

Reply to Anonymous Referee #1

General comments:

This article is an interesting study demonstrating the importance of including short-term (hourly) variability in atmospheric CO₂ concentrations in calculations of air-sea CO₂ flux for the Baltic Sea and Danish inner waters. Currently, large-scale air-sea CO₂ exchange estimates for coastal margins and seas are poorly constrained due to large spatial and temporal variability in these environments and a lack of measurements. Past studies presenting estimates of air-sea CO₂ flux both in this study region and in coastal regions generally use low temporal resolution atmospheric CO₂ (i.e., averaged weekly, monthly, or yearly) in addition to low temporal resolution surface ocean pCO₂.

Recent studies have shown that atmospheric CO₂ concentrations can vary significantly over marine areas that border populated regions and/or regions with large fluxes between the atmosphere and terrestrial biosphere. This study uses a model with nests over Europe and northern Europe capable of reproducing variability in the atmospheric CO₂ concentrations on a 16.7 x 16.7 km grid over the study region at hourly intervals. The authors acknowledge that even at this resolution the model underestimates the diurnal variability in atmospheric CO₂ during the Northern Hemisphere summer. The study also provides an estimate for the contribution of air-sea CO₂ exchange for the territorial waters of Denmark to its national carbon budget.

The study region is found to be an annual sink for CO₂ with strong summer uptake partially offset by winter outgassing. The magnitude of the sink from a simulation including short-term atmospheric CO₂ variability is significantly smaller than the magnitude of the sink in a simulation where constant (i.e., monthly averaged) atmospheric CO₂ values are used. The authors indicate that this bias is due in part to diurnal boundary layer dynamics where constant atmospheric CO₂ values are too high relative to observations during the day when wind speeds are typically strongest. The authors emphasize that since diurnal variability in the model is smaller than observed, the magnitude of this bias may be larger than indicated in the current study. The choice of gas exchange parameterization has an even larger impact on the magnitude of the regional CO₂ sink – the parameterization of Weiss et al. (2007) yields a CO₂ sink more than three times greater than a simulation using the Wanninkhof (1992) parameterization. This study represents a contribution to the growing literature on air-sea CO₂ exchange in coastal regions and inland seas.

Reply: We thank the reviewer for pointing out that this is an interesting study. We also thank the reviewer for constructive review. In the following we answer the reviewer point by point and describe the related changes we have made to the manuscript.

p. 4, line 3: What about the impact of short-term variability in atmospheric CO₂ concentrations on large-scale estimates of air-sea CO₂ flux? Are there studies that demonstrate the potential bias of omitting short-term atmospheric CO₂ variability on estimates of air-sea CO₂ flux for the coastal seas as a whole?

Reply: To our knowledge no such studies have previously been conducted.

p. 10, lines 24-26: Wanninkhof (1992) is now out of date (use Sweeney et al. 2007 or another more recent parameterization) – the Sweeney et al. (2007) parameterization was used by Wanninkhof himself in a recent study of global air-sea CO₂ flux (Wanninkhof et al., 2013). See discussion of the gas transfer coefficient (k) in section 3.1 p. 1988-1989 of this paper. The Nightingale et al. (2000) parameterization yields k values for wind speeds from 5 to 10 m s⁻¹ that are close to Sweeney et al. (2007) and could also be appropriate since it is based on experiments conducted close to the study region. The Weiss et al. (2007) parameterization yields k values that are significantly greater than all other parameterizations typically used for open ocean studies; this should be mentioned in the text.

Reply: The choice of using the parameterisation by Wanninkhof 1992 was made, as to be able to compare with results from previous studies within the study area, as many of these have also used this parameterisation (Löffler et al., 2012; Rutgersson et al., 2008; Wesslander et al., 2010). Thus, the uncertainty bound to the choice of transfer velocity parameterisation is for this comparison eliminated. However, we have then tested the sensitivity of the choice of parameterisation by executing simulations, where Nightingale et al. 2000 and Weiss et al. 2007 have been used. N00 and Weiss07 were chosen amongst the many existing parameterisations, as these experiments have been made close to and within the study region. With this said, other parameterisations could also have been applied such as Sweeney et al. 2007, especially since the study by Sweeney et al. 2007 is based on an updated and improved version ocean bomb D14C inventory. We will in any future studies also include this parameterisation.

A few changes will be made in the text:

Change on page 17005 line 9 from:

In the present study we use the parameterisation of Wanninkhof (1992) (hereafter referred to as W92), which is the parameterisation most frequently applied. This transfer velocity is a function of the wind speed at 10 m above the surface (u_{10}) and when normalised to Sc at 20°C in salt water it has the form

To

In the present study we use the parameterisation of Wanninkhof (1992) (hereafter referred to as W92). This parameterisation has been used in many previous studies within the study area (Löffler et al., 2012; Rutgersson et al., 2008; Wesslander et al., 2010), and by using W92 this allows for a direct comparison of the estimated fluxes. W92 is a function of the wind speed at 10 m above the surface (u_{10}) and when normalised to Sc at 20°C in salt water it has the form

Text added to page 17005 line 21:

The parameterisation by Weiss et al. (2007) often yields greater values than other transfer velocity parameterisations; however, it will be applied here, as the experiment was conducted within the study area.

Change on page 17019 line 6-12 from:

The largest uncertainty connected to the estimated air-sea flux is related to the choice of transfer velocity. The results from the VAT simulation presented here were calculated using the parameterisation by Wanninkhof (1992), but model simulations using parameterisation of Nightingale et al. (2000) and Weiss et al. (2007) have also been conducted. With these parameterisations the annual flux for the study area is changed to -667 and -858 GgCyr⁻¹, respectively

To

As to assess the uncertainty connected to the choice of transfer velocity on the estimated air-sea flux model, simulations using parameterisations of Nightingale et al. (2000) and Weiss et al. (2007) have also been conducted. Throughout the seasons the parameterisation by Weiss et al. (2007) gives more extreme values than Nightingale et al. (2000), but the annual sum for the study area results in -667 and -858 Gg C yr⁻¹ for Nightingale et al. (2000) and Weiss et al. (2007), respectively. Other transfer velocity parameterisations could also have been interesting to use in the presents study. An example is the parameterisation by Sweeney et al. (2007), which is based on an updated and improved version of the radiocarbon method used in W92. Here, the two different parameterisations by Weiss et al. (2007) and Nightingale et al. (2000) were chosen, as these experiments were conducted within and close to the study area, respectively.

p. 15, line 23: Could indicate the interannual variability in the air-sea CO₂ flux for the study region here and mention whether this is believed to represent method uncertainty or the actual interannual variability.

Reply: Due to the limitation of pCO₂ data for the study area, we have made and used a climatology for the pCO₂. Thus, the inter-annual variability arising will only be a result of the variation in the atmospheric CO₂. Therefore, it is not reasonable to examine the inter-annual variability in the air-sea flux. When more pCO₂ data exists for the study area, the inter-annual variability could be investigated.

Text added to page 17011 line 10

Here, the annual average of 2616 Gg C yr⁻¹ is reported. The inter-annual variability of the estimated flux will solely be a result of the inter-annual variations in the atmospheric CO₂, as a climatology is used for the surface water pCO₂, due to the limited amount of data.

p. 20, lines 9-10: Isn't there a reduction in winter outgassing in the CAT simulation relative to the VAT simulation (i.e., seen from comparison of Fig. 3b top left panel and Fig. 8)?

Reply: yes, the outgassing is reduced in the CAT simulation relative to the VAT simulation. And yes, there has been made a mistake in text here.

The text on p. 20 line 9-10 will be change from

The deviation between the two simulations in the study region is mainly caused by a reduction in the winter uptake in the CAT simulation
To

The deviation between the two simulations in the study region is mainly caused by the reduced winter outgassing in the CAT simulation relative to the VAT simulation.

p. 22, line 16: Since the Nightingale et al. (2000) gas exchange parameterization typically yields smaller k values (except at wind speeds lower than 4 m s⁻¹) in comparison to Wanninkhof (1992) I would have thought that the magnitude of the uptake using N00 would be smaller than the simulation using W92. I also would have thought that the magnitude of uptake calculated using the Weiss et al. (2007) parameterization would have been nearly twice that calculated with N00.

Reply: The seasonality in the surface water pCO₂ allows for uptake of atmospheric CO₂ during summer and release of CO₂ to the atmosphere during winter. Using N00 gives smaller release of CO₂ during winter than W92, and a smaller uptake during summer. However, on an annual net basis the total flux sums up to give a greater uptake when using N00 than W92. The same is the case for N00 vs. Weiss, where using Weiss results in greater uptake during summer than when using N00, and greater release of CO₂ during winter. On a monthly basis the deviation between the two parameterisations is on average 35%, but because of the sign difference in the flux during the course of the year, the difference of net annual flux between Weiss and N00 is only 22%.

To make this more clear in the text we have changed the text on page 17019 line 6-12 from:

The largest uncertainty connected to the estimated air-sea flux is related to the choice of transfer velocity. The results from the VAT simulation presented here were calculated using the parameterisation by Wanninkhof (1992), but model simulations using parameterisation of Nightingale et al. (2000) and Weiss et al. (2007) have also been conducted. With these parameterisations the annual flux for the study area is changed to -667 and -858 GgCyr⁻¹, respectively

To

As to assess the uncertainty connected to the choice of transfer velocity on the estimated air-sea flux model, simulations using parameterisations of Nightingale et al. (2000) and Weiss et al. (2007) have also been conducted. Throughout the seasons the parameterisation by Weiss et al. (2007) gives more extreme values than Nightingale et al. (2000), but the annual sum for the study area results in -667 and -858 Gg C yr⁻¹ for Nightingale et al. (2000) and Weiss et al. (2007), respectively. Other transfer velocity parameterisations could also have been interesting to use in the presents study. An example is the parameterisation by Sweeney et al. (2007), which is based on an updated and improved version of the radiocarbon method used in W92. Here, the two different parameterisations by Weiss et al. (2007) and Nightingale et al. (2000) were chosen, as these experiments were conducted within and close to the study area, respectively.

Technical/grammatical corrections/suggestions:

Reply: all grammatical corrections have been implemented. When suggestions of re-writing and additions to the text have been made, the changes can be seen accordingly below.

Throughout paper: Could use "pCO₂surf" to represent surface ocean pCO₂

Reply: pCO₂^w has been used throughout the paper for the surface ocean pCO₂.

p. 2, line 19: "Biogeochemical" should be "biogeochemically"

p. 3, line 4: "though" should be "through"

p. 3, line 28: Could change "not always can be ignored" to "can't always be ignored"

p. 3, line 29: For clarity, indicate that uncertainty in the transfer velocity is much greater than the uncertainty related to temporal variability in atmospheric CO₂.

Reply: a sentence has been added here with, thus

Further, Rutgersson et al. (2008) note that the uncertainties connected with the transfer velocity are much greater.
has been changed to

Further, Rutgersson et al. (2008) note that the uncertainties connected with the transfer velocity are much greater than uncertainties related to temporal variations in atmospheric CO₂

p. 4, lines 5-8: Could combine these two sentences. Example: "The present study aims to determine the importance of variability in atmospheric CO₂ concentrations on the net air-sea CO₂ flux of the Baltic Sea and Danish inner waters (which consist of Kattegat, the Danish Straits, Oresund and the Belt Seas)."

Reply: The above suggestion has been implemented.

p. 4, line 12: "resolutions" should be "resolution"

p. 4, line 13: "did" should be "do"

p. 4, line 16: "details" should be "detail"

p. 4, line 19: "in" should be "for"

p. 4, line 24-26: This description of the organization of the paper could be omitted.

p. 5, line 3-4: It's already been indicated that the Danish inner waters consist of Kattegat and the Danish Straits. Could simply state: "The marine areas investigated in this study are shown in Fig. 1."

Reply: The above suggestion has been implemented.

p. 5, line 9: "relative" should be "relatively"

p. 5, line 10: "low-saline" should be "low-salinity"

p. 5, line 11: "high-saline" should be "high-salinity"

p. 5, line 23: No need to capitalize "Northern" (This is the case when direction refers to a general area)

p. 6, line 23: "Kortzinget" should be "Kortzinger"

p. 8, line 3: "month" should be "months"

p. 8, line 5: "value increase," should be "increases" with no comma

p. 8, line 7: "particularly" should be "particular"

p. 8, lines 10-11: Could rewrite sentence for clarity.

Reply: Page 17002 line 1-2 is changed from:

In general a good accordance between the pCO₂ values calculated from the monitoring stations and underway pCO₂ data from the sub-domains exists.

To

The calculated pCO₂ values at the monitoring stations agree well the underway pCO₂ data

p. 8, line 22: "use" should be "uses"

p. 9, line 3: delete “in the present study”

p. 9, lines 5-6: No need for a new paragraph for this statement.

p. 9, lines 23-24: Could rewrite for clarity. Example: “For the European area, CT values are replaced by a fossil fuel emission inventory ...”

Reply: Page 17003 line 19 – 21 is changed from

CT is for the European area substituted by a fossil fuel emission inventory with a higher spatiotemporal resolution (hourly, 10 km x 10 km) developed by the Institute of Energy Economics and the Rational Use of Energy (Pregger et al., 2007).

To

For the European area, the CT values are replaced by a fossil fuel emission inventory with a higher spatiotemporal resolution (hourly, 10 km x 10 km) developed by the Institute of Energy Economics and the Rational Use of Energy (Pregger et al., 2007).

p. 13, line 22: “is contributing” should be “contributes”

p. 13, line 23: Could insert “atmospheric” before “CO2” for clarity.

p. 13, lines 27-29: This sentence should be rewritten for clarity. Example: “In order to investigate the effect of short-term variability in atmospheric CO2 concentration on the air-sea CO2 flux, two different model simulations were conducted.”

Reply: The above suggestion has been implemented.

p. 14, line 17: Insert “the” before “east”

p. 15, line 10: “has” should be “have”

p. 15, line 12: Could also indicate the interannual variability in this section

Reply: see reply to the similar comment above.

p. 15, line 27: “EZZ” should be “EEZ”

p. 16, line 15: “represent” should be “represents”

p. 16, line 17: Replace “Further” with “In addition” or “Furthermore”

p. 16, line 20: “determines” should be “determine”

p. 17, lines 3-5: These two sentences could be combined for clarity

p. 17, line 25: Conclude sentence with a period

p. 18, line 16: Remove “Although,”

p. 18, line 22: Could replace “across the marine areas in focus here.” with “ across the study area.

Reply: The above suggestion has been implemented.

p. 19, lines 8-10: Could indicate the range of annual estimates either here or in section 3 above.

Reply: The above suggestion has been implemented.

p. 19, line 11: Delete “as”

p. 19, line 12: Reference Table 3

p. 19, line 14: Insert “the” before “eddy”

p. 19, line 25: “while” should be “and”

p. 19, line 26: delete “in”

p. 19, line 27: “Additional” should be “Additionally”

p. 20, line 5: insert “in this region” after “annual air-sea CO₂ flux”

p. 20, lines 7-8: This sentence could be clarified since wind speeds are the same in both simulations.

Page 17016 line 19-20 is changed from:

But large differences are also found over open water areas in spite of a less variable atmospheric CO₂ concentration here. The generally higher wind speeds over open water might lead to the large flux difference here.

To

But large differences are also found over open water areas in spite of a less variable atmospheric CO₂ concentration here, i.e. a smaller difference in the atmospheric CO₂ concentration between the two simulations. Despite the small concentration difference, the tendency to higher wind speeds over open oceans leads to the large flux difference here. The same wind fields are applied in both simulations.

p. 21, line 11: “arears,” should be “areas” with no comma

Fig. 3b: Indicate in the caption for this figure that fluxes are from the VAT simulation.

Fig. 7: Indicate in the caption and/or title which simulation (i.e., VAT or CAT) these fluxes represent.

Table 3: Column heading to the far right should be “Present study” or “This study”

Reply to Anonymous Referee #2

General comments:

The manuscript is an interesting study on the sensitivity of the air-sea CO₂ flux to the atmospheric short term variability. The role of the Baltic Sea in the global carbon budget is small, but the research in the area is important, not only locally, but also in understanding the shelf seas in general. The results from the Baltic Sea area have been contradictory, and although the present manuscript does not solve the issue, it is a step forward in understanding the complex system of carbon cycle. The manuscript is well written and the subject is handled in a concise manner.

Reply: We thank the reviewer for the positive and detailed review. In the text below we give a detailed answer to each of the issues raised by the reviewer and present the subsequent changes we have made to the manuscript.

Study area:

16998, line 15. How typical the ice conditions were in the simulated years 2005-2010?

Reply: To clarify this, below text is added to the text.

Added to text page 16998 line 17:

The ice extent in the Baltic Sea during 2005-2010 fluctuated between average conditions in the winter 2005-2006 (ice cover of 210.000 km²), a general mild period in the winters between 2007-2009 (with a minimum ice cover of 49.000 km² in 2007-2008) and a severe winter condition in 2010-2011 where the sea ice extent reached a maximum value of 309.000 km² (Vainio et al., 2011). Thus, there was no apparent trend of the sea ice extent in the simulation period

16999, line 18. How many years of measurements were there? 13? What was the depth of the measurements, both in ships and stations?

Reply: Measurements at the stations are from the period 2000-2012, and measured at 0m-5m depth. Ship-borne measurements are from the period 2000-2011 and are measured at the surface layer.

Text changed page 16999 line 17-19 from:

All available data collected since year 2000 is included in the analysis (Fig. 1). From the two data sets monthly mean values for each sub-domain are determined.

To

All available data collected since year 2000 is included in the analysis (Fig. 1). Hence, measurements from a depth of 5 m from all stations were averaged for the period 2000-12, and underway pCO₂ measurements from the surface layer (surface intake approximately 5m) were averaged for the period 2000-11. From the two data sets monthly mean values for each sub-domain are determined.

Figures 3 and 8 (and S1) show also Lake Lagoda but there is no mention of the data from there in the text.

Reply: Lake Lagoda is as such not included in this study of the air-sea fluxes of the Baltic Sea, and there has therefore not been any focus on the pCO₂ data from this area. A programming feature in the model setup is extrapolating the oceanic pCO₂ values to all marine surfaces that have no pCO₂ values by a nearest neighbour principle. However, as to eliminate the confusion of including Lake Lagoda in the figure, the lake has now been removed from all the figures (see the new uploaded figures 3, 8 and S1). This will not have an impact on the results.

Maybe the weakest point in this and previously published results from the Baltic Sea is the amount of the pCO₂ data available. Only one station in the Bay of Bothnia is not enough to describe the whole area, and it is questionable if the Gulf of Finland can be treated as one area: the conditions can be quite different in the eastern section than in the western section. Although the Baltic Sea can be regarded as "coastal" waters, there can be quite large spatial variations of pCO₂ in the surface water due e.g. upwelling or different biological activity at the coast and open sea areas. It is understandable that the fluxes over the whole Baltic Sea are interesting, but care should be taken in interpreting the whole Baltic Sea as a sink or source, especially when the scarce measurements have to be extended over a large area. The authors have discussed the subject in the Discussion section, which is good, although a more

profound discussion would have been in place. I would still stress that the differences between the two simulations are the most important results in the manuscript. The absolute values are quite uncertain.

Reply: We completely agree that this is a huge limitation. We simply do not have the data, and we believe that it is still valid to make a sensitivity study based on the available data. We have addressed these matters by making a more thorough discussion of the available pCO₂ data in the Baltic Sea (see the alterations made below). Further, it has been stated more clearly in the text that the difference between the VAT and CAT simulations is the main result of our study.

Page 17014 line 10-20 are changed from:

The representation of surface pCO₂ values in the sub-domains by a monthly averaged value does not account for the temporal variability during each month and the spatial variability in the relatively large areas. Also, the inter-annual variability is not accounted for by the average values. However, the simplified description of the conditions in the Baltic Sea in a number of sub-domains is currently the best solution in order to obtain a surface field of pCO₂ that spatially covers the whole model domain for this study. The estimated surface fields of pCO₂ are based on relatively few observations, and therefore, it has not been possible to include neither spatial, nor short-term or inter-annual variability. Although, underway pCO₂ measurements (Schneider and Sadkowiak, 2012) have increased the data coverage in the central Baltic Sea significantly in the most recent years.

To

The representation of surface pCO₂ values in the sub-domains by a monthly averaged value does not account for the temporal variability during each month and the spatial variability in the relatively large areas. The estimated surface fields of pCO₂ are based on all available data, however, the amount of available observations can be considered to be relatively small compared to the large study area - although, underway pCO₂ measurements (Schneider and Sadkowiak, 2012) have increased the data coverage in the central Baltic Sea significantly in the most recent years.

The choice of applying surface map of pCO₂ for six domains in the Baltic of course introduces some biases on the flux estimates, as mechanisms, such as upwelling and algae blooms that act on a smaller spatial scale than the sub-division are not specifically accounted for. It was essential for the present study to obtain a surface map of pCO₂ that covered the entire region, as to be able to study the effect of short term variability in atmospheric CO₂ on the air-sea CO₂ flux within the Baltic Sea region. Despite the possible biases of ignoring short term and small scale variability in ocean pCO₂, the simplified description of the conditions in the Baltic Sea in a number of sub-domains was evaluated to be the best solution in order to obtain a surface field of pCO₂ that spatially covers the whole model domain for the present study.

As to stress that the difference between the two simulations VAT and CAT are the most important findings of this paper, a few alterations have been made:

Page 16994 line 26 –page 16995 line 2 changed from

However, the present study underlines the importance of including short term variability in the atmospheric CO₂ concentration in future model studies of the air-sea exchange in order to minimise the uncertainty.

To

However, as a significant difference of 184 Gg C yr⁻¹ is obtained between the VAT and CAT simulations, the present study underlines the importance of including short term variability in the atmospheric CO₂ concentration in future model studies of the air-sea exchange in order to minimise the uncertainty.

Page 17020 line 11-18 deleted

Page 17020 line 19-23 from changed from

In order to test the importance of short term (hourly) variations in the atmospheric CO₂ in relation to the yearly air-sea flux, two different model simulations have been made. The first simulation includes the short-term variations (the VAT simulation), while the other simulation includes a monthly constant air concentration (the CAT simulation).

To

The importance of short term (hourly) variations in the atmospheric CO₂ in relation to the yearly air-sea flux was tested with two different model simulations. One simulation includes the short-term variations (the VAT simulation), while the other simulation includes a monthly constant atmospheric CO₂ concentration (the CAT simulation).

Page 17021 line 7-11 changed from

The uncertainty in estimating the air-sea CO₂ exchange has many contributions. The largest is found to be the parameterisation of the transfer velocity, which supports previous findings. The present study, however, underlines the importance of including short term variability in the atmospheric CO₂ in order to minimise the uncertainties in the air-sea CO₂ flux

To

Uncertainties are bound to the results in particularly in connection with transfer velocity parameterisation and the applied surface pCO₂^w climatology. However, in the present study with the two model simulations that only differ in the atmosphere CO₂

concentration, a distinguishable difference in the air-sea CO₂ flux is obtained. This, therefore, stresses the importance of including short term variability in the atmospheric CO₂ in order to minimise the uncertainties in the air-sea CO₂ flux.

Results

3.1 Model evaluation

What is the reason for that the weekly means agree better in Fig. 5 than in Fig. 4?

Reply: Figure 4 consists of two stations – one is at a continental site with anthropogenic influence (LUT), the other is a marine site in the Baltic Sea (OST). In Figure 5 the weekly correlations are calculated for three stations; MHD (marine station influenced by the Atlantic air masses); PAL (a continental, but remote station); WES (a station that depending on wind speed both can be influenced by marine air masses and continental/anthropogenic air masses). The lowest weekly correlations are obtained at stations that can be influenced by anthropogenic activities (LUT and WES), and the highest are found at the more remote stations, where anthropogenic influence is much smaller (MHD, PAL). Furthermore, the weekly correlation in Figure 5 is calculated based on data from the period 2005-2010, while the weekly correlation in Figure 4 only is based on one year (2007). The seasonal cycle of the CO₂ concentration will also contribute to the higher weekly correlations in Figure 5.

Please, state clearly what stations represent conditions over land and what over sea.

Reply the following changes will be made:

Page 17007 line 19-21 delete the following sentence:

The site at Lutjewad is on the other hand both influenced by background air from the North Sea and the polluted air from the continent depending on wind direction.

Page 17008 line 11-13 changed from

Flask measurements of CO₂ at F3, the Netherlands (54°51 N, 4°44 E) (van der Laan-Luijckx et al., 2010) are compared to hourly modelled averages (Fig. 5) during the six year simulated period

To

Flask measurements of CO₂ at F3, an oil and gas platform in the Dutch Exclusive Economic Zone of the North Sea approximately 200 km north of the Dutch coast (54°51 N, 4°44 E) (van der Laan-Luijckx et al., 2010) are compared to hourly modelled averages (Fig. 5) during the six year simulated period

Page 17008 line 19-20 will be changed from

...for the three remaining stations Mace Head, Ireland (MHD, 53°20 N, 9°54 W) (Biraud et al., 2000), Pallas-Sammaltunturi, Finland (PAL, 67°58 N, 24°07 E) (FMI, 2013) and Westerland, Germany (WES, 54°56 N, 8°19 E) (UBA, 2014) for the six year period (Fig. 5).

To

... for the two marine stations Mace Head, Ireland (MHD, 53°20 N, 9°54 W) (Biraud et al., 2000) and Westerland, Germany (WES, 54°56 N, 8°19 E) (UBA, 2014), and the remote continental station, Pallas-Sammaltunturi, Finland (PAL, 67°58 N, 24°07 E) (FMI, 2013) for the six year period (Fig. 5).

3.2.1 Variable atmospheric CO₂ concentration

17010 (and 17017). The model underestimates the diurnal variation of the atmospheric CO₂: is there a way to estimate the error caused by this underestimation?

Reply:

3.2.2 Constant atmospheric CO₂ concentration

17011-17012 (and 17016) What is the reason for the difference in pCO₂ between the CAT and VAT, especially during winter? This is not clearly explained. Due to the different signs, Figure 8 is quite difficult to interpret.

Reply: This is now clarified in both the result (3.2.2) and the discussion (4.3) sections. The general idea has been to present the results and explain the figures in section 3.2.2., and then in section 4.3 explain in more details the difference between the two simulations.

Changes in the text page 17012 line 16-24 from:

For both months pCO₂^a_{VAT} fluctuates around the constant pCO₂^a_{CAT}. During the first half of February, a period of anti-correlation between pCO₂^a_{VAT} and u₁₀ is seen. This anti-correlation is greatest during the second week with a weekly correlation coefficient (r) equal to -0.69. During the last week of February, a positive correlation of r = 0.62 between the two is obtained

with wind speeds above 10ms^{-1} and high $p\text{CO}_2$ levels in the atmosphere. In February no clear diurnal cycle is seen in the mixing height, but it seems to follow the pattern of the wind speed with decreases in h_{mix} during periods with low wind speeds and increases in h_{mix} during high wind speeds. The correlation between these two parameters in February is $r = 0.72$.

To

For both months $p\text{CO}_2^{\text{a}}_{\text{VAT}}$ fluctuates around the constant $p\text{CO}_2^{\text{a}}_{\text{CAT}}$. During the first half of February, a period of anti-correlation between $p\text{CO}_2^{\text{a}}_{\text{VAT}}$ and u_{10} is seen. This anti-correlation is greatest during the second week with a weekly correlation coefficient (r) equal to -0.69 . Thus, for this period the episodes of high wind speed tend to dilute the $p\text{CO}_2^{\text{a}}$ levels allowing for a greater $\Delta p\text{CO}_2$ in the VAT simulation than in the CAT simulation. During the last week of February, a positive correlation of $r = 0.62$ between the two parameters is obtained with wind speeds above 10 m s^{-1} and high $p\text{CO}_2^{\text{a}}$ levels in the atmosphere. This gives smaller $\Delta p\text{CO}_2$ in the VAT simulation than in the CAT simulation, which results in greater fluxes in the CAT simulation. In February no clear diurnal cycle is seen in the mixing height, but the mixing height seems to follow the pattern of the wind speed with decreases in h_{mix} during periods with low wind speeds and increases in h_{mix} during high wind speeds. The correlation between these two parameters in February is $r = 0.72$. Hence, in February the $p\text{CO}_2^{\text{a}}_{\text{VAT}}$ levels are dominated by horizontal transport.

Changes in the text Page 17012 line 25 – page 17013 line 2 from:

In July a clear diurnal variability is seen in $p\text{CO}_2^{\text{a}}_{\text{VAT}}$, and an anti-correlation between h_{mix} and $p\text{CO}_2^{\text{a}}_{\text{VAT}}$ is evident throughout the month with the highest anti-correlation during the last week (with $r = -0.72$). In the VAT simulation the so-called diurnal rectifier effect is modelled. The collaboration between terrestrial ecosystems and boundary layer dynamics that act towards lowering $p\text{CO}_2^{\text{a}}$ during the day and increase it during night is known as the rectifier effect. In particular during the growing season the rectifier effect is apparent (Denning et al., 1996).

To

In July a clear diurnal variability is seen in $p\text{CO}_2^{\text{a}}_{\text{VAT}}$, and an anti-correlation between h_{mix} and $p\text{CO}_2^{\text{a}}_{\text{VAT}}$ is evident throughout the month with the highest anti-correlation during the last week (with $r = -0.72$). During July the so-called diurnal rectifier effect is modelled by the VAT simulation. The rectifier effect is most apparent during the growing season and can be described as the collaboration between terrestrial ecosystems and boundary layer dynamics that act towards lowering $p\text{CO}_2^{\text{a}}$ during the day and increase it during night (Denning et al., 1996). Due to the constant level of atmospheric CO_2 in the CAT simulation, the rectifier effect is absent here. This results in a greater uptake of atmospheric CO_2 in the CAT simulation than the VAT simulation during the growing season.

In the discussion section 4.3 page 17016 line 21-27 are change from

The deviation between the two simulations in the study region is mainly caused by a reduction in the winter uptake in the CAT simulation. An optimal situation where higher uptake during winter occurs in the VAT simulation is seen, when high wind speeds coincide with lower $p\text{CO}_2^{\text{a}}$ in the VAT than the CAT simulation. Thereby, $\Delta p\text{CO}_2$ is greater in the VAT simulation than in the CAT simulation. In combination with the nonlinearity of the wind speed in the parameterisation of the transfer velocity, this leads to a larger outgassing of CO_2 in the VAT simulation

To

The deviation between the two simulations in the study region is mainly caused by a reduction in the winter uptake in the CAT simulation. The winter outgassing is reduced in CAT, when the $p\text{CO}_2^{\text{a}}$ of the CAT is greater than the $p\text{CO}_2^{\text{a}}$ of the VAT simulation. Thereby, $\Delta p\text{CO}_2$ is smaller in the CAT simulation than the VAT simulation, and the flux will be reduced. Furthermore, the nonlinearity of the wind speed in the parameterisation of the transfer velocity can amplify this reduction, in particular, when high wind speeds coincide with greater $\Delta p\text{CO}_2$ in the VAT simulation than in CAT simulation (eg. as seen in Fig.9 first week of February 2007). This mechanism must have a significant influence, as it results in a greater winter uptake in the VAT simulation than in the CAT simulation.

With regards to figure 8, a better explanation in the caption could be added, as to make this figure easier to interpret:

In winter both the fluxes in VAT and CAT are positive, but VAT is larger than CAT, and thus the difference is positive. In summer both the fluxes in VAT and CAT are negative, but CAT is numerical larger than VAT, and thus the difference is also positive.

A line explaining the mixing length would be good. Why this parameter was chosen as explanatory parameter?

Reply: The mixing length was chosen as an explanatory parameter, as it can contribute to describe boundary layer dynamics and in particular the height of the boundary layer and the vertical mixing. The influence of the boundary layer on the surface concentration of CO₂ is in particular seen during the growing season.

A line explaining this will be inserted into to text on page 17012 line 9, thus will be changed from
Time series of wind velocity at 10 m, u10, and the atmospheric mixing height, hmix, are also plotted

To

Time series of wind velocity at 10 m, u10, and the atmospheric mixing height, hmix, are also plotted, as to get indications of horizontal transport and vertical mixing.

4.2 Air-Sea CO₂ fluxes

17015. The annual changes have been discussed in earlier studies as well. What about the annual variation in pCO₂ in the surface water? Could it be so large that it would be meaningful?

Reply: The available data of pCO₂ for the study area shows that the annual variations of pCO₂ can be quite substantial. We chose not to look on the influence of annual changes in pCO₂, due to the sparseness of pCO₂ data in the study area, but we made a surface pCO₂ climatology instead. (see also reply to the first reviewer)

4.3 Impact of atmospheric short term variability

7016. The coastal site south of Sweden, why this specific place was chosen? Were the wind directions such that the place represent marine conditions?

Reply: This site was chosen, as it depending of wind direction can be influenced by air masses both form land and sea. This is interesting because we wanted to examine a site, where the atmospheric concentration of CO₂ could vary on a short time scale and also how CO₂ dynamics over land could influence the air-sea CO₂ fluxes.

Text added on page 17012 Line 8

This site is chosen, as it can be influence by air masses from both land and sea, depending on the wind direction.

4.4 Uncertainties

17017, last paragraph. How coastal are the central parts of the Baltic Sea after all? Any proof for this?

Reply: It is not completely clear to us, what paragraph us refereed to here...

We have now tried to specify that with 'coastal', we mean the coastal part of the Baltic Sea, not the central part.

Text change page 17018 line 28 from

Thus, in the present study the fluxes at the near-coastal areas within the sub-domain could be affected by this short term variability, and could possibly modify the total flux for the sub-domains.

To

Thus, in the present study the fluxes at the near-coastal areas within the sub-domain could be affected by this short term variability, and as a result possibly modify the total flux for these sub-domains.

17019. Due to the uncertainties in the distribution of pCO₂ in the surface waters, I am not convinced that the transfer velocity is the largest source of uncertainty. Of course it does not mean that it would not be an important, and still open, factor.

Reply: This is an excellent comment, and yes we agree that the distribution of pCO₂ is a large uncertainty, if not the largest, as is here stated.

Thus the text will be change at page 17019 line 6-15 from

The largest uncertainty connected to the estimated air-sea flux is related to the choice of transfer velocity. The results from the VAT simulation presented here were calculated using the parameterisation by Wanninkhof (1992), but model simulations using parameterisation of Nightingale et al. (2000) and Weiss et al. (2007) have also been conducted. With these parameterisations the annual flux for the study area is changed to -667 Gg C yr⁻¹ and -858 Gg C yr⁻¹, respectively. The present study supports the findings briefly touched upon by Rutgersson et al. (2009), who conclude that the uncertainty due to the value of atmospheric CO₂ is small compared to uncertainty in transfer velocity. We, however, stress that ignoring short term variability in marine and atmospheric pCO₂ introduces a bias in the estimates of the air-sea CO₂ flux.

To

As to assess the uncertainty connected to the choice of transfer velocity on the estimated air-sea flux model, simulations using parameterisations of Nightingale et al. (2000) and Weiss et al. (2007) have also been conducted. Throughout the seasons the parameterisation by Weiss et al. (2007) gives more extreme values than Nightingale et al. (2000), but the annual sum for the study area results in -667 and -858 Gg C yr⁻¹ for Nightingale et al. (2000) and Weiss et al. (2007), respectively. Other transfer velocity parameterisations could also have been interesting to use in the presents study. An example is the parameterisation by Sweeney et al. (2007), which is based on an updated and improved version of the radiocarbon method used in W92. Here, the two different parameterisations by Weiss et al. (2007) and Nightingale et al. (2000) were chosen, as these experiments were conducted within and close to the study area, respectively.

The present study supports the findings briefly touched upon by Rutgersson et al. (2009), who conclude that the uncertainty due to the value of atmospheric CO₂ is small compared to uncertainty in transfer velocity. Introducing a surface pCO₂ climatology in 6 sub-basins adds substantial to the uncertainty, as short term variability in both space and time is ignored in this parameter. However, we have chosen to use the surface pCO₂ climatology, as to get full spatial and temporal coverage of surface pCO₂. This allows us to investigate in the present study of the effect of short term variability in atmospheric CO₂ concentration on the air-sea CO₂ flux.

Figures

Figure 1. The yellow lines in the Gulf of Bothnia and the eastern Gulf of Finland are hard to see. It might be good to add the places given as coordinates in the text to the figure.

Reply: We have increased the size of the yellow bullets so it is easier to see.

Figure 2, panel e. The red dots are not visible. Could the panels be arranges so that a and b, c and d are side by side? Now the panels are quite small.

Reply: The red dot is visible now (only from a single month). We have kept the panels in one column so the seasonal variation is easy to compare among the different areas.

Figure 4. Please use same y-scale in both panels.

Reply: the y-scale is now the same. Please see the uploaded figure.

Figure 5. Please use same y-scale in all panels. "2005-2011" should be "2005-2010" in the caption.

Reply: The y-scale is now the same, and the caption has been changed. Please see the uploaded figure.

Figure 7. This is the VAT simulation?

Reply: yes, and this is now specified in the caption.

Supplement

Figure S1. The year should be 2005, I believe. The figure is not referred to in the text, though.

Reply: The year is 2005, and the text is now referred to in the text

Text change on page 17001 line 11 from

(Fig. 2, Table S1 in the Supplement)

To

(Fig. 2, Table S1 and Fig. S1 in the Supplement)

Typos

Loffler et al. 2012 in the text and reference list: use the Scandinavian letters in the authors' names.

Reply: This has now been corrected throughout the paper.

Bothnian Bay should be the Bay of Bothnia.

Reply: This has now been corrected throughout the paper.

16999, line 15: the Bothnain Sea -> the Bothnian Sea 17010, line 16: the Bothnain Sea -> the Bothnian Sea

17017, line27: arears -> areas

Reply: All the typos have now been corrected.