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 issued 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 km^2 (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 pCO_2 that spatially covers the whole model domain for this study. The estimated surface fields of pCO_2 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 pCO_2 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 CO_2 on the air-sea CO_2 flux within the Baltic Sea region. Despite the possible biases of ignoring short term and small scale variability in ocean pCO_2, 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 CO_2 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 CO_2 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 CO_2 in relation to the yearly air-sea flux, two different mode 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 CO_2 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 CO_2 concentration (the CAT simulation).

Page 17021 line 7-11 changed from

The uncertainty in estimating the air-sea CO_2 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 CO_2 in order to minimise the uncertainties in the air-sea CO_2 flux

To

Uncertainties are bound to the results in particularly in connection with transfer velocity parameterisation and the applied surface pCO_2^w climatology. However, in the present study with the two model simulations that only differ in the atmosphere CO_2

concentration, a distinguishable difference in the air-sea CO_2 flux is obtained. This, therefore, stresses the importance of including short term variability in the atmospheric CO_2 in order to minimise the uncertainties in the air-sea CO_2 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 station; MHD (marine station influences by the Atlantic air masses); PAL (a continental, but remote station); WES (a station that depending on wind speed both can be influences 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 influence by background air from the Norht Sea and the polluted iar from the continent depending on wind direction.

Page 17008 line 11-13 changed from

Flask measurements of CO_2 at F3, the Netherlands (54°51́ N, 4°44́ E) (van der Laan-Luijkx et al., 2010) are compared to hourly modelled averages (Fig. 5) during the six year simulated period

To

Flask measurements of CO_2 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°51́ N, 4°44́ E) (van der Laan-Luijkx 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°20́ N, 9°54́ W) (Biraud et al., 2000), Pallas-Sammaltunturi, Finland (PAL, 67°58́ N, 24°07́ E)(FMI, 2013) and Westerland, Germany (WES, 54°56́ N, 8°19́ E) (UBA, 2014) for the six year period (Fig. 5).

To

… for the two marine stations Mace Head, Ireland (MHD, 53°20́ N, 9°54́ W) (Biraud et al., 2000) and Westerland, Germany (WES, 54°56́ N, 8°19́ E) (UBA, 2014), and the remote continental station, Pallas-Sammaltunturi, Finland (PAL, 67°58́ N, 24°07́ 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 pCO_2^a_VAT fluctuates around the constant pCO_2^a_CAT. During the first half of February, a period of anti-correlation between pCO_2^a_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. During the last week of February, a positive correlation 20 of r = 0.62 between the two is obtained *with wind speeds above 10ms−1 and high pCOa2 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 hmix during periods with low wind speeds and increases in hmix during high wind speeds. The correlation between these two parameters in February is r = 0.72.*

To

For both months pCO_2^a_VAT fluctuates around the constant pCO_2^a_CAT. During the first half of February, a period of anti-correlation between $pCO_2^a\_VAT$ 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 pCO_2^a levels allowing for a greater dpCO2 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 pCO_2^a levels in the atmosphere. This gives smaller ΔpCO_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 pCO_2^a_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 pCO_2^a_VAT, and an anti-correlation between h_{mix} and $pCO_2^a\_VAT$ 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 pCO_2^a during the day and increase it during night is known as the rectifier effect. In particularly during the growing season the rectifier effect is apparent (Denning et al., 1996).

To

In July a clear diurnal variability is seen in $pCO_2^a\_VAT$, and an anti-correlation between h_{mix} and $pCO_2^a\_VAT$ 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 pCO_2^a during the day and increase it during night (Denning et al., 1996). Due to the constant leve of atmosphere 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 pCO_2^a in the VAT than the CAT simulation. Thereby, ΔpCO2 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 CO2 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 pCO_2^a of the CAT is greater than the pCO_2^a of the VAT simulation. Thereby, ΔpCO_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 dpco2 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 then 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 CO_2 is small compared to uncertainty in transfer velocity. We, however, stress that ignoring short term variability in marine and atmospheric pCO_2 introduces a bias in the estimates of the air-sea CO_2 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.