***Reviewer 1***

*We would like to thank reviewer #1 for the detailed review of our manuscript and the thoughtful suggestions that will help to improve our manuscript. In the following, we will answer each of the reviewers comment.*

Zscheischler et al. pull together a variety of surface to air CO2 flux estimates and ask the question "Do these add up to a globally balanced budget?" This is a worthwhile effort, and the authors are using state of the art estimates. As alluded to in the text, the primary goal of this work is to create a combined data product that can be used as input to future data assimilation efforts. Unfortunately, there are vital errors the analysis. Large annual cycles of CO2 flux are taken into account for land, but entirely ignored for the ocean.

*We believe this is a misunderstanding. We do consider annual cycles of all variables – where these were available. In particular, we consider annual cycles over the main fluxes over land* and *ocean. This is also highlighted in Table 1, where the temporal resolution of each dataset is listed. The ocean fluxes are spatiotemporally explicit at monthly time scale and were estimated by Rödenbeck et al (2014) and Landschützer et al (2014) as explained in section 2.2.1.*
*State-of-the-art observation-based estimates of shelf areas and inland waters are however still missing the seasonal representation. This kind of gap analysis is exactly what we intend to do here: demonstrate where we currently miss information to achieve a comprehensive and purely data driven description of the surface-atmosphere CO2 exchange. We believe that this is the best way forward to improve our future understanding and fill these knowledge gaps.*

The authors suggest that they are looking at the full "background" of natural CO2 fluxes, but only consider the anthropogenic perturbation in the ocean. To be correct and consistent with the statements of a full accounting for natural background fluxes, Table 1 and Figure 1 should have large fluxes in the ocean that are of the order of the GPP and TER on land. Furthermore, just assembling these data-based estimates into one with global coverage is not sufficient for publication.

*To the best of our knowledge this is the first critical appraisal of data driven estimates of surface-atmosphere CO2 fluxes, which may be relevant for wide community working in C cycle science. For the ocean we provide estimates of the contemporary carbon fluxes, i.e. a combination of natural and anthropogenic fluxes. Based on surface ocean pCO2 observations the natural and anthropogenic components cannot be separated (see also below).*

The analysis here is too thin, and the findings are poorly presented. Based on how the independent products have been produced, no one should expect that they would add up to a balanced budget – this finding is no surprise.

*Indeed, we don't expect the readers to be surprised that individual components do not close the carbon budget. However, our spatially explicit description of data uncertainty and budget mismatch is of key importance to guide future research efforts. Alternatively, it is crucial to show where the independent products do not add up and where the largest observational knowledge gaps and uncertainties are. Our effort is the first to do this systematically across all components of the surface-atmosphere $CO_2$ exchange global carbon cycle.*

The authors do not do enough to explain what are the major sources of the uncertainty, nor do they do enough to make it clear how they estimate this uncertainty.

*We apologize if we did not achieve a sufficient description of how we estimate uncertainty. To improve the presentation and to make it more clear how we derive our uncertainties, we have made substantial revisions of the text explaining the uncertainty propagation and also included a visual description of the work flow (see new Figure 1 in the revised manuscript and explanation below).*

They need to do a lot more with the products that they have before this manuscript is acceptable for publication.

*We agree that the data we present here would allow much more analysis and we would encourage the community to use the datasets and add additional analysis. Overall, however, we would like to reemphasize that the main aim of this study is not to simply check whether data-driven surface-atmosphere* $CO_2$ *fluxes add up to a balanced budget. Given the difficulties of guaranteeing a consistent and contiguous global C monitoring system, this simply cannot be expected. And the current data-driven knowledge about many of the relevant fluxes cannot compensate this. But – and we find this an important contribution – we provide global spatiotemporal estimates of the net carbon flux combining a variety of heterogeneous datasets and consistently propagate their uncertainties. We have identified regions of high and low uncertainty, guiding new monitoring campaigns and novel scientific approaches to reduce specific uncertainties. Our NCE estimates specify contemporary fluxes over the whole Earth surface, thus including background and anthropogenic fluxes, as explained below. Note also that this paper is not considered a normal Research paper but a Synthesis (see manuscript types of Biogeosciences).*

Major Comments

1. The authors indicate that their goal is to not just address anthropogenic carbon uptake, but to also address the background carbon fluxes (Page 3). Yet their methodology is inconsistent across land vs ocean in this respect. While on land, they separate GPP uptake of CO2 from TER efflux, they completely ignore the comparable cycle in the ocean. See Figure 6.1 of Ciais et al. 2013 (IPCC WG1, Chapter 6) where it is clear that the naturally occurring cycle in the ocean creates an exchange flux of 80 PgC/yr out of the ocean and 78.4 PgC/yr into the ocean; this is comparable in magnitude to the GPP and TER (+-100 PgC/yr), but the authors here simply ignore these ocean fluxes by only presenting their sum. They also appear to ignore these large fluxes in their assessment of uncertainty (though detail on how uncertainty is accounted for is so thin that it is hard for the reviewer to be sure on this point). The full background cycle in the ocean must be included in this analysis must be remedied in this analysis.

*The reviewer is correct that we have only displayed aquatic net fluxes (not only for the open ocean but throughout the whole aquatic system). This is a result of data availability. We also concur that the gross fluxes may have individually larger uncertainties attached to them. We do, however, disagree, that we „ignore“ these fluxes or their uncertainty. The uncertainty of the net flux presented in this study is comparable to other uncertainty estimates such as the IPCC report or the Global Carbon Budget (e.g. Le Quéré et al 2015). The reason for the smaller net uncertainty stems from the correlation between air-sea and sea-air fluxes and their uncertainty. The largest source of uncertainty between individual flux elements (sea-air or air-sea) stem from the gas transfer formulation (see also answer to a more specific comment below), i.e., a systematic source of uncertainty which likewise impacts fluxes in both directions leading to a much smaller net flux difference and attached uncertainty. This is also stated in the caption of the IPCC mentioned by the reviewer: "Individual gross [air–sea exchange] fluxes and their changes since the beginning of the Industrial Era have typical uncertainties of more than 20%, while their differences (Net land flux and Net ocean flux in the figure) are determined from independent measurements with a much higher accuracy (see Section 6.3).*

*Therefore, to achieve an overall balance, the values of the more uncertain gross fluxes have been adjusted so that their difference matches the Net land flux and Net ocean flux estimates."*

*Over land we have used TER and GPP because these fluxes are available at the spatiotemporal grid which we required. This is not the case for the ocean. However, we agree with the reviewer that this is inconsistent. In the revised version, we therefore only used the directly upscaled NEP product from FLUXCOM, which reduces the sample size of the NEP estimates from 16 to 8 (the uncertainty related to the flux separation (split of NEP into GPP and TER) is dropped, as it is not relevant for the uncertainty estimation of the net fluxes). The uncertainty in the upscaled NEP product is 2.1PgC/yr (compared to 3.4PgC/yr when using TER-GPP), which is still much larger than the uncertainty of the net flux over the ocean (0.15PgC/yr). Using directly upscaled NEP leads to similar global mean estimates than using TER-GPP (the difference is <0.7PgC/yr, i.e., <5%).*

*In response to the reviewer's comments we have also added above explanation regarding net uncertainty of ocean fluxes in the text. We do however avoid the term „background fluxes" as this term can be easily confused with „natural fluxes", whereas we cannot separate natural and anthropogenic components. All our flux estimates are the aggregates of natural fluxes and anthropogenic disturbance (i.e. the contemporary flux). We have made this explicit in the introduction by writing "Unlike the GCP global budget of anthropogenic* $CO_2$*, we consider here the full contemporary exchange of surface-atmosphere* $CO_2$ *fluxes."*
*More details regarding the ocean fluxes are added below in direct response to an additional comment by this referee.*

2. A coherent explanation for the large imbalance in the final "budget" is never presented, instead the reader is left is a laundry list (e.g. page 16) of possibilities and no clarity of what the authors have identified as the likely most important uncertainties. It seems quite likely that the large GPP and TER fluxes, or the comparable ocean fluxes, are biased high or low. Their uncertainties are the only ones on the same order as the NCE uncertainty. This issue is even more obvious at the regional scale. This issue should be more directly addressed.

*In the revised version we have more clearly emphasized and discussed the most likely reasons for this imbalance. In our opinion it is most likely a combination of*

*i) a bias in NEP, most probably in the tropics where only very few eddy covariance sites lead to a weak observational constraint (section 4.1).*
*ii) missing sources (as listed in section 4.2), especially emissions from wetlands and VOCs.*

*This was also added to the Conclusion section.*

a. One clear place to do this would be on Page 12, where it is stated that in 13% of their runs, the global C source is consistent with the atmospheric growth rate. If this finding is meaningful, these 13% of runs need to be analyzed and presented clearly so that the reader can understand what is different about them. A simple explanation for the uncertainty in the budget could be that GPP is overestimated by 10%, and if all of these 13% of runs have GPP on the low side, then it would be useful to identify such a pattern.

*In the original version, 13% of the runs were consistent with the atmospheric growth rate only when assuming neutral exchange in tropical forests. In the revised version we use directly upscaled NEP and none of the runs is consistent with the atmospheric growth rate. This is related to the fact that the uncertainty related to flux separation (dividing NEP into TER and GPP) is not included anymore,* *which is more consistent because NEP is measured directly by eddy-covariance towers. In addition the large amount of missing fluxes may also inhibit such a constraining exercise, since the magnitude of these omitted fluxes would largely determine which runs would get selected.*

3. There are many inconsistencies in the data products used here. For example, for the ocean flux the parameterization of gas exchange is Wanninkhof (1992) with ERA-interim winds, but for the shelf it is Wanninkhof et al. (2013) with CCMP winds. These differences could make a significant difference to the ultimate fluxes even though based on the same pCO2 database. On the one hand, this reviewer recognizes that these differences are due to choices made by the providers of these previously-published flux products, and cannot be easily changed by these authors. Nevertheless, some evaluation of these effects should be performed. One possibility for such evaluation could be in the overlap regions of the three products that go into the merged Marine flux field.

*We agree that there are inconsistencies between the data products. As noted by the referee, it is not the aim of the study to re-calculate estimates, but rather bring together existing knowledge. By including inconsistencies between currently available state-of-the-art estimates we also implicitly sample uncertainty. Nevertheless, we have tried to account for many inconsistencies, i.e., we calculated flux estimates at the same spatial and temporal resolution, we have unified the uncertainty calculation procedure, we have recalculated overlap areas to avoid double accounting, etc, but as rightfully noted by the referee, there are still some other sources we have not accounted for. The referee highlights the gas exchange formulation as an example and we concur that this is a factor that has a significant impact on the air-sea exchange of CO2. However, as explained above, the net effect of the gas flux formulation is of lesser importance when the net flux is considered. We would also like to note that while the open ocean estimates use the formulation of Wanninkhof et al 1992, i.e., a quadratic dependency between gas flux and wind speed at 10m, they use more recent gas transfer coefficients (Rödenbeck et al and Landschützer et al scale their estimates to match a mean transfer velocity of 16cm/hr as suggested by Wanninkhof et al 2013). However, we concur with the reviewer that there is an additional uncertainty related to the transfer. In this way, uncertainty in ocean estimates is probably underestimated. This is, however, also true for land based estimates. E.g. in FLUXOM, all models use the same set as predictors. We welcome the suggestion of the reviewer to use the overlap area for testing, however, this overlap area is very local and is biased towards coastal zones. We have added a paragraph at the beginning of section 4.5 discussing this probable underestimation of uncertainty:*

*"Our uncertainty estimates of ocean and land C exchange likely underestimate the true uncertainty. In particular, Landschützer et al. (2014) estimated that the choice of transfer formulation and the $pCO_2$ mapping mismatch (also including other relationships than quadratic) lead to an uncertainty of 37% for the global average over sea-air exchange between 1998-2011, with the majority of this uncertainty stemming from the gas transfer formulation. Furthermore, the uncertainty of NEP is likely underestimated because all upscaling methods in FLUXCOM use the same set of driver data (Tramontana et al., 2016). Hence, the uncertainty estimates only cover the uncertainty related to the upscaling method but does not cover uncertainties related to the selection of optimal drivers or observational uncertainty of the drivers themselves."*

4. The text is difficult to follow, particularly in the discussion and conclusion sections. These sections read as a list of possibilities, without clarity as to what is really important. The authors need to do more to provide this needed clarity.

*We have rewritten large parts of the text to achieve a better readability. We have reformulated the* *discussion and conclusion sections to emphasize and discuss our main results better. In particular, we have added an introductory overview paragraph in the discussion. We have also rearranged the subsections of the discussion according to their relevance. Our conclusions now focus on the following main results:*

i) *Current spatiotemporally explicit observation-driven estimates of surface-atmosphere CO2 exchange are not constrained well enough to close the carbon budget at the global scale.*
ii) *The most likely candidate for inducing the mismatch between data-driven surface-atmosphere CO2 exchange and the atmospheric CO2 growth rate is land NEP, in particular tropical NEP estimates appear to be strongly overestimated (too large sink). Understanding this bias will help designing better upscaling approaches (e.g. by including currently missing relevant drivers) and pinpointing variables that need to be (better) monitored in the future.*
iii) *Regionally, those estimates are partly well constrained and may be used for model-data integration studies and validation of models. These regions include Europe, Russia, South Asia, East Asia, Australia and most oceanic regions. Better constraining C fluxes in regions with currently high uncertainties should be a priority of future research.*

Minor comments
Page 2
- Line 15 “limitations.”

*Thanks.*

- Line 24 Which regions have the large net sink? The authors specify several regions with flux to the atmosphere, then the sum of all is large and negative, presumably due to the tropics. The reader should be able to better understand where this large negative is coming from geographically based on the abstract.

*The large C is over found over most of the tropical land, i.e., Amazon, Congo and Indonesia. We have revised this section in the abstract as follows: “Our NCE estimates give a likely too large $CO_2$ sink in tropical areas such as the Amazon, Congo and Indonesia. Overall, and because of the over-estimated $CO_2$ uptake in tropical lands, our global bottom-up NCE amounts to a net sink of -5.4±2.0 PgC/yr. By contrast, the accurately measured mean atmospheric growth rate of $CO_2$ over 2001-2010 indicates that the true value of NCE is a net $CO_2$ source of 4.3±0.1 PgC/yr.”*

Page 3
- Line 15: "background CO2 fluxes over land and ocean," This analysis only accounts for background fluxes in the land, not in the ocean. Instead this analysis suggests there is no net background ocean flux, only the anthropogenic residual! In contrast to Figure 6.1 of IPCC WG1 (Ciais et al. 2013), this analysis ignores background, natural ocean exchanges. This is a major error that must be remedied.

*We believe that this is a misunderstanding. The provided flux estimate is neither natural nor anthropogenic but the contemporary flux, i.e., a combination of both natural and anthropogenic. All our estimates, both one land and over the ocean, represent this contemporaneous flux. We have made this clearer by revising the sentence about the GCP: “The budget of the GCP focuses on annual values integrated at the global scale. An important point is that the GCP budget quantifies solely the anthropogenic perturbation of $CO_2$ fluxes, i.e., it provides information about the fate of anthropogenic $CO_2$ emissions in natural reservoirs” Furthermore, later on in the introduction we now state “Unlike* *the GCP global budget of anthropogenic $CO_2$, we consider here the full contemporary exchange of surface-atmosphere $CO_2$ fluxes."*

Page 5

- Line 2 What is the meaning of "resampled". Is this averaging of all points in a 1x1 grid? If data are at coarser resolution, what is done? Please be more specific. Show that global mean values of the variables considered are conserved by this method.

*All datasets have at least 1x1 degree resolution (1x1 degree or finer), such that resampling here means averaging to this coarser resolution. All global means are conserved by this averaging (by taking the land-ocean masks into account). We have rewritten this section as:*
*"Each dataset was aggregated to 1 x 1 degree spatial resolution. All datasets have an original spatial resolution of at least 1 x 1 degree such that no information was lost through re-gridding. The temporal resolution is monthly. For datasets that were only available at yearly time scale or once over the complete time period (Table 1), we distributed fluxes evenly across all months."*

- Line 25 "For NCE estimates, we randomly combined all datasets, using a single realization of each flux, to generate an estimate of NCE." What is the meaning of "randomly combined all datasets"? How is this random if all datasets are used? If the "random combination" applies only to the 2 fluxes (ocean and LUC) that have multiple sources according to Table 1, then the result here is an incomplete estimate of uncertainty. More explanation is needed here so that the reader can have confidence in the uncertainty estimate being made.

*The random combination applies always to all fluxes contributing to NCE. That is, we create multiple estimates of NCE by summing up different random combinations of the source datasets on the right side of Eq. 1. Uncertainty is then estimated based on the newly generated NCE ensemble. We have rewritten section 2.1 to better explain how uncertainties were propagated. See also the response to the comment below.*

- Overall it is hard to understand how the uncertainty is propagated. Bits and pieces are mentioned under each of the flux products below, but a coherent picture is not made clear. Perhaps this lack of clarity could be partially remedied with a schematic figure that clarifies how many different realizations of each flux and how the sampling across them is performed.

*We have introduced a schematic figure to better explain how the uncertainties are propagated, as the reviewer suggested (new Figure 1). Each of the 200 NCE ensemble members consists of the sum of randomly selected members of the fluxes contributing to NCE (see Eq. 1). In principle, we could create 10*10*50*8*10*2=800.000 different NCE estimates by combining all the available members (see the #Runs shown in Table 1). We limit ourselves to 200 NCE estimates as a representative sample for the whole distribution due to the prohibitive computational expense of running all 800.000 combinations. All NCE uncertainty estimates are then derived from these 200 runs. This approach implicitly contains information on the spatiotemporal uncertainty structure of the NCE estimates (i.e., the error covariance matrix). In this way, regional or continental NCE uncertainties can be computed by aggregating each of the 200 NCE estimates over the desired region, automatically taking correlated errors into account. This was for example done for Figures 5 and 6.*

Page 6

- Line 16 "schused" is a typo

*Thanks, should be "used" and has been changed.*

Page 8
- Line 15 If the same FLUXCOM product is being used to separate the gpp and ter, the ocean fluxes out vs in should also be separated (Figure 6.1, Ciais et al. 2013). It is inconsistent to take different approaches with land vs ocean, and skews the reader impression of the magnitude of local fluxes and their uncertainty.

*As explained above, in the revised version we have only used the directly upscaled NEP product over land to be consistent and to focus the attention on the uncertainties that are related to the net fluxes only.*

Page 10
- Line 8: A reference for EDGAR is likely warranted.

*As suggested by the EDGAR-Terms of use, we have acknowledged the EDGAR data providers in the revised version.*

- Line 24 "Not all inversions were available till 2010." What is done if this is the case?

*The mean and uncertainty for each year is taken over all available inversions for that year. We have specified this in the revised version in the section on inversions.*

Page 11
- Line 6: That this imbalance is not real, but an artefact of the uncertainty of the data should be made explicitly clear here; not just left for section 4.

*We agree with the reviewer that this statement may be misunderstood. We report the mismatch which is obtained when combining all currently available spatiotemporal data-driven surface-atmosphere fluxes. This statement thus highlights that our current knowledge on C fluxes is not sufficient to close the C budget in this way (i.e., leaving out process-based models). We have added the following comment to this mismatch: "Thus, there is a large mismatch with our NCE, which over-estimates the $CO_2$ sink at the surface by 9.7±2.0 PgC / year. This highlights that our observation-based NCE is biased towards a too large sink."*

- Line 12: "whereas in fact many errors might be correlated as this is clearly the case for GPP and TER." The same statement will almost certainly be appropriate in the case of uncertainty in ocean fluxes, once they are appropriately accounted for.

*This is true (as also argued above). However, in contrast to what the reviewer is implying here, correlated errors lead to smaller uncertainties. As stated above, the uncertainties in the gross fluxes over the ocean are indeed highly correlated, resulting in much smaller uncertainties for the net fluxes (see also the caption of the IPCC figure mentioned by the reviewer). By using the ocean net flux estimates for NCE, these correlated uncertainties are automatically accounted for. As stated before, in the revised version we only used directly upscaled NEP over land. Hence, the comparison of the uncertainties is now consistent and we could omit this statement.*

- Line 22: "Due to the small contribution of the oceans, absolute uncertainties are barely discernible." Comment: This will probably be different once out vs in is considered separately.

*As outlined in our response to the reviewer's major comment above, the net sink uncertainty is in fact much smaller than air-sea and sea-air flux uncertainty, due to the correlation between the uncertainties between the individual components. Using NEP over land (instead of TER-GPP) in the revised manuscript decreases this difference slightly (see Figure 3 in the revised manuscript).*

Page 12
- Line 14 "We use the land cover map of 2005 from the European Space Agency (http://www.esa-landcover-cci.org/) to identify tropical forests (all pixels where broadleaved evergreen trees dominate). " Why use satellite product, when FLUXCOM model is what your estimate is based on. The FLUXCOM land cover product should be used.

*Thank you for this comment, we have now used the land cover map of FLUXCOM.*

Page 13
- Line 3-11: This section overstates the level of agreement with Ciais et al. (in revision). It suggests that Figure 3 illustrates "good agreement" except for a few regions, but when one looks closely, only 5 land regions agree, including Australia that is basically zero, while 4 do not. Overstatement is exemplified by this sentence "Given that Ciais et al. (revision) rely on an independent method, this demonstrates that a good understanding of net C fluxes exists for non-tropical areas, North America excluded." This section should be written more carefully to acknowledge that lack of agreement is as common as agreement.

*We agree with the reviewer and have formulated this more carefully in the revised version, better highlighting the large uncertainties and biases. The revised sentences read "Given that Ciais et al. (revision) rely on an independent method, this demonstrates that a relatively good understanding and observational coverage of net C fluxes exists for EU, RU, AU, and EA to some extent. It is somewhat surprising that both approaches largely differ over North America, where good observational coverage for instance through eddy-covariance towers exist."*

Page 14
- Line 6: NEP should be defined again as its not been defined for many pages.

*Thanks, NEP is now used repeatedly as one of the key variables in the revised version such that there is no need to define it again.*

- Line 23-end: This reads as it may be one hypothesis of many. Or is it a leading one? The reader needs the authors to be more clear.

*This is the leading one. We have emphasized this more in the revised version by starting the sentence with "We suspect that…". To test this hypothesis rigorously, the complete upscaling procedure needs to be redone with including a forest age map as a predictor, which should be done in future research.*

Page 15
- Line 8: "often not too far off but given that different top-down studies using different atmospheric models provide conflicting information on the adjustments needed to align modelled concentrations with measured ones, this information cannot be used to provide clear uncertainty ranges." This is not understandable to someone doesn't work with these models or know this jargon.

*We have rephrased the section regarding uncertainties in fire emission referring to a recent paper on global fire emissions by van der Werf et al, currently in discussion for Earth System Science Data (van der Werf et al., 2017). Here it is stated that assuming 50% uncertainty overall is a best guess assessment, and better quantifying this uncertainty requires an assessment of the burned area estimates as well as new field data on fuel consumption and emission factors. We cannot, however, propagate this uncertainty into the NCE estimates as this would require spatiotemporal error covariance matrices.*

- Line 13 "To better constrain C exchange on a monthly basis, however, the seasonal cycles of those fluxes would be necessary." Comment: Awkward phrasing.

*We have rephrased this statement as "Estimates of the seasonal variation in these fluxes are necessary to better constrain seasonal variations in NCE."*

- Line 23 "at similar latitudes."

*Thanks.*

Page 16
- The degree to which the unaccounted fluxes (list) could be large enough to impact the global "budget" should be discussed. Each of these fluxes should be quantified to the best degree possible so as to put in context with the overall budget. The laundry list approach is not helpful to the reader, particularly when so many of the proposed fluxes are left entirely unquantified, and the authors do not discuss the list at all after it is presented. What is the reader to meant to conclude?

*Thank you for this comment. We have provided estimates for those fluxes, which have been quantified in the past. The remaining fluxes can be assumed to be rather minor, though little is currently known. We have discussed to what degree the missing fluxes affect the obtained mismatch by adding the following paragraph at the end of this section: "All known missing fluxes add up to an additional C release of about 4 PgC / yr. Although substantial, they do not cover the mismatch of more than 9 PgC / yr by far (Sect. 3.1). However, they would suffice to close the budget if tropical forests are assumed to be C neutral (tropical forests are responsible for a net C sink of about 5 PgC / year, Sect. 3.2). This significant amount of missing fluxes prohibits constraining FLUXCOM runs with all the remaining fluxes. In other words, we cannot be certain of the bias in upscaled NEP as long as the major fluxes are not quantified in a spatially explicit manner. Emissions from VOCs and wetlands should thus receive particular attention if a consistent spatiotemporal picture of vertical $CO_2$ exchange is to be obtained."*

Page 17
- Line 14: Regions such as the North Atlantic (Schuster et al. 2013, Biogeosciences) should also be noted as having large uncertainty at seasonal timescales and beyond.

*The RECCAP initiative has shown that the largest uncertainties are in the southern hemisphere, i.e., in Schuster et al 2013, the South Atlantic has shown much less agreement between methods than the North Atlantic when low frequency signals – such as IAV and trends – are considered, whereas, methods generally agree seasonally where the seasonal cycle is dominated by the temperature variability, i.e., subtropics. In general, the ocean RECCAP studies (Sarma et al, Ishii et al, Schuster et al, Lenton et al and Wanninkhof et al) have shown regionally substantial differences between methods, however, few of these papers provide estimates based on observations beyond the seasonal cycle* *(mainly derived from the Takahashi et al 2009 climatology). Therefore, we do believe that our observation-based estimate provides new insight beyond the results from the RECCAP project, yet in turn we agree that our new estimates need to be put in perspective with previous findings. Therefore, we have added a comparison between the ocean RECCAP results and the results from this study. The new figure 6 shows that estimates of mean annual C exchange are consistent for most ocean regions, including the North Atlantic (see also the new section 3.3.2). Only in the Southern Ocean (SO)are the estimates are substantially different. Overall, our estimates have smaller uncertainty ranges, which is to be expected as the RECCAP studies include many more approaches (including process-based models, atmospheric and ocean inversions) in their estimates.*

Section 5 overall:
- This section is also poorly organized. It reads as a listing of issues largely already mentioned prior. It needs to be rewritten to focus on the key findings of this work – What are the take-home messages that the reader should be getting?

*We have rewritten the conclusions by focusing only on topics that we believe warrant the most attention in future research. These topics are highlighted as a response to major comment #4 (see above).*

Table 2: - should note that negative is from the atmosphere.

*Thanks, clarification has been added.*

- If the label is –GPP then GPP should be 108.29 not -108.29

*GPP is always positive. Hence, -GPP should receive a negative number. In the revised version we use NEP instead of GPP and TER. Also here, –NEP gets negative numbers to maintain consistency with all fluxes in the table.*

- A consistent number of significant figures should be used, unless the authors can justify the greater precision of the numbers with 5 significant figures (GPP) as opposed to those with only 2 or 3. This is important because it is uncertainty in GPP that drives most of the NCE uncertainty. The GPP numbers is clearly not actually known to 5 significant figures.

*We use two digits after the comma for all estimates. The uncertainties reported here are not used to calculate NCE uncertainties. Rather, the ensemble of NCE estimates (see response above explaining the uncertainty propagation) is used to estimate this uncertainty. In this way, rounding errors do not propagate through the uncertainty estimation.*

- All numbers should have the same fontsize, or if the different sizes have a meaning, it should be noted

*Thanks, we have corrected this. All font sizes should be equal.*

- The full decomposition of the "marine" should be noted in this table, so as to be consistent with Figure 1

*We list here only those fluxes that are used to estimate NCE (see also Eq. 1). Adding Estuaries and Shelves would be confusing because they don't enter the NCE calculation individually. We added them in Figure 1 (now Figure 2) for completeness. We have made this explicit in the title of the revised* *table.*

- The natural fluxes of the ocean need to be accounted for in a manner comparable to GPP and TER.

*As outlined above, we believe this is a misunderstanding. Our estimate comprises a combination of natural and anthropogenic fluxes, hence we do already account for natural „background" fluxes. Furthermore, as discussed above, we have used directly upscaled NEP in the revised version to be more consistent between land and ocean.*

Figure 1
- The units on the 815 are presumably PgC. This should be noted explicitly on the figure or in the caption.

*We have omitted the amount of carbon in the atmosphere to be more consistent overall and only show fluxes/changes in atmospheric C.*

- The ocean should have two arrows, one in and one out. The picture from this figure should be consistent with Figure 6.1 of IPCC in that both the ocean and the land have a large background, natural cycle on top of which the anthropogenic is superimposed.

*See above, all our estimates account for natural and background fluxes. Over land we have only used NEP in the revised version. Hence we have deleted the arrows related to the gross fluxes over land.*

Figure 2
- The colorbar in panel a is mislabeled as "%"

*Thank you, the label should be gC  m-2 yr-1. Has been changed.*

Figure 3
- The x-axis needs a label

*Thank you, we have added the label "Latitude".*

Figure 4
- What are the circles? Presumably outliers? Clarify in caption.
- The regions indicated by each acronym should be noted in the caption.

*Thank you, yes, the circles are outliers. Due to the use of NEP in the revised version, no outliers appear anymore. We have also explained the acronyms.*

**Reviewer 2**

This paper puts together a wide range of spatially explicit bottom-up surface-atmosphere CO2 flux data sets aiming to reconcile the carbon budget from bottom-up estimation and the atmospheric CO2 growth rate. While this type of research is needed for improving our understanding of carbon cycle, this study has serious flaws in generating the data and is lack of validation and deep analysis of the combined data set. The language is vague in many places. At this stage, I don't recommend publishing the paper.

Major comments:

1. The added value of the new combined dataset is very limited.
The authors simply put different data streams together, and there is no effort trying to harmonize the data, even though some of the datasets do not cover the same time period, e.g., the crops cover 2005 to 2010.

*We strongly disagree with the impression that "there is no effort trying to harmonize… ". On the contrary, we have made major efforts to homogenize the various datasets comprising the current knowledge of spatiotemporally explicit, data-driven surface-atmosphere CO2 exchange. The chosen time period (2001-2010), spatial (1x1 degree) and temporal (monthly) resolution are a compromise arising from the availability of the different datasets. For several datasets, only one (annual mean) estimate for the chosen time period is available, including for Shelves, Estuaries, Rivers, Lakes, Wood harvest and the land use change flux (Eluc). All other datasets cover the entire time period with at least monthly time resolution and an original spatial resolution of 1x1 degree or finer such that resampling does not induce inconsistencies. Crop respiration data was extended backwards through linear extrapolation at each pixel. This is explained on p. 9 line 3. We have highlighted these aspects better at the beginning of section 2 an also introduced a schematic figure to better explain the consistent propagation of uncertainties. Note also that this paper is not considered a normal Research paper but a Synthesis (i.e., the goal is to "summarize the status of knowledge and outline future directions of research", see manuscript types of Biogeosciences).*

2. The paper compares the bottom-up estimations with the top-down inversion results (Figures 3 and 4, section 3.4), but it is lack of discussion about why these two approaches have different results, and which estimation is closer to reality.

*We have added a more in-depth discussion regarding these differences (see revised section 4). We believe that our estimates overestimate carbon uptake in tropical land areas and carbon release in tundra regions. This may explain many of the differences visible in Figs. 4 and 5. For areas where the different estimates converge (mid-latitudes, Europe, Russia, South Asia, East Asia, Australia) we can state with some confidence that we know net carbon exchange. With respect to regions where estimates diverge strongly, an overall judgment which estimates are closer to reality cannot be made given current knowledge.*

3. In section 3.4, it says that "both estimates agree well in the extratropics", but the figure 3d shows that the NCE-FF and atmospheric inversion results also have large differences in the NH high latitudes (between 60N and 75N), with the NCE-FF indicating a source to the atmosphere, while the atmospheric inversion indicating a weak sink.

*We agree with the reviewer and have added more discussion on this point in the revised version. At very high latitudes, in the tundra region, very few flux tower observations are available. Hence the FLUXCOM runs are not well constrained in those regions. In contrast to the tropics where this leads to an unrealistically large carbon sink, in the high latitudes the FLUXCOM runs show a strong source. We have added in section 4.1 "In addition to the above difficulties, some regions are undersampled by eddy-covariance towers and thus NEP is not well constrained. This is the case for tropical forests and the northern high latitudes. In the tropics, undersampling leads to a large overestimation of net $CO_2$ uptake in comparison to inversion and forest inventories (Peylin et al., 2013; Pan et al., 2011) whereas in the high latitudes it leads to a comparably large $CO_2$ release (Figure 4)."*

4. Even though the latitudinal pattern of the inversion results follows a pattern similar to that of the

aquatic fluxes (Figure 3c), there is no direct evidence indicating the propagation of the marine signal into continents during atmospheric inversion. I suggest removing the discussion on the pattern comparison between aquatic fluxes and atmospheric flux inversion results in section 3.4.

*We agree and have omitted this discussion.*

5. Section 4.5 discusses the possible application of the combined dataset in model-data integration studies. It is an interesting idea. However, with such large uncertainties (with more than 10GtC disagreement with the atmospheric CO2 growth rate) in the combined dataset and a mixture of all different carbon flux components, it is not clear how such product can be used in carbon cycle data assimilation that focuses primarily on land carbon fluxes. What is the added value of using such data set compared to directly using flux tower observations? In addition, if such product were to be used as "observations" in a data assimilation system, a rigorous validation against independent observations is needed.

*Our main aim is to exploit the explicit spatiotemporal nature of the NCE flux in tandem with the spatially explicit uncertainties for model-data fusion. The most relevant application would be using these data at the regional scale, as one goal of the study is to pinpoint regions of small and large uncertainties in the NCE estimates. In some regions, uncertainties are so large that nearly no meaningful information on the mean NCE flux can be obtained with currently available observational networks and statistical approaches. This is, for example, the case for many tropical land regions. But, and we see this as a key advantage of our study, the included uncertainties clearly indicate the merit of such a data compilation, especially in contrast to flux tower observations: our study includes all the major fluxes, such as fire emissions, inland aquatic fluxes, tropical land use change estimates, and emissions related to harvested wood and crop products. This is much closer related (and more directly comparable) to the actual net carbon exchange fluxes as they are resolved by inversions (if fossil fuel emissions are omitted). All the datasets used in this study have been validated individually against independent sources, and those studies are referenced in the respective sections. We do not know of any independent observation that can be used to validate the obtained NCE flux at such high spatial and temporal scale. An exception may be inversions and the regional aggregates obtained in the RECCAP synthesis, and we compare our estimates to RECCAP in the manuscript. We have now also included a similar comparison for the ocean regions (section 3.3.2). This comparison shows that the estimates from the synthesis and RECCAP agree well in all regions except the Southern Ocean. At finer spatial and temporal scale, and in some regions, especially the tropics and northern high latitudes, independent trustworthy references are lacking.*

6. In section 3.2, it says that "13% of our runs we obtain a global C source that is consistent with the atmospheric growth rate", what are the spatial distributions of the fluxes from these 13% runs?

*In the original version, 13% of the runs were consistent with the atmospheric growth rate only when assuming neutral exchange in tropical forests. In the revised version we use directly upscaled NEP and none of the runs is consistent with the atmospheric growth rate. This is related to the fact that the uncertainty related to flux separation (dividing NEP into TER and GPP) is not included anymore, which is more consistent because NEP is measured directly by eddy-covariance towers. In addition the large amount of missing fluxes may also inhibit such a constraining exercise, since the magnitude of these omitted fluxes would largely determine which runs would get selected.*

7. L26 (P14): what is the distribution of the different age classes of forests in FLUXNET? Is there solid evidence showing that the year and regrowing forests are overrepresented in FLUXNET?

*So far, this is only a hypothesis and it has not been shown. This hypothesis is a strong candidate in explaining the overestimation of the carbon sink in the tropics. Future research has to demonstrate whether these hypotheses are valid. We have made this clearer in the revised version by writing "Given the difference between NCE and inversions in the tropics (Figure 4), we can assume that a bias of FLUXCOM NEP towards a too high* $CO_2$ *sink is the main reason why the C budget is not closed in our approach. This raises the question why upscaled NEP has such a strong systematic bias towards a sink, particularly in the tropics (see also Jung et al., 2011). We suspect that the eddy-covariance towers collected in FLUXNET, which provide the empirical basis for the global data driven estimates (see Sect. 2.3.1) do not represent the different age classes of forests very well. For instance, young and regrowing forests with a generally higher-than average NEP are possibly overrepresented in FLUXNET. However, such an age-dependency (Amiro et al., 2010; Coursolle et al., 2012; Hyvönen et al., 2007; Magnani et al., 2007) has not yet been included in global upscaling of NEP. This hypothesis should be tested in future upscaling exercises."*

8. Section 3.5 discusses seasonal cycle and monthly variability. It would be helpful to put this discussion in perspective, e.g., comparing to other independent estimations, so that the readers would know the credibility of this result. It is not clear what are the latitude ranges for the NH and SH in Figure 6.

*The ranges are 90 S-0 for SH and 0-90 N for NH. We have now included a comparison with inversions for the seasonal cycle, which are the only independent estimates based on observational data (section 3.5). As annual variability is already compared to inversions demonstrating large discrepancies (Figure 7) we refrain from comparing monthly variability.*

9. Line 6 (p15), what is the basis for the 50% uncertainty?

*Here we refer to a recent paper on global fire emissions by van der Werf et al, currently in discussion for Earth System Science Data (van der Werf et al., 2017). Estimating uncertainties in fire emission estimates is notoriously difficult. Assuming 50% uncertainty for estimated fire emissions is a best guess assessment, and better quantifying this uncertainty requires an assessment of the burned area estimates as well as new field data on fuel consumption and emission factors. We have rephrased this section as "While GFED4 burned area estimates come with regional uncertainty estimates (Giglio et al., 2013), the actual uncertainty of C emissions from fires are probably much larger, on the order of 50% (van der Werf et al., 2017). The uncertainties of fire emission estimates depend regionally and temporally on the various input data sets such as burned area, small fire burned area, biomass loadings, and combustion completeness. Better quantifying this uncertainty requires an assessment of the burned area estimates as well as new field data on fuel consumption and emission factors. In this study we cannot propagate this uncertainty into the NCE estimates as this would require spatiotemporal error covariance matrices."*

Minor comments

1. In the abstract, "would require an offsetting surface C source of 4.27 +- 0.10 PgC/yr", should the offset be 4.27 + 6.07 PgC/yr in order to have 4.27 PgC atmospheric CO2 growth rate?

*Yes, that is correct. We have reformulated this as "Overall, and because of the over-estimated* $CO_2$

*uptake in tropical lands, our global bottom-up NCE amounts to a net sink of -5.4±2.0 PgC/yr. By contrast, the accurately measured mean atmospheric growth rate of* $CO_2$ *over 2001-2010 indicates that the true value of NCE is a net* $CO_2$ *source of 4.3±0.1 PgC/yr. This mismatch of nearly 10 PgC/yr highlights observational gaps and limitations of data-driven models in tropical lands, but also in North America." (The numbers have slightly changed in the revision because we now use directly upscaled NEP instead of GPP-TER).*

2. Line 13-16 (p3), it is not clear what the "background CO2 fluxes" means.

*With background fluxes we mean the fluxes before human disturbance (i.e., before the large increase in fossil fuel emissions). Those are not included in the estimates of the Global Carbon Project, which only discusses the human perturbation. In the revised version, we have avoided the term to avoid confusion and just state "Unlike the GCP global budget of anthropogenic* $CO_2$*, we consider here the full contemporary exchange of surface-atmosphere* $CO_2$ *fluxes"*

3. Line 23 (p4), "goal of this study the" should be "goal of this study to"

*Thank you.*

4. Line 16 (p6): what is "schused"?

*Should be "used", has been changed.*

5. Line 21 (p14): What does the "relevant drivers" refer to? Be more specific.

*Additional drivers relevant for upscaling NEP could be, for instance, the disturbance history (e.g. time since the last disturbance) or, closely related, forest age. This is mentioned a few lines higher up. Furthermore soil moisture estimates and information on management practices would help. We now use 'predictors' instead of 'drivers' and have rephrased the sentence as "However, not all of the relevant predictors (i.e. disturbance maps, management practices, soil moisture) are currently available to be included in empirical upscaling exercises (Tramontana et al., 2016)."*

6. Line 29 (p14): what does the "global driver" refer to?

*By this we refer to the fact that there is no global map of forest age, which could be used as an additional driver for upscaling NEP (see also comment above). We have omitted the part with the "global driver" and reformulated this section. We also use the term 'predictor' instead of 'driver', which is more intuitive. See reply to major comment 7 for the complete text.*

## ***Additional References:***

*van der Werf et al.: Global fire emissions estimates during 1997–2015, Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2016-62, in review, 2017.*

# An empirical spatiotemporal description of the global surface-atmosphere carbon fluxes: opportunities and data limitations

Jakob Zscheischler[1,2], Miguel D. Mahecha[2,3,4], Valerio Avitabile[5], Leonardo Calle[6], Nuno Carvalhais[2,7], Philippe Ciais[8], Fabian Gans[2], Nicolas Gruber[9], Jens Hartmann[10], Martin Herold[5], Kazuhito Ichii[11,12], Martin Jung[2], Peter Landschützer[9,13], Goulven. G. Laruelle[14], Ronny Lauerwald[14,15], Dario Papale[16], Philippe Peylin[7], Benjamin Poulter[6,17], Deepak Ray[18], Pierre Regnier[14], Christian Rödenbeck[2], Rosa M. Roman-Cuesta[5], Christopher Schwalm[19], Gianluca Tramontana[16], Alexandra Tyukavina[20], Riccardo Valentini[21], Guido van der Werf[22], Tristram O. West[23], Julie E. Wolf[23], and Markus Reichstein[2,3,4]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Universitätstr. 16, 8092 Zurich, Switzerland

[2]Max Planck Institute for Biogeochemistry, Hans-Knöll-Str. 10, 07745 Jena, Germany

[3]German Centre for Integrative Biodiversity Research (iDiv), Deutscher Platz 5e, 04103 Leipzig, Germany

[4]Michael Stifel Center Jena for Data-Driven and Simulation Science, 07743 Jena, Germany

[5]Wageningen University & Research, Laboratory of Geo-Information Science and Remote Sensing, Droevendaalsesteeg 3, 6708 PB Wageningen, the Netherlands

[6]Institute on Ecosystems and Department of Ecology, Montana State University, Bozeman, MT 59717, USA

[7]CENSE, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa, Caparica, Portugal

[8]Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, F-91191, Gif sur Yvette, France

[9]Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zurich, Switzerland

[10]Institute for Geology, CEN- Center for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany 55, D-20146 Hamburg, Germany

[11]Department of Environmental Geochemical Cycle Research, Agency for Marine-Earth Science and Technology, Yokohama, Japan.

[12]Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan.

[13]Max Planck Institute for Meteorology, Bundesstr. 53, Hamburg, Germany

[14]Dept. Geoscience, Environment & Society (DGES), CP160/02, Université Libre de Bruxelles, 1050 Bruxelles, Belgium

[15]College of Engineering, Mathematics and Physical Sciences, University of Exeter, EX4 4QE Exeter, Devon, UK

[16]Department for Innovation in Biological, Agro-food and Forest systems (DIBAF), University of Tuscia, Viterbo, 01100, Italy

Jakob 20/3/2017 11:32
**Gelöscht:** Y.

[17]NASA Goddard Space Flight Center, Biospheric Sciences Laboratory, Greenbelt, MD 20771, USA
[18]Institute on the Environment, University of Minnesota Twin-Cities, USA
[19]Woods Hole Research Center, Falmouth MA 02540, USA
[20]Department of Geographical Sciences, University of Maryland, College Park, MD, USA
[21]CMCC, Via A. Imperatore, 16, 73100, Lecce, Italy
[22]Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, the Netherlands
[23]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA
*Correspondence to*: J. Zscheischler (jakob.zscheischler@env.ethz.ch) and M. D. Mahecha (mmahecha@bgc-jena.mpg.de).

**Abstract**. Understanding the global carbon (C) cycle is of crucial importance to map current and future climate dynamics relative to global environmental change. A full characterization of C cycling requires detailed information on spatiotemporal patterns of surface-atmosphere fluxes. However, relevant C cycle observations are highly variable in their coverage and reporting standards. Especially problematic is the lack of integration of the carbon dioxide ($CO_2$) exchange of the ocean, inland freshwaters and the land surface with the atmosphere. Here we adopt a data-driven approach to synthesize a wide range of observation-based spatially explicit surface-atmosphere $CO_2$ fluxes from 2001 and 2010, to identify the state of today's observational opportunities and data limitations. The considered fluxes include net exchange of open oceans, continental shelves, estuaries, rivers, and lakes, as well as $CO_2$ fluxes related to net ecosystem productivity, fire emissions, loss of tropical aboveground C, harvested wood and crops, as well as fossil fuel and cement emissions. Spatially explicit $CO_2$ fluxes are obtained through geostatistical and/or remote sensing-based upscaling; thereby minimizing biophysical or biogeochemical assumptions encoded in process-based models. We estimate a bottom-up net C exchange (NCE) between the surface (land, ocean, and coastal areas) and the atmosphere. Though we provide also global estimates, the primary goal of this study is to identify key uncertainties and observational shortcomings that need to be prioritized in the expansion of in-situ observatories. Uncertainties for NCE and its components are derived using resampling. In many regions, our NCE estimates agree well with independent estimates from other sources such as process-based models and atmospheric inversions. This holds for Europe (mean±1 SD: 0.8±0.1 PgC/yr, positive numbers are sources to the atmosphere), Russia (0.1±0.4 PgC/yr), East Asia (1.6±0.3 PgC/yr), South Asia (0.3±0.1 PgC/yr), Australia (0.2±0.3 PgC/yr) and most of the Ocean regions. Our NCE estimates give a likely too large $CO_2$ sink in tropical areas such as the Amazon, Congo and Indonesia. Overall, and because of the over-estimated $CO_2$ uptake in tropical lands, our global bottom-up NCE amounts to a net sink of -5.4±2.0 PgC/yr. By contrast, the accurately measured mean atmospheric growth rate of $CO_2$ over 2001-2010 indicates that the true value of NCE is a net $CO_2$ source of 4.3±0.1 PgC/yr. This mismatch of nearly 10 PgC/yr highlights observational gaps and limitations of data-driven models in tropical lands, but also in North America. Our uncertainty assessment provides the basis for setting priority regions where to increase carbon observations in the future. High on the priority list are tropical land regions, which suffer from a lack of in-situ observations. Second, extensive $pCO_2$ data are missing in the Southern Ocean. Third, we lack observations that could enable seasonal estimates of shelf, estuary and inland

Jakob 20/3/2017 11:32
**Gelöscht:** vertical oceanic, inland freshwaters and terrestrial…he carbon dioxide ($CO_2$) exchang ... [1]

water-atmosphere C exchange. Our consistent derivation of data uncertainties could serve as prior knowledge in multi-criteria optimization such as the Carbon Cycle Data Assimilation System (CCDAS) and atmospheric inversions, without over- or under- stating bottom-up data credibility. In the future, NCE estimates of carbon sinks could be aggregated at national scale to compare with the official national inventories of $CO_2$ fluxes in the land use, land use change and forestry sector, upon which future emission reductions are proposed.

Jakob 20/3/2017 11:32
**Gelöscht:** Also, extensive $pCO_2$ measurements are missing in the Southern Ocean. Most importantly, tropical land C fluxes suffer from a lack of in-situ observations. The…ur consistent derivation ... [2]

## 1 Introduction

The global carbon (C) cycle is crucial for sustaining life on Earth (Vernadsky, 1926). Humans have largely modified the C cycle over centuries if not millennia (Ruddiman, 2003; Pongratz et al., 2009). In the Industrial Era, the human-caused perturbation of the C cycle is largely driven by emissions of $CO_2$ from burning fossil fuel C previously in geological deposits, and changes in land use, which transfer $CO_2$ from C stocks in the land biosphere to the atmosphere, but can also result into $CO_2$ removal and increase of land stocks. As those anthropogenic C emissions are partly taken up by oceans and terrestrial ecosystems not affected by land-use change, the different reservoirs of the global C cycle and the fluxes between them change over time (Houghton, 2007). A precise knowledge of the various stocks and fluxes in the C cycle is a prerequisite to monitor these changes and make well-informed predictions under future climate change.

Jakob 20/3/2017 11:32
**Gelöscht:** ; Ruddiman, 2003…. In recent ti ... [3]

The Global Carbon Project (GCP) has made major efforts in this direction and its annual updates of the global C budget have become a key source of information for the scientific community and policy makers (Le Quéré et al., 2015). The GCP annual C budget quantifies the partitioning of anthropogenic C emissions among the atmosphere, land, and ocean components of the global C cycle, and separates the net land flux into land use change emissions and a so called ‘residual land C sink’ obtained by difference with other terms of the budget and thus corresponding to the net land-atmosphere $CO_2$ flux over non land-use affected ecosystems. The budget of the GCP focuses on annual values integrated at the global scale. An important point is that the GCP budget quantifies solely the anthropogenic perturbation of $CO_2$ fluxes, i.e., it provides information about the fate of anthropogenic $CO_2$ emissions in natural reservoirs (Ciais et al., 2013). According to the GCP, about 44% of the anthropogenic $CO_2$ emissions each year stay in the atmosphere, the rest being taken up by the oceans (26%) and land (30%) (Le Quéré et al., 2015).

Jakob 20/3/2017 11:32
**Gelöscht:** crucial…ey source of informatio ... [4]

Recently, a case has been made for a globally policy-relevant integrated C observation and analysis system (Ciais et al., 2014). This system would go beyond the update of global budgets, for which the $CO_2$ growth rate accurately measured at a single station (e.g. Mauna Loa) is sufficient to constrain the global annual time-space integral of all $CO_2$ sources and sinks. It proposes to quantify regional $CO_2$ fluxes with sufficient spatial details to monitor the effectiveness of $CO_2$ mitigation and to detect and monitor trends of $CO_2$ losses and gains by land and terrestrial systems. This is partly relevant for monitoring country-level Intended Nationally Determined Contributions (INDCs) to incept a $CO_2$ emission trajectory consistent with global warming below 2 degrees Celsius (UNFCCC, 2015). In such a policy-relevant C observing system, an uncertainty assessment for each data stream and $CO_2$ fluxes at different spatial and temporal scales is important to, for instance, identify significant regional emission hotspots and trends in emissions and sinks (Ciais et al., 2014).

Jakob 20/3/2017 11:32
**Gelöscht:** carbon… observation and analys ... [5]

The steadily increasing number of Earth observations, in particular since the start of the satellite era, has improved our knowledge of the Earth system (Berger et al., 2012; Tatem et al., 2008). Especially C cycle science has benefited from globally available satellite observations and community efforts to unify in-situ observational networks such as FLUXNET on land (Baldocchi, 2014), the Surface Ocean $CO_2$ Atlas (SOCAT) (Bakker et al., 2014) and more recently $CO_2$ outgasing from lakes and rivers (Raymond et al., 2013). Combining these available point measurements of either $CO_2$ fluxes (e.g., from eddy-covariance towers on land), or variables that can be directly related to $CO_2$ fluxes (e.g., $pCO_2$ over aquatic surfaces) with climate fields and remotely sensed variables (e.g., vegetation greenness), provides a basis to robustly upscale surface-atmosphere $CO_2$ exchange to larger areas using statistical models (Jung et al., 2011; Rödenbeck et al., 2015).

In this study we aim at characterizing the ability of current C cycle observations on ground for quantifying a spatiotemporally explicit picture of the net $CO_2$ exchange between the Earth's surface (terrestrial and aquatic) and the atmosphere (NCE). Unlike the GCP global budget of anthropogenic $CO_2$, we consider here the full contemporary exchange of surface-atmosphere $CO_2$ fluxes. We focus our analysis on fluxes that can be directly derived from observations. That is, we use data-driven empirical models instead of process-based models that are only indirectly constrained by observations. Further, we only consider 'bottom-up' estimates derived from measurements at the Earth's surface or from satellites. Inversions, which largely rely on atmospheric measurements in combination with a transport model, are not directly included but used for comparison. The goal of this analysis is to test the up-scaling of local flux-related observations to regional and global budgets, and point out the limitations of the current observational networks and data-driven models used to interpolate point-scale $CO_2$ fluxes across larger scales, for quantifying the most important $CO_2$ fluxes exchanged between the Earth's surface and the atmosphere.

One of the major innovations of this study is combining data-driven estimates of oceanic, inland waters and terrestrial ecosystems $CO_2$ exchange and providing spatially explicit maps of the $CO_2$ exchange between the surface and the atmosphere at a monthly scale for the decade 2001-2010. At the same time, by adding emissions from fossil fuels and cement production and comparing with the annual growth rate of $CO_2$, we identify the limits of a C budget purely driven by surface data. We characterize regions in which surface-atmosphere $CO_2$ fluxes are most uncertain based on the currently available data and the models used for upscaling, and thus point out regions where either more observations or a better understanding of the processes are necessary. It is not the primary goal of this study to provide the best global $CO_2$ flux inventory, but rather to identify the key uncertainties and observational shortcomings that need to be prioritized in the expansion of in-situ observatories.

The paper is structured as follows. In Sect. 2 we introduce the different data streams used in the analysis, including spatially explicit estimates of aquatic and terrestrial $CO_2$ exchange. In Sect. 3 we present the resulting combined synthesis as global maps, regionally aggregated fluxes, absolute and relative uncertainties, latitudinal averages and seasonal cycles. Sect. 4 addresses the benefits and limits of the current observational system for constraining global net $CO_2$ fluxes. Sect. 5 provides an outlook on future requirements to achieve better observation-based net $CO_2$ flux estimates and discusses the necessity for more consistent uncertainty estimates.

Jakob 20/3/2017 11:32
**Gelöscht:** about

Jakob 20/3/2017 11:32
**Gelöscht:** ) and

Jakob 20/3/2017 11:32
**Gelöscht:** over water

Jakob 20/3/2017 11:32
**Gelöscht:** ).

Jakob 20/3/2017 11:32
**Gelöscht:** now abundantly

Jakob 20/3/2017 11:32
**Gelöscht:** 2014

Jakob 20/3/2017 11:32
**Gelöscht:** to characterize

Jakob 20/3/2017 11:32
**Gelöscht:** maturity

Jakob 20/3/2017 11:32
**Gelöscht:** .

Jakob 20/3/2017 11:32
**Gelöscht:** both natural background and anthropogenic

Jakob 20/3/2017 11:32
**Gelöscht:** Here, anthropogenic fluxes consist of those fluxes that occur as the result of past a ... [6]

Jakob 20/3/2017 11:32
**Gelöscht:** , which

Jakob 20/3/2017 11:32
**Gelöscht:** upscaling

Jakob 20/3/2017 11:32
**Gelöscht:** them

Jakob 20/3/2017 11:32
**Gelöscht:** carbon

Jakob 20/3/2017 11:32
**Gelöscht:** data-

Jakob 20/3/2017 11:32
**Gelöscht:** C budget

Jakob 20/3/2017 11:32
**Gelöscht:** the

Jakob 20/3/2017 11:32
**Gelöscht:** would

Jakob 20/3/2017 11:32
**Gelöscht:** addressed

Jakob 20/3/2017 11:32
**Gelöscht:** future measurement campaigns ... [7]

Jakob 20/3/2017 11:32
**Gelöscht:** observationally

## 2 Data and Methods

We collected ensembles of data-driven estimates of the net $CO_2$ exchange between the Earth's surface and the atmosphere (NCE) for the major subsystems of the Earth from 2001-2010 (Table 1). Each dataset was aggregated to 1 x 1 degree spatial resolution. All datasets have an original spatial resolution of at least 1 x 1 degree such that no information was lost through re-gridding. The temporal resolution is monthly. For datasets that were only available at yearly time scale or once over the complete time period (Table 1), we distributed fluxes evenly across all months. In this synthesis, we include net $CO_2$ exchange from open oceans, continental shelves, estuaries, rivers, lakes, and terrestrial ecosystems, which we combine with estimates of fossil fuel and cement emissions (FF). The terrestrial ecosystem component accounts for fire emissions (Fire), loss of tropical above-ground biomass assumed to be released as $CO_2$ to the atmosphere ($E_{LUC}$), emissions of the $CO_2$ contained in harvested wood (Wood) and crops (Crops), and Net Ecosystem Productivity (NEP). We combine fluxes from oceans, shelves, and estuaries into a homogeneous marine flux product in order to account for overlapping or missing regions from the different aquatic products (Marine, Sect. 2.2.6). We further compare the net $CO_2$ exchange derived from the combination of all the above products with the growth rate of atmospheric $CO_2$ (CGR). Data scarcity precludes including all known vertical $CO_2$ fluxes in this study. Missing fluxes include geological $CO_2$ fluxes, erosion related fluxes, non-$CO_2$ fluxes, wood product pools decay, and biofuel burning. Combining all fluxes, the overall net $CO_2$ exchange (NCE) between the Earth's surface and the atmosphere is given as:

$$NCE = Marine + Lakes + Rivers - NEP + Crops + Wood + E_{LUC} + Fire + FF. \quad (1)$$

All units were transformed into fluxes of C per unit time. If all $CO_2$ fluxes were included, NCE would translate into the CGR. By convention negative fluxes indicate an uptake by the Earth surface.

### 2.1 Uncertainty estimation and propagation

To estimate NCE including spatiotemporally explicit uncertainties, we combine randomly drawn ensemble members from all of the 9 datasets contributing to NCE (Eq. 1). With the available realizations, we could in principle create 10x10x50x8x10x2 = 800000 spatiotemporal explicit estimates of NCE (see Table 2 for the available number of realizations per dataset). From these 800000 possible NCE estimates we randomly select 200 to construct the NCE ensemble, which is used in the rest of the paper. This resampling approach is illustrated in Figure 1 and ensures a consistent propagation of spatiotemporally correlated uncertainties. For instance, by aggregating each member of NCE to the desired region and estimating uncertainty through the 200 members, we can compute regional uncertainties. In addition, we computed mean fluxes, uncertainty (defined as one standard deviation (SD) of the annual mean across all realizations), interannual variability (IAV, defined here as one SD of annual means across all available years) and the coefficient of variation (CV = IAV/mean) for each of the 9 flux terms in Eq. 1.

Jakob 20/3/2017 11:32
**Gelöscht:** resampled

Jakob 20/3/2017 11:32
**Gelöscht:** and

Jakob 20/3/2017 11:32
**Gelöscht:** step; a compromise that minimizes aggregation/spatialization

Jakob 20/3/2017 11:32
**Gelöscht:** different data products

Jakob 20/3/2017 11:32
**Gelöscht:** the land surface

Jakob 20/3/2017 11:32
**Gelöscht:** land surface

Jakob 20/3/2017 11:32
**Gelöscht:** terrestrial ecosystem fluxes which are divided into Gross Primary Production (GPP) and Terrestrial Ecosystem Respiration (TER).

Jakob 20/3/2017 11:32
**Gelöscht:** – GPP + TER

Jakob 20/3/2017 11:32
**Gelöscht:** are

Jakob 20/3/2017 11:32
**Gelöscht:** are

Jakob 20/3/2017 11:32
**Gelöscht:** should equal

Jakob 20/3/2017 11:32
**Gelöscht:** In contrast,

Jakob 20/3/2017 11:32
**Gelöscht:** NCE indicates

Jakob 20/3/2017 11:32
**Gelöscht:** of $CO_2$

Jakob 20/3/2017 11:32
**Gelöscht:** Earth's

Jakob 20/3/2017 11:32
**Gelöscht:** All data used in this study are listed in Table 1 and for convenience available from the GEOCARBON website http://www.bgc-jena.mpg.de/geodb/geocarbon/Home.php; direct access and citation of the data as pre-processed here is possible via https://dx.doi.org/10.17871/GEOCARBON_synth_obs_v1.

Jakob 20/3/2017 11:32
**Gelöscht:** For each flux term in Eq. (1) we computed mean fluxes over all available realizations of a given product

Jakob 20/3/2017 11:32
**Gelöscht:** ). For NCE estimates, we randomly combined all datasets, using a single realization of each flux, to generate an estimate of NCE. T ... [8]

## 2.2 Aquatic fluxes

### 2.2.1 Oceans

For the global open ocean flux estimate we used two complementary data-driven estimates (Table 1). Both approaches computed maps of the sea surface partial pressure of $CO_2$ ($pCO_2$). They relied on the surface ocean $CO_2$ observations from the SOCATv2 database (Bakker et al., 2014) and filled data gaps by either establishing relationships between auxiliary driver data and observations, which can then be applied to extrapolate $pCO_2$ in regions without data coverage (SOM-FFN, Landschützer et al., 2014), or by assimilating the available observations in a mass-balance model of the mixed layer and directly interpolating data gaps (Jena CarboScope mixed-layer scheme oc_v1.2, Rödenbeck et al., 2014). To test the established predictor-target relationship, the SOM-FFN method holds back a certain fraction of the observations proportional to the methods degrees of freedom for internal validation. Repeating this relationship building process and withholding different sets of validation data has created the 5 ensemble members used for this study. For the Jena CarboScope mixed-layer scheme, we used the 5 sensitivity cases with changes in correlation length etc. as described in Rödenbeck et al (2014).

The $pCO_2$ fields of both methods have been validated against independent observations (Landschützer et al., 2014; Landschützer et al., 2015; Rödenbeck et al., 2014) and were compared with other complementary data based interpolation methods (Rödenbeck et al., 2015), illustrating their good performance in reconstructing interannual variation.

Both methods calculate the air-sea flux using a bulk formulation of the air-sea $CO_2$ transfer, driven by the air-sea $pCO_2$ difference ($\Delta pCO_2$) (Jähne et al., 1987) and a quadratic dependence of the wind speed at a height of 10 meters (Wanninkhof, 1992) updating the gas transfer coefficient to fit a mean transfer velocity of 16 cm per hour following Wanninkhof (2013). High-resolution wind speeds at 10 meters are calculated from the u and v wind components of the ERA-interim wind speed analysis (Dee et al., 2011) and atmospheric pCO2 fields, required to calculate the $\Delta pCO_2$, are calculated are estimated from the GLOBALVIEW-CO2, 2012 Marine Boundary Layer CO2 product.

### 2.2.2 Shelves

For continental shelf seas we derived the $\Delta pCO_2$ from $3x10^6$ surface pCO2 measurements extracted from the SOCATv2 database (Bakker et al., 2014) and observational atmospheric $pCO_2$ data (GLOBALVIEW-CO2, 2012). The local $CO_2$ air-sea flux values were then obtained using a wind-dependent quadratic formulation parameterized as in Wanninkhof et al. (2013) and wind speeds extracted from a cross-calibrated multiplatform (CCMP) high-resolution data product for ocean surface winds (Atlas et al., 2011). The resulting local fluxes were then integrated spatially over 150 coastal regions (COSCATs - COastal Segmentation and related CATchments; Laruelle et al. (2013); Meybeck et al. (2006)) using distinct integration methods depending on the data density (Laruelle et al., 2014). In addition, a temporal integration was also performed at the monthly, seasonal or yearly time scale depending on the data coverage. These temporally and regionally averaged air-sea $CO_2$ fluxes were then disaggregated using a 1-degree resolution map excluding land areas and open ocean waters using the shelf break as outer limit (Laruelle et al., 2014).

Jakob 20/3/2017 11:32
**Gelöscht:** $e_{NCE} = \sqrt{\sum_{i=1}^{n} e_i^2}$, (2) ... [9]

Unknown
**Formatiert:** Tiefergestellt durch 9 pt

Jakob 20/3/2017 11:32
**Gelöscht:** schused

Jakob 20/3/2017 11:32
**Gelöscht:** , Sweeney et al., 2007

Jakob 20/3/2017 11:32
**Gelöscht:** .5

Jakob 20/3/2017 11:32
**Gelöscht:** Nägler (2009

Jakob 20/3/2017 11:32
**Gelöscht:** 2011).

Jakob 20/3/2017 11:32
**Gelöscht:** broad

### 2.2.3 Estuaries

The $CO_2$ emissions from estuaries were derived from 161 annually averaged local $CO_2$ air-water exchange rates reported in the literature (Laruelle et al., 2013). The data were allocated to one of the 45 coastal MARCATS regions (MARgins and CATchments Segmentation) defined in Laruelle et al. (2013) and further categorized among the 4 dominant estuarine types (i.e., small deltas, tidal systems, lagoons, fjords, see (Dürr et al., 2011)) to calculate regionally-averaged, type specific $CO_2$ emission rates. In MARCATS regions devoid of estuarine data, the global average type-dependent air-water $CO_2$ flux was used from Laruelle et al. (2013). These flux densities were then multiplied by the estuarine surface areas for each type, estimated at 1-degree resolution from the length of the coastline and a type-specific length to estuarine surface ratio (Dürr et al., 2011).

### 2.2.4 Marine

We combined open oceans, shelves, and estuaries to a consistent marine product. For pixels with observations from multiple products (e.g., estuaries and oceans) we follow a "priority rule" whereby the shelves, estuaries, or oceans observation value only (in that order) is retained. Empty pixels are gap-filled with 3 x 3 mean window. This same filter is also applied to the rest of the merged dataset to smooth out hard borders between the different estimates. This application does not significantly change the overall flux estimates, but arguably results in a more realistic interface. Note that in the merged Marine product, uncertainty and IAV could only be assessed for the ocean flux.

Jakob 20/3/2017 11:32
**Gelöscht:** all non-inland aquatic fluxes (

Jakob 20/3/2017 11:32
**Gelöscht:** )

### 2.2.5 Rivers

Estimates of $CO_2$ evasion from streams and rivers were derived from a spatially explicit, empirical model of river water $pCO_2$ and global maps of stream surface areas and gas exchange velocities at a resolution of 0.5 degree (Lauerwald et al., 2015). The empirical $pCO_2$ model was trained on 1182 river catchments from the GLORICH database (Hartmann et al., 2014) for which averages of $pCO_2$ could be calculated. Steepness of terrain, terrestrial net primary production, average air temperature as well as population density were identified as predictors ($R^2$=0.47). The global maps of stream surface area and gas exchange velocities were obtained by a GIS-based application of published empirical scaling laws (Raymond et al., 2013; Raymond et al., 2012) using topography (Lehner et al., 2008) and runoff (Fekete et al., 2002). The $CO_2$ evasion was calculated as product of water-air $pCO_2$ gradient (assuming an atmospheric $pCO_2$ of 390 µatm), river surface areas, and gas exchange velocities. A Monte-Carlo simulation based on standard errors of the predictors in the $pCO_2$ model and uncertainty ranges for estimates of stream surface area and gas exchange velocity was run to produce 50 $CO_2$ evasion estimates.

Jakob 20/3/2017 11:32
**Gelöscht:** robust

Jakob 20/3/2017 11:32
**Gelöscht:**

### 2.2.6 Lakes

Estimates of $CO_2$ evasion from lakes and reservoirs were taken from Raymond et al. (2013), which reports average lake $pCO_2$, total lake/reservoir surface area, and total $CO_2$ evasion for 231 COSCAT regions (including endorheic regions). For the total lake/reservoirs surface area, data from the Global Lakes and Wetland Data base (GLWD, Lehner and Döll, 2004) were combined with an estimate for small lakes and reservoirs not represented in the GLWD using a scaling law. Here, we used the GLWD data to downscale the estimates of Raymond et al. (2013) to a continuous 1-degree resolution. For this purpose, we combined a uniform air-water $CO_2$ flux (per unit surface area) within each COSCAT region with a spatially explicit estimate of the lakes/reservoirs surface at this resolution. The small lakes/reservoirs not represented in the GLWD were assumed evenly distributed over the COSCAT area.

## 2.3 Terrestrial fluxes

### 2.3.1 NEP

We used empirical, machine learning based products from FLUXCOM (www.fluxcom.org) for net ecosystem productivity (NEP), derived from more than 200 FLUXNET sites and exclusively remote-sensing based predictor variables (“FLUCOM-RS”, see Tramontana et al., 2016). The eight machine learning methods used here include artificial neural networks, four variants of model or regression tree ensembles, kernel methods (support vector machines, kernel ridge regression), and multivariate adaptive regression splines (Tramontana et al., 2016). All methods were trained on 8-daily tower based NEP estimates.

### 2.3.2 Crops

About 42% of global crop biomass is harvested, transported, and respired off site (Wolf et al., 2015a). The impact of this lateral C transport on fluxes can be seen at the country scale in the form of import and exports, but even more so at sub-regional scales where the movement of crop biomass to feed livestock and humans is evident (Hayes et al., 2012; West et al., 2011). To capture the spatial distribution of $CO_2$ fluxes from agricultural harvest, we used livestock and human $CO_2$ emissions estimates (Wolf et al., 2015b) that are available from 2005-2011 at 0.05 degree spatial resolution. $CO_2$ that has previously been taken up from the atmosphere by the harvested biomass of crops is included in the NEP estimates from FLUXCOM. We aggregated best estimates of the data to 1 degree, added all uncertainty estimates within one 1 degree pixel and used them as estimates for one standard deviation on the new 1 degree grid. Assuming Gaussian distributed errors we sampled 1000 values at each pixel and used 10 maps of the 5th, 15th,…, 95th quantiles as different ensemble members. Data was then linearly extrapolated back to 2001-2004. In a final step, and because it is not known in which months the emissions occur, we further distributed the annual estimates equally across all 12 months.

### 2.3.3 Wood

We used globally gridded forest harvesting data around year 2000 as described in the Supplementary Information S1. These data include fuelwood and roundwood harvested volumes in m$^3$. We translated wood volumes into units of C using a value of 0.275 MgC/m$^3$ from FAO (http://www.fao.org/docrep/w4095e/w4095e06.htm), assuming wood density of 0.55 t/m$^3$. To avoid double counting wood harvest with aboveground biomass loss in tropical areas exposed to land use change, we use wood harvesting data only in locations where the amount of harvested wood (in C) exceeds $E_{LUC}$ (Sect. 2.3.4). We assume that 100% of the harvested wood is respired back to the atmosphere within a year, thus assuming no change in C stock of wood products and constant harvesting rates across years. However, C contained in harvested wood is usually emitted at a

Jakob 20/3/2017 11:32
**Gelöscht:** <#>**GPP and TER**

Jakob 20/3/2017 11:32
**Gelöscht:** GPP and TER,

Jakob 20/3/2017 11:32
**Gelöscht:** GPP and TER estimates from two NEP flux partitioning approaches (Lasslop et al., 2010; Reichstein et al., 2005) such that 16 ensemble members are available for GPP and TER (see Tramontana et al. (2016) fo details).

Jakob 20/3/2017 11:32
**Gelöscht:** biogenic

Jakob 20/3/2017 11:32
**Gelöscht:** production

Jakob 20/3/2017 11:32
**Gelöscht:** Because

Jakob 20/3/2017 11:32
**Gelöscht:** is

Jakob 20/3/2017 11:32
**Gelöscht:** implicitly

Jakob 20/3/2017 11:32
**Gelöscht:** , we only used $CO_2$ emissions related to livestock and human respiration

Jakob 20/3/2017 11:32
**Gelöscht:** use

Jakob 20/3/2017 11:32
**Gelöscht:** exceed the average of

different location than where the harvest took place. We thus incorporated lateral shifts of harvested wood by redistributing wood harvest according to the consumption of wood as explained in the Supplementary Information S1 (see also Fig. S2).

### 2.3.4 $E_{LUC}$

We used two estimates for $CO_2$ fluxes due to tropical deforestation and degradation. It is assumed here that 100% of biomass loss is converted to a $CO_2$ flux being released instantly (within a year) to the atmosphere. In reality, a fraction of lost tropical biomass decays in ecosystems (belowground biomass and slash) and a fraction is used in wood products of various lifetime. However, slash is decomposed fast and biomass from deforested areas is transformed on average to short-lived products (≈ 5 years after Earles et al. (2012)).

1) Gross tropical deforestation emissions were taken from Harris et al. (2012). They represent total (above- and belowground) C loss from gross forest cover loss in the tropical regions due to human or natural causes (e.g. disturbances without forest recovery) for the period of 2000-2005.

2) More recent estimates of aboveground C loss in the tropics from stand-replacement disturbance of forest cover due to human or natural causes were provided by Tyukavina et al. (2015). Sample-based estimates of mean 2000-2012 aboveground C loss for each 30-m resolution forest C stratum were attributed to all pixels of the corresponding stratum and averaged to the 1x1 degree resolution.

We used $E_{LUC}$ only in those pixels where the average of 1) and 2) exceeds wood harvesting (Sect. 2.3.3).

### 2.3.5 Fire

We used fire emissions from the Global Fire Emissions Database version 4 with small fires (GFED4s, http://www.globalfiredata.org) based on burned area from Giglio et al. (2013) and Randerson et al. (2012) and an updated version of the biogeochemical modelling framework of van der Werf et al. (2010) to convert burned area to C emissions. We included all fire types except tropical deforestation and degradation fires, which are included in $E_{LUC}$ and should thus not be counted twice (Sect. 2.3.4). For an earlier version of fire emissions (GFED3) a Monte Carlo simulations indicated an uncertainty of about 20% (1σ) for continental-scale estimates but these estimates turned out to be not very reliable (van der Werf et al., 2017). For example, the inclusion of small fire burned led to an increase in burned area exceeding the previously assumed uncertainty and the current version therefore has no uncertainty assessment at pixel level. Note that GFED fire emissions depend on estimates of net primary production, and combustion factors as computed by the CASA model.

### 2.3.6 FF

We use the IER-EDGARv4.2 product for fossil fuel and cement emissions, which was derived within the CARBONES project by the Institute für Energiewirtschaft und Rationelle Energieanwendung (IER). It is based on the Edgar v4.2 fossil fuel spatial distribution (with the highest spatial resolution of 0.1 x 0.1 degree) and uses national consumption and global production statistics. Based on the sectorial distinguished EDGARv4.2 emissions, sector-specific and country specific temporal profiles were included. A detailed description of the construction of the product is given at http://www.carbones.eu/wcmqs/project/ccdas/#Fossil%20Fuel. It is important to note that FF emissions here are not

Jakob 20/3/2017 11:32
**Gelöscht:** changes in C

Jakob 20/3/2017 11:32
**Gelöscht:** lost

Jakob 20/3/2017 11:32
**Gelöscht:** carbon

Jakob 20/3/2017 11:32
**Gelöscht:** carbon

Jakob 20/3/2017 11:32
**Gelöscht:** us

Jakob 20/3/2017 11:32
**Gelöscht:** downloaded

Jakob 20/3/2017 11:32
**Gelöscht:** conver

Jakob 20/3/2017 11:32
**Gelöscht:** the aboveground biomass loss estimates

Jakob 20/3/2017 11:32
**Gelöscht:** .

Jakob 20/3/2017 11:32
**Gelöscht:** . Moreover, there is currently no uncertainty estimate available at pixel-basis

Jakob 20/3/2017 11:32
**Gelöscht:** (hourly, weekly and seasonal).

observation based as the IER-EDGARv4.2 product is partly based on national estimates from official inventories reported by countries to the UNFCCC.

### 2.4 Atmospheric growth rate

We used the atmospheric rate of change of $CO_2$, which is equal to the space and time integral of all emissions and sinks at the surface, using the calculations made by the GCP (Le Quéré et al., 2015). These calculations and are based on the global growth rate of atmospheric $CO_2$ (CGR) provided by the US National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL) and were derived from multiple stations selected from the marine boundary layer sites with well mixed background air (Ballantyne et al., 2012; Masarie and Tans, 1995). They applied conversion from concentrations to carbon mass is 1 ppm = 2.12 PgC (Prather et al., 2012).

### 2.5 Inversions

For a comparison of yearly variability, spatial patterns and latitudinal bands, we used annual means of 10 inversions collected in Peylin et al (2013), available at the same spatial and temporal resolution. The mean and uncertainty for each year is taken over all available inversions for that year, as not all inversions were available until 2010. Atmospheric $CO_2$ inversions estimate surface $CO_2$ fluxes such that they best fit observed atmospheric constraints. They usually rely on prior information provided by terrestrial and oceanic biogeochemical models but are mostly independent from the bottom-up datasets included in the present synthesis. They further use FF as an input and then provide the surface-atmosphere flux excluding FF.

## 3 Results

### 3.1 Global net carbon exchange

Mean fluxes, their uncertainties, interannual variability (IAV), and CV (the mean-normalized IAV) for all individual fluxes contributing to NCE are presented in Table 2. Mean fluxes are also summarized graphically in Figure 2 (mean over 2001-2010). Our best surface-data driven bottom-up global estimate of NCE is -5.4±2.0 PgC / year. That means, that the observation-based datasets suggests a large net sink, even if FF and $E_{LUC}$ are included in NCE. By contrast, the accurately measured $CO_2$ growth rate constrains NCE being a net $CO_2$ source to the atmosphere 4.3±0.1 PgC / year (2001-2010, Le Quéré et al., 2015). Thus, there is a large mismatch with our NCE, which over-estimates the $CO_2$ sink at the surface by 9.7±2.0 PgC / year. This highlights that our observation-based NCE is biased towards a too large sink. Potential reasons for this mismatch are discussed in Sect. 4. For most fluxes, uncertainty estimates strongly exceed IAV (Table 2). Interestingly, process-based models, which are only indirectly constrained by observations, provide an NCE that matches roughly the $CO_2$ growth rate (Le Quéré et al., 2015). Developers of process-based models have access to $CO_2$ growth rate data and may be in the position to tune their models so that they give realistic NCE values, whereas in our bottom-up approach, we conducted a blind up-scaling of ground measurements without trying to match the $CO_2$ growth rate.

Jakob 20/3/2017 11:32
**Gelöscht:** estimate

Jakob 20/3/2017 11:32
**Gelöscht:** burden

Jakob 20/3/2017 11:32
**Gelöscht:** .,

Jakob 20/3/2017 11:32
**Gelöscht:** resolution after regrinding the original flux estimates

Jakob 20/3/2017 11:32
**Gelöscht:** monthly

Jakob 20/3/2017 11:32
**Gelöscht:** Not

Jakob 20/3/2017 11:32
**Gelöscht:** till

Jakob 20/3/2017 11:32
**Gelöscht:** CO2 concentration gradients, using a transport model.

Jakob 20/3/2017 11:32
**Gelöscht:** (especially at continental scale).

Jakob 20/3/2017 11:32
**Gelöscht:** 1

Jakob 20/3/2017 11:32
**Gelöscht:** 6.07±3.38

Jakob 20/3/2017 11:32
**Gelöscht:** our data

Jakob 20/3/2017 11:32
**Gelöscht:** . However, the amount of C

Jakob 20/3/2017 11:32
**Gelöscht:** is increasing by an estimated rate of 4.27±0.10

Jakob 20/3/2017 11:32
**[1] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**Gelöscht:** . Combining both

Jakob 20/3/2017 11:32
**Gelöscht:** , we obtain a C imbalance of 10.34±3.38

Jakob 20/3/2017 11:32
**Gelöscht:** (=NCE-CGR).

Jakob 20/3/2017 11:32
**[2] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**Gelöscht:** Section 4.

### 3.2 Spatial patterns of net carbon exchange

The 200-member NCE ensemble and the uncertainty distribution of each flux component enables us to provide a best estimate for a gridded average surface-atmosphere $CO_2$ flux map for the time period 2001-2010 (Figure 3a). According to these estimates, tropical land areas are a larger $CO_2$ sink than the mid-latitudes despite the visible forest bands in North America and Russia that function as sinks. In contrast, the high latitudes indicate a relatively small source. In the ocean, these patterns are reversed, with sources in the tropics and a sink in the mid-latitudes. Clearly, there is a strong land-sea contrast and land NCE is much higher in magnitude compared to ocean NCE. In areas with high human population densities and active industry (Europe, Eastern China, US, South Africa), emissions from fossil fuels and cement production clearly dominate over land $CO_2$ fluxes.

Absolute uncertainty of NCE generally scales with the mean flux and is highest in the most productive areas over land (Amazon basin, Congo basin, Indonesia; Figure 3b). Due to the small contribution of the oceans, absolute uncertainties are barely discernible there. Although gross air-sea exchange fluxes have typical uncertainties of more than 20%, their differences are determined from independent measurements with a much higher accuracy (Ciais et al., 2013).

Relative uncertainties however show very distinct patterns (Figure 3c). These are high on land in semi-arid and arid, and in mountainous regions (i.e., rather unproductive areas with near-zero mean) such as Australia, the Middle East, the Midwest US, the Sahel, South Africa, the Andes, and around the Tibetan Plateau. Marine-atmosphere $CO_2$ exchange is most uncertain in relative terms in the Bay of Bengal and in the Southern Ocean, which is known to be under-sampled, and where the two data-driven NCE fluxes show substantial regional patterns (Landschützer et al., 2014; Rödenbeck et al., 2014). In addition, linear features with high relative uncertainty are visible, especially in the Southern Hemisphere. These are related to the borders of the clusters used for deriving homogenous regions of sea-air exchange in one of the ocean-exchange products, which result in this product in strong spatial gradients in the sea surface $pCO_2$ (Landschützer et al., 2014). Relative uncertainties are mostly below 100% for the median across latitudinal bands (Figure 3c). Only in the Southern Ocean the relative uncertainty is substantially higher, reflecting difficulties in reconstructing seasonal to interannual variabilities with sparse observational constraints (Landschützer et al., 2014; Rödenbeck et al., 2014). Nevertheless, Landschützer et al. (2015) have shown that there is a better agreement between the estimates of Landschützer et al. (2014) and Rödenbeck et al. (2014) when low frequency variability, such as decadal variability, is analysed.

Averaged over latitudinal bands, the tropics are clearly a $CO_2$ sink (Figure 4a), a feature of the FLUXCOM models used for NEP, whereas mid-latitudes form a net $CO_2$ source, mostly due to fossil fuel and cement emissions surpassing natural $CO_2$ sinks. This latitudinal pattern is strongly driven by the terrestrial fluxes (Figure 4b). Marine and land aquatic $CO_2$ exchange in turn is about 4 times smaller in magnitude and shows $CO_2$ sources in the tropics and $CO_2$ sinks in the extratropics (Figure 4c). The aquatic $CO_2$ source in the tropics is not only the result of the ocean air-sea exchange, but also of the very intense river outgassing in low latitude regions (Lauerwald et al., 2015). NCE in the mid-latitudes is dominated by fossil fuel

Jakob 20/3/2017 11:32

**[2] nach oben verschoben:** . For most fluxes, uncertainty estimates strongly exceed IAV (Table 2).

Jakob 20/3/2017 11:32

**Gelöscht:** Using the ensemble approach we obtain an uncertainty in NCE of ±3.38 PgC / year. With quadrature error accumulation, taking into account the uncertainties in Marine, Rivers, GPP, TER, Crops, and $E_{LUC}$ (Eq. 1) the uncertainty of NCE is ±5.12 PgC / year. The higher uncertainty for the quadrature error accumulation is to be expected as in Eq. 1 all errors in the flux observations are assumed to be independent, whereas in fact many errors might be correlated as this clearly the case for GPP and TER

Jakob 20/3/2017 11:32

**Gelöscht:**

Jakob 20/3/2017 11:32

**Gelöscht:** Building a…he 200-member N( ... [10]

Jakob 20/3/2017 11:32

**Gelöscht:** 2b…b). Due to the small contri ... [11]

Jakob 20/3/2017 11:32

**Gelöscht:** 2c…c). These are high on land ... [12]

Jakob 20/3/2017 11:32

**Gelöscht:** C…$O_2$ sink (Figure 3a…a), a fe ... [13]

emissions (blue line in Figure 4d shows NCE-FF). FF have little contribution in the tropics and the high-latitudes but offset land and ocean $CO_2$ sinks in the northern mid-latitudes so that the net $CO_2$ balance of this latitude band is a net $CO_2$ source. We use the land cover map of FLUXCOM to identify tropical forests (all pixels where broadleaved evergreen trees dominate). Tropical forest, which covers about 3.5% of the Earth's surface, are allocated a $CO_2$ sink of -5.0±0.6 PgC / year, which is unrealistic, if compared to e.g. forest biomass inventories (Pan et al., 2011). Without this large sink, global NCE would be of -0.4±1.8 PgC / year. This corrected estimate (assuming neutral C exchange in tropical forests) is still a sink more than 4 PgC / year larger than the global NCE accurately constrained by $CO_2$ growth rate observations (4.3±0.1 PgC / year). Including missing fluxes (e.g. biogenic fluxes and emissions from wetlands, see Sect. 4.2) for which we do not have spatially explicit estimates (see Sect. 4.4) could close this gap. These considerations suggest that the $CO_2$ sink of tropical forests from FLUXCOM is probably strongly overestimated and responsible for at least half of the global mismatch with the observed $CO_2$ growth rate (see Sect. 4.1).

### 3.3 Net carbon exchange over the RECCAP regions

#### 3.3.1 RECCAP over land

Here we compare our NCE estimates over land with largely independent estimates of net ecosystem exchange (NEE) over continental-scale regions collected in RECCAP (REgional Carbon Cycle Assessment and Processes). The RECCAP budgets were based on inventories, and in some instances on process models results. NCE components between RECCAP and this study that are not independent from each other are fire emissions, and FF emissions. For $E_{LUC}$, RECCAP publications used regional datasets or bookkeeping models, that are independent from estimates gathered in Secti. 2.3.4. These regions include North America (NA, King et al., 2015), South America (SA, Gloor et al., 2012), Europe (EU, Luyssaert et al., 2012), Africa (AF, Valentini et al., 2014), Russia (RU, Dolman et al., 2012), East Asia (EA, Piao et al., 2012), South Asia (SAs, Patra et al., 2013), and Australia (AU, Haverd et al., 2013). No regional study is yet available for Southeast Asia (SEA). Greenland, Middle East, Ukraine, Kazakhstan and New Zealand are omitted in regional RECCAP studies because of the difficulty to obtain local ground-based observations. Ciais et al. (in revision) collected the regional estimates and combined them with estimates of lateral transport to estimate C budgets for each region. NEE in Ciais et al. (in revision) minus C export by rivers should in principal be equal to our NCE estimates without FF over the same regions (Figure 5). In regions without tropical forest except NA (that is, EU, RU, EA, SAs, and AU) the estimates by Ciais et al (in revision) are within the interquartile range of our assessment. For NA and regions containing the tropics, our approach shows a much stronger C sink.

Using our methodology, the annual NCE-FF for all RECCAP regions amounts to -11.0±1.9 PgC / yr in contrast to -1.3±0.6 PgC / yr in Ciais et al. (in revision). If we exclude SA, AF and SEA, the numbers are -2.8±1.0 PgC / yr and -1.5±0.4 PgC / yr, respectively, bringing both estimates in each other's uncertainty range. For SA, AF and SEA, the two estimates even differ in sign. While our estimates indicate strong C sinks of -4.3±0.5, -2.7±0.9, and -1.2±0.3 PgC / yr, respectively, Ciais et al. (in revision) report 0.1±0.3, 0.1±0.3, and 0.0±0.2 PgC / yr.

Jakob 20/3/2017 11:32
**Gelöscht:** 3d…d shows NCE-FF). FF hav ... [14]

Jakob 20/3/2017 11:32
**Gelöscht:** 2005 from the European Space Agency (http://www.esa-landcover-cci.org/)…LUX ... [15]

Jakob 20/3/2017 11:32
**Gelöscht:** carbon… budgets for each regi ... [16]

Jakob 20/3/2017 11:32
**Gelöscht:** Annual…sing our methodology ... [17]

Given that Ciais et al. (revision) rely on an independent method, this demonstrates that a relatively good understanding and observational coverage of net C fluxes exists for EU, RU, AU, and EA to some extent. It is somewhat surprising that both approaches largely differ over North America, where good observational coverage for instance through eddy-covariance towers exist. The comparison also reveals the high uncertainties and biases in bottom-up estimates of NCE over tropical forests (see Sect. 3.2, but also Gloor et al. (2012) and Valentini et al. (2014)) and underlines the importance of long-term ground based measurement campaigns (e.g. RAINFOR, http://www.rainfor.org/, Malhi et al. (2002), and ATTO, Andreae et al. (2015), Zhou et al. (2014)).

### 3.3.2 RECCAP over ocean

We compare our estimates of mean annual C exchange over the ocean with estimates from the RECCAP initiative. The Pacific Ocean is divided into North Pacific extratropics (NP), Tropical Pacific (TP) and South Pacific extratropics (SP) (Ishii et al., 2014). The Atlantic Ocean is divided into Arctic Ocean (AR), Northern Subtropics (NS), Equatorial (EQ) and Southern Subtropics (SS) (Schuster et al., 2013). Further, there are estimates for the Northern (NI) and Southern Indian Ocean (SI) (Sarma et al., 2013) as well as for the Southern Ocean (SO) (Lenton et al., 2013). The RECCAP estimates of NCE over oceans are independent from the two estimates that we use in this study (Sect. 2.2.1). Overall, the estimates from both sources agree very well (Fig. 6) and show ocean net C release in tropical regions (TP, EQ and NI) and net C uptake in all other regions. In SO our estimates predict a smaller sink compared to the RECCAP estimates, a difference probably owing to the weak observational constraint (Landschützer et al., 2014; Rödenbeck et al., 2014). Our estimates generally have smaller uncertainty ranges, which is  because i) the RECCAP studies include many more approaches (including process-based models, atmospheric and ocean inversions) in their estimates and ii) in our analysis we include the uncertainty from the ocean pCO2 products and their realizations but do not account for the uncertainty in the kinetic gas transfer.

### 3.4 Comparison with inversions

We compare NCE without FF (NCE-FF) with annual values from 10 inversions estimating the surface-atmosphere $CO_2$ flux without FF (Peylin et al., 2013). While both estimates agree well in the mid-latitudes, they show opposite patterns in the tropics and northern high latitudes (Figure 4d). The estimates of NEP in our NCE-FF probably have a substantial bias towards too much uptake over tropical land (Sect. 4.1). The comparison suggests that C fluxes are comparably well constrained in the mid-latitudes where bottom-up and top-down approaches agree. Similar results have been obtained in a comparison of a bottom-up upscaling approach with a more recent inversion based on $CO_2$ concentration data from the Greenhouse gases Observing SATellite (GOSAT, Kondo et al., 2015). The temporal evolution between both estimates show little agreement except the trend towards more net C uptake by the Earth's surface (Figure 7). The comparison suggests that NCE-FF estimated from this study has lower interannual variability compared to inversion estimates. Uncertainties are very high for our NCE-FF. In addition, the mean annual C uptake in our estimates is nearly 10 PgC/yr higher than for inversions.

Jakob 20/3/2017 11:32
**Gelöscht:** non-tropical areas,

Jakob 20/3/2017 11:32
**Gelöscht:** excluded. Yet it

Jakob 20/3/2017 11:32
**[3] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**Gelöscht:** land

Jakob 20/3/2017 11:32
**Gelöscht:** extratropics

Jakob 20/3/2017 11:32
**Gelöscht:** 3d

Jakob 20/3/2017 11:32
**Gelöscht:** latitudinal pattern of the inversions follows a pattern similar to that of the aquatic fluxes in the present synthesis (Figure 3c), possibly related to the fact that the interiors of many continents are widely undersampled (Peylin et al., 2013), propagating the marine signal into continents. On the other hand, the

Jakob 20/3/2017 11:32
**Gelöscht:** GPP-TER

Jakob 20/3/2017 11:32
**Gelöscht:** .

Jakob 20/3/2017 11:32
**Gelöscht:** extratropics

Jakob 20/3/2017 11:32
**Gelöscht:** -

Jakob 20/3/2017 11:32
**Gelöscht:** 5).

Jakob 20/3/2017 11:32
**Gelöscht:** (Figure 3d).

Jakob 20/3/2017 11:32
**Gelöscht:** estimate

Jakob 20/3/2017 11:32
**Gelöscht:** about

### 3.5 Monthly variability and mean seasonal cycle

NCE in the Northern hemisphere (NH) exhibits a much stronger mean seasonal cycle compared to the Southern hemisphere (SH), ranging from a net C uptake of nearly 2 PgC (per month) in July to a net C release of about 0.9 PgC in December and January (Figure 8). The SH is always a net C sink, ranging between slightly under 0.8 PgC uptake in January to roughly 0.1 PgC in August and September. This illustrates the 'breathing of the Earth', that is, vegetation activity largely follows the annual cycle of the sun. NH NCE is strongly offset by fossil fuel emissions. The uncertainties for the SH seasonal cycle are generally much lower than for the NH fluxes due to the larger contribution of the latter to the overall flux pattern, which is related to the distribution of land areas. If compared to inversions, we find that both estimates only match in the summer of the NH. In all other months and in the SH, our NCE estimates show a consistently much larger surface C sink. In addition, the NCE estimates from this synthesis show a smaller amplitude of the mean seasonal cycle compared to the inversions. The difference in amplitude of the mean seasonal cycle is on average 0.7 PgC for the NH and 0.4 PgC for the SH.

## 4 Current limitations of a bottom-up spatiotemporal assessment of net carbon exchange

Our study shows that today's spatiotemporally explicit and independent bottom-up observation-driven estimates of surface-atmosphere $CO_2$ exchange suffer from large bias, such that they do not match the global NCE well constrained from the $CO_2$ growth rate. This statement is not downgrading the advances in the area, but rather a systematic reflection of the state of current research and monitoring. In fact, at the regional scale, those estimates are often well constrained and may be used for model-data integration studies and validation purposes. The regions where observation-driven $CO_2$ exchange is constrained the best include Europe, Russia, South Asia, East Asia, Australia and all oceanic regions except the Southern Ocean. The most likely candidate for inducing the mismatch between data-driven estimates and the atmospheric $CO_2$ growth rate is terrestrial NEP. In particular, tropical NEP estimates suggest a too large tropical sink. In the following sections, we discuss (i) the possible reasons for the large bias in NEP (Sect. 4.1), (ii) which fluxes are missing in our synthesis (Sect. 4.2), (iii) how this synthesis dataset could be used for model-data fusion (Sect. 4.3), (iv) uncertainties in fire emissions (Sect. 4.4), and (v) the impact of missing seasonal cycles in some of the datasets (Sect. 4.5).

### 4.1 Difficulties in estimating NEP over land

Correctly predicting NEP from remote sensing requires establishing universal relationships between those predictors and respiratory processes (Jägermeyr et al., 2014; Tramontana et al., 2016). However, predicting such processes still poses major challenges to researchers (Trumbore, 2006). The $CO_2$ flux related to heterotrophic decomposition processes, for instance, relates to factors controlling biological activity via temperature, moisture availability, and the decomposable substrate material. The question how soil respiration or total ecosystem respiration depends on these variables is not yet entirely understood. Advancing our knowledge on these processes is challenging due to both a lack of theory of respiration and the difficulty of obtaining relevant data to test models (Trumbore, 2006).

Jakob 20/3/2017 11:32
**Gelöscht:** ,

Jakob 20/3/2017 11:32
**Gelöscht:** about

Jakob 20/3/2017 11:32
**Gelöscht:** 6

Jakob 20/3/2017 11:32
**Gelöscht:** Southern hemisphere

Jakob 20/3/2017 11:32
**Gelöscht:** 1

Jakob 20/3/2017 11:32
**Gelöscht:** February

Jakob 20/3/2017 11:32
**Gelöscht:** 2

Jakob 20/3/2017 11:32
**Gelöscht:** "

Jakob 20/3/2017 11:32
**Gelöscht:** Earth",

Jakob 20/3/2017 11:32
**Gelöscht:** Northern hemispheric

Jakob 20/3/2017 11:32
**Gelöscht:** Southern hemispheric

Jakob 20/3/2017 11:32
**Gelöscht:** about 1.5-2 times

Jakob 20/3/2017 11:32
**Gelöscht:** Northern hemispheric

Jakob 20/3/2017 11:32
**Gelöscht:** **TER and**

Jakob 20/3/2017 11:32
**Gelöscht:** drivers

Jakob 20/3/2017 11:32
**Gelöscht:** ecosystem respiration (TER) (

Jakob 20/3/2017 11:32
**Gelöscht:** respiratory

Jakob 20/3/2017 11:32
**Gelöscht:** microbial

Jakob 20/3/2017 11:32
**Gelöscht:** such as

Jakob 20/3/2017 11:32
**Gelöscht:** How

Jakob 20/3/2017 11:32
**Gelöscht:** well

In addition to a good theory for respiration, information on disturbance history (e.g., time since last fire) and forest age would improve the upscaling of NEP from sites to regions (Ciais et al., 2014). Disturbances that cause physical damage to vegetation properties tend to temporarily increase respiration and reduce photosynthesis and thus alter the balance between gross C uptake and release. Disturbed ecosystems are thus initially assumed to be strong C sources until plant production recovers. However, how these regrowth processes compensate a given disturbance regime cannot yet be quantified at global scales, as the area covered by disturbed ecosystems is variable and unknown (Ciais et al., 2014). For example, regrowth of vegetation after fires and other disturbances is not well sampled neither in the FLUXNET stations nor in the set of predictors used by the FLUXCOM models and is assumed to be implicit in our NEP estimate. Furthermore, management can have strong effects on annual NEP of croplands, which form large parts of the land surface (Jung et al., 2011). However, not all of the relevant predictors (i.e. disturbance maps, management practices, soil moisture) are currently available to be included in empirical upscaling exercises (Tramontana et al., 2016).

In addition to the above difficulties, some regions are undersampled by eddy-covariance towers and thus NEP is not well constrained. This is the case for tropical forests and the northern high latitudes. In the tropics, undersampling leads to a large overestimation of net $CO_2$ uptake in comparison to inversion and forest inventories (Peylin et al., 2013; Pan et al., 2011) whereas in the high latitudes it leads to a comparably large $CO_2$ release (Figure 4).

Given the difference between NCE and inversions in the tropics (Figure 4), we can assume that a bias of FLUXCOM NEP towards a too high $CO_2$ sink is the main reason why the C budget is not closed in our approach. This raises the question why upscaled NEP has such a strong systematic bias towards a sink, particularly in the tropics (see also Jung et al., 2011). We suspect that the eddy-covariance towers collected in FLUXNET which provide the empirical basis for the global data driven estimates (see Sect. 2.3.1) do not represent the different age classes of forests very well. For instance, young and regrowing forests with a generally higher-than average NEP are possibly overrepresented in FLUXNET. However, such an age-dependency (Amiro et al., 2010; Coursolle et al., 2012; Hyvönen et al., 2007; Magnani et al., 2007) has not yet been included in global upscaling of NEP. This hypothesis should be tested in future upscaling exercises.

### 4.2

### 4.3

### 4.4 Missing fluxes

Due to a focus on spatially explicit maps, not all known fluxes between land surface and atmosphere are considered in our analysis. We assume that including the following fluxes may have an influence on the regional and global flux estimates (estimates of the flux magnitude are given in brackets if known):

Jakob 20/3/2017 11:32
**Gelöscht:** TER and…f NEP from sites to ... [18]

Jakob 20/3/2017 11:32
**Gelöscht:** If

Jakob 20/3/2017 11:32
**Gelöscht:** , this… This raises the question ... [19]

Jakob 20/3/2017 11:32
**[4] nach unten verschoben: Uncertainties in fire emissions**
Fire emission estimates combine satellite-based fire data with ecosystems models. Uncertainties in global fire emission estimates are substantial and different fire products vary largely by location, vegetation type and fire weather (Ciais et al., 2014; French et al., 2011).

Jakob 20/3/2017 11:32
**Gelöscht:** While GFED4 burned area estimates come with uncertainty estimates (Giglio et al., 2013), the actual uncertainty of C emissions from fires might be larger, in the order of 50% and depend regionally and temporally on the various input data sets such as burned area, small fire burned area, biomass loadings, combustion completeness, etc. Top-down assessments using for example carbon monoxide (CO) have indicated that estimates on regional scales are often not too far off but given that different top-down studies using differe ... [20]

Jakob 20/3/2017 11:32
**[5] nach unten verschoben: Seasonality for coastal and inland waters, wood and crop harvest emissions** ... [21]

Jakob 20/3/2017 11:32
**[6] nach unten verschoben:** For inland waters, seasonality has so far only been investigated at regional scale (Laruelle et al., 2015; Rich ... [22]

Jakob 20/3/2017 11:32
**Gelöscht:** 2013).

Jakob 20/3/2017 11:32
**[7] nach unten verschoben:** These estimates indicate that seasonal differences in shelf net C exchange are as high as the annually integra ... [23]

Jakob 20/3/2017 11:32
**[8] nach unten verschoben:**
Biogenic C emissions related to tropical aboveground biomass loss as well as crop ar ... [24]

Jakob 20/3/2017 11:32
**Gelöscht:** To better constrain C exchange on a monthly basis, however, the seasonal cycles of those fluxes would be necessary.

Jakob 20/3/2017 11:32
**Gelöscht:** under similar latitudes (Takahashi et al., 2009).

Jakob 20/3/2017 11:32
**Gelöscht:** for instance…that including th ... [25]

- Emissions from biogenic volatile organic compounds (VOCs) amount to approximately 0.76PgC / year globally (Sindelarova et al., 2014)
- $CO_2$ emissions from wetlands, estimated globally at around 2.1 PgC /year (Aufdenkampe et al., 2011)
- $CH_4$ emissions from biogenic sources and animals
- Crop residues burning in households
- Biofuel burning
- Changes in land management, e.g. shifts in agriculture, soil tillage, grassland ploughing and grazing
- Geological fluxes
- Raymond et al. (2013) estimate a much higher river evasion (1.8 PgC / year instead of 0.65 PgC / year used in this study).

All known missing fluxes add up to an additional C release of about 4 PgC / yr. Although substantial, they do not cover the mismatch of more than 9 PgC / yr by far (Sect. 3.1). However, they would suffice to close the budget if tropical forests are assumed to be C neutral (tropical forests are responsible for a net C sink of about 5 PgC / year, Sect. 3.2). This significant amount of missing fluxes prohibits constraining FLUXCOM runs with all the remaining fluxes. In other words, we cannot be certain of the bias in upscaled NEP as long as the major fluxes are not quantified in a spatially explicit manner. Emissions from VOCs and wetlands should thus receive particular attention if a consistent spatiotemporal picture of vertical $CO_2$ exchange is to be obtained.

### 4.5 Uncertainty estimates and model-data fusion

Our uncertainty estimates of ocean and land C exchange likely underestimate the true uncertainty. In particular, Landschützer et al. (2014) estimated that the choice of sea-air gas transfer formulation (also including other relationships than quadratic) and the $pCO_2$ mapping mismatch lead to an uncertainty of 37% for the global average over sea-air exchange between 1998-2011, with the majority of this uncertainty stemming from the gas transfer formulation. Furthermore, the uncertainty of NEP is likely underestimated because all upscaling methods in FLUXCOM use the same set of predictors (Tramontana et al., 2016). Hence, the uncertainty estimates only cover the uncertainty related to the upscaling method but do not contain uncertainties related to the selection of predictors or observational uncertainty of the predictors themselves.

A comprehensive spatiotemporally explicit bottom-up estimate of NCE can be a powerful ingredient for model-data integration exercises (Rayner et al., 2005). Yet, model-data integration requires uncertainty characteristics of all used data streams (Raupach et al., 2005). Furthermore, it is important that uncertainties can be described in terms of random errors (Ciais et al., 2014). Error estimates at the local or regional level are difficult to use if no spatial error covariance matrix is available. The uncertainty analysis presented in this study obtained through Monte Carlo sampling aims to be of use for modal-data-integration studies. Errors are automatically propagated through different spatial resolutions by aggregating the individual ensembles of NCE. Naturally, efforts should be made to obtain error estimates for all integrated datasets (i.e., Wood, Fires, Shelves, Estuaries, and Lakes). Nevertheless, this first integrated NCE estimate offers new possibilities for approaches such as the Carbon Cycle Data Assimilation System (CCDAS, Rayner et al., 2005), by not only providing a full spatiotemporal grid of fluxes, but also a transparent and consistent error propagation scheme. This can have also practical applications, for instance for designing new measurement campaigns in regions with high uncertainties to reduce knowledge gaps in the global $CO_2$ fluxes.

### 4.6 Uncertainties in fire emissions

Jakob 20/3/2017 11:32
**[4] verschoben (Einfügung)**

Fire emission estimates combine satellite-based fire data with ecosystems models. Uncertainties in global fire emission estimates are substantial and different fire products vary largely by location, vegetation type and fire weather (Ciais et al., 2014; French et al., 2011).

While GFED4 burned area estimates come with regional uncertainty estimates (Giglio et al., 2013), the actual uncertainty of C emissions from fires are probably much larger, on the order of 50% (van der Werf et al., 2017). The uncertainties of fire emission estimates depend regionally and temporally on the various input data sets such as burned area, small fire burned area, biomass loadings, and combustion completeness. Better quantifying this uncertainty requires an assessment of the burned area estimates as well as new field data on fuel consumption and emission factors. In this study we cannot propagate this uncertainty into the NCE estimates as this would require spatiotemporal error covariance matrices.

### 4.7 Seasonality for coastal and inland waters, wood and crop harvest emissions

Jakob 20/3/2017 11:32
**[5] verschoben (Einfügung)**

Recently, major steps have been undertaken to resolve the spatial variability of coastal and inland water $CO_2$ fluxes (Laruelle et al., 2013; Laruelle et al., 2014; Lauerwald et al., 2015; Raymond et al., 2013). Estimates of the seasonal variation in these fluxes are necessary to better constrain seasonal variations in NCE. For inland waters, seasonality has so far only been investigated at regional scale (Laruelle et al., 2015; Richey et al., 2002). For shelves some seasonal estimates are currently available in temperate and high latitudes, indicating that net C uptake is highest in spring whereas C release is highest in summer (Laruelle et al., 2014, 2017). These estimates indicate that seasonal differences in shelf net C exchange are as high as the annually integrated latitudinal gradient. An analysis performed over Atlantic shelves suggests that the seasonal variability in the air-sea $CO_2$ exchange is most pronounced over temperate latitudes. In these regions, shelves generally behave as strong $CO_2$ sinks in winter and spring, partly sustained by $CO_2$ fixation during the spring phytoplankton bloom, but can become mild $CO_2$ sources to the atmosphere in summer due to the effect of temperature-driven decrease $CO_2$ solubility in water (Laruelle et al., 2014). Such behaviour is consistent with that of the open ocean at similar latitudes (Takahashi et al., 2009). In the continental shelves surrounding other oceanic basins, however, a recent study suggests more complex seasonal patterns involving the contributions of processes other than temperature to the seasonality of coastal $pCO_2$ (Laruelle et al., 2017).

Jakob 20/3/2017 11:32
**[6] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[7] verschoben (Einfügung)**

Biogenic C emissions related to tropical aboveground biomass loss as well as crop and wood harvest are equally distributed across months in this study. When exactly C emissions from humans and livestock occur is difficult to predict and would require more detailed consumption data (Wolf et al., 2015a).

Jakob 20/3/2017 11:32
**[8] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**Gelöscht:** ... [26]

## 5 Conclusions

From the presented synthesis, we draw the following main conclusions:

i) Current estimates of surface-atmosphere $CO_2$ exchanges that are spatiotemporally explicit and entirely driven by surface observation are not sufficiently well constrained to close the C budget at the global scale. The data-driven estimates show a large bias towards too much C uptake by the Earth surface of nearly 10 PgC / year.

ii) The most likely candidate for inducing the mismatch between data-driven surface-atmosphere $CO_2$ exchange and the atmospheric $CO_2$ growth rate is land NEP. In particular tropical NEP estimates appear to be strongly overestimated (too large land sink). Understanding this bias will help designing better upscaling approaches (e.g., by including currently missing relevant predictors) and pinpointing variables that need to be (better) monitored in the future.

iii) Regionally, the estimates of NCE are partly well constrained and may be used for model-data integration studies, validation of models, and evaluating claims and potentials of net C uptake within the framework of the Paris agreement (UNFCCC, 2015). These regions include Europe, Russia, South Asia, East Asia, Australia and most oceanic regions. Better constraining C fluxes in regions with currently high uncertainties should be a priority of future research.

**Acknowledgements**

This study was funded by the European Union in the context of the FP7 project GEOCARBON (grant agreement #283080). Authors affiliated with [2] and [16] further acknowledge the EU for support via the H2020 project BACI (grant agreement #640176). Authors affiliated with [5] thank the SAMPLES project as part of the CGIAR research program CCAFS, and CIFOR from the governments of Australia (grant agreement #46167) and Norway (grant agreement #QZA-10/0468). N.C. acknowledges funding from the NOVA grant UID/AMB/04085/2013. G.G.L. is 'Chargé de recherches F.R.S.-FNRS' at ULB. R.L. received funding from ANR (ANR-10-LABX-0018) and BRIC at ULB. J.H. and R.L. received funding from the German Science Foundation DFG (HA4472/6-1 and the cluster of excellence CLISAP, DFG EXEC 177, Hamburg). L.C. acknowledges funding from a NASA Earth and Space Science Fellowship. We also acknowledge the European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) for providing the Emission Database for Global Atmospheric Research (EDGAR), release version EDGARv4.2.

Jakob 20/3/2017 11:32

**Gelöscht:** If we exclude FF from the NCE estimate, we end up with a net $CO_2$ uptake by the Earth surface of 13.6±3.4 PgC / year. Assuming neutral $CO_2$ exchange for tropical forests (Sect. 3.2) still requires an additional source of about 4 PgC / year (2.5 PgC / year with river outgassing from Raymond et al., 2013), and potential candidates were suggested in Sect. 4.4. The estimate of 19 PgC / year for NEP seems rather high and in fact exceeds the estimate by Ciais et al. (in revision) over the RECCAP regions by nearly 9 Pg / year (7.5 Pg / year if the river outgassing by Raymond et al., 2013 is used). In particular, our analysis probably strongly overestimates $CO_2$ uptake in South America, Africa Southeast Asia, and North America. A comparison between upscaled ecosystem fluxes with a satellite-based inversion using GOSAT data lead to similar results (Kondo et al., 2015). One has to recall that the study aims for a transparent appraisal of the available and empirically derived pieces of information. It thus offers a quantitative approach to better identify knowledge gaps that should be addressed with future observation missions in to better constrain NCE in specific regions. In fact, we find that the uncertainty range of this synthesis of data-driven $CO_2$ fluxes is still too large to provide any confidence for a budget based on bottom-up information only. ... [27]

Jakob 20/3/2017 11:32

**[1] nach oben verschoben:** et al., 2015).

Jakob 20/3/2017 11:32

**[3] nach oben verschoben:** 2014; Rödenbeck et al., 2014).

Jakob 20/3/2017 11:32

**Gelöscht:** ... [28]

Jakob 20/3/2017 11:32

**Gelöscht:** Plans for new comprehensive sampling expeditions are underway (Newman et al., 2 ... [29]

## References

Amiro, B. D., Barr, A. G., Barr, J. G., Black, T. A., Bracho, R., Brown, M., Chen, J., Clark, K. L., Davis, K. J., Desai, A. R., Dore, S., Engel, V., Fuentes, J. D., Goldstein, A. H., Goulden, M. L., Kolb, T. E., Lavigne, M. B., Law, B. E., Margolis, H. A., Martin, T., McCaughey, J. H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J. T., Starr, G., and Xiao, J.: Ecosystem carbon dioxide fluxes after disturbance in forests of North America, Journal of Geophysical Research-Biogeosciences, 115, 2010.

Andreae, M. O., Acevedo, O. C., Araùjo, A., Artaxo, P., Barbosa, C. G. G., Barbosa, H. M. J., Brito, J., Carbone, S., Chi, X., Cintra, B. B. L., da Silva, N. F., Dias, N. L., Dias-Júnior, C. Q., Ditas, F., Ditz, R., Godoi, A. F. L., Godoi, R. H. M., Heimann, M., Hoffmann, T., Kesselmeier, J., Könemann, T., Krüger, M. L., Lavric, J. V., Manzi, A. O., Lopes, A. P., Martins, D. L., Mikhailov, E. F., Moran-Zuloaga, D., Nelson, B. W., Nölscher, A. C., Santos Nogueira, D., Piedade, M. T. F., Pöhlker, C., Pöschl, U., Quesada, C. A., Rizzo, L. V., Ro, C. U., Ruckteschler, N., Sá, L. D. A., de Oliveira Sá, M., Sales, C. B., dos Santos, R. M. N., Saturno, J., Schöngart, J., Sörgel, M., de Souza, C. M., de Souza, R. A. F., Su, H., Targhetta, N., Tóta, J., Trebs, I., Trumbore, S., van Eijck, A., Walter, D., Wang, Z., Weber, B., Williams, J., Winderlich, J., Wittmann, F., Wolff, S., and Yáñez-Serrano, A. M.: The Amazon Tall Tower Observatory (ATTO): overview of pilot measurements on ecosystem ecology, meteorology, trace gases, and aerosols, Atmos. Chem. Phys., 15, 10723-10776, 2015.

Atlas, R., Hoffman, R. N., Ardizzone, J., Leidner, S. M., Jusem, J. C., Smith, D. K., and Gombos, D.: A Cross-Calibrated Multiplatform Ocean Surface Wind Velocity Product for Meteorological and Oceanographic Applications, Bulletin of the American Meteorological Society, 92, 157-+, 2011.

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E., and Yoo, K.: Riverine coupling of biogeochemical cycles between land, oceans and atmosphere, Frontiers Ecology Environ., 9, 53–60, 2011.

Bakker, D. C. E., Pfeil, B., Smith, K., Hankin, S., Olsen, A., Alin, S. R., Cosca, C., Harasawa, S., Kozyr, A., Nojiri, Y., O'Brien, K. M., Schuster, U., Telszewski, M., Tilbrook, B., Wada, C., Akl, J., Barbero, L., Bates, N. R., Boutin, J., Bozec, Y., Cai, W. J., Castle, R. D., Chavez, F. P., Chen, L., Chierici, M., Currie, K., de Baar, H. J. W., Evans, W., Feely, R. A., Fransson, A., Gao, Z., Hales, B., Hardman-Mountford, N. J., Hoppema, M., Huang, W. J., Hunt, C. W., Huss, B., Ichikawa, T., Johannessen, T., Jones, E. M., Jones, S. D., Jutterström, S., Kitidis, V., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Manke, A. B., Mathis, J. T., Merlivat, L., Metzl, N., Murata, A., Newberger, T., Omar, A. M., Ono, T., Park, G. H., Paterson, K., Pierrot, D., Ríos, A. F., Sabine, C. L., Saito, S., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Sieger, R., Skjelvan, I., Steinhoff, T., Sullivan, K. F., Sun, H., Sutton, A. J., Suzuki, T., Sweeney, C., Takahashi, T., Tjiputra, J., Tsurushima, N., van Heuven, S. M. A. C., Vandemark, D., Vlahos, P., Wallace, D. W. R., Wanninkhof, R., and Watson, A. J.: An update to the Surface Ocean CO2 Atlas (SOCAT version 2), Earth Syst. Sci. Data, 6, 69-90, 2014.

Baldocchi, D.: Measuring fluxes of trace gases and energy between ecosystems and the atmosphere - the state and future of the eddy covariance method, Global Change Biology, 20, 3600-3609, 2014.

Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P., and White, J. W. C.: Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years, Nature, 488, 70-72, 2012.

Berger, M., Moreno, J., Johannessen, J. A., Levelt, P. F., and Hanssen, R. F.: ESA's sentinel missions in support of Earth system science, Remote Sensing of Environment, 120, 84-90, 2012.

Canadell, J. G., Ciais, P., Gurney, K., Le Quéré, C., Piao, S., Raupach, M. R., and Sabine, C. L.: An International Effort to Quantify Regional Carbon Fluxes, Eos, Transactions American Geophysical Union, 92, 81-82, 2011.

Ciais, P., Dolman, A., Bombelli, A., Duren, R., Peregon, A., Rayner, P., Miller, C., Gobron, N., Kinderman, G., and Marland, G.: Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system, Biogeosciences, 11, 3547-3602, 2014.

Ciais, P., Gasser, T., Lauerwald, R., Peng, S., Raymond, P. A., Wang, Y., Canadell, J. G., Peters, G. P., Andres, R. J., Chang, J., Yue, C., Dolman, A. J., Haverd, V., Hartmann, J., Laruelle, G., King, A. W., Liu, Y., Luyssaert, S., Maignan, F., Patra, P. K., Peregon, A., Regnier, P., Piao, S., Poulter, B., Shvidenko, A., Valentini, R., Wang, R., van Dijk, A. I. J. M., Broquet, G., Yin, Y., Zscheischler, J. and Zhu, D.: Observed regional carbon budgets imply reduced soil heterotrophic respiration, Nature, in revision.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S., and Thornton, P.: Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change, Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Coursolle, C., Margolis, H. A., Giasson, M. A., Bernier, P. Y., Amiro, B. D., Arain, M. A., Barr, A. G., Black, T. A., Goulden, M. L., McCaughey, J. H., Chen, J. M., Dunn, A. L., Grant, R. F., and Lafleur, P. M.: Influence of stand age on the magnitude and seasonality of carbon fluxes in Canadian forests, Agricultural and Forest Meteorology, 165, 136-148, 2012.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Holm, E. V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553-597, 2011.

Dolman, A. J., Shvidenko, A., Schepaschenko, D., Ciais, P., Tchebakova, N., Chen, T., van der Molen, M. K., Belelli Marchesini, L., Maximov, T. C., Maksyutov, S., and Schulze, E. D.: An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion methods, Biogeosciences, 9, 5323-5340, 2012.

Dürr, H. H., Laruelle, G. G., van Kempen, C. M., Slomp, C. P., Meybeck, M., and Middelkoop, H.: Worldwide Typology of Nearshore Coastal Systems: Defining the Estuarine Filter of River Inputs to the Oceans, Estuaries and Coasts, 34, 441-458, 2011.

Earles, J. M., Yeh, S., and Skog, K.E.: Timing of carbon emissions from global forest clearance, Nature Climate Change 2, 682-685, 2012.

Fekete, B. M., Vorosmarty, C. J., and Grabs, W.: High-resolution fields of global runoff combining observed river discharge and simulated water balances, Global Biogeochem Cy, 16, 2002.

French, N. H. F., de Groot, W. J., Jenkins, L. K., Rogers, B. M., Alvarado, E., Amiro, B., de Jong, B., Goetz, S., Hoy, E., Hyer, E., Keane, R., Law, B. E., McKenzie, D., McNulty, S. G., Ottmar, R., Perez-Salicrup, D. R., Randerson, J., Robertson, K. M., and Turetsky, M.: Model comparisons for estimating carbon emissions from North American wildland fire, Journal of Geophysical Research-Biogeosciences, 116, 2011.

Giglio, L., Randerson, J. T., and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), Journal of Geophysical Research-Biogeosciences, 118, 317-328, 2013.

GLOBALVIEW-CO2: Cooperative atmospheric data integration project-Carbon dioxide. Multi-laboratory compilation of synchronized and gap-filled atmospheric carbon dioxide records for the period 1979-2011., NOAA ESRL, Boulder, 2012.

Gloor, M., Gatti, L., Brienen, R., Feldpausch, T. R., Phillips, O. L., Miller, J., Ometto, J. P., Rocha, H., Baker, T., de Jong, B., Houghton, R. A., Malhi, Y., Aragão, L. E. O. C., Guyot, J. L., Zhao, K., Jackson, R., Peylin, P., Sitch, S., Poulter, B., Lomas, M., Zaehle, S., Huntingford, C., Levy, P., and Lloyd, J.: The carbon balance of South America: a review of the status, decadal trends and main determinants, Biogeosciences, 9, 5407-5430, 2012.

Harris, N. L., Brown, S., Hagen, S. C., Saatchi, S. S., Petrova, S., Salas, W., Hansen, M. C., Potapov, P. V., and Lotsch, A.: Baseline Map of Carbon Emissions from Deforestation in Tropical Regions, Science, 336, 1573-1576, 2012.

Hartmann, J., Lauerwald, R., and Moosdorf, N.: A brief overview of the GLObal RIver CHemistry Database, GLORICH, Geochemistry of the Earth's Surface Ges-10, 10, 23-27, 2014.

Haverd, V., Raupach, M. R., Briggs, P. R., Canadell, J. G., Davis, S. J., Law, R. M., Meyer, C. P., Peters, G. P., Pickett-Heaps, C., and Sherman, B.: The Australian terrestrial carbon budget, Biogeosciences, 10, 851-869, 2013.

Hayes, D. J., Turner, D. P., Stinson, G., McGuire, A. D., Wei, Y., West, T. O., Heath, L. S., de Jong, B., McConkey, B. G., Birdsey, R. A., Kurz, W. A., Jacobson, A. R., Huntzinger, D. N., Pan, Y., Post, W. M., and Cook, R. B.: Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data, Global Change Biology, 18, 1282-1299, 2012.

Houghton, R. A.: Balancing the global carbon budget, Annual Review of Earth and Planetary Sciences, 35, 313-347, 2007.

Hyvönen, R., Agren, G. I., Linder, S., Persson, T., Cotrufo, M. F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I. A., Jarvis, P. G., Kellomaki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R. J., Oren, R., Pilegaard, K., Ryan, M. G., Sigurdsson, B. D., Stromgren, M., van Oijen, M., and Wallin, G.: The likely impact of elevated [CO2], nitrogen deposition,

Jakob 20/3/2017 11:32

**Gelöscht:** Gasser, T. and Ciais, P.: A theoretical framework for the net land-to-atmosphere CO2 flux and its implications in the definition of "emissions from land-use change", Earth Syst. Dynam., 4, 171-186, 2013.

increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review, New Phytologist, 173, 463-480, 2007.

Ishii, M., Feely, R. A., Rodgers, K. B., Park, G.-H., Wanninkhof, R., Sasano, D., Sugimoto, H., Cosca, C E., Nakaoka, S., Telszewski, M., Nojiri, Y., Mikaloff Fletcher, S E., Niwa, Y., Patra, P K., Valsala, V., Nakano, H., Lima, I., Doney, S. C., Buitenhuis, E. T., Aumont, O., Dunne, J P., Lenton, A., and Takahashi, T.: Air–sea $CO_2$ flux in the Pacific Ocean for the period 1990–2009, Biogeosciences, 11, 709-734, 2014.

Jägermeyr, J., Gerten, D., Lucht, W., Hostert, P., Migliavacca, M., & Nemani, R.: A high□resolution approach to estimating ecosystem respiration at continental scales using operational satellite data, Global Change Biology, 20, 1191-1210, 2014.

Jähne, B., Munnich, K. O., Bosinger, R., Dutzi, A., Huber, W., and Libner, P.: On the Parameters Influencing Air-Water Gas-Exchange, Journal of Geophysical Research-Oceans, 92, 1937-1949, 1987.

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J. Q., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F., and Williams, C.: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations, Journal of Geophysical Research-Biogeosciences, 116, 2011.

King, A. W., Andres, R. J., Davis, K. J., Hafer, M., Hayes, D. J., Huntzinger, D. N., de Jong, B., Kurz, W. A., McGuire, A. D., Vargas, R., Wei, Y., West, T. O., and Woodall, C. W.: North America's net terrestrial CO2 exchange with the atmosphere 1990–2009, Biogeosciences, 12, 399-414, 2015.

Kondo, M., Ichii, K., Takagi, H. and Sasakawa, M.: Comparison of the data-driven top-down and bottom-up global terrestrial CO2 exchanges: GOSAT CO2 inversion and empirical eddy flux upscaling, J. Geophys. Res. Biogeosci., 120, 1226–1245, 2015.

Landschützer, P., Gruber, N., Bakker, D. C. E., and Schuster, U.: Recent variability of the global ocean carbon sink, Global Biogeochem Cy, 28, 927-949, 2014.

Landschützer, P., Gruber, N., Haumann, F. A., Rödenbeck, C., Bakker, D. C. E., van Heuven, S., Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., Tilbrook, B., and Wanninkhof, R.: The reinvigoration of the Southern Ocean carbon sink, Science, 349, 1221-1224, 2015.

Laruelle, G. G., Durr, H. H., Lauerwald, R., Hartmann, J., Slomp, C. P., Goossens, N., and Regnier, P. A. G.: Global multi-scale segmentation of continental and coastal waters from the watersheds to the continental margins, Hydrol Earth Syst Sc, 17, 2029-2051, 2013.

Laruelle, G. G., Lauerwald, R., Pfeil, B., and Regnier, P.: Regionalized global budget of the CO2 exchange at the air-water interface in continental shelf seas, Global Biogeochem Cy, 28, 1199-1214, 2014.

Laruelle, G. G., Lauerwald, R., Rotschi, J., Raymond, P. A., Hartmann, J., and Regnier, P.: Seasonal response of air-water CO2 exchange along the land-ocean aquatic continuum of the northeast North American coast., Biogeosciences, 12, 1447-1458, 2015.

Laruelle, G. G., Landschützer, P., Gruber, N., Tison, J.-L., Delille, B., and Regnier, P.: Global high resolution monthly $pCO_2$ climatology for the coastal ocean derived from neural network interpolation, Biogeosciences Discuss., doi:10.5194/bg-2017-64, in review, 2017.

P., Lauerwald, R., Laruelle, G. G., Hartmann, J., Ciais, P., and Regnier, P. A. G.: Spatial patterns in CO2 evasion from the global river network, Global Biogeochem Cy, 29, 534-554, 2015.

Le Quéré, C., Moriarty, R., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Friedlingstein, P., Peters, G. P., Andres, R. J., Boden, T. A., Houghton, R. A., House, J. I., Keeling, R. F., Tans, P., Arneth, A., Bakker, D. C. E., Barbero, L., Bopp, L., Chang, J., Chevallier, F., Chini, L. P., Ciais, P., Fader, M., Feely, R. A., Gkritzalis, T., Harris, I., Hauck, J., Ilyina, T., Jain, A. K., Kato, E., Kitidis, V., Klein Goldewijk, K., Koven, C., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lima, I. D., Metzl, N., Millero, F., Munro, D. R., Murata, A., Nabel, J. E. M. S., Nakaoka, S., Nojiri, Y., O'Brien, K., Olsen, A., Ono, T., Pérez, F. F., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Rödenbeck, C., Saito, S., Schuster, U., Schwinger, J., Séférian, R., Steinhoff, T., Stocker, B. D., Sutton, A. J., Takahashi, T., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Vandemark, D., Viovy, N., Wiltshire, A., Zaehle, S., and Zeng, N.: Global Carbon Budget 2015, Earth Syst. Sci. Data, 7, 349-396, 2015.

Jakob 20/3/2017 11:32
**[9] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[10] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[11] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[12] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**Gelöscht:** Lasslop, G., Reichstein, M., Papale, D., Richardson, A. D., Arneth, A., Barr,

Jakob 20/3/2017 11:32
**[13] nach unten verschoben:** A.,

Jakob 20/3/2017 11:32
**[12] nach oben verschoben:** P.,

Jakob 20/3/2017 11:32
**Gelöscht:** Stoy,

Jakob 20/3/2017 11:32
**Gelöscht:** and Wohlfahrt, G.: Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation, Global Change Biology, 16, 187-208, 2010.

Lehner, B. and Döll, P.: Development and validation of a global database of lakes, reservoirs and wetlands, Journal of Hydrology, 296, 1-22, 2004.

Lehner, B., Verdin, K., and Jarvis, A.: New Global Hydrography Derived From Spaceborne Elevation Data, Eos, Transactions American Geophysical Union, 89, 93-94, 2008.

Lenton, A., Tilbrook, B., Law, R. M., Bakker, D., Doney, S. C., Gruber, N., Ishii, M., Hoppema, M., Lovenduski, N. S., Matear, R. J., McNeil, B. I., Metzl, N., Mikaloff Fletcher, S. E., Monteiro, P. M. S., Rödenbeck, C., Sweeney, C., and Takahashi, T.: Sea–air $CO_2$ fluxes in the Southern Ocean for the period 1990–2009, Biogeosciences, 10, 4037-4054, 2013.

Luyssaert, S., Abril, G., Andres, R., Bastviken, D., Bellassen, V., Bergamaschi, P., Bousquet, P., Chevallier, F., Ciais, P., Corazza, M., Dechow, R., Erb, K. H., Etiope, G., Fortems-Cheiney, A., Grassi, G., Hartmann, J., Jung, M., Lathière, J., Lohila, A., Mayorga, E., Moosdorf, N., Njakou, D. S., Otto, J., Papale, D., Peters, W., Peylin, P., Raymond, P., Rödenbeck, C., Saarnio, S., Schulze, E. D., Szopa, S., Thompson, R., Verkerk, P. J., Vuichard, N., Wang, R., Wattenbach, M., and Zaehle, S.: The European land and inland water CO2, CO, CH4 and N2O balance between 2001 and 2005, Biogeosciences, 9, 3357-3380, 2012.

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P. G., Kolari, P., Kowalski, A. S., Lankreijer, H., Law, B. E., Lindroth, A., Loustau, D., Manca, G., Moncrieff, J. B., Rayment, M., Tedeschi, V., Valentini, R., and Grace, J.: The human footprint in the carbon cycle of temperate and boreal forests, Nature, 447, 848-850, 2007.

Malhi, Y., Phillips, O. L., Lloyd, J., Baker, T., Wright, J., Almeida, S., Arroyo, L., Frederiksen, T., Grace, J., Higuchi, N., Killeen, T., Laurance, W. F., Leano, C., Lewis, S., Meir, P., Monteagudo, A., Neill, D., Vargas, P. N., Panfil, S. N., Patino, S., Pitman, N., Quesada, C. A., Rudas-Ll, A., Salomao, R., Saleska, S., Silva, N., Silveira, M., Sombroek, W. G., Valencia, R., Martinez, R. V., Vieira, I. C. G., and Vinceti, B.: An international network to monitor the structure, composition and dynamics of Amazonian forests (RAINFOR), Journal of Vegetation Science, 13, 439-450, 2002.

Masarie, K. A. and Tans, P. P.: Extension and Integration of Atmospheric Carbon-Dioxide Data into a Globally Consistent Measurement Record, Journal of Geophysical Research-Atmospheres, 100, 11593-11610, 1995.

Meybeck, M., Durr, H. H., and Vorosmarty, C. J.: Global coastal segmentation and its river catchment contributors: A new look at land-ocean linkage, Global Biogeochem Cy, 20, 2006.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., and Hayes, D.: A Large and Persistent Carbon Sink in the World's Forests, Science, 333, 988-993, 2011.

Patra, P. K., Canadell, J. G., Houghton, R. A., Piao, S. L., Oh, N. H., Ciais, P., Manjunath, K. R., Chhabra, A., Wang, T., Bhattacharya, T., Bousquet, P., Hartman, J., Ito, A., Mayorga, E., Niwa, Y., Raymond, P. A., Sarma, V. V. S. S., and Lasco, R.: The carbon budget of South Asia, Biogeosciences, 10, 513-527, 2013.

Peylin, P., Law, R. M., Gurney, K. R., Chevallier, F., Jacobson, A. R., Maki, T., Niwa, Y., Patra, P. K., Peters, W., Rayner, P. J., Rodenbeck, C., van der Laan-Luijkx, I. T., and Zhang, X.: Global atmospheric carbon budget: results from an ensemble of atmospheric CO2 inversions, Biogeosciences, 10, 6699-6720, 2013.

Piao, S. L., Ito, A., Li, S. G., Huang, Y., Ciais, P., Wang, X. H., Peng, S. S., Nan, H. J., Zhao, C., Ahlström, A., Andres, R. J., Chevallier, F., Fang, J. Y., Hartmann, J., Huntingford, C., Jeong, S., Levis, S., Levy, P. E., Li, J. S., Lomas, M. R., Mao, J. F., Mayorga, E., Mohammat, A., Muraoka, H., Peng, C. H., Peylin, P., Poulter, B., Shen, Z. H., Shi, X., Sitch, S., Tao, S., Tian, H. Q., Wu, X. P., Xu, M., Yu, G. R., Viovy, N., Zaehle, S., Zeng, N., and Zhu, B.: The carbon budget of terrestrial ecosystems in East Asia over the last two decades, Biogeosciences, 9, 3571-3586, 2012.

Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M.: Effects of anthropogenic land cover change on the carbon cycle of the last millennium, Global Biogeochem Cy, 23, 2009.

Poulter, B.: Global Wood Harvest, Operational Global Carbon Observing System – GEOCARBON Project Report, 2015 (data available upon request).

Prather, M. J., Holmes, C. D., and Hsu, J.: Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry, Geophys. Res. Lett., 39, L09803, doi:10.1029/2012GL051440, 2012.

Randerson, J. T., Chen, Y. , van der Werf, G. R., Rogers, B. M., and Morton, D. C.: Global burned area and biomass burning emissions from small fires, J. Geophys. Res., 117, G04012, doi:10.1029/2012JG002128, 2012.

Jakob 20/3/2017 11:32
**[14] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[13] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[15] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[16] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**Gelöscht:** Naegler, T.: Reconciliation of excess $^{14}$C-constrained global $CO_2$ piston velocity estimates, Tellus B, 61, 372–384, 2009. ... [30]

Jakob 20/3/2017 11:32
**[17] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[18] verschoben (Einfügung)**

Raupach, M. R., Rayner, P. J., Barrett, D. J., DeFries, R. S., Heimann, M., Ojima, D. S., Quegan, S., and Schmullius, C. C.: Model-data synthesis in terrestrial carbon observation: methods, data requirements and data uncertainty specifications, Global Change Biology, 11, 378-397, 2005.

Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P., and Guth, P.: Global carbon dioxide emissions from inland waters, Nature, 503, 355-359, 2013.

Raymond, P. A., Zappa, C. J., Butman, D., Bott, T. L., Potter, J., Mulholland, P., Laursen, A. E., McDowell, W. H., and Newbold, D.: Scaling the gas transfer velocity and hydraulic geometry in streams and small rivers, Limnology and Oceanography: Fluids and Environments, 2, 41-53, 2012.

Rayner, P. J., Scholze, M., Knorr, W., Kaminski, T., Giering, R., and Widmann, H.: Two decades of terrestrial carbon fluxes from a carbon cycle data assimilation system (CCDAS), Global Biogeochem Cy, 19, 2005.

T., E., A., E., T., D., S., Richey, J. E., Melack, J. M., Aufdenkampe, A. K., Ballester, V. M., and Hess, L. L.: Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO2, Nature, 416, 617-620, 2002.

Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A. R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., Park, G. H., Peylin, P., Rodgers, K. B., Sasse, T. P., Schuster, U., Shutler, J. D., Valsala, V., Wanninkhof, R., and Zeng, J.: Data-based estimates of the ocean carbon sink variability first - results of the Surface Ocean pCO(2) Mapping intercomparison (SOCOM), Biogeosciences, 12, 7251-7278, 2015.

Rödenbeck, C., Bakker, D. C. E., Metzl, N., Olsen, A., Sabine, C., Cassar, N., Reum, F., Keeling, R. F., and Heimann, M.: Interannual sea-air CO2 flux variability from an observation-driven ocean mixed-layer scheme, Biogeosciences, 11, 4599-4613, 2014.

Ruddiman, W. F.: The anthropogenic greenhouse era began thousands of years ago, Climatic Change, 61, 261-293, 2003.

Sarma, V. V. S. S., Lenton, A., Law, R. M., Metzl, N., Patra, P. K., Doney, S., Lima, I. D., Dlugokencky, E., Ramonet, M., and Valsala, V.: Sea–air $CO_2$ fluxes in the Indian Ocean between 1990 and 2009, Biogeosciences, 10, 7035-7052, 2013.

Schuster, U., McKinley, G. A., Bates, N., Chevallier, F., Doney, S. C., Fay, A. R., González-Dávila, M., Gruber, N., Jones, S., Krijnen, J., Landschützer, P., Lefèvre, N., Manizza, M., Mathis, J., Metzl, N., Olsen, A., Rios, A. F., Rödenbeck, C., Santana-Casiano, J. M., Takahashi, T., Wanninkhof, R., and Watson, A. J.: An assessment of the Atlantic and Arctic sea–air $CO_2$ fluxes, 1990–2009, Biogeosciences, 10, 607-627, 2013.

K., Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Muller, J. F., Kuhn, U., Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years, Atmospheric Chemistry and Physics, 14, 9317-9341, 2014.

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S. D., Murray-Tortarolo, G., Ahlström, A., Doney, S. C., Graven, H., Heinze, C., Huntingford, C., Levis, S., Levy, P. E., Lomas, M., Poulter, B., Viovy, N., Zaehle, S., Zeng, N., Arneth, A., Bonan, G., Bopp, L., Canadell, J. G., Chevallier, F., Ciais, P., Ellis, R., Gloor, M., Peylin, P., Piao, S. L., Le Quéré, C., Smith, B., Zhu, Z., and Myneni, R.: Recent trends and drivers of regional sources and sinks of carbon dioxide, Biogeosciences, 12, 653-679, 2015.

M., Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., Hales, B., Friederich, G., Chavez, F., Sabine, C., Watson, A., Bakker, D. C. E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y., Kortzinger, A., Steinhoff, T., Hoppema, M., Olafsson, J., Arnarson, T. S., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R., Wong, C. S., Delille, B., Bates, N. R., and de Baar, H. J. W.: Climatological mean and decadal change in surface ocean pCO(2), and net sea-air CO2 flux over the global oceans (vol 56, pg 554, 2009), Deep-Sea Research Part I-Oceanographic Research Papers, 56, 2075-2076, 2009.

Tatem, A. J., Goetz, S. J., and Hay, S. I.: Fifty years of earth-observation satellites - Views from space have led to countless advances on the ground in both scientific knowledge and daily life, American Scientist, 96, 390-398, 2008.

Tramontana, G., Jung, M., Schwalm, C. R., Ichii, K., Camps-Valls, G., Ráduly, B., Reichstein, M., Arain, M. A., Cescatti, A., Kiely, G., Merbold, L., Serrano-Ortiz, P., Sickert, S., Wolf, S., and Papale, D.: Predicting carbon dioxide and energy fluxes across global FLUXNET sites with regression algorithms, Biogeosciences, 13, 4291-4313, 2016.

Trumbore, S.: Carbon respired by terrestrial ecosystems - recent progress and challenges, Global Change Biology, 12, 141-153, 2006.

**[16] nach oben verschoben:** . G.,

Jakob 20/3/2017 11:32
**Gelöscht:** Regnier, P., Friedlingstein, P., ... [31]

Jakob 20/3/2017 11:32
**[14] nach oben verschoben:** S.,

Jakob 20/3/2017 11:32
**[17] nach oben verschoben:** J.,

Jakob 20/3/2017 11:32
**[19] nach unten verschoben:** T.,

Jakob 20/3/2017 11:32
**[9] nach oben verschoben:** . E.,

Jakob 20/3/2017 11:32
**[22] nach unten verschoben:** D.,

Jakob 20/3/2017 11:32
**[20] nach unten verschoben:** A.,

Jakob 20/3/2017 11:32
**[10] nach oben verschoben:** E.,

Jakob 20/3/2017 11:32
**[21] nach unten verschoben:** T.,

Jakob 20/3/2017 11:32
**[18] nach oben verschoben:** D.,

Jakob 20/3/2017 11:32
**Gelöscht:** Lauerwald, R., Luyssaert, S., ... [32]

Jakob 20/3/2017 11:32
**Gelöscht:** Joos, F., LaRowe, D

Jakob 20/3/2017 11:32
**Gelöscht:** Leifeld, J., Meysman, F. J. R., ... [33]

Jakob 20/3/2017 11:32
**Gelöscht:** Spahni, R., Suntharalingam, P., ... [34]

Jakob 20/3/2017 11:32
**Gelöscht:** Baldocchi, D., Papale, D., Aubi ... [35]

Jakob 20/3/2017 11:32
**Gelöscht:** Havrankova, K., Ilvesniemi, H., Janous,

Jakob 20/3/2017 11:32
**Gelöscht:** Knohl, A., Laurila, T., Lohila, ... [36]

Jakob 20/3/2017 11:32
**Gelöscht:** Matteucci, G., Meyers, T., Mig ... [37]

Jakob 20/3/2017 11:32
**Gelöscht:** Rotenberg, E., Sanz, M., Tenhunen,

Jakob 20/3/2017 11:32
**Gelöscht:** Seufert, G., Vaccari, F., Vesala ... [38]

Jakob 20/3/2017 11:32
**[23] verschoben (Einfügung)** ... [39]

Jakob 20/3/2017 11:32
**[20] verschoben (Einfügung)** ... [40]

Jakob 20/3/2017 11:32
**Gelöscht:** Schimel, D., Pavlick, R., Fisher ... [41]

Jakob 20/3/2017 11:32
**[11] nach oben verschoben:** K.,

Jakob 20/3/2017 11:32
**Gelöscht:** and Cox, P.: Observing terrestri ... [42]

Jakob 20/3/2017 11:32

Jakob 20/3/2017 11:32

Jakob 20/3/2017 11:32

Jakob 20/3/2017 11:32

Jakob 20/3/2017 11:32
... [43]

Tyukavina, A., Baccini, A., Hansen, M. C., Potapov, P. V., Stehman, S. V., Houghton, R. A., Krylov, A. M., Turubanova, S., and Goetz, S. J.: Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012, Environmental Research Letters, 10, 2015.

UNFCCC: http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx 2015.

Valentini, R., Arneth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., Ciais, P., Grieco, E., Hartmann, J., Henry, M., Houghton, R. A., Jung, M., Kutsch, W. L., Malhi, Y., Mayorga, E., Merbold, L., Murray-Tortarolo, G., Papale, D., Peylin, P., Poulter, B., Raymond, P. A., Santini, M., Sitch, S., Vaglio Laurin, G., van der Werf, G. R., Williams, C. A., and Scholes, R. J.: A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities, Biogeosciences, 11, 381-407, 2014.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707-11735, doi:10.5194/acp-10-11707-2010, 2010.

van der Werf, G. R., Randerson, J T., Giglio, L., van Leeuwen, T T., Chen, Y., Rogers, B. M., Mu, M., van Marle, M. J. E., Morton, D. C., Collatz, G. J., Yokelson, R. J., and Kasibhatla, P. S.: Global fire emissions estimates during 1997–2015, Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2016-62, in review, 2017.

Vernadsky, V.: The Biosphere (New York: Copernicus, Springer), 1926. 1926.

Wanninkhof, R.: Relationship between wind speed and gas exchange over the ocean, J. Geophys. Res.-Oceans, 97, 7373–7382, 1992.

Wanninkhof, R., Park, G. H., Takahashi, T., Sweeney, C., Feely, R., Nojiri, Y., Gruber, N., Doney, S. C., McKinley, G. A., Lenton, A., Le Quéré, C., Heinze, C., Schwinger, J., Graven, H., and Khatiwala, S.: Global ocean carbon uptake: magnitude, variability and trends, Biogeosciences, 10, 1983-2000, 2013.

West, T. O., Bandaru, V., Brandt, C. C., Schuh, A. E., and Ogle, S. M.: Regional uptake and release of crop carbon in the United States, Biogeosciences, 8, 2037-2046, 2011.

Wolf, J., West, T. O., Le Page, Y. L., Kyle, G. P., Zhang, X., Collatz, G. J., and Imhoff, M. L.: Biogenic carbon fluxes from global agricultural production and consumption, Global Biogeochem Cy, doi: 10.1002/2015GB005119, 2015a.

Wolf, J., West, T. O., Le Page, Y. L., Kyle, G. P., Zhang, X., Collatz, G. J., and Imhoff, M. L.: CMS: Carbon Fluxes from Global Agricultural Production and Consumption, 2005-2011. ORNL DAAC, Oak Ridge, Tennessee, USA, 2015b.

Zhou, L. M., Tian, Y. H., Myneni, R. B., Ciais, P., Saatchi, S., Liu, Y. Y., Piao, S. L., Chen, H. S., Vermote, E. F., Song, C. H., and Hwang, T. H.: Widespread decline of Congo rainforest greenness in the past decade, Nature, 509, 86-90, 2014.

Jakob 20/3/2017 11:32
**[19] verschoben (Einfügung)**

Jakob 20/3/2017 11:32
**[21] verschoben (Einfügung)**

**Table 1. Datasets used in this study including reference, time period and number of ensemble runs. If not specified, temporal resolution is monthly.**

| Data set | Reference | Time period used | # Runs |
|---|---|---|---|
| Ocean | Landschützer et al. (2014)<br>Rödenbeck et al. (2014) | 2001-2010 | 5+5 |
| Shelf | Laruelle et al. (2014) | 1 estimate | 1 |
| Estuaries | Laruelle et al. (2013) | 1 estimate | 1 |
| Marine | | 2001-2010 | 10 |
| Rivers | Lauerwald et al. (2015) | 1 estimate | 50 |
| Lakes | Raymond et al. (2013) | 1 estimate | 1 |
| NEP | Tramontana et al. (2016) | 2001-2010 | 8 |
| Crops | Wolf et al. (2015b) | 2005-2010, annual | 10 |
| Wood | Poulter (2015) | 2000, 1 estimate | 1 |
| Fire | Giglio et al. (2013) | 2001-2010 | 1 |
| $E_{LUC}$ | Tyukavina et al. (2015)<br>Harris et al. (2012) | 2000-2010, 1 estimate<br>2000-205, 1 estimate | 2 |
| FF (Fossil Fuels) | CARBONES | 2001-2010 | 1 |
| Atmospheric growth rate | NOAA | 2001-2010 | 1 |

Jakob 20/3/2017 11:32
**Gelöscht:** GPP / TER

Jakob 20/3/2017 11:32
**Gelöscht:** 16

**Table 2. Net carbon exchange for different subsystems and variables that contribute to NCE (Eq. 1, negative numbers are surface uptake). Uncertainty (Unc.) is SD over ensemble runs, IAV is SD over annual values time (2001-2010), CV is coefficient of variation, computed as IAV divided by Mean.**

| Variable | Marine | Rivers | Lakes | -NEP | Crops | Wood | $E_{LUC}$ | FF | Fire | NCE |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | -1.60 | 0.65 | 0.32 | -18.41 | 2.68 | 0.71 | 0.83 | 7.78 | 1.81 | -5.45 |
| Unc. | 0.15 | 0.08 | | 2.08 | 0.21 | | 0.16 | | | 1.99 |
| IAV | 0.36 | | | 0.36 | 0.09 | | | 0.75 | 0.11 | |
| CV | 0.22 | | | 0.02 | 0.03 | | | 0.10 | 0.06 | 0.11 |

Jakob 20/3/2017 14:56
**Gelöscht:** ….that contribute to NCE (E ... [44]

Jakob 20/3/2017 15:00
**Gelöscht:** GPP

Jakob 20/3/2017 15:00
**Gelöscht:** TER

Jakob 20/3/2017 15:00
**Gelöschte Zellen** ... [45]

Jakob 20/3/2017 15:00
**Gelöscht:** 108.29

Jakob 20/3/2017 15:00
**Gelöscht:** 89.24

Jakob 20/3/2017 15:00
**Gelöscht:** 6.07

Jakob 20/3/2017 15:00
**Gelöscht:** 3.62

Jakob 20/3/2017 15:00
**Gelöscht:** 3.60

Jakob 20/3/2017 15:00
**Gelöscht:** 3.38

Jakob 20/3/2017 15:00
**Gelöscht:** 69

Jakob 20/3/2017 15:00
**Gelöscht:** 0. 33

Jakob 20/3/2017 15:00
**Gelöscht:** 0.63

Jakob 20/3/2017 15:00
**Gelöscht:** 006

Jakob 20/3/2017 15:00
**Gelöscht:** 004

Jakob 20/3/2017 15:00
**Eingefügte Zellen** ... [46]

Jakob 20/3/2017 15:00
**Eingefügte Zellen** ... [47]

Jakob 20/3/2017 15:00
**Gelöscht:** 034

Jakob 20/3/2017 15:00
**Gelöschte Zellen** ... [48]

Jakob 20/3/2017 15:00
**Gelöschte Zellen** ... [49]

Jakob 20/3/2017 15:00
**Gelöscht:** 096

Jakob 20/3/2017 15:00
**Gelöscht:** 0.061

Jakob 20/3/2017 15:00
**Gelöschte Zellen** ... [50]

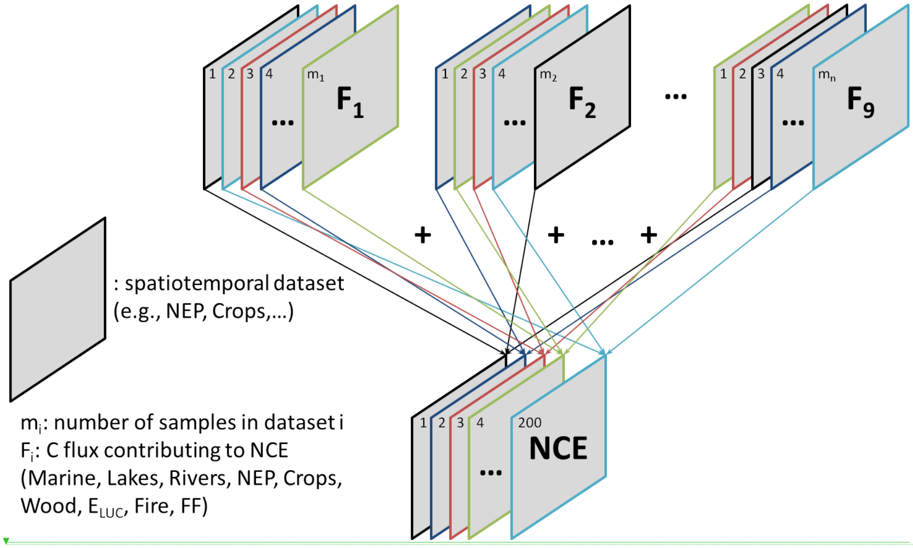
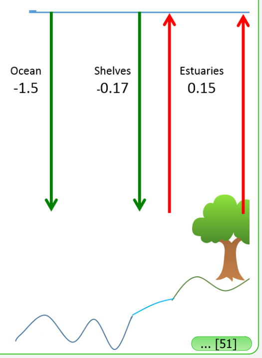


**Figure 1. Schematic explanation of the uncertainty propagation. Each spatiotemporal estimate of NCE is computed as the sum of randomly selected estimates of the 9 fluxes contributing to NCE (see Eq. 1, here denoted by $F_i$). For this study we compute 200 estimates of NCE. Uncertainties can be assessed at different spatial scales by first aggregating all NCE estimates to the desired scale and then using the 200 members for uncertainty estimation.**

Jakob 20/3/2017 11:32



**Gelöscht:** ... [51]

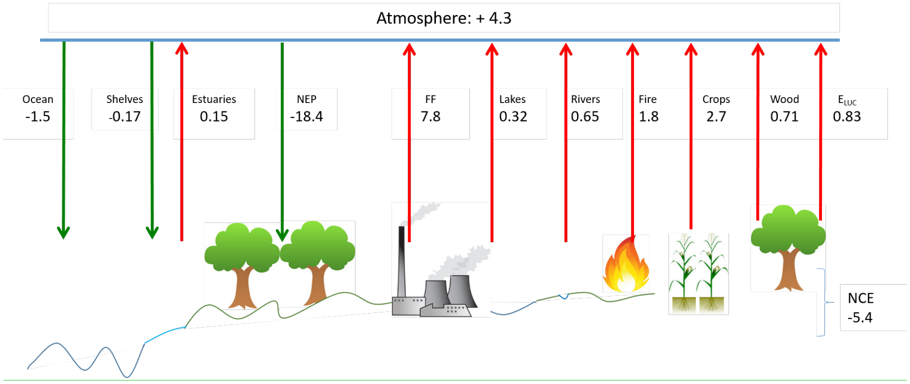
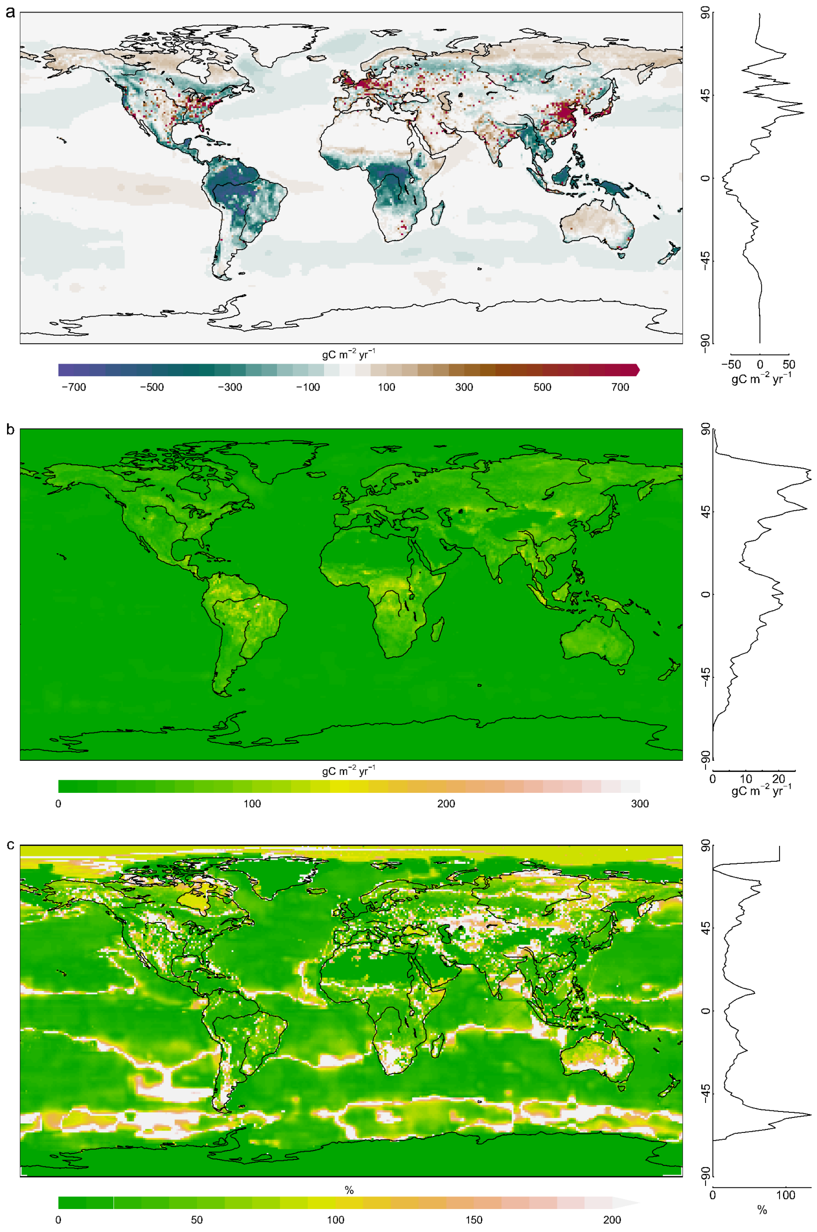


**Figure 2. Different components of observation-driven C exchange between the Earth's surface and the atmosphere. Red arrows denote a flux from the surface to the atmosphere (net source), green arrows denote a flux from the atmosphere to the surface (net sink). Units are in PgC / year.**


a
gC m$^{-2}$ yr$^{-1}$
−700
−500
−300
−100
100
300
500
700
90
45
0
−45
−90
−50
0
50
gC m$^{-2}$ yr$^{-1}$
b
gC m$^{-2}$ yr$^{-1}$
0
100
200
300
90
45
0
−45
−90
0
10
20
gC m$^{-2}$ yr$^{-1}$
c
%
0
50
100
150
200
90
45
0
−45
−90
0
100
%

**Gelöscht:**

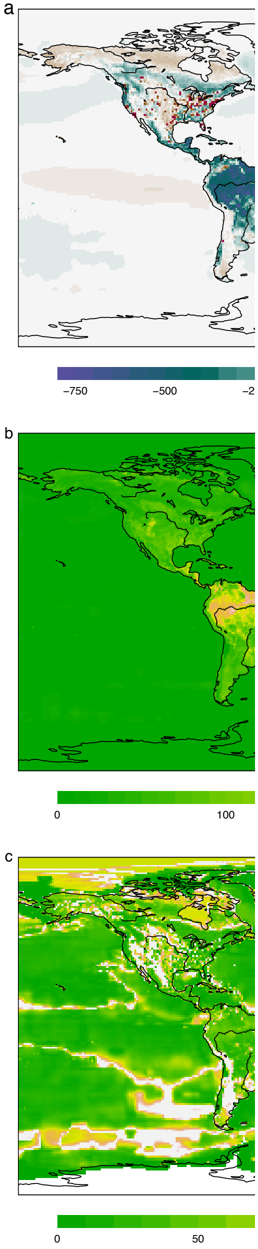

a
−750
−500
−2
b
0
100
c
0
50

**Figure 3. Gridded spatial patterns of NCE. a) 2001-2010 decadal mean. b) Uncertainty; 1SD across the NCE ensemble. c) Relative uncertainty; uncertainty normalized by absolute mean. Latitudinal plots in b) and c) denote median across latitudes.**

Jakob 20/3/2017 11:32

**Gelöscht:** 2

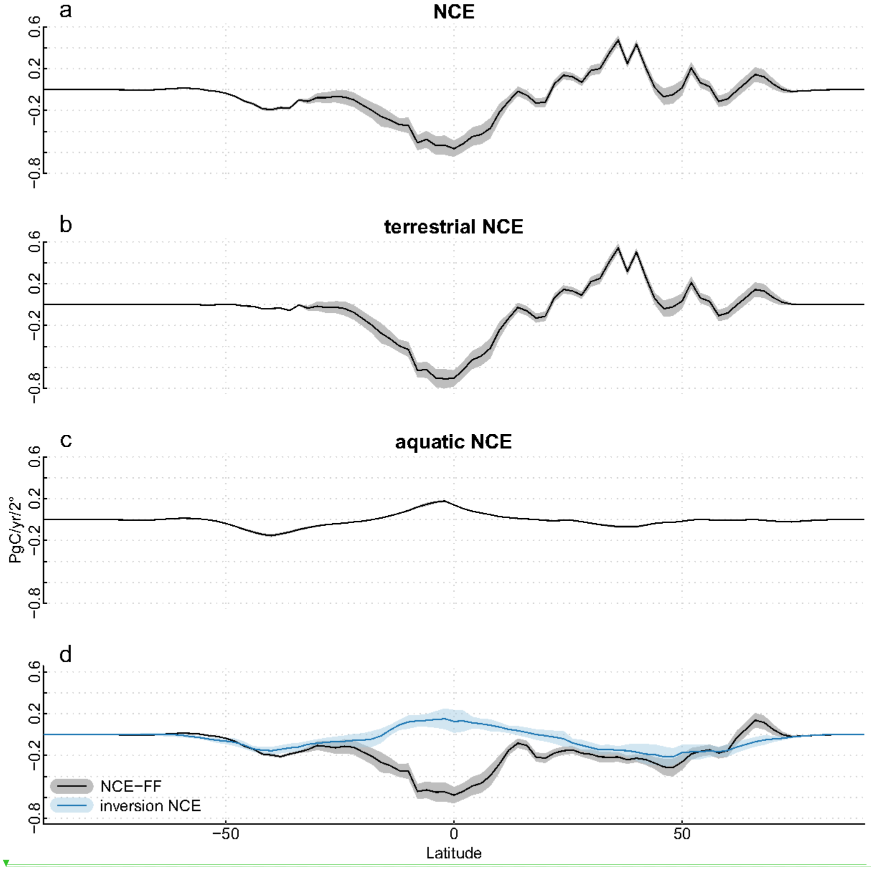
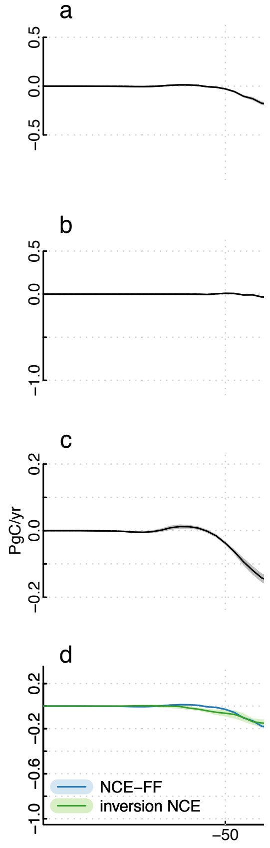


Figure 4. Mean and uncertainty (1 SD) of different subsets of NCE (2001-2010 decadal mean). a) All fluxes. b) Terrestrial fluxes. c) Aquatic fluxes. d) NCE without fossil fuels from this synthesis (black) and from inversions (blue).

Jakob 20/3/2017 11:32



**Gelöscht:** Figure 3.

Jakob 20/3/2017 11:32

**[24] verschoben (Einfügung)**

Jakob 20/3/2017 11:32

**Gelöscht:** .

Jakob 20/3/2017 11:32

**Gelöscht:** (blue

Jakob 20/3/2017 11:32

**Gelöscht:** NCE

Jakob 20/3/2017 11:32

**Gelöscht:** by construction without fossil fuels, green

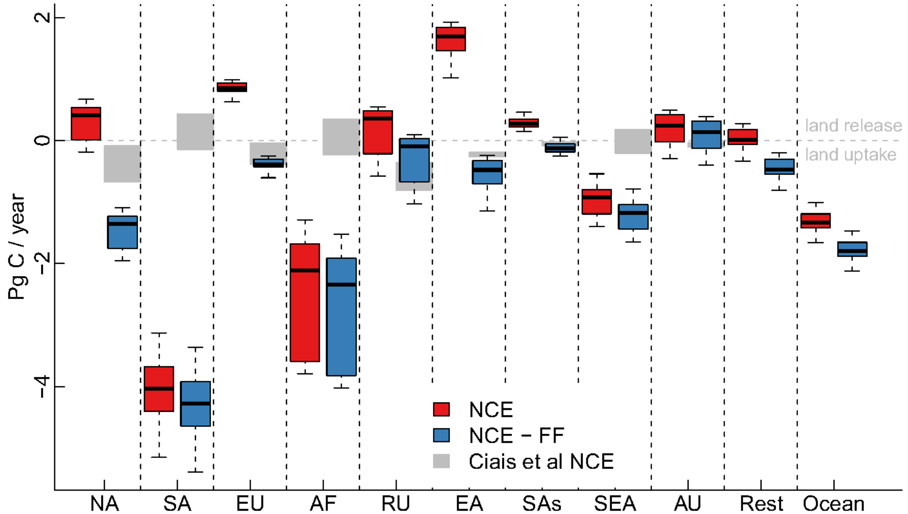
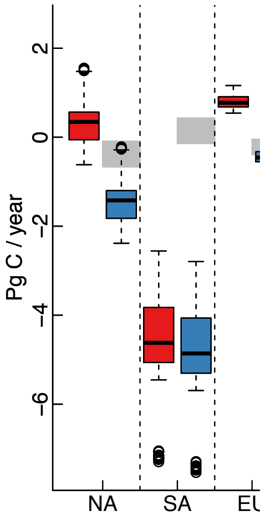


**Figure 5. NCE (2001-2010 decadal mean) in RECCAP regions over land, including (red) and without fossil fuels (blue). Shown are median, interquartile range (box) and 1.5 x interquartile range (whiskers). The regional estimates including uncertainties of NCE collected in Ciais et al (in revision) are underlain in grey. NA: North America, SA: South America, EU: Europe, AF: Africa, RU: Russia, EA: East Asia, SAs: South Asia, SEA: South East Asia, AU: Australia, Rest: remaining land areas.**

Jakob 20/3/2017 11:32



**Gelöscht:**

Jakob 20/3/2017 11:32

**[24] nach oben verschoben:** Figure 4.

Jakob 20/3/2017 11:32

**Gelöscht:** NCE over

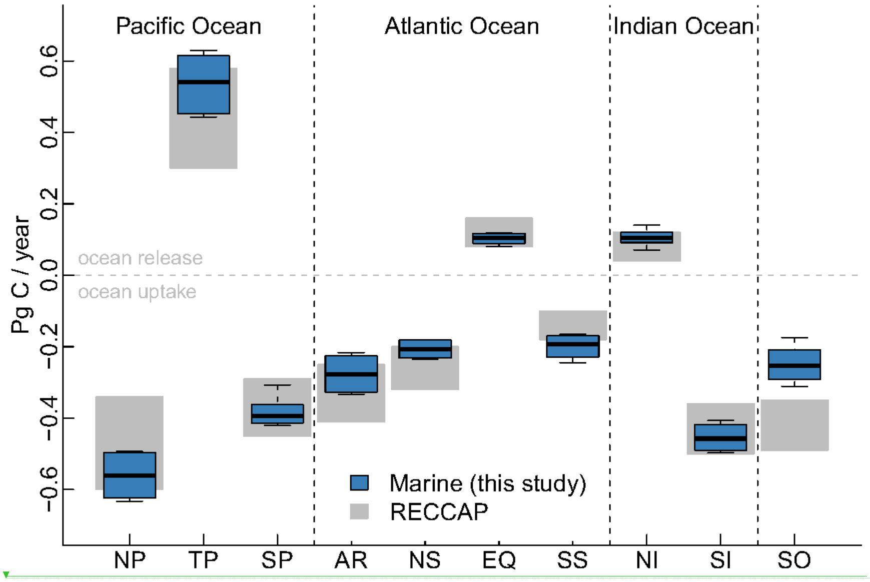
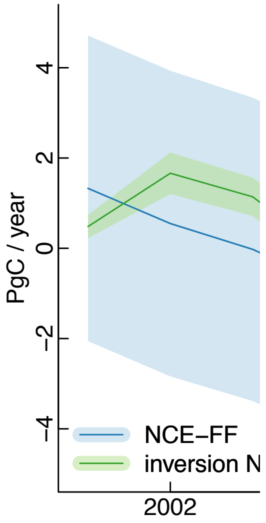


Figure 6. NCE in RECCAP regions over the ocean. Shown are median, interquartile range (box) and 1.5 x interquartile range (whiskers) of the Marine fluxes. The RECCAP estimates including uncertainties are underlain in grey. NP: North Pacific extratropics, TP: Tropical Pacific, SP: South Pacific extratropics, AR: Arctic Ocean, NS: Northern Subtropics, EQ: Equatorial, SS: Southern Subtropics, NI: Northern Indian Ocean, SI: Southern Indian Ocean, SO: Southern Ocean.

Jakob 20/3/2017 11:32



**Gelöscht:**
**Figure 5.**

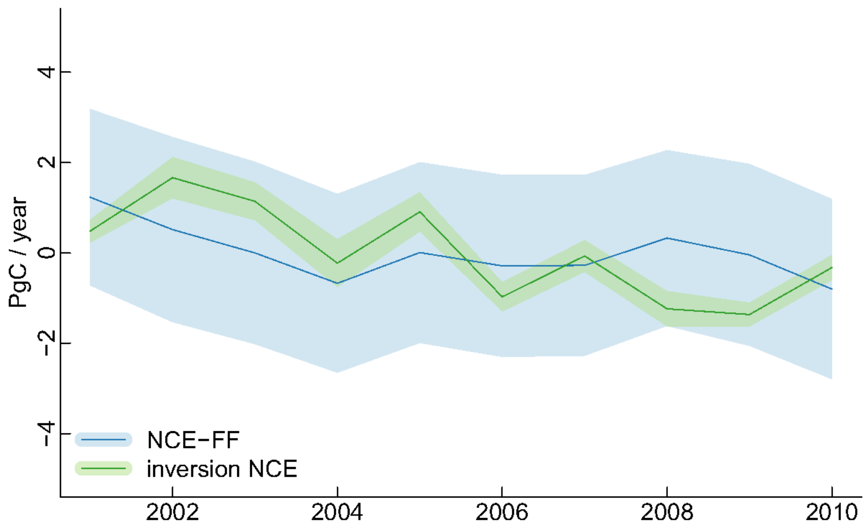


**Figure 7.** **Comparison of NCE-FF with NCE from inversions (by construction without FF) on interannual time scales. Both time series were zero-centered by adding an offset of 13.23 PgC / year for NCE-FF and 3.74 PgC / year for NCE from inversions. Lines show mean, shading is 1 SD.**

Jakob 20/3/2017 11:32

**Gelöscht:** 87

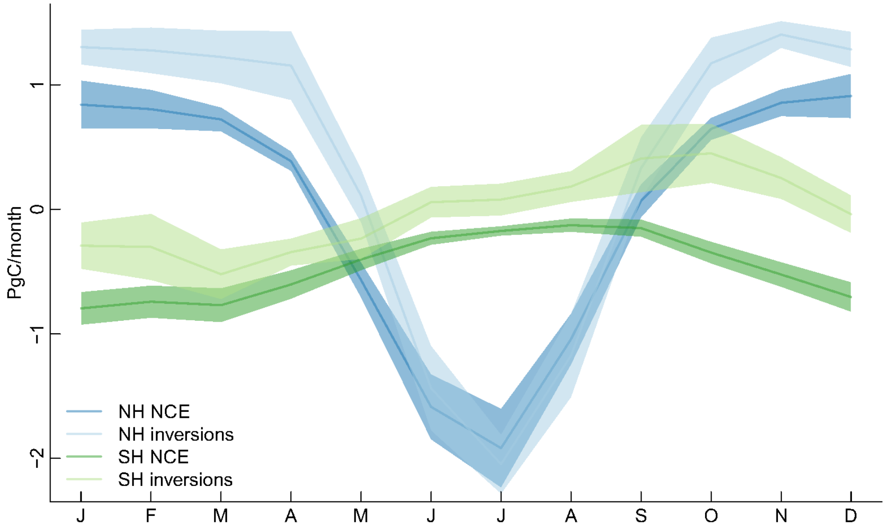
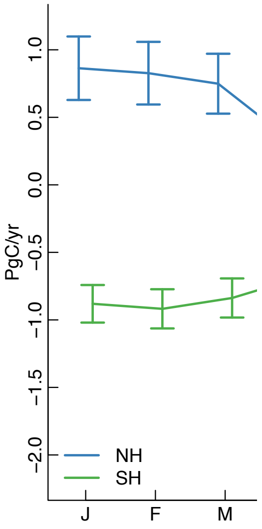


**Figure 8. NCE mean seasonal cycle and uncertainty (1 SD) for Northern (NH, 0°-90°N, blue) and Southern hemisphere (SH, 90°S-0°, green) for estimates from this study (dark colours) and inversions (light colours).**

Jakob 20/3/2017 11:32



**Gelöscht:**