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Interactive comment on "Simulating the atmospheric CO_2 concentration across the heterogeneous landscape of Denmark using a coupled atmosphere-biosphere mesoscale model system" *by* Anne Sofie Lansø et al.

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We would like to thank Reviewer 1 for taking his/hers time to complete the review of our paper and provide very constructive comment that will lead to an improvement of the quality of our manuscript. We appreciate that the reviewer acknowledges our well-structured manuscript. Reviewer 1 points out that our scientific results must be emphasized. This will be accomplished by strengthening the storyline of the manuscript with a deeper focus on coastal vs. land fluxes in the introduction and throughout the manuscript, while incorporating the suggestions made by both reviewers. As both Re-

viewer 1 and Reviewer 2 have asked for additional analysis and figures, we will add a supplement to the manuscript, where some of the new figures will be included.

The general and specific comments and suggestions made by Reviewer 1 will be addressed below, and outlines how the manuscript will be revised.

General comments: 1. This study uses a coupled biosphere-atmosphere model to simulate CO2 surface fluxes and concentrations at a horizontal resolution of 5.6 km. Yet it's unclear whether and to what ex-tent model performance will be improved with this fine resolution. Have you done any sensitivity test with coarser resolutions to show model improvement? Or have you compared results from your simulation to those from global models or regional models? How much are they different in terms of flux estimates and annual budgets?

Reply: To show how the results are improved with the higher spatial resolution we will add the following: Extract the annual CT optimised biosphere Danish flux and compare it the national fluxes obtained by the developed model system. The CT fluxes is 1 degree by 1 degree, while our system has a resolution of 5.6 km by 5.6 km. Moreover, a comparison of the atmospheric concentration at the Risø tall tower site between the main domain and the 3 nests will be included, thus the atmospheric CO2 concentration will be compared for grids with different spatial resolution (from 150 km to 5.6 km). In particular, during the growing season the biosphere will have an impact on the concentrations measured at the tall tower site (see Fig. 1 at the end of this document).

2. The simulated CO2 concentrations are evaluated against only one site in Denmark. It is relevant to include other European sites around the study area if there is any (e.g. MHD) to see: 1) whether the boundary conditions and regional transport are good enough for the nested coupled simulation; 2) whether the high resolution coupled model over Denmark improves representation of CO2 variabilities at those sites.

Reply: Simulated atmospheric CO2 concentrations by the model system have previously been validated for Northern Europe (see Lansø et al., 2015), where comparison to MHD together with other Northern European atmospheric sites showed that the model system was both capable of capturing the boundary conditions and the regional transport. In the manuscript, we will add a new section on atmospheric validation, and include this reference in a sentence:" Moreover, long-range transport and boundary conditions of atmospheric CO_2 concentrations have previously been shown to be well captured by the model system in and around the study area (Lansø et al., 2015)."

3. The authors attribute uncertainties in simulating CO_2 surface fluxes using SPA to PFT-specific parameters regulating carbon allocation and turnover, as well as accuracy of PFT maps (especially agricultural-related landcover types). Have you examined whether the cli-mate drivers and wind fields simulated by DEHM are in good quality? How much uncertainty in these variables?

Reply: The meteorological fields used to drive the DEHM model are provide by the WRF model, which is a highly used model with a worldwide community of registered users (https://www.mmm.ucar.edu/weather-research-and-forecasting-model. DEHM and its meteorological drives have previously been used in well validated air pollution studies (see e.g. Im et al., 2018). We will include a new section on the atmospheric drivers and a validation of these in order to shed light on these questions. An example from the analysis can be seen in the Fig. 2, which shows that 2 m temperature is well captured with R^2 of above 0.92 for 9 measurement sites.

4. In Section 4.3, the authors discuss the reasons why signals from the Roskilde Fjord system is not detected. While there are certainly representation errors in terms of grid size and uncertainties related to surface water pCO_2, another important source of uncertainties comes from transport errors. For example, the vertical resolution of DEHM is only 29 layers, which is rather coarse compared to its horizontal resolution. And the physical schemes related to boundary layer mixing are probably not capable to capture the land-sea breeze and diurnal variations of boundary layer height. This should be addressed and discussed in the manuscript.

Reply: In DEHM approximately 10 of the 29 vertical layers are in the boundary layer. The diurnal variability is well captured, which can be seen in Fig. 1 in the end of the document, which will be included in the manuscript. We agree that air-sea breezes most likely are difficult to capture at this scale. We will elaborate on this more in the discussion.

5. For the "Abstract" section, it's too long and the description of the model setup is too detailed, which dilute the scientific message and significance that you would like to convey. An abstract should be concise, well-structured and focus on the most important findings and implication from the study, rather than simply listing the main results.

Reply: The abstract will be shortened and re-written to allow for an emphasize on the main scientific message.

Specific comments: Page 2 Lines 23–26 The statement is not accurate. There are numbers of studies on regional inversions over regions less covered by observational networks compared to US and Europe, like East Asia, South Asia, Amazonia, Siberia, etc., although with larger uncertainties.

Reply: The aim of this sentence was to show that the accuracy of inversions at a higher spatial scale is limited by available measurements. Therefore, only studies within areas of dense observational network was mentioned. As pointed out by Reviewer 1, the wished-for message does not come across this sentence. However, this paragraph will be deleted to allow for space in the introduction to improve the storyline in relation to the coastal vs. terrestrial fluxes.

Page 3 Lines 15–25: Please rephrase this paragraph. The description of the study area should be an independent section (see the next comment). And you should summarize here each section in the fol-lowing manuscript.

Reply: As suggested by the reviewer, we will include a section describing the study area. Thus, all characteristic of the study area will be omitted from this paragraph.

Instead it will be included in a designated section for the study region. We will conclude the introduction with a short paragraph detailing the rest of the content of the paper: “Sect. 2 is dedicated to describe the study region, which is followed by a detailed description and validation of the atmospheric and biospheric model components of the developed model system in Sect. 3 Sect. 4 contains results, while discussion and conclusion follow in Sect. 5 and 6.”

Page 3 Line 26: There should be a section before model setup to describe the study area, including the landcover classification, coastal lines, major cities, important geographic characteristics (e.g., Roskilde Fjord system), etc.

Reply: We will include a section describing the study area including the abovementioned characteristics. Moreover, the description of the instrumentation at the Risø site will be included here in its own subsection: “The study area comprises of Denmark, a country that is characterised by a mainland (Jutland) and many smaller islands all containing varied land mosaic of urban, forest and agricultural areas. With more than 7,300 km of coastline encircling approximately 43,000 km2 of land, many land-sea borders are found throughout the country adding to the complexity. Denmark is positioned in the transition zone between the Baltic Sea and the North Sea. Bordering the Baltic Sea, the Danish inner waters are rich on nutrients and organic material (Kulinski and Pempkowiak, 2011). This fosters high biological activity in spring and summer lowering surface water pCO2 allow-ing for uptake of atmospheric CO2. In winter, mineralisation increases pCO2 (Wesslander et al., 2010), and out-gassing of CO2 to the atmosphere takes place. The North Sea is a persistent sink of atmospheric CO2, where a continental shelf-sea pump removes pCO2 from the surface water and transport it to the North Atlantic Ocean (Thomas et al., 2004). This study uses the Danish exclusive economic zone (EEZ) to estimate the Danish air-sea CO2 exchange, as the coastal state (in this case Denmark) has the right to explore, exploit and manage all resources found within its EEZ (United Nations Chapter XXI: Law of the Sea, 1984). The Danish EEZ is approximately 105,000 km2.

A tiling approach with the seven most common biospheric landcover classification were selected for the current study including deciduous forest, evergreen forest, winter wheat and other winter crops, winter barley, spring barley and other spring crops, grassland and agricultural other, but excluding urbanised areas. The agricultural other landcover classification includes all agricultural that does not classify as grain crop types (winter wheat, winter barley and spring crops), and as such find root crops, fruits, corn, hedgerows and agricultural ‘undefined’ are included in this classification. This classification cor-responds to the actual crop distribution of 2011 (Jepsen and Levin, 2013). Denmark is dominated by agriculture, and more than 60 % of the used classification is agricultural land.”

Subsection on Observations of atmospheric CO2:” On the eastern inner shore of Roskilde Fjord tall tower atmospheric continuous measurements have been conducted at the Risø site between 2013 and 2015. The tower is located on small hill 6.5 m above sea level (Sogachev and Dellwick, 2017). Roskilde Fjord is a narrow microtidal estuary 40 km long with a surface area of 123 km$ˆ2$ and a mean depth of 3 m (Mørk et al., 2016). The city of Roskilde with 50,000 inhabitants is positioned approximaetly 5 km southwest of the site, while Copenhagen lies 20 km east.

The tall tower continuous measurements of atmospheric CO2 concentrations at Risø were made by a Picarro G1301 placed in a heated building. The inlet was 118 m above the surface and the tube flow rate was 5 slpm. The Picarro was new and calibrated by the factory. The calibration was checked by a standard gas of 1000 ppm CO2 in atmospheric air (Air Liquide). During the measurement period from the middle of 2013 to the end of 2015, the instrument showed no other drift than the general in-crease in the global atmospheric concentration.”

Page 4 Line 5: How many vertical layers are there in the planetary boundary layers? Reply: In DEHM approximately 10 of the 29 vertical layers are in the boundary layer. We will add this information to Page 4 line 5: “DEHM has 29 vertical levels distributed from the surface to the 100 hPa surface with approximately 10 levels in the boundary layer."

Page 5 Line 26: It would be better to mark the locations of EC flux sites and the tall tower for CO_2 measurements on a map.

Reply: A map is produced for the study area, where the locations of the EC flux sites and the tall tower are added (see Fig 3 at the of the document). The figure will be included in the section describing the study area.

Page 6 Line 4: How about the model performance on diurnal and daily variations of NEE? As you focused on a storm event during Oct. 19–29, 2013 in section 3.2, it would be better to have an idea of the capability of SPA to capture short-term variabilities.

Reply: A figure showing the diurnal variability of NEE will be included together with a short discussion of SPAs performance at the diurnal scale.

Page 6 Line 10: Why rapid leaf growth in response to environmental drivers would cause a delay in spring photosynthesis?

Reply: We acknowledge that the original sentence can cause some confusion, and thus to better explain, it will be changed from: "The evergreen plant functional type in SPA experiences phenological problems with rapid leaf growth in response to environmental drivers, which causes a delay in spring photosynthesis" To: "The evergreen plant functional type in SPA lacks a labile / non-structural carbohydrate store needed to driver rapid leaf expansion with the onset of spring; instead leaf expansion is dependent on available photosynthate on a given time step. Therefore, SPA's LAI is lower early in the growing season resulting in a biased slow photosynthetic activity and an underestimate in the magnitude of NEE as seen at Gludsted (Figure 1)."

Page 6 Line 25: What's included in "agricultural other"? It seems that it has substantial contribution to monthly GPP and respiration.

Reply: The agricultural other includes all other agricultural that does not classify as one of the grain crop types (winter wheat, winter barley and spring crops). Thus, here

we find root crops, fruits, corn, hedgerows and agricultural undefined. The information will be added to page 6 line 25: "The agricultural other landcover classification includes all agricultural that does not classify as grain crop types (winter wheat, winter barley and spring crops), and as such find root crops, fruits, corn, hedgerows and agricultural undefined are included in this classification"

Page 6 Line 30: What is the altitude of this site? Can you further describe the dominant wind directions for each season (from observations), and potential influences from local pollution and vegetation activity? Again, it would be better to have location of this station on the map.

Reply: The Risø tall tower is located 6.5 m above sea level just on the shore of Roskilde fjord. Unfortunately, we do only have measurement of wind speed and directions for six months, thus it is not possible to extract information on dominant wind direction as it can vary between season and year. But more details regarding local influence at the Risø site will be included in the section describing the study area.

Page 7 Line 3: How much does landcover classification vary over years? Do areas for certain land-cover classifications vary a lot? If not, I would suggest to include the period 2012–2014 as well to calculate GPP, respiration, annual carbon budget, etc.

Reply: The largest variations in landcover classification area are found for crops. The contribution from winter wheat, winter barley and spring crops to the total area covered in grain crops can for each vary with around 10% between years (Statistics Denmark, Statistikbanken). Since the variability only amounts to 10 % we will include the years 2012-2014 in the calculation of GPP and NEE. Therefore, the following line (page 7 line 3) will be deleted: "Given that the land-use classification corresponds to the actual distribution of 2011 an emphasis will be put on the terrestrial fluxes for this particular year during the analysis together with an estimation of the annual Danish carbon budget."

Page 7 Lines 14–24: It would be better to demonstrate the seasonal variations of GPP/respiration and contribution from landcover classifications with plots compared to tables.

Reply: This suggestion will be implemented. See Fig. 4 at the end of this document as an example.

Page 7 Line 16: The monthly contribution should also depend on the productivity of each land classification.

Reply: For clarification the sentence will be changed form: “The monthly contributions to the country-wide total inherently reflect the total area for each land-use class.” To “The monthly contributions to the country-wide total reflect both the productivity and total area for each landcover classification.”

Page 8 Lines 14–17 Better to show the seasonal variations of CO2 fluxes in coastal areas in a figure in the supplementary material.

Reply: We would like to keep the figure of the seasonal CO2 fluxes in the coastal areas in the main part of the manuscript, as we will strengthen the storyline by focusing more on the coastal fluxes vs. the terrestrial fluxes.

Page 8 Line 31 Do you have observations of wind direction and speed corresponding to each CO2 measurements? It would be nice to plot concentration roses also based on observed CO2 and wind datasets, and see if model captures them well.

Reply: Sadly no, we do not have wind velocity and wind direction for the corresponding CO2 measurements. It would indeed have been interesting to plot the concentration roses for the measurements.

Page 11 Line 31: I think it's not precise to say that Roskilde fjord is not in the footprint of the tower. It could be in the footprint of the tower. As you mentioned, the marine signals cannot be seen because they are rather weak compared to land signals, or the current model is not capable to represent the complex topography, surface water pCO2 or transport. And as mentioned in the general comments, there are also uncertainties related to transport errors

Reply: We agree that the current formulation is not precise. It will be changed to: “. . . or (iii) Roskilde fjord is not in the simulated footprint of the tower, or (iv) the fjord only had a minor impact on the atmospheric CO2 concentrations at Risø.”

Throughout the manuscript, the authors use “land-use classifications” to indicate different vegetation types. In my opinion, it would be more appropriate to use “landcover classifications” as “land-use” emphasizes more human-induced influences (see https://oceanservice.noaa.gov/facts/lclu.html). Reply: We apologize for this mash-up. The correction to landcover classifications will be made throughout the manuscript.

Technical corrections: We thank the reviewer for capturing these small errors. All the technical corrections will be conducted.

References

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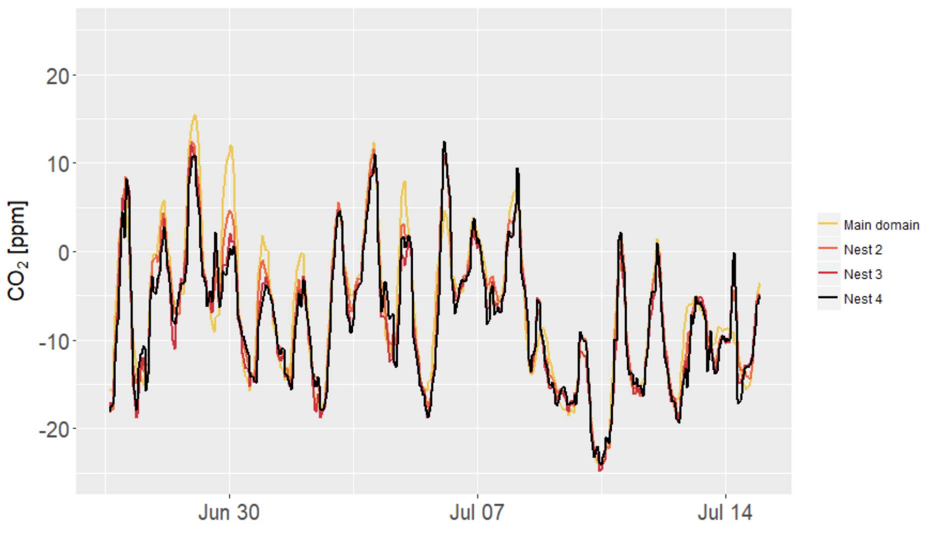

Fig. 1. Simulated atmospheric CO2 concentrations at the Risø tall tower site extracted from the main domain and three nests of DEHM. The rectifier effect is amplified in the main domain of DEHM.

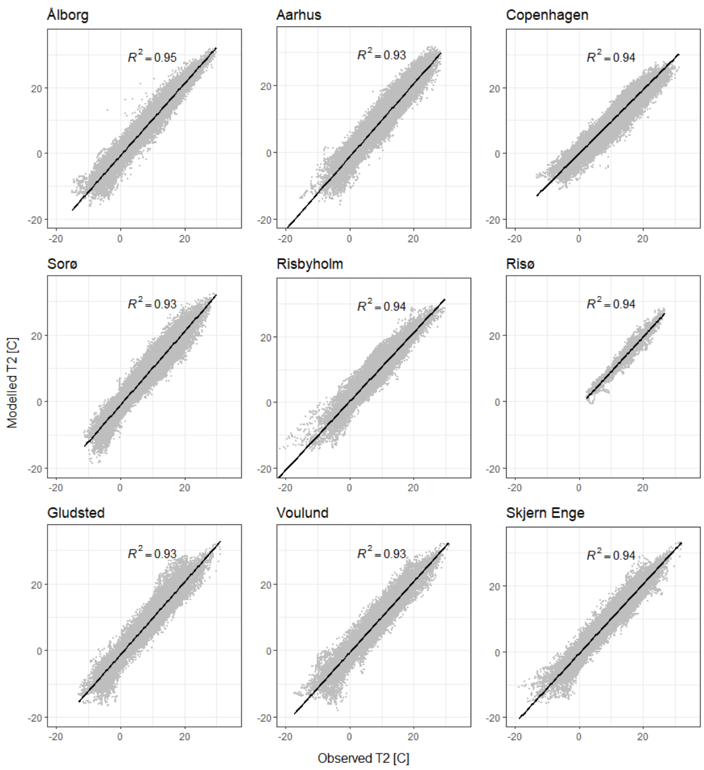

Fig. 2. Scatter plots of measured and modelled 2 m temperature for the five EC sites used in the study, the Risø tall tower site and three additional air pollution monitoring sites.

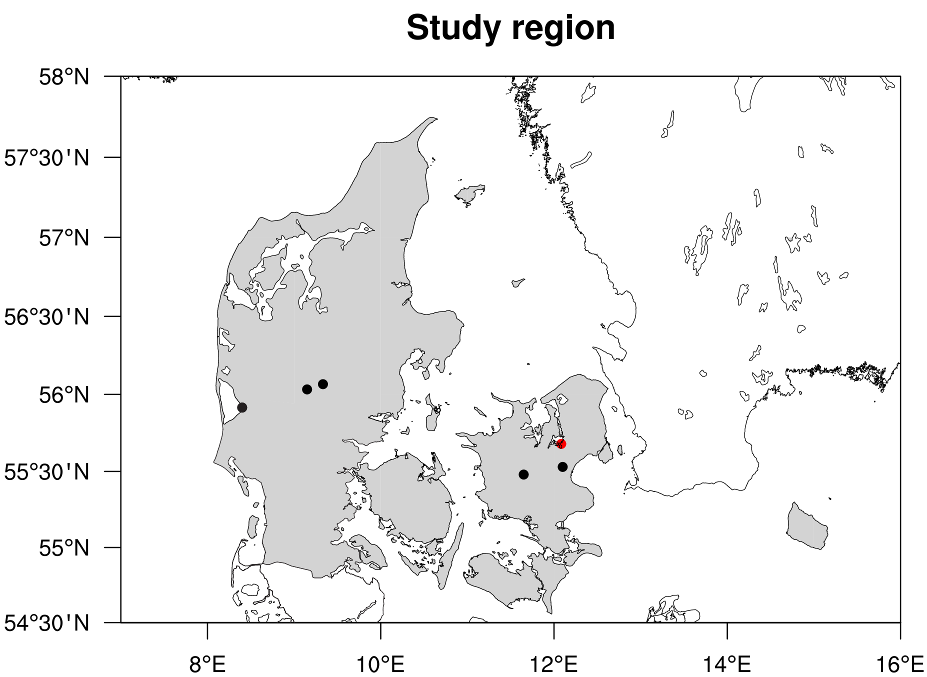

Fig. 3. The study region of Denmark (landmasses in grey) with the location of the five EC sites shown in black and the Risø tall tower site indication red.

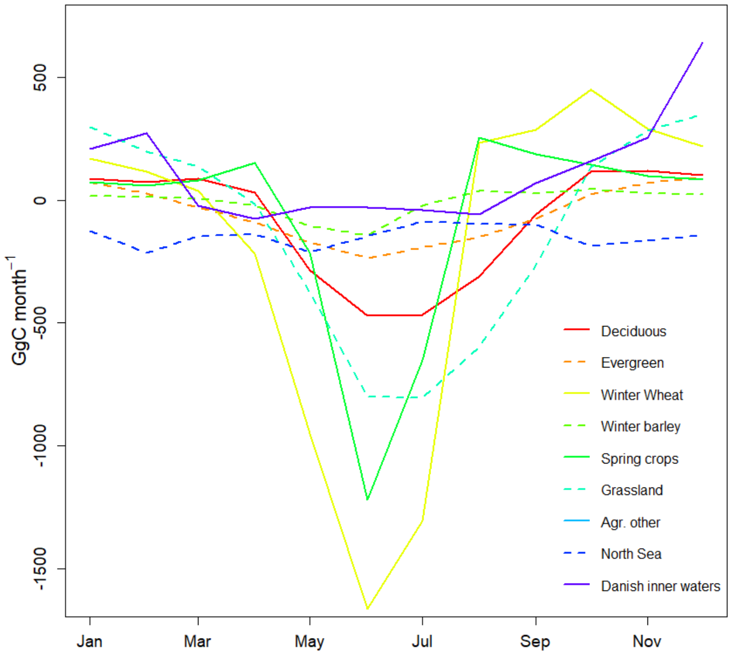

Fig. 4. The total monthly fluxes from the 7 landcover classifications and the fluxes from the marine areas surrounding Denmark. The marine area has been divided into the North Sea and the Danish inner waters