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Upwelling characteristics in the Gulf of Finland (Baltic Sea) as revealed by Ferrybox measurements in 2007–2013

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Response to Anonymous Referee #1

This study presents ferry observations of T and S in the Gulf of Finland. The data is used to document upwelling on both the north and south coasts. However, their findings agree with results by Lehmann et al. (2012). Their explanation why the southerly upwelling coincides with less wind stress than the northerly upwelling was also suggested by Liblik and Lips (2015). Thus, it is unclear what NEW findings this paper contributes, apart from publishing fascinating ferry observations.

Response: We tried to be more clear in specifying what are the new findings. First, our results do agree with findings of Lehmann et al. (2012) but only if remote sensing is regarded. The results differ from the modelling results presented by Lehmann et al. (2012) as well as by Myrberg and Andrejev (2003). One of the main findings of the paper is that upwelling events occur with similar frequency and intensity along the both coasts although the prevailing wind forcing would suggest more upwelling events along the northern coast. Major difference in comparison to Liblik and Lips (2015, submitted manuscript) is in the focus and used data sets. Here we use very large number of cross-gulf profiles but do not use the data of vertical sections analyzed by Liblik and Lips (2015). In the present paper, upwelling statistics/characteristics in the surface layer is analyzed while in Liblik and Lips (2015), main focus is on vertical thermohaline structure across the gulf. The results of these two papers support each other.

Spatial gradients in wind stress also cause up or downwelling (Ekman pumping). The authors have access to model wind data. Can this data be used to compute Ekman pumping and compare it with coastal upwelling?

Response: It is not a subject of the present study, which is focused on coastal upwelling events. The spatial resolution of the atmospheric model is more than 10 km while we are interested in processes in sea with spatial scales of 10-20 km. Thus, the atmospheric model data used in the study characterize well the local wind forcing but not well enough the spatial variability of it in the gulf with lateral scales of 50-80 km. Furthermore, we assume that the coastal upwelling events dominate here over the Ekman pumping caused by the spatial variability of wind stress (since the gulf is not very wide).

Before this work can be published, I suggest improving on the English and clarity of the paper. The discussion section needs some rewriting. The paper would greatly improve if the authors could make their discussing more physical and possibly correlate their findings with some simple dynamical models and sketches of the upwelling phenomena.

Response: English has been revised for clarity. We also tried to be more clear in highlighting the findings and added some discussion.

Detailed comments:

P6, l16: use ‘avoid sediments’
Response: Done

P7, L7: ‘19 s interval are averaged and recorded as measurements at every 20 s.’ This means that every ~20 samples there is a gap of ~20 seconds (no data)? Please clarify. Are the data interpolated to 20 seconds?
Response: Different sensors collect data with different frequencies but all data are recorded as 20-s average values (19-s is used for data collection and the last second for storing the average values from a 20-s period). No gaps in the data, no interpolation, just averaging.

P8, L14. ‘A failure of the system occurred late August 2012 and therefore the data are not available from September 2012 (since 29 August).’ Till when was data not available?
Response: Data were not available until 18.10.2012; the sentence is rephrased "… data are not available from 29 August until the end of September 2012."

P9 L9 ‘against the daily average temperature values over the entire ferry route’. I find this not very clear. Can you explicitly say that you computed ONE daily mean temperature value, computed over all the recorded temperatures over the entire day. Why did you compute this daily and transect-mean temperature as opposed to a weakly or biweekly mean temperature for each 0.5 km grid cell?
Response: We hope it is explained now better in the revised manuscript. Average temperature for every crossing was calculated and horizontal profile of deviations from that average was obtained.

P9, L14. ‘For each crossing, a sum of negative temperature deviations’. Does this mean that if there was a positive anomaly it was discarded? Please explain. If so, you may get a bias towards upwelling, if all but one of the 40 cells is positive?
Response: Yes, positive deviations were discarded. It is done intentionally, assuming that the use of average values of the crossing gives slightly lower intensities of upwelling than in reality (since temperature in the upwelling area is taken into account when calculating the average value) and summing up only negative values (and excluding positive ones) compensates this.

P10, L3. How did you define n1 and n2? What is the end of the upwelling cycle? You cannot have positive UIs, so n2 occurs when CU become zero? I suggest being clear about this.
Response: It is explained in the next paragraph – we used a threshold of 40 °C that corresponds to a situation when a negative temperature deviation of 1 °C was in the entire 20-km wide area.

P10, L24. You use model data, but then only model data that is located close to a meteo station that is ~50 km from the ferry transect. Why not use an area averaged wind speed locally at the ferry transect? In this paper you ignore the effect of Ekman pumping: vertical velocity w=1/f*(dtau_y/dx - dtau_x/dy), where tau is the wind stress. The horizontal shear in the windstress may be important, especially near topography. The wind model data would provide insight if Ekman pumping is important relative to coastal upwelling w~V/L, where V = -tau_x/f and L is the distance over which upwelling occurs (in your case~20 km).

Response: It is answered above. The spatial resolution of the atmospheric model is more than 10 km while we are interested in processes in sea with spatial scales of 10-20 km. Thus, the atmospheric model data used in the study characterize well the local wind forcing but not well enough the spatial variability of it in the gulf with lateral scales of 50-80 km. Furthermore, we assume that the coastal upwelling events dominate here over the Ekman pumping caused by the spatial variability of wind stress (since the gulf is not very wide).

P12, l5. 'course'; you mean 'trends'?
Response: We prefer to use the term "seasonal course" meaning an average temperature increase in spring – early summer and a following temperature decrease from mid-August.

P12, l24. In Fig4 you show the mean variability within one day. What is the 'value' of using this metric for such a short time? How does this short time scale relate to the upwelling phenomena? Why not plot the deviation from a longer term mean value which is computed over an upwelling time scale? This short time scale explains why the mean temperature is almost flat. However, it is then confusing why the salinity is changing so fast over this short time scale in (b). I assume the ferry leaves Tallinn and then returns to it at the end of the day. Over this day, on average, the salinity has increased. Can this be a bias in the sensor? This bump in salinity on the south shore coincides with the sheltered part of the transect, west of the peninsula. The upwelling and circulation must be greatly affected by this topography. Can you explain why the salinity mean is positive on the South shore?
Response: It has been misunderstood; we tried to explain it better in the revised text. Figure 4 shows horizontal profiles of mean and RMSE of T and S deviations for all measurements in May-September 2007-2013 (Fig. 4a,b) and separately in 2009 (Fig. 4c,d) and 2010 (Fig. 4e,f). The mean curves correspond to the mean horizontal distributions of T and S for the whole period under consideration (from May to September in all years or in a particular year) where mean values of T and S for the same period were subtracted. The aim of this figure is to show what are the mean temperature and salinity distributions. No bias in salinity. The figures show that, on average, the surface layer salinity is higher near the southern coast and the minimum is somewhere in the northern part of the gulf. RMSE values indicate the temporal variability of T and S deviations (deviations are calculated for each crossing but the RMSE values are estimated for every cell over the whole study period).

P12, l25. Can you explicitly say that the deviation is computed from the daily and transect-mean value? At first, I thought that it was the daily-mean value for each grid cell.
Response: Yes, we made it clear in the revised text.

P15 l 27. 'We also found the total sum of upwelling indexes (divided by 40) off the both coasts regardless whether the set upwelling criterion was met or not.' I do not understand what you mean here.
Response: Upwelling index was calculated for each day as an average index of two crossings. The total sum referred here is just a sum of all index values during the study period divided by 40. We deleted the reference to the threshold that is not relevant here and moved the sentence to the next paragraph.

P17, l19 'However, the average along-gulf wind stress was close to zero indicating that the wind from both directions had almost similar occurrence.' I am not sure if this is correct. This would

apply to a Gaussian distribution, but if the wind blows with -10 m/s for one hour and +1 m/s for 9 hours, the average is close to zero, but the occurrence is not.
Response: We changed the sentence "… indicating that the cumulative wind forcing was almost equal from both directions".

P17, l25. 'It can be concluded that the difference between the wind impulses needed for the generation of coastal upwelling events near the opposite coasts with a comparable intensity in regard of the introduced cumulative upwelling index is related to the average wind stress value in the region.'. It is unclear what the authors are concluding here. Please break up this sentence.
Response: The sentence is shortened: "It can be concluded that the difference between the wind impulses needed for the generation of upwelling events with comparable intensity near the opposite coasts is related to the average wind stress value in the region."

P18, l3 'Daily measurements are too scarce yet to describe the temporal evolution of upwelling events in detail since the inertial period in the Gulf of Finland is approximately 14 h (about half a day).' Please explain the relation between the scarcity of the data and the inertial period.
Response: The meaning of this sentence is that daily measurements would not allow to describe the evolution of the upwelling events in detail since the wind stress could generate the transport in the surface layer in a time shorter or comparable to the inertial period, see e.g. Lehmann and Myrberg (2008) and references therein. We added reference to the mentioned publication (Lehmann, A., Myrberg, K., 2008. Upwelling in the Baltic Sea – A review. *J. Mar. Syst.*, 74, S3-S12).

P19, 8. 'the westward current jet along the front'. Can you provide references or further explanations of the relation between the salinity minimum and the jet?
Response: A reference is added – Laanemets, J., Väli, G., Zhurbas, V., Elken, J., Lips, I., Lips, U., 2011. Simulation of mesoscale structures and nutrient transport during summer upwelling events in the Gulf of Finland in 2006 *Boreal Envir. Res.*, 16A, 15-26.

P20, l5 'the two crossings same day' ... on the same day
Response: Corrected

P20, l20 'but we argue that the analysis of temperature deviations along meridional transects is more appropriate in the Gulf of Finland' ... .. than in Uiboupin and Laanemets (2009)'s study?
Response: It refers to the approach by Lehman et al. (2012) where zonal horizontal profiles were used for upwelling detection. We applied analysis of meridional horizontal profiles and argue that this is more appropriate in the Gulf of Finland elongated from west to east.

P20, l23 'and when using meridional transects the results are not biased by the different temporal dynamics of surface layer temperature in the open Baltic Proper and in the relatively narrow Gulf of Finland. For instance, the seasonal warming and cooling are faster in the gulf than in the open Baltic.' These sentences are unclear and need more explanation.
Response: We tried to be more clear – "This conclusion is justified by the fact that, on average, the north-south temperature gradient is negligible in the gulf (see Fig. 4a) while the west-east temperature gradient could exist between the shallower and narrower Gulf of Finland and the deeper and wider Northern Baltic Proper due to differential warming and cooling."

P21, l7. Use better English: ‘in regard their resolution’
It shows that the models with their current resolution and parametrization of sub-grid processes should be improved. (?)
Response: The sentence is rephrased.

P21, l13: ‘there’ = ‘their’
Response: Done

P21, l16 ‘Partly, this outcome can be explained by the higher position of the thermocline, steeper slope and greater depths in the southern part of the gulf’. Please explain to the reader how depth, slope and thermocline explain this outcome.
Response: This statement is made based on findings/suggestions in the referred papers (Väli et al., 2011; Laanemets et al. 2009).

P21, l18 ‘However, one could suggest that the thermohaline structure of the Gulf of Finland is adapted to the general prevalence of westerly-south-westerly winds.’ It would be great if the authors could add some more physics in their discussion why southerly upwelling is linked to weaker winds to the west. A conceptual drawing would also greatly help. Is it that SW winds cause a deeper TC on the south side? As soon as these winds relax and become easterly, the TC bounces up and little more easterly wind is needed to cause even more upwelling? The opposite would be true on the north shore, where more westerly winds are needed.
Response: In general, the thermocline has a shallower position in the southern part of the gulf (Liblik and Lips, 2016). It is related to the prevailing south-westerly winds and freshwater inflow at the eastern end of the gulf. Thus, in cases of winds with the same strength from east and west the upwelling could be seen earlier (and could be more intense) along the southern coast than that along the northern coast. In addition, the south-westerly winds cause eastward transport and north-easterly westward transport in the surface layer of the gulf. Thus, southwesterly winds (although causing upwelling along the northern coast) in general could cause deepening of the thermocline in the gulf and therefore work against the upwelling development. We added relevant text in the revised manuscript.

Fig.1. Can you add colorbars, so the reader knows how deep it really is?
Response: Colorbar is added to the Fig 1b.

Fig.3 labels indicating T and S would make for faster reading.
Response: There are labels in the plots.

Fig.5 the small labels are hard to read
Response: Labels are updated.