Kiel, 11th July 2016

Dear Editor,

Please consider our revised manuscript "Effects of surface current/wind interaction in an eddy-rich general ocean circulation simulation of the Baltic Sea" for publication in Ocean Science.

Both reviewers were concerned that the presentation in the previous version of the manuscript implied that our results are inconsistent with findings of others regarding the eddy/wind effect. The reviewers were right that this could not be proved with our experimental setup. We are sorry for the confusion. This has not been our intention.

The aim of the manuscript is to explore the effects of surface current/wind interaction in an eddy-rich general ocean circulation of the Baltic Sea rather than proving Martin and Richards (2001) right or wrong. To make this clearer we rephrased respective sentences and paragraphs (as you will see in the point-by-point responses to the reviewers comments) and deleted "eddy/wind effect" in the abstract.

We acknowledge the time and effort of the two anonymous reviewers. We think they helped us to make the revised manuscript more appealing to a wider audience.

In any case, thank you for your time!

Yours sincerely,
the authors

Answer to Anonymous Referee #1
The referee's comments are typed in **bold**.

I find the narrative to be less than perfectly clear, however, mainly due to distracting phrases sprinkled throughout, a bit of a muddled notion of equivalence, and some clumsiness in crafting the storyline.

We acknowledge the referee's time and effort. We are especially thankful for his many constructive comments and suggestions!

The biggest problem I see is the notion that these results are inconsistent with Martin and Richards (2001), who discussed Ekman pumping within coherent vortices, not the general impact of surface-current-wind interactions on vertical exchange. Here the authors seem to indicate that regions where vertical exchange is enhance with current-wind turned on are consistent with Martin and Richards (2001), even though these regions are not operating with the same physics; i.e., coastal upwelling south of Sweden versus coherent vortices.

The main topic of the paper are "effects of surface current/wind interaction in an eddy-rich general ocean circulation simulation of the Baltic Sea". It is motivated by (1) published theoretical considerations which hint towards a strong effect of surface current/wind interaction, (2) by the fact that, only very recently, the spatial resolution of Baltic Sea model configurations allows for a fairly realistic representation of surface currents. Combining (1) and (2) raises the question if and to what extent previous (coarser resolution) model configurations are flawed - a question which is highly relevant in the Baltic as all projections into a warming future are based on (coarser resolution) models that do miss most or even all of the current/wind effect.

The referee is right in pointing out that we did not prove Martin and Richards (2001) wrong. The referee is also right in pointing out that coastal upwelling off Sweden is not to be confused with coherent vortices. We revised the manuscript rephrasing all respective clumsy passages with the aim to make the following line of thought much clearer: (1) theoretical considerations suggest that surface current/wind interaction may give rise to substantial vertical upwelling and downwelling. (2) This raises the question if and to what extent previous (coarser resolution) model configurations are flawed in terms of their vertical transports of heat and nutrients. (3) To explore this we compare two simulations: one comprising the surface current/wind effect with one neglecting the effect. (4) We find that vertical exchange is, on average, damped. Locally, however, as e.g. south of Sweden, the vertical exchange is increased.

Specifically we:
- deleted the reference to "eddy/wind" in the abstract (now on pg. 1, ln. 4)
- rephrased the summary and conclusions (now on pg. 13, ln. 5 to ln. 18)

pg 2, ln 9-10: the implication here is that adjoint methods are correcting stress estimates because of uncertainty in the stress formulation. Is that really the case? This methods is correcting for all source of uncertainty in the forcing, including the data describing the wind fields themselves.

The implication is not the case. We are sorry for the confusion. Rather: the wind stress formulation is so uncertain that modifications within is substantial uncertainty can "compensate" most of the other sources of uncertainty. We rephrased the respective sentence (now on pg. 2, ln. 10 to 11).

pg 2, ln 21-22: I don't understand the sentence, "It is based on the success of the concept Ekman Pumping." Martin and Richards (2001) describe how eddy-wind interaction results in Ekman pumping within eddies.

We will deleted " ... the success of ..." (now on pg. 2, ln. 21).

pg 3, ln 29: The word, “competitive” is not appropriate.

We removed the word (now on pg. 3 ln.29).

It seems odd to report the resolution in nautical miles with the relevant metrics about scaling (Rossby radius) are in km. I would report the resolution in km.

We report the resolution now in km (pg. 3 ln 30). We keep a reference to the nautical mile, though, because it has been "a computational barrier" in the Baltic Sea Modelling community for some time.

pg 3, ln 32: KPP –> K-profile parameterization (KPP)

Changed, now on pg. 4, ln. 1.

pg 4, ln 14: I find the phrase, “REF is identical to MOMBA 1.1” confusing. REF is a simulation and MOMBA 1.1 is a model? What “earlier Baltic Sea models” are you referring to?

We clarified/specified this; now on pg.4 ln. 13 to 15.

pg 4, ln 23: I have difficulty parsing this text: “...detailed in Large and Yeager (2004); Large (2006) which has matured to a reference in the field (e.g. Griffies et al., 2014).” What does that mean?

We deleted " ... which has matured to a reference in the field ... " (now on pg. 4, ln. 23 to ln. 24).

pg 4, ln 24: This sentence is unnecessarily complicated: “The setup noCW is identical to REF except for that the traditional (similar to, e.g., Meier et al., 1999, their Eq. 30), physically less plausible way to force an ocean model, which neglects the effect of surface currents on the wind stress, is applied.” Also, use of the word “traditional” may be confusing to some readers with different levels of experience with ocean modeling— it is not necessary to characterize the approach this way.

We rephrased; now on pg. 4, ln. 25 to ln. 27.

pg 4, ln 30: What does “...to an apparently especially realistic model behaviour” mean? A period where the model compares especially favorably to observations?

Yes. Rephrased (now on pg. 4, ln. 31).

pg 4, ln 31: why is bit-reproducibility relevant here?

We added some information (now on pg. 4, ln. 32 to pg. 5 , ln. 2).

Fig 1. add panel showing SST and heat flux time-series?

Very good idea! We changed Fig. 1 accordingly (now on pg. 6).

pg 5, ln 10-17: I find this explanation hard to follow. What is the change in mean SST? Does stratification increase in REF relative to noCW? What happens to MLD? It seems that this is an obtuse angle from which to attack the differences in the simulations.

Sorry! We rephrased the section (now on pg. 5, ln. 1 to ln. 32) and modified Fig. 1 following your very good idea.

pg 5, ln 19: This sentence, "A gedankenexperiment reveals that by accounting for the ocean's movement in the calculation of wind stress exerted on the ocean's surface –overall – less energy is transferred to the ocean: winds and surface currents can – in addition to having a perpendicular component to one another – either oppose one another, or run along into the same direction" is confusing: why resort to a thought experiment when you have actual numerical experiments? What are you actually saying? Perhaps present Fig 2 first, then describe the mechanisms operating to cause this change.

We rephrased the whole section (now on pg. 5, ln. 1 to ln. 32) and hope it is much clearer now.

pg 6, ln 1: Fig 2 confirms that there is less net energy transferred—if you rely on the reader to spatially integrate the difference field. Maybe point out that this is what you really mean.

We added this information (now on pg. 6, ln. 1).

pg 6, ln 5: Fig 3 looks like it has some mesoscale variability retained in the climatological field. Are the wintertime difference really the same sign everywhere? This figure indicates that mixed layers are not shoaling everywhere. This is not reflected in the text—again, you are leaving out a step, it is the spatial integral of this map, not the map itself, that indicates net shoaling over the domain.

We clarified this (now on pg. 6 ln. 6 to 8).

pg 6, ln 9: "supply" –> "transfer"

Adopted; now on pg. 7, ln.2.

pg 7, ln 9: I would have said these winds are southwesterly.

Thank you! Now on pg. 8, ln. 1.

Fig 6: how is persistent defined? It's okay to provide a reference, but we should at least be provided with some minimum information to interpret what's plotted.

We added the definition (now on pg. 11, caption of Figure 7).

pg 7, ln 13: "Consistently, " –> "Consistent"

We made this mistake two times - thank you! Corrected; now on pg. 6, ln. 3 and pg. 8, ln. 5.

pg 8, ln 5-7: Martin and Richards (2001) point to Ekman pumping in the interior of eddies. You only have an inconsistency, then, if you posit that the ocean surface is wholly dominated by coherent vortices. I am not sure that the Martin and Richards (2001) result can really be extended to make inferences about net momentum transfer with and without the surface-current effect on wind stress.

We changed to "... apparently inconsistent with OUR initial considerations ..." (pg. 8, ln. 10).

Our initial considerations are based on ideas of Dewar and Flierl (1987) and Martin and Richards (2001). But the reviewer is right: reverse reasoning is not admissible here i.e. the fact that our initial considerations were not met in our Baltic Sea model does not prove neither Dewar and Flierl (1987) nor Martin and Richards (2001) wrong. We hope that this becomes much clearer now that we rephrased pg. 13, ln. 5 to ln. 14.

pg 10, ln 5: "...prevails [over] the effects...." It's not clear what is meant be "increase horizontal inhomogeneity." Please remind the reader of this concept as discussed in the introduction.

Rephrased, now pg. 9, ln.9 to 10.

pg 11, ln 4: I don't think you have demonstrated this. You have presently only mean quantities, leaving open the possibility of effects with cancelation.

True. We will change the sentence from " ... any additional near-surface ... " to " ... any additional net near-surface ...". Now on pg. 11, ln. 9.

pg 12, ln 18: I don't see how this is consistent; you are talking about coastal upwelling and Martin and Richards (2001) discuss Ekman pumping within coherent vortices.

We changed the corresponding sentence to "Consistent with the argumentation of D&F(1987) and M&R(2001) concerning the effects of surface currents on Ekman Upwelling these coastal anti-cyclonic surface currents effect an additional upwelling that is dominant and persistent enough to drive distinct local SST anomalies in summer."

Answer to Anonymous Referee #2
The referee's comments are typed in **bold**.

We acknowledge the refee's time and effort!

The two simulations, one with and one without the relative wind correction, result in very different eddy fields. The simulation without the relative wind correction has much higher EKE. As a result of this fundamental difference in the two solution, I do not see a clear path as to how one could use this comparison to quantify the influence of the relative wind correction on vertical exchange. This has been one of the primary critaizum of previous efforts to make such comparisons (e.g., Eden and Dietze, 2009). Without some sort of correction to account for the differences between the magnitude of the kinematic variability between the two simulation, the reader is left to wonder if the difference highlighted by the authors are indeed a result of the relative wind correction, or just the manifestation of a (likely) significantly less energetic solution in the simulations including the influence of the surface current on the surface stress. This could be address by redoing the simulations and using some other adjustment to bring the EKE of the two solutions closer together. Another option, and likely the easier one, would be to focus on mesoscale features and how the vertical exchange between them differer in the two simulations. This would also be more in-line with the current and previous research into this topic that highlights the influence of eddy-induced surface currents on imparting a curl in the surface stress.

Only very recently it has become computationally feasible to resolve small-scale surface currents such as coastal currents or part of the mesoscale variability in general ocean circulation model configurations of the Baltic Sea. Among other processes, this - for the first time - introduces a new mechanism: the surface current/wind effect. Theoretical considerations suggest that this should alter the vertical exchange of heat, salt and nutrients substantially. If so, previous models simulations of the Baltic which do not resolve this effect would be flawed. This is of some concern as such simulation are involved in political processes where expensive international decisions concerning future nutrient loads are made.

The aim of our manuscript "Effects of surface current/wind interaction in an eddy-rich general ocean circulation of the Baltic Sea" is to explore to what extend earlier model simulations/configurations of the Baltic Sea are potentially biased due to unresolved effects of surface current/wind interaction.

We deleted the reference to "eddy/wind" in the abstract (pg. 1, ln. 4) and stressed the above point on (pg. 13, ln. 5 to ln. 9).

Minor: - The discussion of how these results compare to some of the most important previous works in this field is missing. Once particularly appalling omission is the discussion of how this work builds on the fundamental work by Dewer and Flierl, 1987.

We will included the respective reference in the revised version (pg. 2, ln. 20).

- On page 11, starting at line 4, the authors state that the inclusion of the relative wind correction on the surface stress "does not drive any additional near-surface diapycnal transport ..." This is not surprising as the use of the relative wind generates upwelling and downwelling, which alone, do not drive diapycnal transport. As such, this statement is moot.

We rephrased the respective sentence (pg. 11, ln. 11 to 12) making clear that upwelling and downwelling - in combination with typical horizontal diffusive processes and air-sea buoyancy fluxes - do typically drive diapycnal fluxes: e.g. dense water is upwelled to the surface where it is heated by air sea fluxes. Thereby it looses density. When it is subsequently downwelled, the net effect is a diapycnal transport.

Effects of surface current/wind interaction in an eddy-rich general ocean circulation simulation of the Baltic Sea

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Abstract. Deoxygenation in the Baltic Sea endangers fish yields and favours noxious algal blooms. Yet, vertical transport processes ventilating the oxygen-deprived waters at depth and replenishing nutrient-deprived surface waters (thereby fuelling export of organic matter to depth), are not comprehensively understood. Here, we investigate the effects of the interaction between surface currents and winds ~~also referred to as eddy/wind effects~~ on upwelling in an eddy-rich general ocean circulation model of the Baltic Sea. Contrary to expectations we find that accounting for current/wind effects does inhibit the overall vertical exchange between oxygenated surface waters and oxygen-deprived water at depth. At major upwelling sites, however, as e.g. off the south coast of Sweden and Finland, the reverse holds: the interaction between topographically steered surface currents with winds blowing over the sea results in a climatological sea surface temperature cooling of 0.5 K. This implies that current/wind effects drive substantial local upwelling of cold and nutrient-replete waters.

1 Introduction

A century ago, Taylor et al. (1916) proposed that the stress describing the exchange of momentum between a moving atmosphere and the earth's surface may be expressed as being proportional to the windspeed squared times the density of air. As for the respective proportionality constant, often referred to as the drag coefficient, Taylor et al. (1916) calculated values between 0.002 and 0.003 " ... for the ground at Salisbury Plain, where the wind observations were made".

Numerous studies, targeted at improving the fidelity of this seminal relationship for oceanic applications, have been published ever since. Among them those exploring the dependency of the drag coefficient on (a) wind speed (e.g. Smith and Banke, 1975), (b) atmospheric stability (e.g. Hsu, 1974) and (c) wind-wave interaction (e.g. Hsu, 1973). Even so, the transfer of momentum from the atmosphere to the ocean is still associated with considerable uncertainties. For example, data assimilation experiments suggest that recent surface stress estimates **may be substantially altered within their "accepted" uncertainty in order to reconcile *in situ* observations with circulation models (Stammer et al., 2004; Köhl et al., 2007)**. To this end, it is somewhat conspicuous, that the respective wind stress corrections are especially large in regions of strong surface currents such as in the Gulf Stream, Kuroshio, Leeuwin Current and the Antarctic Circumpolar Current. The nearby conclusion, that the drag coefficient is substantially influenced by strong ocean currents is, however, supposedly wrong (Kara et al., 2007).

In contrast to ongoing controversial discussions on the drag coefficient, there is now consensus that the calculation of the stress, exerted by the wind on a circulating ocean, should be based on the wind vectors relative to the ocean currents - rather than being based on the wind vectors only (Fairall et al., 2003). This may be surprising given the rather high uncertainties of the drag coefficient (discussed above), and that ocean currents are typically orders of magnitudes smaller than atmospheric winds which – in turn – suggests that the neglect of the (slow) movement of the ocean's surface should not alter the stress calculation significantly within its already-substantial uncertainty. Martin and Richards (2001) building on **Dewar and Flierl** (1987) put forward a striking argument to consider the ocean's movement at the surface in the stress calculation nonetheless. **It is based on the concept *Ekman Pumping***. *Ekman Pumping* is considered a major agent via which the atmosphere drives the general oceanic circulation (Stommel, 1957) and it is key to our understanding how energy is transferred into the interior ocean (e.g. Roquet et al., 2011). *Ekman Pumping* depends on the curl of the wind stress which is composed of spatial derivatives; and thus comes the relevance of ocean surface currents: oceanic currents typically vary on spatial scales that are much smaller than the winds associated to relatively large-scale atmospheric weather systems. So the argument here is that, in terms of their effect on *Ekman Pumping* which is a major control on circulation, ocean surface currents compensate for their rather weak magnitude by relatively large changes on small spatial scales.

The study of Martin and Richards (2001) includes a drastic demonstration of this effect. The authors argue that even a spatially uniform wind blowing over an ocean eddy should yield significant wind stress curls and an associated vertical *Ekman Pumping* of the order of $\approx 0.5\,\mathrm{m\,day^{-1}}$ in typical open-ocean conditions. Direct observations of this so-dubbed *eddy/wind effect* in a North Atlantic eddy by McGillicuddy et al. (2007) and Ledwell et al. (2008) confirmed both the existence of the process and its magnitude. The associated local effects on marine biota were so pronounced that the authors speculated that the, hitherto unaccounted, eddy/wind effect could resolve a long-standing discrepancy between nutrient supply to, and oxygen consumption below the euphotic zone of the subtropical gyre (e.g. Oschlies et al., 2003; Dietze and Oschlies, 2005; Kähler et al., 2010). This, however, has been discussed controversially by Eden and Dietze (2009).

This study sets out to constrain the **large-scale** effects of surface current/wind interaction in the Baltic Sea, a marginal sea in central northern Europe where eddy/wind effects should be especially prominent: as explained above, the spacial scales of surface currents are key to the magnitude of the effect. Rough scaling suggests that an energetic prevalent spacial scale of oceanic circulation is the Rossby radius of deformation. In typical mid-latitude open-ocean conditions (such as explored by Eden and Dietze, 2009) the Rossby radius is of the order of 50 km and the associated eddy/wind effect would be of the order of $\approx 0.5\,\mathrm{m\,day^{-1}}$, as explained above. In the Baltic Sea, however, effected by shallower water depths and strong stratification, the Rossby radii are typically an order of magnitude smaller (1.3 to 7 km, Fennel et al., 1991) which, in turn, suggests that eddy/wind effects are an order of magnitude stronger than in the open ocean. If so, this effect should be a major process in the Baltic effecting vertical exchange between the well-oxygenated surface waters and the dense oxygen-depleted deep waters. As such surface current/wind effects should rank among the first oder processes controlling the intermittent deoxygenation of the Baltic Sea which endangers fish yields and favours noxious algal blooms.

So far, surface current/wind effects have not been explicitly investigated in the Baltic. Among the reasons are the small Rossby radii in the Baltic which call for much higher horizontal resolution and associated computational cost than is the case for open-ocean model studies. It is only recently that advances in compute hardware have rendered this feasible.

This paper sets out to explore current/wind effects in the Baltic with the recently-developed high-resolution general ocean circulation model configuration MOMBA 1.1 (Dietze et al., 2014). Section 2 describes the model configuration and the numerical experiments. Section 3 presents model results followed by a discussion in Section 4. We close with a summary and conclusions in Section 5.

2 Method

We conduct a numerical twin experiment with the general circulation ocean model configuration MOMBA 1.1 (Dietze et al., 2014): the reference simulation *REF* includes the surface current/wind effect while the other simulation *noCW* (short for **no** **c**urrent/**w**ind effect) does not account for this effect. A major difference compared to previous studies that cover the Western Mediterranean (Olita, 2015) and the North Atlantic (Eden and Dietze, 2009), is our focus on the shallow Baltic Sea where, as outlined above, current/wind effects should be most prominent.

2.1 Model Configuration

All experiments are based on a regional ocean-ice model setup of the Baltic Sea, called MOMBA 1.1. The configuration is extensively documented in Dietze et al. (2014), and accessible via www.baltic-ocean.org. **The model features a horizontal resolution of** $\approx 1.9\,km$ **corresponding to one nautical mile**; it is eddy-rich in that it starts to resolve the relevant spacial scales (c.f. Fennel et al., 1991). The model domain is bounded by 4.2°E and 30.3°E and 53.8°N to 66°N. The vertical discretisation comprises 47 levels. There are no open boundaries, i.e., the model domain is surrounded by solid walls. We use the **K-profile parameterization (KPP)** (Large et al., 1994) with parameters identical to those applied in the eddy-permitting global configurations of Dietze and Kriest (2012); Dietze and Löptien (2013) and Liu et al (2010). The atmospheric boundary conditions driving MOMBA 1.1 are based on dynamically downscaled ERA-40 reanalysis data (Uppala et al., 2005). The respective downscaling is performed by the Rossby Centre Regional Atmosphere model version 3 (hereafter RCA3), which takes ERA-40 reanalysis data as boundary conditions. RCA3 features an enhanced (relative to ERA-40) horizontal resolution of 25 km (Jones et al., 2004; Samuelsson et al., 2011). These atmospheric boundary conditions are identical to those applied to the "RCO"-models, used e.g. by Hordoir et al. (2013); Löptien et al (2013) and Meier and Faxen (2002).

Results from a 1987 to 1999 hind cast simulation showcased in Dietze et al. (2014) illustrate that the model's fidelity is competitive to other Baltic Sea models. Remarkably, MOMBA 1.1 simulates very realistic sea surface temperatures which is indicative of a correct representation of near-surface diabatic processes.

2.2 Experiments

In the following Section 3, we compare two numerical experiments, *REF* and *noCW*. *REF* refers to the reference simulation including the surface current/wind effect, while the other simulation *noCW* does not account for the current/wind effect. **The simulation *REF* is based on the exact same MOMBA 1.1 configuration described in Dietze et al. (2014). *REF* has, in contrast to previously-published Baltic Sea models (e.g. Meier et al., 1999; Meier and Faxen, 2002; Meier et al., 2012)**, a better representation of the feedback of ocean surface currents, $\boldsymbol{u}_o$, on the wind stress, $\boldsymbol{\tau}_{ref}$ because (a) it explicitly accounts for ocean currents in the calculation of the wind stress as recommended by e.g., Large and Yeager (2004); Fairall et al. (2003), and (b) in contrast to the previous generation of ocean circulation models, MOMBA 1.1 features a relatively high horizontal resolution of 1 nautical mile which starts to resolve mesoscale processes in the Baltic.

The stress $\boldsymbol{\tau}_{ref}$ exerted on the ocean's surface by winds blowing with a velocity $\boldsymbol{u}_a$ over an oceanic current moving with a velocity $\boldsymbol{u}_o$ is calculated in experiment *REF* as:

$$\boldsymbol{\tau_{ref}} = \rho_a c_D |\boldsymbol{u}_a - \boldsymbol{u}_o| (\boldsymbol{u}_a - \boldsymbol{u}_o), \tag{1}$$

with the density of air ρ_a, and the dimensionless drag coefficient c_D. **Note that c_D is not constant as we apply the formulation detailed in Large and Yeager (2004); Large (2006).**

The setup *noCW* does not include the effects of surface current/wind interaction. Other than that it is identical to the setup *REF*. More specifically, the stress $\boldsymbol{\tau}_{noCW}$ exerted on the ocean's surface in experiment *noCW* is calculated (similar to, e.g., Meier et al., 1999, their Eq. 30) as:

$$\boldsymbol{\tau_{noCW}} = \rho_a c_D |\boldsymbol{u}_a| \boldsymbol{u}_a. \tag{2}$$

Both simulations start from rest on 1 January 1987 and are integrated till 31 December 1993. In the following analysis we explore the model output starting from 1 January 1988 thus allowing for a 1 year spin-up phase. We stop the simulation on 31 December 1993 **which constrains the period to one where the models compares especially favourably to observations. Contrary to Dietze et al. (2014) we compile the fortran model code with *ifort* version 14.0.0 using non-aggressive com-**

piler options ("-msse4.2 -i4 -r8 -align all"). This ensures that the differences discussed here are due to actually differing model formulations rather than being caused by "computational uncertainty" (c.f. Sec. 3.8 in Dietze et al., 2014).

3 Results

One major focus here is on simulated sea surface temperatures (SSTs) and causes of SST differences in the simulations *REF* and *noCW*. We argue that SST is prominent because (1) it controls the velocity of biogeochemical turnover in the sun-lit surface, as e.g. enzyme-catalyzed reactions feature a sensitivity corresponding to roughly 10% increase per Kelvin increase. (2) SST controls sea fog. This is of interest since the Baltic hosts up to 15% of the world's international maritime cargo (HELCOM , 2009) and because around 10% of all collisions are apparently related to sea fog (Tuovinen et al., 1984). (3) SST variation is a proxy for diabatic processes. Consequently, simulated SST differences can be related to differing nutrient transports to the sun-lit surface, associated export of organic matter to depth and oxygen consumption at depth.

3.1 Basin-scale effects

The upper two panels in Fig. 1 show seasonal cycles of simulated basin-averaged SSTs and air-sea heat fluxes in the simulation REF. During boreal summer the Baltic is heated up to $\approx 18°$C and cooled down to almost $0°$C in winter. The 3rd panel in Fig. 1 shows that that the amplitude of the seasonal cycle in air-sea heat fluxes is reduced when accounting for surface current/ wind effects. At the same time the seasonal amplitude in SSTs increases (lowermost panel in Fig. 1). Hence, our simulations show that surface-current/wind effects drive increased SST warming (cooling) in summer (winter) even though, air-sea heat fluxes are supplying less heat (less cooling). From this, we conclude that the diabatic exchange of heat is reduced by current/wind effects - or, in other words, the summer time warming (winter time cooling) is distributed over a shallower water column such that it is resulting in an increased amplitude of the seasonal SST cycle. This conclusion is contrary to expectations outlined in the introduction: due to the anticipated strong eddy wind interactions, we would rather have expected an increase in basin-scale diabatic transports and, consequently, a reduced amplitude of the basin-scale seasonal SST cycle. As this does not apply other, counteracting mechanisms must prevail on large scales.

The reduced diabatic transports associated with current/wind effects become reasonable when considering the transfer of kinetic energy to the ocean. We argue that accounting for the ocean's movement in the calculation of wind stress exerted on the ocean's surface – overall – less energy is transferred to the ocean because a combination of the following conditions are on hand: (1) surface currents may be aligned perpendicular to the wind which does neither yield increased nor decreased stress exerted on the ocean's surface. (2) surface currents may oppose the winds such that the ocean's movement is slowed down with the current/wind effect accelerating the oceanic energy drain. (3) surface currents may run along with the winds such that the current/wind effect reduces the drag so less momentum and energy is transferred to the ocean. Thus, depending on the direction of the wind relative to the surface currents, the local contemporary energy transfer is either unchanged or decreased, but never increased.

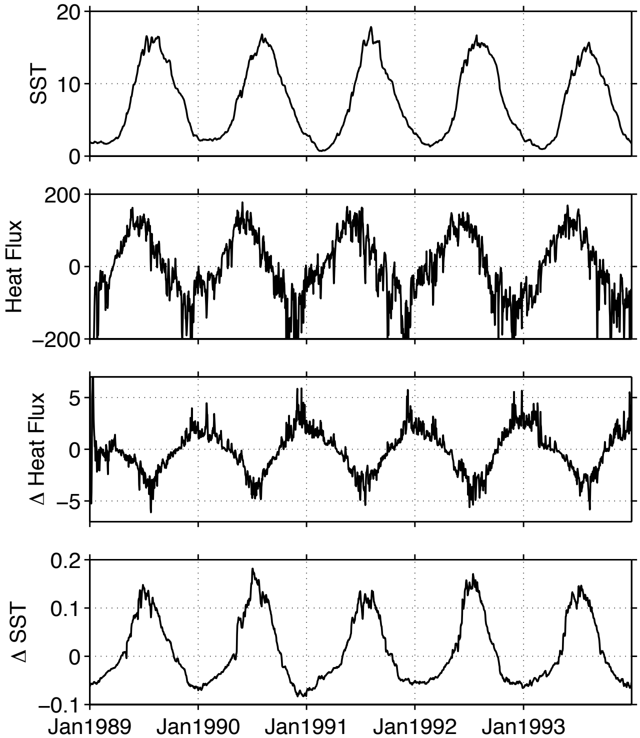

Figure 1. Basin-scale averaged temporal evolution of (1) sea surface temperature (upper panel, units $^\circ$C), (2) air-sea heat fluxes (2nd panel, units $W\,m^{-2}$), (3) air-sea heat flux differences (3rd panel, units $W\,m^{-2}$), and (4) sea surface temperature differences (lowermost panel, units K). The differences Δ are calculated as experiment *REF* - *noCW*. Positive (negative) Δ heat flux values denote reduced cooling (warming) in winter (summer) by surface current/wind effects. Likewise, positive Δ SST (negative) values indicate warming (cooling) by surface current/wind effects.

Fig. 2 confirms the reduced energy transfer showing that in experiment *REF* the net **basin-scale** energy transfer by winds is less than in experiment *noCW*. This reduced net **transfer** of kinetic energy yields weaker surface currents and, consequently, weaker vertical shear of horizontal velocities. This, in turn, reduces shear-induced turbulent mixing. **Consistent** with this argument we find, on **basin-scale** average, shallower surface mixed layers in experiment *REF*: Fig. 3 shows the simulated differences in summer. The differences in winter have the same sign but are one order of magnitude larger (not shown). **Basin-scale** shallower surface mixed layers result in **the reduced "thermal momentum" of that surface layer (which is in contact with the atmosphere) and result, as described above, in higher (lower) SSTs in summer (winter).**

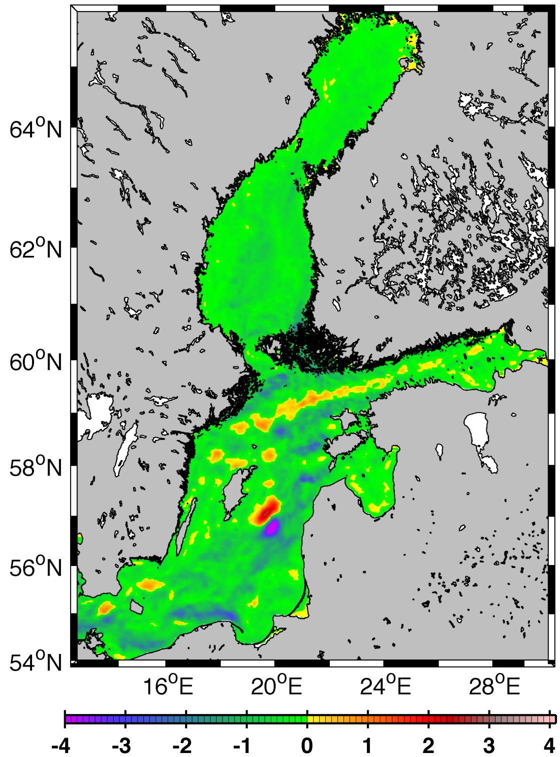

Figure 2. Differences in power driving the oceanic surface circulation in units $\mathrm{m\,W\,m^{-2}}$ (calculated as experiment *REF* - *noCW*, averaged over the simulated years 1989 - 1993). Positive (negative) values indicate that more (less) kinetic energy is supplied to the ocean if surface current/wind effects are accounted for.

3.2 Local effects in upwelling regions

The previous section showed that current/wind effects reduce the overall net **transfer** of kinetic energy to the ocean. **This mechanism is so dominant that, contrary to our initial expectations, current/wind effects reduce basin-scale diabatic transports.**

Fig. 4 shows that the effects are not uniform over the whole basin. Locally, and at times during the season cycle, current/wind effects do drive – consistent with initial expectations – reduced SSTs in summer. Intriguingly this applies especially to what Lehmann et al. (2012) dubbed the Baltic's "... most favourable upwelling region ..." off the southernmost coast of Sweden, off Karlshamn and off the Kalmarsund (marked by the magenta ellipse Fig. 4). An analysis of simulated local air-sea heat fluxes in this region reveals that current/wind effects increase the heat supplied to the ocean by 1 to $5\,\mathrm{W\,m^{-2}}$ (compared to a basin-averaged *decrease* of $\approx 5\,\mathrm{W\,m^{-2}}$). This indicates that locally – indeed – diabatic heat fluxes must be augmented. In order to understand the underlying mechanisms we investigate winds and currents at the southernmost coast of Sweden. The winds blowing over the ocean's surface in these regions are according to Fig. 5 not peculiar: winds in July are typically

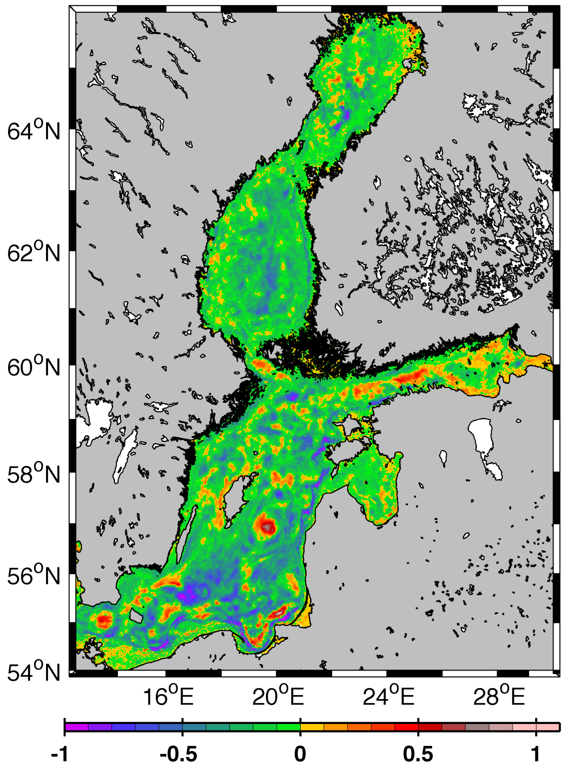

Figure 3. Surface mixed layer depths (as defined by Large et al., 1994, their equation 21) differences in units m (calculated as experiment *REF* - *noCW*, climatological July based on the simulation period 1989 - 1993). Positive (negative) values indicate a surface mixed layer that is deepened (shallowed) when surface current/wind effects are accounted for.

southwesterly with the only irregularities being that (1) the winds are stronger over the sea than on land (and its wake) where surface roughness and associated drag is enhanced, and that (2) the winds' persistencies decreases as they travel **in a north eastward direction** (not shown). What is however peculiar in the region is the distinct anticyclonic circulation in Fig. 6: the currents follow the Swedish coastline on its way to the east and return westwards some 10 nautical miles offshore. These two eastward/westward branches are rather persistent and follow closely the topography (Fig. 7). **Consistent** , with our initial considerations we find that the winds blowing over this coastal anti-cyclonic circulation yield additional upwelling. Expressed as a climatological *Ekman pumping* representative for July the current/wind effects cause an additional local upwelling of $0.2\,\mathrm{m\,day}^{-1}$ (Fig. 8). This increase in *Ekmann Pumping* is reflected in reduced SSTs (mangenta ellipse in Fig. 4).

4 Discussion

Our numerical twin experiment yields results that are apparently inconsistent with **our** initial theoretical considerations (Sec. 1). Based on the persuasive sketch of Martin and Richards (2001) (their Fig. 7) we expected that a proper representation of

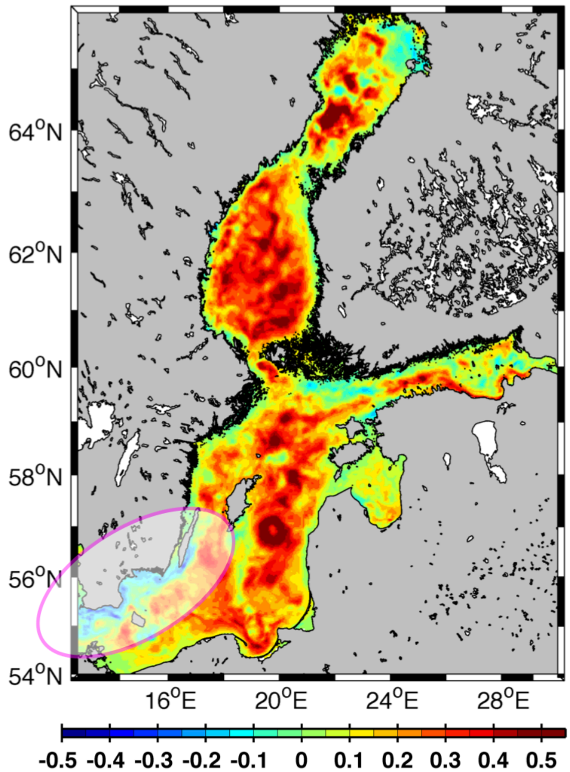

Figure 4. Simulated sea surface temperature differences in units K (calculated as experiment *REF* - *noCW*, climatological July based on simulated years 1989 - 1993). The magenta ellipse encompasses a region off southern Sweden where surface current/wind effects cool the surface.

surface current/wind effects will increase diabatic transport. What we find on a basin scale, however, is the contrary **and** we get apparently less diapycnal mixing. In Sec. 3.1 we reconciled this inconsistency by an argumentation based on energy supply: when surface current/wind effects are accounted for, less energy is transferred to the ocean (c.f. Fig. 2).

An equivalent explanation can be put forward based on wind stress: the climatological, basin-scale wind stress received by the ocean is, on average, less in the configuration which accounts for surface current/wind effects than in the simulation that does not account for this effect (not shown). Here, again, the explanation is associated with the fact that, (even) on a rotating planet, the oceanographic response to wind forcing is typically enhanced surface flow in the direction of the wind (in addition to a perpendicular component). If accounted for in the calculation of wind stress this reduces the stress acting on the ocean. **Somewhat unexpected, this reduction in wind stress and associated reduction in wind-driven up- and downwelling prevails, the eddy/wind effect.** This however holds only for averages in time and space. Locally, and at times, the increased horizontal stress inhomogeneity can drive additional *Ekman Pumping*. We calculated that maximum climatological values peak at 0.2 $m\ day^{-1}$ on the south coast of Sweden. This drives, as initially expected, indeed additional diabatic fluxes, as is indicated by pronounced SST anomalies (particularly in summer). It is noteworthy, however, that the magnitude of actual

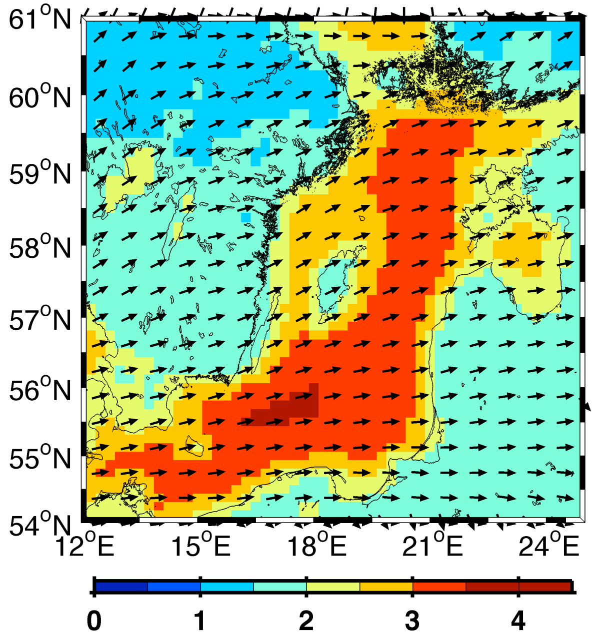

Figure 5. July climatology of the 10 m winds driving the simulations. The calculation is based on 1989-1993 3-hourly snapshots of RCA3 (Sec. 2.1). The arrows show the direction of the winds. The colour denotes the speed in units $\mathrm{m\,s^{-1}}$.

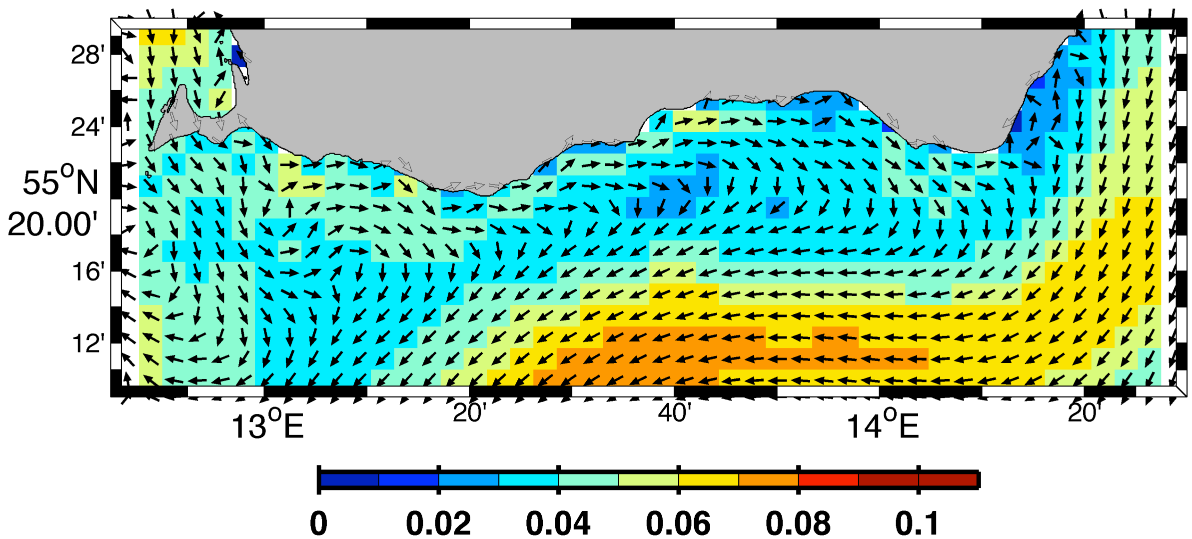

Figure 6. Surface circulation off the southernmost coast of Sweden in summer (climatological July calculated from model output comprising the years 1989 to 1993). The arrows show the direction of the currents. The colour denotes the speed in units $\mathrm{m\,s^{-1}}$.

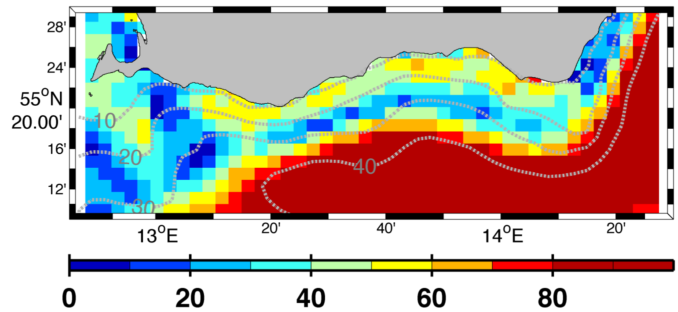

Figure 7. Persistency of surface currents and topography. The colour denotes the persistency of currents **defined as the ratio between vector and scalar mean speeds** corresponding to climatological July in units % (c.f. Dietze et al., 2014, their equation 15). The grey, dashed contours refer to isobaths with 10 m spacing.

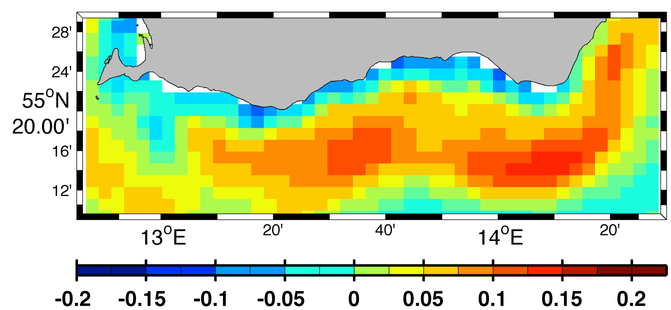

Figure 8. *Ekman Pumping* effected by current/wind interaction (calculated as the difference between experiment *REF - noCW*; climatological July based on simulated years 1989 - 1993) in units $\mathrm{m\,day^{-1}}$. Positive values denote additional upwelling.

vertical velocities calculated from daily averages are unexpectedly small compared to *Ekman* velocities diagnosed from the wind stress. This mismatch between *Ekman Pumping* calculated from the wind stress and actual vertical velocities suggests that some preconditions mandatory for the applicability of the *Ekman Theorie* are violated. Among these preconditions that are not met are (1) the assumption that boundaries have no effect, i.e. *Ekman Theorie* applies only to a waterbody of infinite extend in all three spacial dimensions – a certainly overoptimistic assumption in the shallow marginal Baltic Sea. (2) The theory assumes a viscosity that is constant with depth – an assumption certainly violated given that the KPP boundary layer parameterisation (Large et al., 1994) which is applied in our simulations has been specifically designed to reproduce observed *non*-constant vertical profiles of diffusivities and viscosities.

Our model results show that accounting for current/wind effects does not drive any additional near-surface **net** diapycnal transport on a basin-scale. This is somewhat unexpected because our initial theoretical considerations suggested increased wind-induced upwelling and downwelling events (**which - in combination with air-sea buoyancy fluxes - would have resulted in net diapycnal transports**). This does not imply that current/wind effects are irrelevant. It merely means that the physically less plausible formulation of not accounting for them does not necessarily underestimate diapycnal fluxes because antagonistic effects are at play: on the one hand surface current/wind effects reduce the kinetic energy supply to the ocean, and at the other hand these effects increase wind stress curl and associated vertical transports. Getting more specific, we can now (based on our analysis of air-sea heat fluxes, kinetic energy supply, surface mixed layer dynamics, SST, surface currents and winds) pigeonhole ocean circulation model configurations into the following classes:

– **Coarse & no current/wind effect:** Eddy permitting Baltic Sea model configurations have only recently become computationally feasibly. Elder configurations do neither resolve eddies nor small-scale near-coastal circulation patterns. Additional simplifications in some of these configurations do comprise the neglect of current/wind effects in the wind-stress calculation. Insights gained in the present study suggest that these configurations (1) overestimate the supply of kinetic energy to the ocean, and (2) underestimate the horizontal inhomogeneity of the wind stress and its associated *Ekman Pumping*. As these spurious effects oppose one another the sign of the net effect on diapycnal transport is unclear. It is, however, evident that this class of configurations misses the substantial modulation of upwelling by the interaction of persistent near-coastal current features with the winds at major upwelling sites.

– **Coarse & current/wind effect:** Some of the elder coarse-resolution model configurations may include the representation of surface current/wind effects in their calculation of the wind stress. These configurations do not overestimate the supply of kinetic energy to the extent the latter class does. The overall *Ekman Pumping* is however – owed to the coarse resolution – still underestimated. Thus we speculate that the net effect on basin-scale is an underestimation of diapycnal fluxes. As concerns major upwelling sites, the modulating effects of persistent small-scale topographically-steered circulation (as described above) is not resolved.

– **Eddies & no current/wind effect:** Most contemporary model configurations strive to resolve the mesoscale. However, not all do explicitly account for current/wind effects. Among the reasons for the neglect are: (1) Increased computational performance (in cases where the calculation of the wind stress is performed by a coupler between the ocean and the atmospheric winds, these couplers can significantly increase wall-clock times). (2) Pragmatic avoidance of subtleties associated with the coupling: eddy-rich configurations are inherently non-linear. Taking current/wind effects into account adds another level level of non-linearity. The solutions become strongly dependent on the coupling time step and the choice is between small time steps requiring high computational costs and larger time steps resulting in diverging solutions. (3) The notion that the effect of surface currents are neglected because they are typically so much smaller than wind velocities.

  The results in Section 3 suggest that these configurations overestimate the supply of energy and momentum supplied to the ocean. In turn, the energy available for diapycnal mixing is unrealistically high. This effect, however, is partly counterbalanced by spuriously reduced *Ekman Pumping*. As regards major upwelling sites, these configurations do resolve the near-coastal, persistent small-scale circulation. Its local effect on *Ekman Pumping* is, however, not considered.

- **Eddies & current/wind effect:** the supply of kinetic energy and momentum to the ocean is not overestimated. Small-scale circulation patterns modulate the wind-induced up- and downwelling. The agreement with SST data is extraordinarily good (c.f. Fig. 8, 9 and 10 in Dietze et al., 2014, which show a comparison of *REF* with data).

5 Summary and Conclusion

We set out to explore effects of surface current/wind interaction in an eddy-rich general ocean circulation simulation of the Baltic Sea at a time where the resolution of mesoscale surface currents in the Baltic has just about become computationally feasible. Triggered by theoretical considerations on individual eddies (Dewar and Flierl, 1987; Martin and Richards, 2001), we expected to find enhanced basin-scale diabatic transports effected by increased wind stress curl and associated *Ekmann Pumping*. Contrary to our expectations we find in our general ocean circulation model simulations that the major, prevailing effect of accounting for current/wind interaction is a large-scale reduction in the overall net supply of kinetic energy to the ocean. **This reduction of energy supply limits the amount of energy that is available for mixing dense water upwards (and light water downward). As a consequence of the reduced diabatic mixing we find shallower surface mixed layer depths and large-scale surface warming (cooling) in summer (winter).**

Locally, however, the pattern is reversed and apparently in-line with our initial considerations: an analysis of winds and currents around the southernmost coast of Sweden (off Karlshamn and off the Kalmarsund) reveals a relatively persistent anti-cyclonic circulation. Consist with the argumentation of **Dewar and Flierl** (1987); Martin and Richards (2001) **concerning the effects of surface currents on *Ekmann Upwelling* these coastal anti-cyclonic surface currents effect an additional upwelling that is dominant and persistent enough to drive distinct local SST anomalies in summer.** The climatological magnitude of these anomalies is around 0.5 K and as such is prone to affect the formation of sea fog in those regions. Yet another effect of the upwelling of cold subsurface waters is associated with strong vertical gradients in nutrients such as phosphate and nitrate which are essential for autotrophic growth. During summer the sun-lit surface of the Baltic is typically depleted in these nutrients and all phytoplankton growth is impeded. Upwelling of cold subsurface waters which are enriched in nutrients do thus drive additional phytoplankton growth.

We conclude that surface current/wind effects are significant. Basin-scale effects correspond to ≈ 0.1 K. Local, climatological effects may be reversed and peak at ≈ 0.5 K. The timing in summer, when oligotrophic conditions prevail, in combination with the substantial magnitude suggests that local current/wind effects exert significant control on the complex biogeochemical cycling of the Baltic Sea.

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