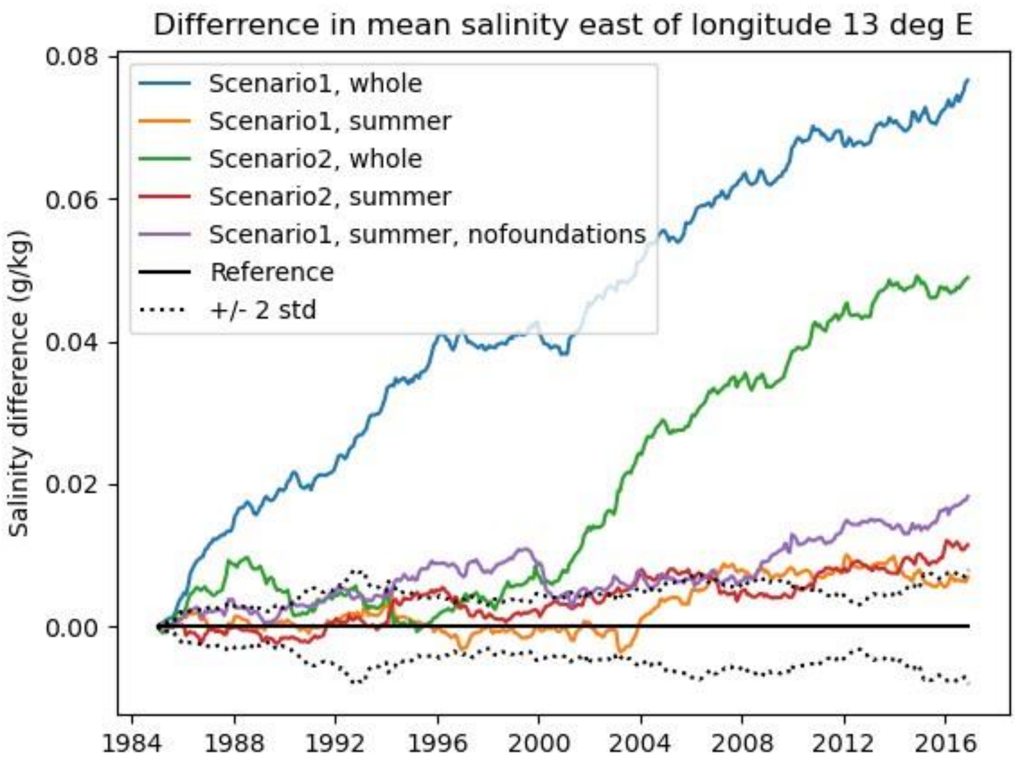

Figure 3: Change in mean salinity east of longitude 13°E for all runs. The change is relative to the mean of the reference runs. The interval +/- 2 standard deviations of the reference runs are shown with dotted lines.

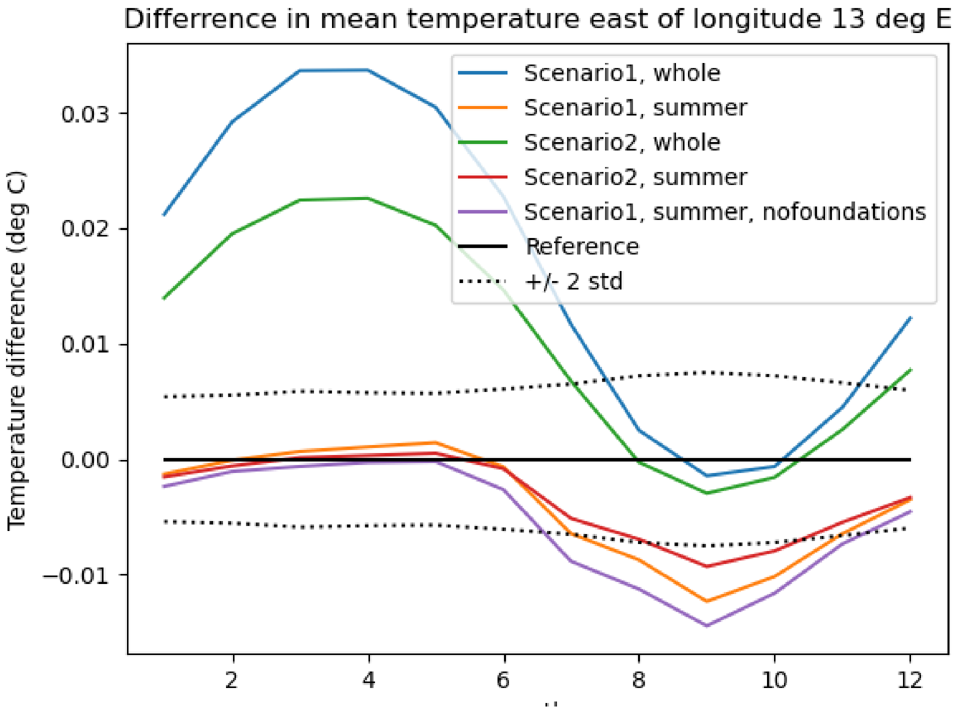

Figure 4: Change in mean temperature east of longitude 13°E as function of month for all runs. The values for each month are averages over the whole period 1985 to 2016. The changes are relative to the reference runs. The interval +/- 2 standard deviations of the reference runs are shown with dotted lines.

4.1.2 Salinity changes at station BY15 in the Eastern Gotland Basin

Monthly averaged salinity changes caused by offshore wind power according to the Scenario1_whole and Scenario2_whole runs are shown as functions of time and depth (Fig. 5) at station BY15 in the Eastern Gotland basin (Fig. 1, Latitude: 57.33 °N, Longitude: 20.05 °E). This station represents, to a large degree, changes in the Baltic proper. Differences are largest in the halocline at about 60 m depth, where the salinity increases with up to 1.5 g/kg in some months for Scenario1_whole and about 1 g/kg for Scenario2_whole. These large values are caused by an upward displacement of the halocline, see also Fig. 7 below. Above the halocline, the difference oscillates between positive and negative values, but below, the difference gradually increases to positive values of about 0.1 - 0.2 g/kg for Scenario1_whole and less than that for Scenario2_whole.

The bottom salinities at the same station are shown as function of time for all runs in Fig. 6. This variability with gradual decreases and abrupt increases is typical for semi-enclosed deep basins such as the Baltic Sea and for fjords. During most of the time, salinities decrease gradually due to mixing and up-/downwelling, but during some strong inflow events the salinity quickly increases. For the Baltic Sea these events are called Major Baltic Inflows. Observations at the same station and depth are also shown, illustrating that the model does capture the main dynamics of the system and even the timing of most of the inflow.

The background variability in the reference run, represented by the interval +/- 2 standard deviations (black curves) is also shown. The two runs with wind wake active during the whole year gradually evolve to salinities clearly above what can be explained by background variability in the reference runs, except for the last couple of years after the last inflow. The three runs with wind wake only during the summer are less discernible from the reference runs, although they tend to be in the upper end of the background variability.

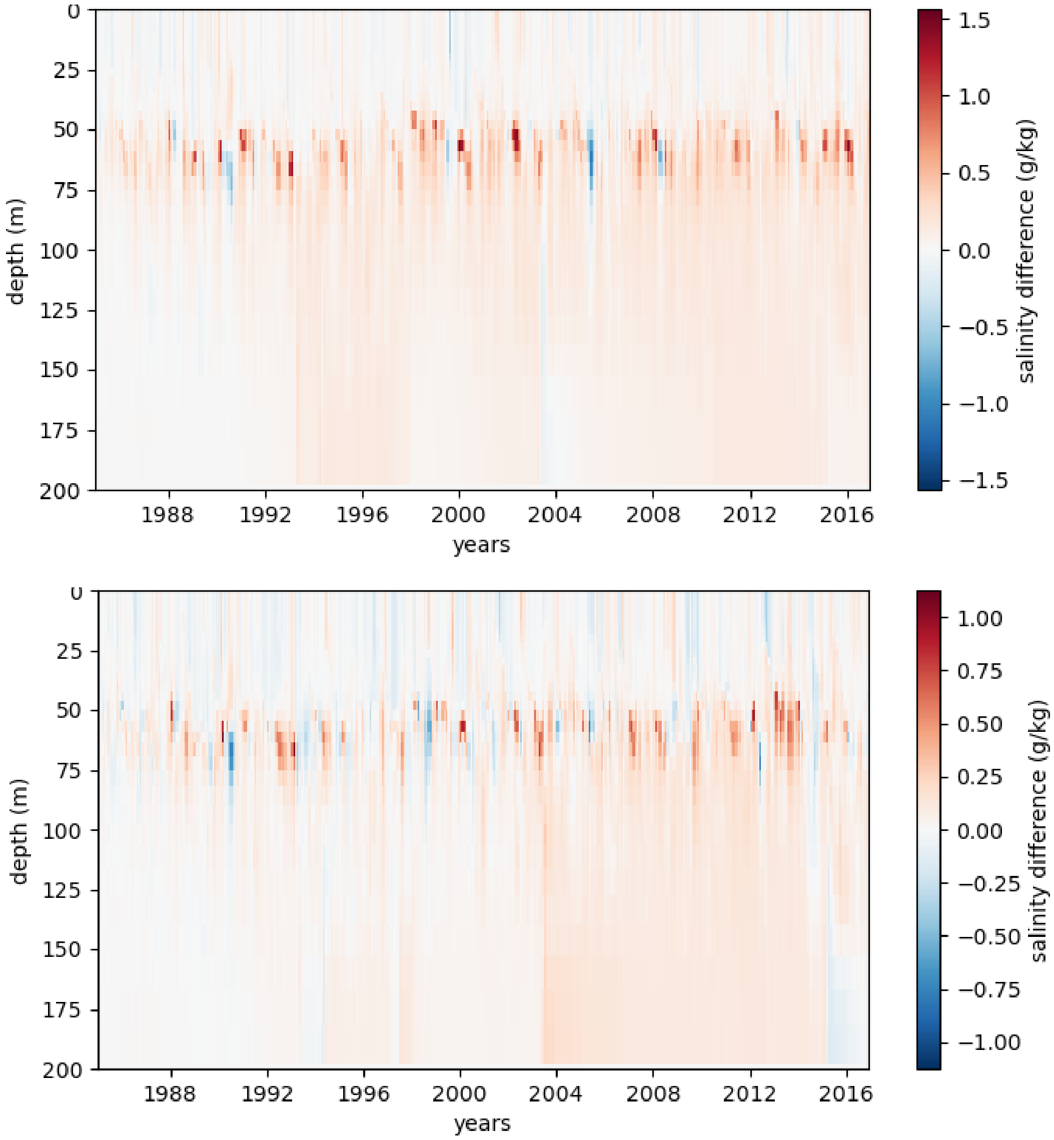

Figure 5. Monthly mean salinity differences as function of time and depth at BY15 in the Eastern Gotland basin, for Scenario1_whole (upper panel) and Scenario2_whole (lower panel). Differences are with respect to the means of the 10 reference runs.

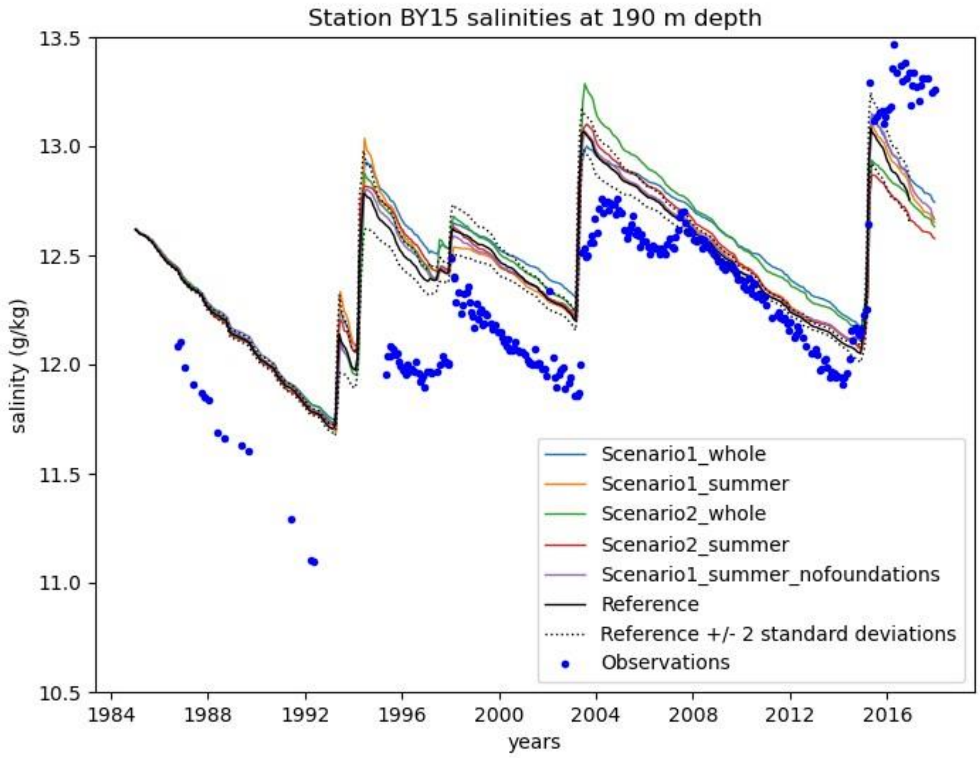

Figure 6: Monthly mean salinities at the bottom of station BY15 as function of time for all runs. Black lines show the mean of reference runs +/- 2 standard deviations of the reference runs.

The mean salinity profiles and salinity change over the period 2006-2016 are shown in Fig. 7 for all runs. This period is chosen to cover the last part of the increasing trend seen in Figs. 3 and 5. All observations for the same period are also shown. Note that the variability of the observations is much larger than that of the modeled mean values. There is a clear bias in most of the water column, and the deep water is more mixed in the model than in the observations. The depth and strength of the halocline are, however, similar in model and observations, which is important for the discussion in Section 5.

The mean salinity increase of both scenarios are clearly outside the background variability range of the reference runs when the wind wake is present during the whole year. The salinity increase is then about 0.27 g/kg in the halocline for Scenario1 and 0.15 g/kg for Scenario2. This corresponds to a rise of the halocline of about 2 – 3 m on average. Below the halocline the salinity increases less with about 0.11 – 0.15 g/kg for Scenario 1 and 0.08 – 0.10 g/kg for Scenario 2. The two runs with wind wake only during the summer are not discernible from the background variability although they are in the upper end of the range. In the upper 40 m the differences are not robust, except Scenario1_whole which has a clear salinity increase all the way to the surface.

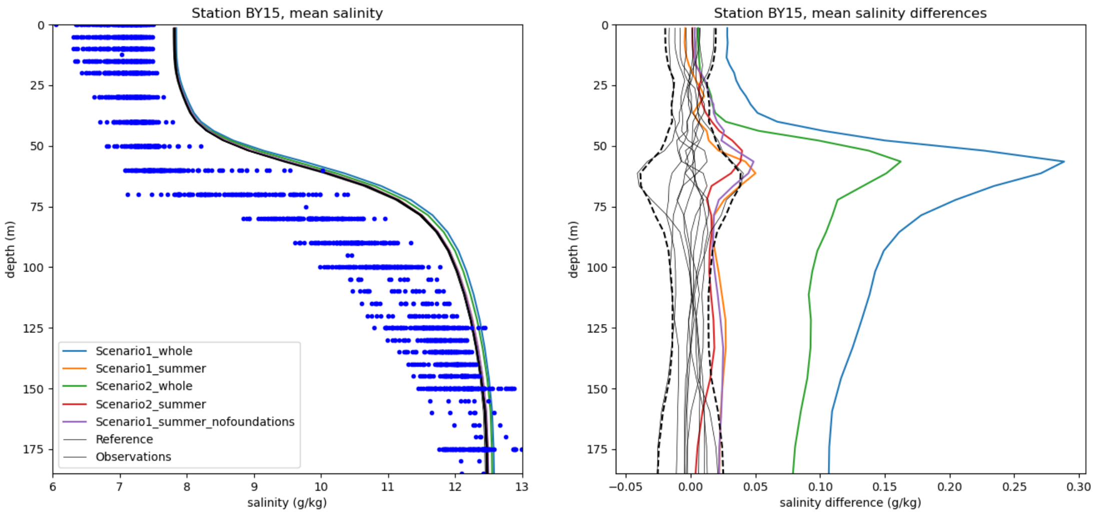

Figure 7: Mean salinity differences (left-hand-side panel) and mean salinities (right-hand-side panel) as functions of depth for all runs for the period 2006 - 2016. Black dashed lines show the +/- 2 standard deviation interval of the reference runs.

4.1.3 Maps of mean bottom and surface salinity changes for the last 10 years

Fig. 8 shows the temporal averages of bottom salinity changes for the most extreme run, Scenario1_whole, for the same wind farm scenario but with wind wake only during the summer, Scenario1_summer, and for the second wind farm scenario with wind wake during the whole year, Scenario2_whole. For the most extreme run, the map shows mainly robust increases in bottom salinity for the whole Baltic Sea, with largest changes at depths in and below the halocline. For the Gulf of Bothnia and shallower regions there are somewhat smaller, but still robust, salinity increases. In the entrance region and in the Arkona basin there are also generally increasing bottom salinities, but some of these are not robust. In the North Sea, the changes are less robust than in the Baltic Sea with some tendency for increasing bottom temperatures in the German Bight and decreasing bottom temperatures further north outside the Danish west coast. For the two other runs, the maps show a similar pattern of changes, but with smaller and generally less robust changes.

Figure 9 shows surface salinity changes. For the most extreme run, Scenario1_whole, there is a small, but generally robust, increase in sea surface salinity in the Baltic Sea. Along the Swedish and Norwegian coasts of Kattegat and Skagerrak, which is the outflow region of Baltic water, the surface salinities are generally decreasing. For the two other runs, the maps show a similar pattern, but with smaller and generally much less robust changes.

4.1.4 Maps of mean bottom and surface temperature changes for the last 10 years

The bottom temperature changes averaged over the last 10 years are shown in Fig. 10 for the same runs as discussed in Section 4.1.3. For the most extreme run, Scenario1_whole, the changes are mainly robust in the deep waters, with a general temperature increase in and below the halocline in the Baltic Sea. In shallower regions of the Baltic sea there are tendencies of bottom temperature decrease, but these changes are less robust.

Maps of sea surface temperature changes are shown in Fig. 11. The results are generally much smaller and much less robust than those for the bottom temperatures.

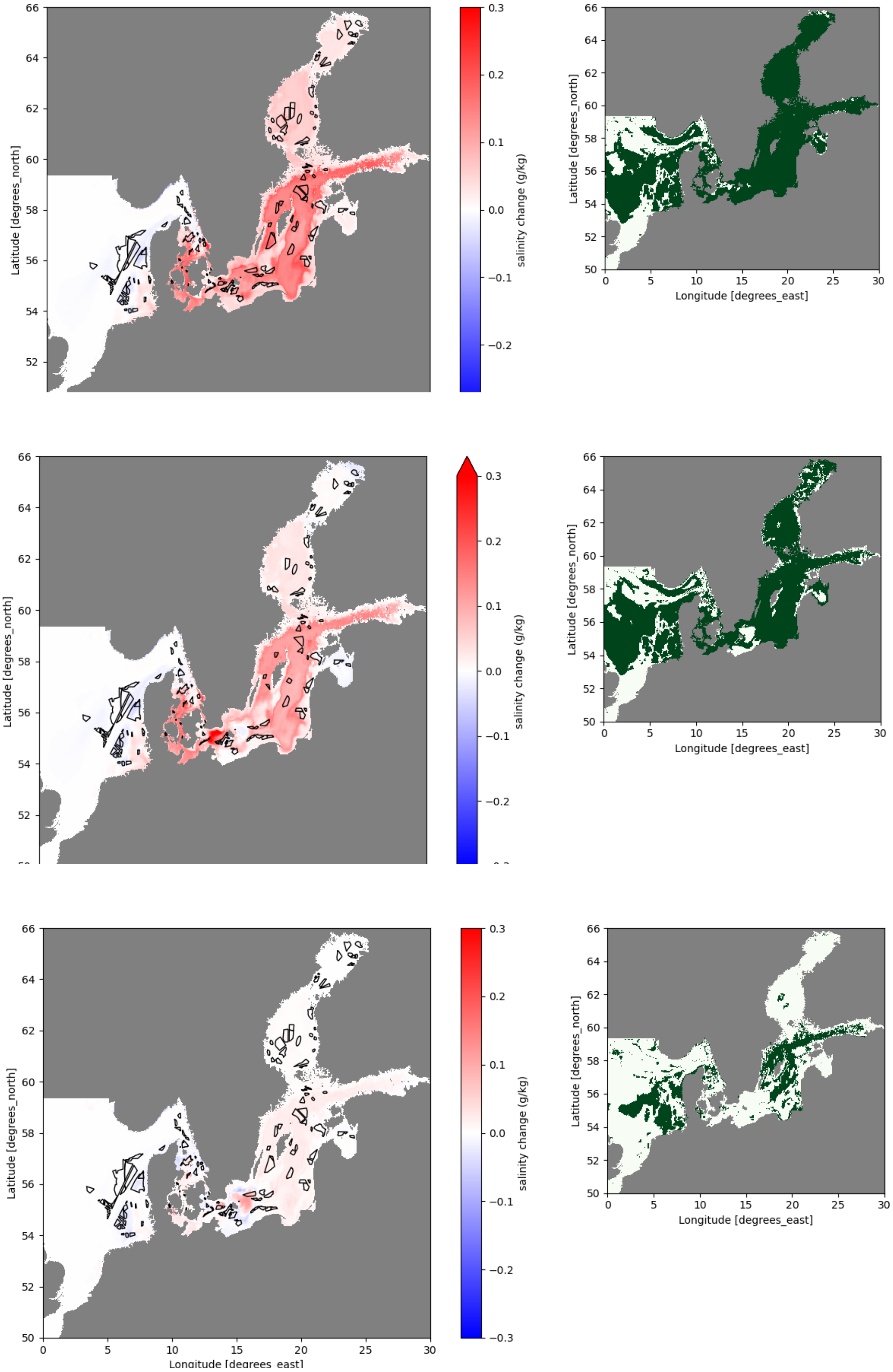

Figure 8: Mean bottom salinity changes for the period 2006-2016 for runs Scenario1_whole (upper panels), Scenario2_whole (central), and Scenario 1_summer (bottom). The black lines show wind farm areas. Right-hand-side panels show whether the results are robust (differ with more than 2 standard deviations from mean of reference runs, green areas) or not (white areas). The remaining runs do in general show smaller changes than Scenario1_summer.

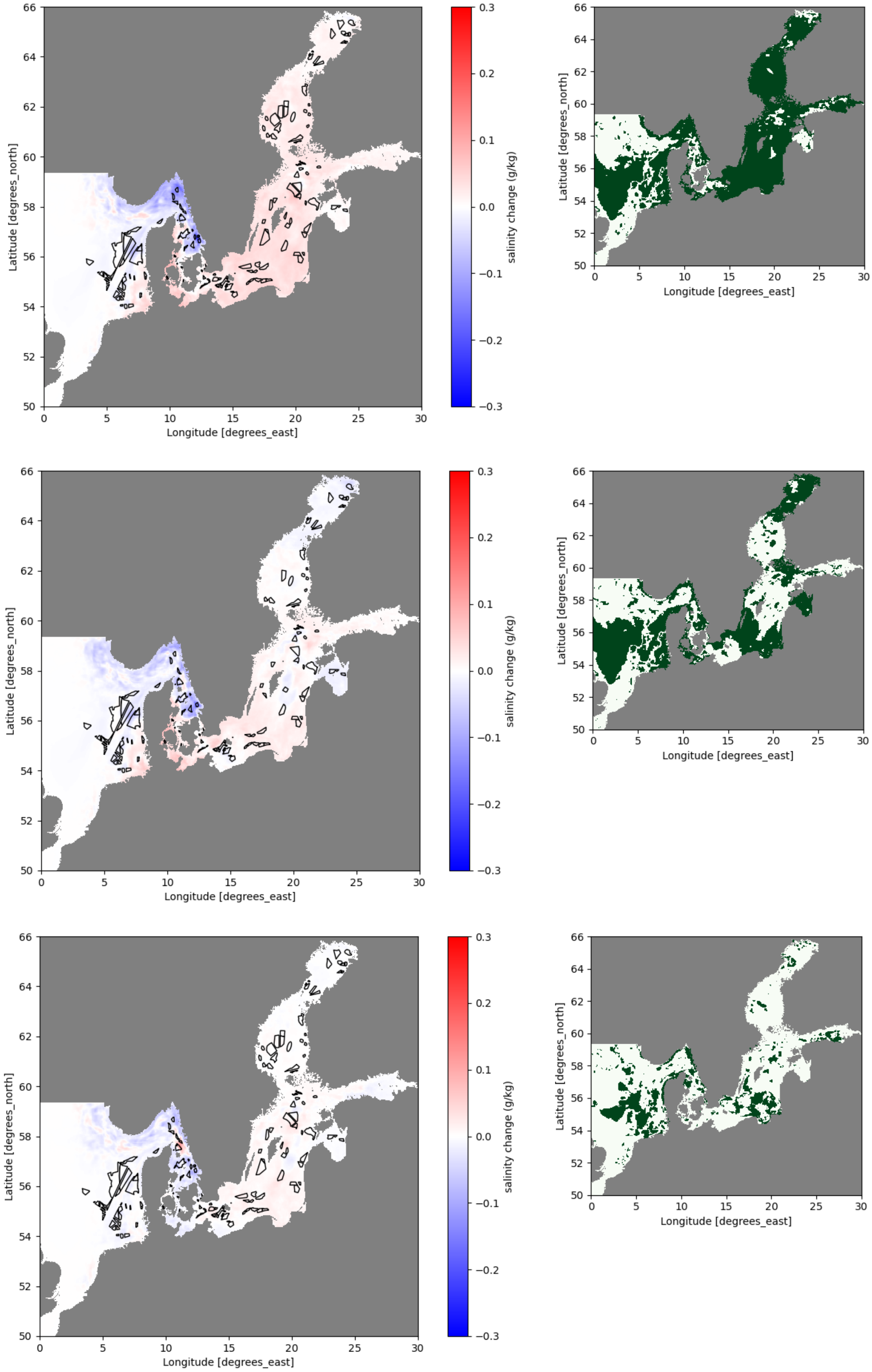

Figure 9. As Fig. 8 but for sea surface salinity.

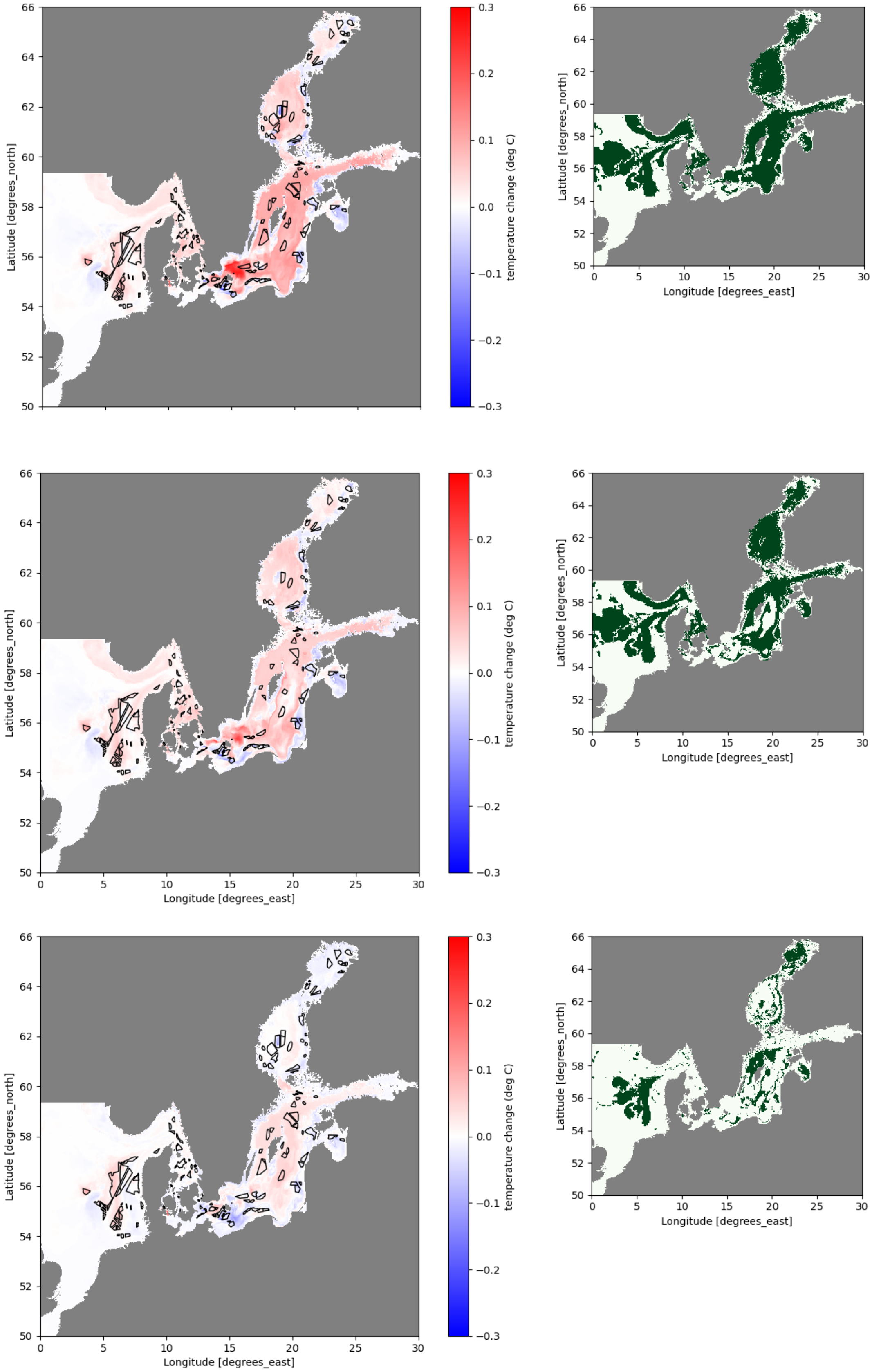

Figure 10. As Figure 8 but for sea bottom temperature

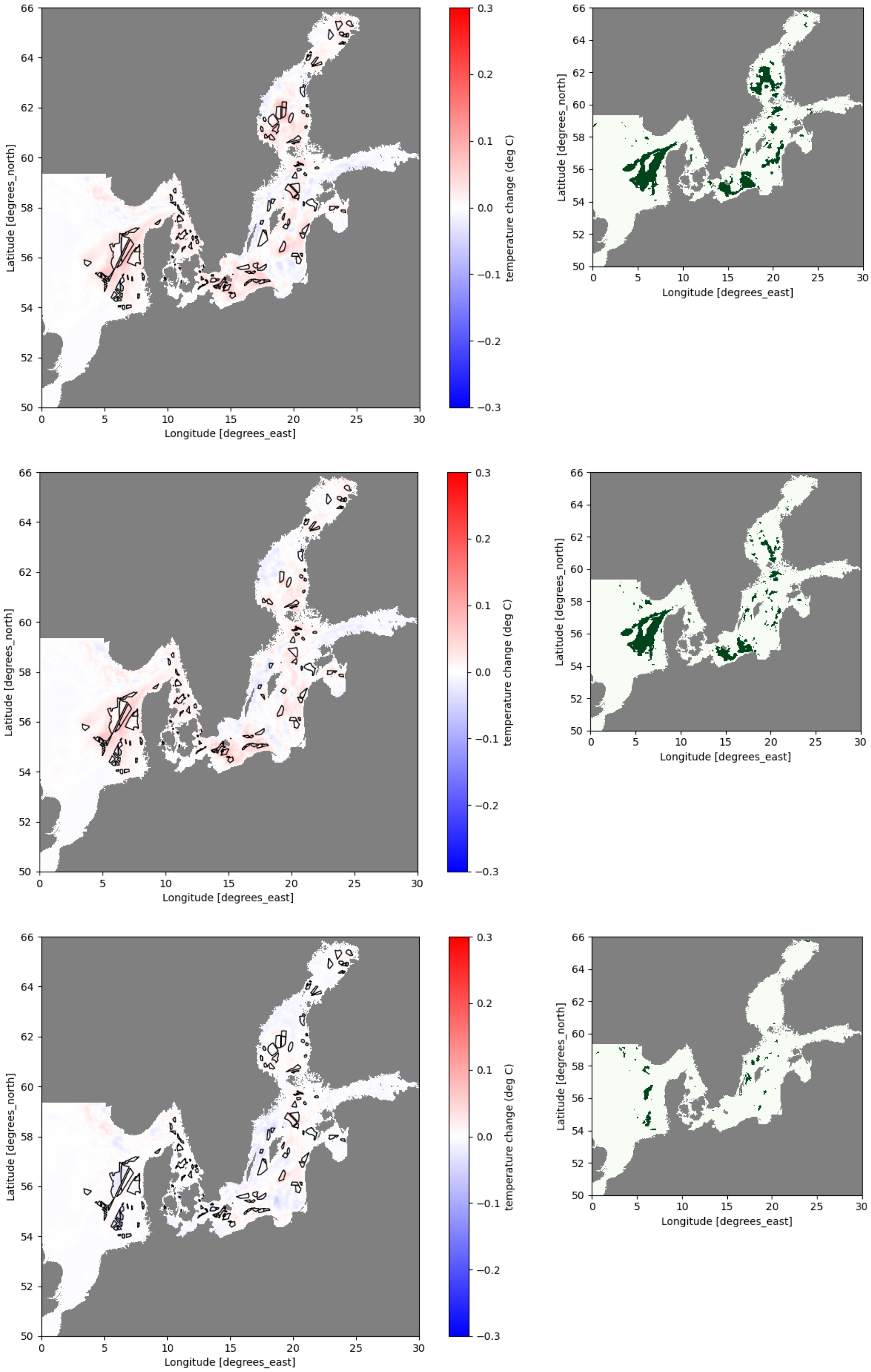

Figure 11. As Figure 8 but for sea surface temperature.

4.2 Changes to wind stress

The decrease in average daily wind stress for the Baltic Sea east of longitude 13 °E for the 10 last years of the runs, i.e. for the same periods plotted in Figs. 8 – 11, are given in Table 3. It is seen that the wind stress reduction is much smaller for wind wakes active only during the summer than for wind wakes active during the whole year. The reason for this large difference is that the winds are stronger during winter months than during summer months and that summer only cover 3 months whereas whole year covers 12 months of reduction.

The wind stress to the power of 3/2 is a measure of energy input to the water, which can be used to mix the water column. The relative change in wind energy input is therefore larger than the change in wind stress input, and the difference between whole year and summer is also larger for wind energy input than for wind stress input.

Table 3: Changes in wind stress and wind energy input averaged over the water surface east of longitude 13 °E and over the period 2006 to 2016

Run	Relative decrease in average wind stress	Relative decrease in wind energy input
Scenario1_summer	0.14 %	0.17 %
Scenario1_whole	1.44 %	2.28%
Scenario2_summer	0.10 %	0.13 %
Scenario2_whole	1.07 %	1.70 %

4.3 Impacts on currents

The change in the mean east and north components of the surface currents are shown in Fig. 12 for Scenario1_whole. The changes are generally small (< 2 cm/s) in absolute terms but also relative to the background variability. The largest changes are some eddy-like features in the vicinity of, but also outside the wind farm areas. Most of these changes are within two standard deviations of the background variability and therefore not robust.

5 Discussion

5.1 Reason for bottom water and halocline changes

The main long-term hydrographic changes in Swedish waters potentially evolving due to offshore wind power, are bottom salinity and bottom temperature increases in the Baltic Sea as well as a shallowing halocline. These changes, and the associated increase in salt content in the Baltic sea do evolve over time and not during inflows, e.g. Figs 3, 5 and 6.

The changes are consistent with what would be expected from decreased vertical mixing (Reissman et al. 2009, Stigebrandt 1987). For long term averages (decadal or more), the Knudsen relations (Knudsen 1900) are expected to hold, i.e. the net flux of salt through the entrance is small, and the net outflow of water is governed by the input of fresh water. This means that the surface layer conditions are governed by the inflow of water and salt to the Baltic sea through the entrance and the input of fresh water. If there are no large changes of inflowing

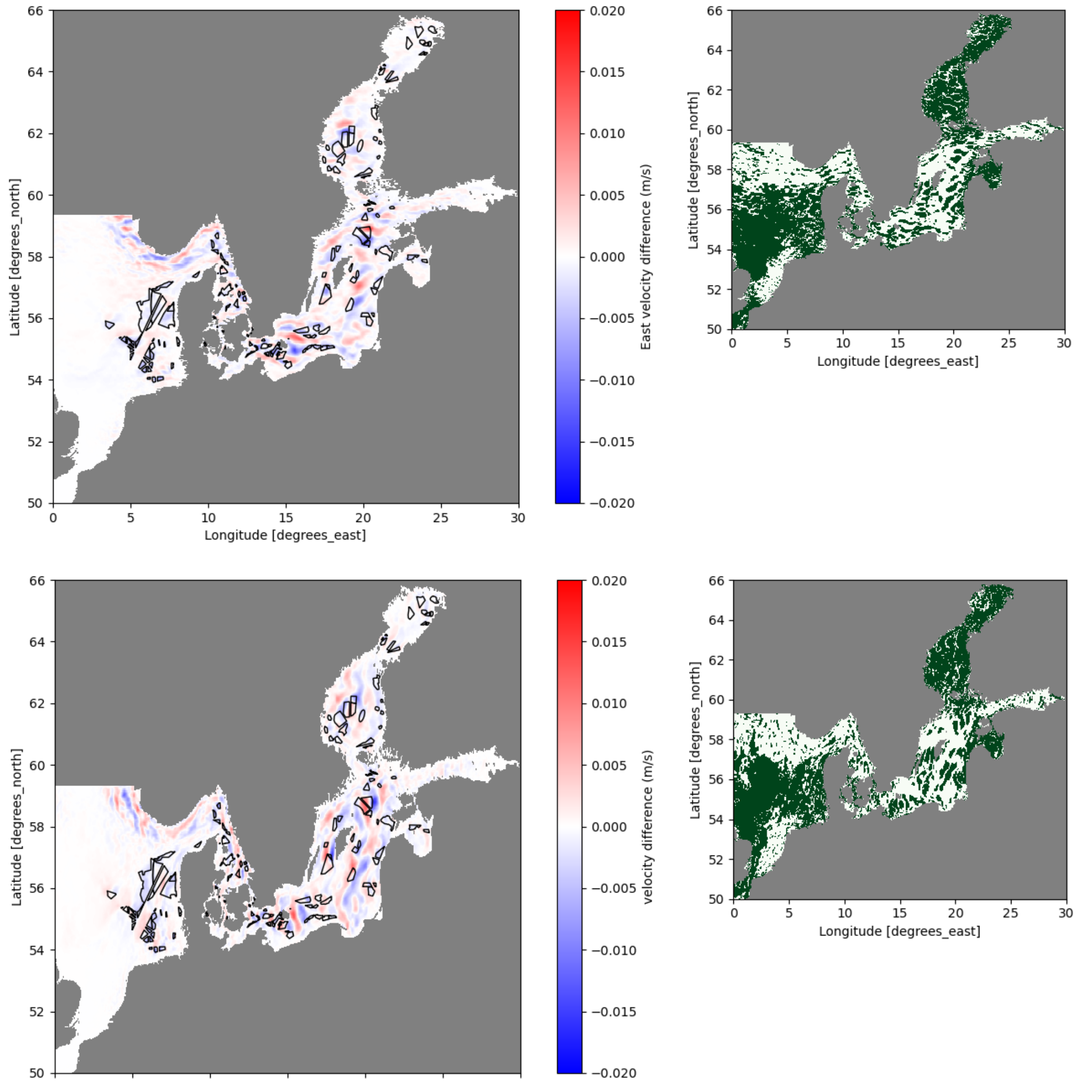

Figure 12. As Fig. 8 but for east (upper panels) and north (lower panels) components of surface velocity for run Scenario1_whole.

saltwater and the fresh water input is unchanged the surface layer changes will also be small. This is the reason why we see small changes in surface salinities. It also means that the same amount of salt needs to be circulated through the Baltic Sea, i.e. get mixed into the surface layer across the halocline by wind forced mixing, before it exits through the entrance. When wind forcing decreases, less energy is available to perform the mixing, and therefore the halocline moves upwards, Fig. 7, in order to reduce the amount of energy needed to mix up the salt into the surface layer. Less wind forcing will also cause less mixing of surface water down into the bottom layer, thereby reducing the gradual reduction of bottom layer salinity seen in Fig. 6. This will gradually lead to increasing bottom layer salinities for the cases with wind power relative to those without. Note though, that the changes are small relative to the temporal variability.

The wind energy input to the Baltic Sea is much smaller during summer than during winter, Section 4.2, which to a large degree can explain why the salinity changes are much smaller for the "summer" experiments than for the "whole" experiments. It is mainly the fall and winter storms that do cause mixing in the Baltic Sea. Adding to this is the summer thermocline that isolates the halocline from wind mixing during the summer, meaning that the wind wakes there mainly influences the thermocline.

All in all, this means that it is the wake effect of the wind farms in the Baltic proper that potentially cause the largest expected changes, not the wind farms in the entrance area. There is a small increase in bottom salinity for the case without bottom foundations relative to the same case with foundations, Fig. 3. This may indicate decreasing salinity in the Baltic deep water due to friction and mixing of inflowing water caused by wind farms in the entrance region. But this effect is much smaller than the Baltic deep water salinity increase due to decreased mixing when the wind wake is active during the whole year.

5.2 Possible importance for biogeochemistry and ecosystems

The decreased mixing manifested in increased bottom salinity indicate qualitatively that also the oxygen concentration will decrease in the bottom waters due to less mixing between oxygen-rich surface waters and oxygen-poor bottom waters. It is though difficult to quantitively assess changes to biogeochemistry without a dedicated modelling study. However, the corresponding change of area which may become hypoxic during periods without inflow can be estimated by following the correlation between this area and the halocline depth in the Baltic Sea suggested in Almroth-Rosell et al. (2021). The halocline rise in the most extreme run is about 2.5 m which would correspond to an (potential hypoxic) area increase of about 2 % of the surface area of the Baltic proper and an increase of about 4000 km^2 that may become hypoxic or anoxic. Climate change will also influence oxygen conditions in a negative way. However, as concluded in (HELCOM/Baltic Earth 2021) oxygen conditions are mainly dependent on scenarios for nutrient loads from land, and the variability between oxygen conditions of different nutrient load scenarios is much larger than the change we expect from the investigated wind farm scenarios

The salinity and temperature changes may also impact the suitability of habitats for various species. The expected temperature increase in the deep water (< 0.1 °C) is much less than the expected increase due to climate change (2 - 3 °C) but adds to that change. The salinity increase counteracts a possible salinity decrease due to climate change, although it actually has become unclear whether salinities will decrease or increase in the future (HELCOM/Baltic Earth 2021). The maximum expected salinity change of about 0.2 g/kg is small relative to the range of uncertainty for changes due to climate change (about 2 g/kg, e.g. SMHI climate scenario service).

5.3 Sensitivity to wind wake parameterization

The results show a very strong sensitivity to the wind wake assumptions. When the wind wake is active during the whole year there are robust changes to the halocline and the water below the halocline in the Baltic Sea, but when the wind wake is active only during the summer the changes are much smaller and less robust. In reality the winds behind the wind farms will also be influenced during winter although probably less than given in the present parameterization. The wind wake parameterization is also based on existing wind farms, which are different than future wind farms which will have larger wind power plants placed with lower densities. The influence of this change on future wind wakes may lead to slightly changed wake geometries, but the authors do not expect that this change is large enough to influence the main results of this work. The resolution of the model used in this study is relatively coarse, which may cause an underestimate of the wake effect, especially for the smaller wind farms. All in all, we expect the real response to be within the range of the maximum (“whole”) and minimum (“summer”) estimates given above, and probably closer to the maximum than the minimum estimate.

Another drawback with the use of wind wake parameterizations as the ones used in this study, is that the dynamic interaction between atmosphere, wind farms, and ocean is not modelled. Recent atmospheric model experiments at the Danish Meteorological Institute show that the increased local atmospheric drag due to the wind farms, results in slight increases in the wind speed away from the wind farms. In other words, part of the wind wake effect on the ocean surface may in some cases be partly compensated by increased wind stress in nearby regions (J.

Murawski, 2024, pers. Comm.). Future investigations may possibly include coupled atmosphere-ocean models which take this feedback into account.

5.4 Relation to earlier work

The order of magnitude of salinity and temperature changes in the North Sea are similar to those found by Christiansen et al. (2022, 2023), although they focus on specific months while we look at long-term averages. It is, however, interesting to see that at least for bottom salinity, the Baltic Sea, which is mainly forced by winds, shows a stronger and more homogeneous response than the North Sea, which is less stratified and more forced by tides than by winds.

6 Conclusions

The largest potential changes to Swedish waters caused by the studied expansion of offshore wind farms is a shallowing of the permanent halocline in the Baltic Sea and increased salinities below the halocline. The changes are caused by decreased energy input to the Baltic Sea due to decreased winds behind the wind farms and thereby decreased mixing of water masses. The magnitude of the change depends to a large degree on assumptions about the atmospheric wind wakes, which are only coarsely represented here with a minimum and maximum estimate of the influence. For the largest and most unrealistic wind farm scenario, the response ranges from a shallowing of the halocline for the maximum impact scenario of about 2.5 m and increased bottom salinities of about 0.15 g/kg to a much smaller response with changes within the background variability for the minimum estimates of wind wake influence. The real response for tested scenarios probably lays somewhere in between these estimates. To narrow down the estimates, the atmospheric wind wakes need to be included in a more realistic manner. Much research is presently ongoing on this topic.

For the more realistic wind farm scenario with less wind farms in Swedish waters the influence on salinity and halocline is reduced in a manner that corresponds to the decrease in total wind farm areas in the Baltic Sea.

The wind farm foundations cause a small salinity decrease in the Baltic Sea deep water, probably due to increased friction and mixing in the entrance region to the Baltic Sea. This effect is much smaller than the wind wake effect when it is active during the whole year.

The bottom temperature in the Baltic Sea has an overall increase due to less mixing. For the most expansive, and unrealistic, wind farm scenario, and the maximum estimate of wind wake effect, this change is 0.1 °C. This is smaller than, but adds to, the expected temperature increases due to climate change.

The shallowing of the halocline and decrease in mixing will decrease the oxygen input to the bottom water and possibly increase the potential areas of hypoxic and anoxic bottoms. This will add to the negative climate impacts on oxygen from increasing overturning of organic material and decreased oxygen solubility in warmer waters.

The surface salinities, temperatures and currents show much smaller and less robust changes than the salinity and temperature changes in the Baltic deep water.

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8 Appendix

Table A1. Foundation type assumed for current existing wind farm's structures.

Name	Total Area (km^2)	Number of turbines per foundation type			
		Monopile	Gravity	Jacket (6 legs/2 turbines)	Jacket (3 legs/turbine)
Anholt	121.54	110			
Arkona Becken Südost	37.25	60			
EnBW Baltic I	29.56	21			
EnBW Baltic II	6.50	39			41
Kriegers Flak	227.73	72			
Nysted	23.05		72		
Rødsand ll	34.84	90			
Wikinger	32.52			70	

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Swedish Meteorological and Hydrological Institute
SE 601 76 NORRKÖPING
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