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Interactive Comment

Interactive comment on "On the ability of a global atmospheric inversion to constrain variations of CO_2 fluxes over Amazonia" *by* L. Molina et al.

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Final response to the comments from Referee 1

The full text has also been provided as a PDF file in the supplementary material.

Questions/comments from the Referee, answers to the comments and changes to the manuscript are presented according with the following notation:

Q) Questions, general, and technical comments A) Answers to the comments C) Changes to the manuscript

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General Comments

Q.1) This paper evaluates CO_2 fluxes over Amazonia that have been calculated using two atmospheric inversions, a control case and one that includes extra atmospheric CO_2 measurements for the Amazonian region. The analysis focuses on the seasonal cycle of fluxes and on interannual variations, particularly years that were notably dry or wet. The overall impression of the results is that the fluxes vary quite substantially across the Tropical South American region and at times it is difficult to determine what extra information the Amazonian CO_2 data adds. The authors acknowledge this, noting in their abstract that 'the results revealed critical limitations that prevent global inversion frameworks from capturing the data-driven seasonal patterns of fluxes across Amazonia' and recommending in their conclusions that denser observing networks and regional models might be required to overcome the limitations.

A) We thank the reviewer for her positive comments and sensible suggestions which made this review very helpful.

Q.2) While I agree that this is a valid conclusion from this study, there are two other suggestions that I would like to make, one which could be incorporated into a revision of this paper, while the other targets future inversion work. Firstly, much of the current analysis looked at, for example, the seasonal cycles averaged across the full time period of the inversion. Given the intermittent nature of the Amazonian atmospheric CO_2 data, I wonder whether analysis targeted at periods when certain sites were active might yield clearer inversion impacts. Some suggestions are given in the specific comments below.

A) We agree with this general comment and we have followed the more specific suggestions provided below to include new analyses and discussions on this topic in the revised manuscript (see our answers to the corresponding comments).

Q.3) Secondly, I think that as an inversion community we need to be smarter about how we include continuous CO_2 measurements into our inversions. Each site has different

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characteristics and each transport model will represent those sites in different ways. We need to understand what parts of the CO_2 record we can most reliably simulate and consequently include in the inversion. Afternoon measurements (as used here) may be appropriate for continental sites with large diurnal cycles, but I would suggest that coastal sites need a different selection strategy. Likewise the choice of sampling location from a transport model (nearest grid-point or an interpolation between points) might be dependent on the characteristics of the observing location.

A) We agree with these recommendations for better fitting the data with the model through site-specific studies. Actually, we feel that they are in line with our preliminary investigations regarding the representation of the diurnal cycle and day-to-day variations of CO_2 at the different sites that we have used. We finally based our data selection on rather traditional criteria (i.e., during the afternoon and when the wind speed is above a given threshold), supported by previous studies (e.g., Butler et al., Tellus (2010), 62B, 550–572; Gatti et al., Tellus (2010), 62B, 581–594), and we finally located the sites in the corresponding (in terms of space coordinates) model grid cells. However, we followed the traditional approach only after a site-by-site investigation of the diurnal cycle and day-to-day time series at each of the nine model grid-cells at and around the site geographical locations. More details on this topic have been included in the revised manuscript, following some of the ideas brought by the reviewer's detailed comments on this topic below (see our answers to the corresponding comments).

Q.4) I recommend that the paper be published with minor revisions to address the technical corrections and to clarify and extend the analysis a little based on the suggestions in the specific comments.

A) We hope that our answers to the reviewer's comments, as well as the corrections applied to the original manuscript, are fully consistent with her suggestions.

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Specific Comments

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Q.5) Sometimes it is not clear which region an analysis has been performed for, with various terms used e.g. 'Tropical South America/TSA', 'whole region' (p 1926,line 15; p 1932, line 17), 'entire study area' (p 1926, line 16). Please ensure that each region is defined. Also in the text the inversion without extra sites is usually referred to as MACCv10.1 while the figures are labelled with CH2010. It would be preferable to use one or the other consistently in text and figures.

A) We have systematically clarified the region that is discussed by using a unique term for a given region and by clearly emphasizing the corresponding notations as soon as they will be used. Labelling the figures using CH2010 was a mistake which we have corrected. For consistency, the term MACCv10.1 now refers to the results or analysis of the control inversion. The term CH2010 is used to refer to results or conclusions from Chevallier et al. (2010) only.

Q.6) p 1924, line 5: Were the ocean fluxes not examined or just not presented in this paper? Just as the discussion of Fig 8 mentioned the possibility of dipoles in the flux across the South American region, a change in fluxes over the land can end up being compensated in the ocean. Given that some of the extra observing sites are coastal, I would expect that it would be worth at least checking the impact of the inversion on the ocean regions around South America.

A) Ocean fluxes were not presented in the original manuscript. Although the focus of our study is on NEE, now we illustrate the impact of the inversions on the ocean fluxes in an updated Fig. 6 (previous Fig. 8), over a larger area than that original shown. Based on this figure, the article now explains that the increments from both inversions (MACCv10.1 and INVSAm) have large patterns which are nearly zonal (or along the prevailing winds) and which overlap continuously the ocean and the land. Therefore, the dipoles oppose different zonal bands rather than some ocean areas vs. some land areas. The zonal positions and strength (i.e. the amplitude of the dipole or of the zonal gradient) of these zonal increments are modified by the inclusion in the inversion of the data from the new stations in region Tropical South America. These effects are more visible when focusing on specific months, while the annual averages smoothens the patterns. In all cases, there is little evidence of direct compensation between land and ocean increments in the area.

C) The revised manuscript now includes a new section: "Sect. 3.2 Characterization of the monthly to annual mean inversion increments to the prior fluxes". In Sect. 3.2, we state: "Figure 6 depicts the increments from both inversions, showing large patterns which are nearly zonal (or along the prevailing winds) and which overlap continuously over land and ocean. Since there is no correlation between the uncertainty in ocean and land fluxes in the B matrix, and given the typical length scale of the correlations in this matrix, this can be directly connected to the signature of atmospheric transport. The contiguous zonal patterns have alternate negative and positive flux increments. There is thus an opposition between corrections in the North and in the South of the TSA region. These corrections are rather negative in the North and positive in the South (positive in the North and negative in the South) during the austral summer (winter). As these corrections are stronger during the austral winter, it results in positive (negative) corrections in the North (South) at the annual scale. Such dipoles are a typical behaviour of inverse modelling systems in data-poor regions (Peylin et al., 2002). However, changes in the amplitude and latitudinal position of this zonal dipole appear to be the main impact from the assimilation of data in the TSA region. This dipole structure may thus yield sensible corrections to the NEE in the TSA area."

Q.7) p 1924, line 9: how does this length scale (500km) compare with the distance between the four sites added to the inversion?

A) Between SAN and GUY the geographical distance is roughly 1000km, but between the other sites it ranges between 2000 and 2600 km approximately. Considering the 500 km correlation length scale in the B matrix only (i.e. ignoring the effect of atmospheric transport), this could suggest that the area directly constrained by the South American sites is relatively small and that GUY and SAN would be the only couple of sites with overlapping areas of influence. However, the station footprint can be signifi-

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cant over land, as illustrated by Fig. 3. Furthermore, as demonstrated by the new Fig. 6, large increments are applied by both inversions, and the South American sites have a large impact on these increments over the entire South America. This is due to the long range extent of the footprints of the South American sites and other sites in the Southern Hemisphere. The South American sites are actually shown to constrain the large scale balance and between the positive and negative corrections north and south of South America and their spatial extent. We now include comments on this topic in the manuscript.

C) We have modified Fig. 3 (see answer to General comment Q.9) in the in the revised manuscript as a response to the comments of Referees on the stations' footprints. It now includes climatological wind speed and direction fields (cf. comment of Referee 3). To address the Referee's comment, Section 2.2 (Assimilated data) in the revised manuscript has been updated: "Typical influence functions of fluxes for observations at GUY and SAN (the observation "footprints", in Fig. 3b and c, respectively) illustrate that the sensitivity of instantaneous mole fractions to the fluxes rapidly decreases with the distance, mainly due to the typically moderate horizontal wind speeds, so that they should bear a strong signature of local fluxes i.e., of the NEE in north-eastern Amazonia. This, and the fact that the geographical distance between the sites in the TSA region ranges from 1000 to 2600km, i.e. up to five times the correlation length scale in matrix B, could suggest that the area well constrained by the sites in the TSA region through inversion is limited. However, as illustrated in Fig. 3, the station footprints also have modest values over very extensive areas which may also result in significant large-scale constraint from the inversion on the land flux estimates."

C) In addition, based on the analysis of Fig. 6, in Sect. 3.2, we now state:

"(...) changes in the amplitude and latitudinal position of this zonal dipole appear to be the main impact from the assimilation of data in the TSA region. This dipole structure may thus yield sensible corrections to the NEE in the TSA area. The dipole has a high amplitude for MACCv10.1, and even higher for INVSAm. The increments from

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INVSAm to the annual fluxes often exceed 150% of the prior estimate in terms of absolute values. The highest increments are obtained during austral winter and when the SAN data are available (during the period 2002-2005, see Fig. S1), which is in line with the fact that this site is located more inland than the others. Such high control of the data in the TSA region (even when checking the SAN and MAX, or the MAX, ABP and GUY datasets only) over the zonal patterns of flux corrections also highlights the very large-extent impact of these data, and of the data in the southern hemisphere in general, despite the relatively small spatial correlation length scales in the B matrix, and the limited area in which the station footprints are very high."

Q.8) p 1925, first paragraph: it would be good to have some additional information about each site e.g. latitude, longitude, a brief site description e.g. the surrounding vegetation, distance from coast, sampling height. For ABP (line 10), are the weekly measurements selectively sampled under onshore flow, i.e. are they intended to minimise continental signals? How is the transport model sampled to represent these sites e.g. interpolation to the site location, nearest grid-cell? An offshore grid-cell can be more appropriate for a coastal site (e.g. Law et al, Tellus, 62B, 810-820, 2010).

A) We now include additional information about each site in the manuscript: geographic location in latitude and longitude, altitude of the station and/or sampling height, conditions of the site (i.e. coastal or inland, dominant vegetation type surrounding the site), and for ABP, the strategy for the weekly sampling. As guessed by the reviewer, the weekly measurements at ABP are sampled under on-shore flow, and are also collected when wind speed > 2 m/s. This could support the idea of representing this coastal site using an off-shore model grid-cell. However, we checked the wind directions from the ECMWF Interim Reanalysis (which drives the LMDZ transport model) during the time of the day when air samples are available at ABP. Figure A.1 shows the resulting frequency distribution of the ECMWF wind direction (i.e., direction from which the wind blows, in degrees, measured clockwise from the geographical North) at ABP when CO_2 is sampled. The figure confirms that according to ECMWF, ABP is

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mostly under marine influence, but this is not systematic and the instantaneous wind measurements that have been used to sample on-shore flow at ABP may hide the fact that these measurements were done under intermittent wind conditions so that the air masses could still bear the signature of land fluxes (e.g., from the North). In any case, our final selection of the best transport model grid-cells to represent each site was based on an objective analysis of the day-to-day variations of the CO2 selected during the analysis window (12:00 to 15:00 local time) and when the wind speed is > 2m/s. For a given station, the measured variations were compared to the ones modelled in the grid-cell corresponding to this station (in terms of space location), and in the 8 neighbouring cells (which encompassed inland and ocean grid cells when analysing CO2 at a coastal site). The figure A.2 shows the resulting time series of observed and modelled CO2 mole fractions at ABP (the layout of the plot corresponds to the geographic layout of the model grid-cells). For this site there is no critical difference between the mole fractions at the coastal and ocean model grid cells, certainly due to the threshold on the wind speed for the data selection. Based on the statistics of the misfits to the observations, we concluded that the grid-cells corresponding to the actual stations locations were systematically better adapted for the representation of these stations, even in the case of ABP. A more flexible method where a given site could be modelled using different grid cells depending on the wind directions may yield better results. We highlight this in the revised manuscript.

C) In the revised manuscript, Sect. 2.2 (Assimilated data) has been update as follows: “MACCv10.1 assimilated measurements of atmospheric CO2, expressed as dry air mole fractions in μmol mol-1 (abbreviated ppm), from 128 surface sites: 35 continuous measurement stations and 93 sites with measurements of CO2 from discrete air samples collected approximately weekly. 29 sites are located in the tropics, but only two had continuous measurements over the analysis period and none of them were in TSA. In a similar inversion conducted specifically for this study, called INVSAm hereafter, we added new data from four surface sites located in the TSA region. Figure 1 shows the measurement sites used by MACCv10.1 and the four stations added in IN-

VSAm. In the following of this section, we focus on the description of these four stations and on the selection and representation of their data. Details on the data selection and representation at the sites used by MACCv10.1 are provided in CH2010. Arembepe (ABP) (12.77° S, 38.17° W, 1 masl) and Maxaranguape (MAX) (5.51° S, 35.26° W, 15 masl) are coastal stations. The ABP site is located at the edge of the beach, where vegetation consists mostly of grass and beach plants. Data were collected at approximately 8 m above the ground, and consisted of weekly measurements of atmospheric CO2 with discrete air samples, specifically under on-shore wind conditions, when wind speed > 2 m/s. Air samples were collected preferentially during the afternoon to avoid the influence of recycled air transported from land to the ocean by land breeze during the night and early morning, and transported back to land by sea-breeze during the morning. The MAX site is located on a cliff right next to the coast, and is surrounded by grass and beach plants. At MAX, CO2 was measured with a continuous analyzer, at approximately 3 m above the ground, and data were reported as 30 min averages. This site is strongly under marine influence: winds are in general > 10 m s-1, and wind direction varies preferentially between 100° and 140° (Kirchhoff et al., 2003) at its location, so that the measurements were taken mostly under on-shore wind conditions. Wind and CO2 measurements at MAX indicate high CO2 variations when the wind comes from land. These variations may be strongly influenced by the emissions from the nearby city of Maxaranguape (Kirchhoff et al., 2003). However, as in ABP, this does not occur during the afternoon, when the wind conditions are dominated by sea-breeze (Law et al. 2010). The Guyaflux site (GUY) (5.28° N, 52.91° W, 40 masl) is located at approximately 11 km from the coast, and is surrounded by undisturbed tropical forest. At GUY, measurements were taken at approximately 55m above the ground (Bonal et al., 2008). They were made with a continuous analyzer, and data were reported as hourly averages. The Santarém site (SAN) (2.85° S, 54.95°W, 78 masl) is located in the tropical Tapajós National Forest, near km 67 of the Santarém-Cuiabá highway, at approximately 750 km from the coast. Measurements were made at 8 vertical levels ranging from ∼1 to ∼62 m above the ground with continuous analyzers, but only data

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from the highest level were used in INVSAm. Data were reported as hourly averages. Figure 2 illustrates the temporal coverage of the observations available in TSA during the simulated period (2002-2010). There is little overlap among the site records, due to calibration problems, interruption of the measurements (e.g., at MAX) and the fact that some stations have been installed only recently (e.g., at GUY). The longest records were from ABP (3 years: 2007-2009) and SAN (4 years: 2002-2005). Data from the four new sites in TSA have been calibrated on the WMO-X2007 CO2 scale, managed by the ESRL/NOAA."

In addition, also in Sect. 2.2, we state: "In a general way, we choose to represent the four measurements sites using the model horizontal grid-cell in which they are located since, for each site, it yields better statistical fit between the prior simulations and the selected measurements than when using neighbour grid-cells."

Q.9) p 1925, line 23 and p 1926, line 5: 'typical' circulation, 'typical' footprints. Is there much of a seasonal shift in circulation? A sentence to comment on this might be helpful.

A) The Fig. 3 has been updated and now depicts a climatology of wind fields from NCEP/NCAR reanalysis (1981-2010), averaged between the surface and a level of 600 hPa, over TSA region during (a) the austral summer (February), (b) austral winter (July), and (c) annual mean. The figure does not show critical seasonal changes in this average atmospheric circulation. The dominant, or typical, mode of horizontal circulation in the lower troposphere across Amazonia throughout the year is characterized by winds entering the Atlantic coast in north-eastern Brazil, through Amazonia and entering back into the Atlantic Ocean south of 20°S. Our selection of figures in Fig. 3 aims at illustrating this pattern. This is now better explained in the revised manuscript.

C) In the original manuscript, p1925, lines 22-25 have been updated:

"Prevailing winds in the lower troposphere across TSA convey air masses entering from the Atlantic Ocean near the Equator across the continent and back into the southern

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Atlantic Ocean generally south of 20°S. There are no critical seasonal variations of the mean winds in the area so that this typical behaviour applies throughout the year. The climatology of wind fields from the NCEP/NCAR reanalysis (over the period 1981-2010) for February, July and annual mean, shown in Fig. 3, illustrates this circulation pattern."

Q.10) p 1925, line 25 to p 1926, line 1: Since MAX is a continuous site, are you able to distinguish in the CO2 observations between periods of onshore vs. offshore flow (e.g. periods of relatively constant 'background' CO2 versus highly variable CO2 events). If so, what proportion of the data is from onshore? Is your afternoon data selection favouring onshore flow e.g. due to a sea-breeze circulation? It seems plausible to me that your data selection may be removing those observations that are more likely to have been influenced by the land region.

A) The time series of hourly CO2 and wind direction measured at the MAX station at any time or selected in the time window 12-15 LT are given figure A.3. The reviewer is right about assuming that we can see a clear signature of on-shore and off-shore flows. Indeed, there are two periods when larger variations in the CO2 observations can be identified, associated to wind directions > 150°: between 2004-07-08 and 2004-09-21, and between 2005-03-20 and 2005-05-12. The rest of the time, CO2 observations are rather stable. The reviewer is also right about assuming that our selection of afternoon data makes us loose on-shore signal as demonstrated by the absence of occurrences of wind directions > 150° and of sub-periods of larger variations in CO2 when selecting 12-15 data. However, assimilating data outside the chosen time window would have been a challenge, given the difficulties of the models to correctly represent the dynamics of the PBL. We agree with the reviewer that this reveals that we could select and represent the data in a more flexible and sensible way than what we do here (see the answer to the previous comment on ABP) and this analysis at MAX will be discussed in the manuscript.

C) In the revised manuscript, in the last paragraph in Sect. 2.2, regarding the site at

MAX we state:

“This site is strongly under marine influence: winds are in general > 10 m s-1, and wind direction varies preferentially between 100° and 140° (Kirchhoff et al., 2003) at its location, so that the measurements were taken mostly under on-shore wind conditions. Wind and CO_2 measurements at MAX indicate high CO_2 variations when the wind comes from land. These variations may be strongly influenced by the emissions from the nearby city of Maxaranguape (Kirchhoff et al., 2003).”

“(...) selection of the afternoon data results in ignoring the measurements of off-shore signal at MAX, as explained above, and as confirmed by the analysis of the MAX CO_2 and measured wind direction time series (not shown), and thus the potential for capturing a clear signature of the regional NEE at this site such as at ABP. However, the off-shore signal is also strongly connected to the local anthropogenic emissions and the inversion cannot exploit reliably such a signature of the regional NEE when the dynamics of the PBL are poorly represented by the atmospheric transport model.”

Regarding the use of a more flexible, sensible strategy for data selection and representation, in the last paragraph in Sect. 4, we state:

“(...) adaptive strategies for the representation of the observations in the model simulations as a function of the sites and of the meteorological conditions (Law et al., 2010) could help loosen the selection of the data for the assimilation.”

Q.11) p 1926, line 18-22:‘root mean square of the annual biases’ It’s not clear to me what exactly has been calculated here- the difference between the CO_2 predicted at a site from the two sets of priors?? ‘given that the mean transport error at the yearly scale should be far smaller according to the hypothesis made when setting-up the inversion system.’ I don’t understand this sentence.

A) Actually, the reviewer correctly describes the comparison and assumptions made, and the text needed some clarification for explaining the aim of this comparison. At

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each site we calculate the quadratic mean of the annual mean differences between the CO2 simulated using the two prior estimates of the fluxes (we do not check the data availability at a given site and just take all simulated afternoon values throughout the 2002-2010 period). These differences revealed that the differences in annual budgets between the two prior estimates of the fluxes should yield strong signals at the annual scale at all sites in South America. Given that the weight of the transport error at the annual scale is, in theory, very small (we assume that there is no temporal correlation in the transport), this strong signal should be easy to detect and correct by the inversion system. Therefore we can hope that the inversion system can control the IAV of the fluxes.

C) In the revised manuscript, we have suppressed the discussion on the experiment with the "flat prior" to capture the signal of interannual variability of NEE from the observations. We concluded that it was not clear for the reader and that the revised sections 3.1 and 3.2 discuss in a deeper, clearer manner our initial idea.

Q.12) p 1927-1928, section 3.1 and figure 4: These figures are quite hard to read as the observations are sometimes obscured but they are probably adequate to illustrate the main points covered by the text. (Figures that showed more detail might lead to more insights into the inversion behaviour?) As noted throughout the section the ABP results do not seem consistent with the other sites. The simplest explanation would be that somehow in the analysis/figure the CH2010 and INVSAm time series have been inadvertently switched. Assuming that this has been checked, it is really difficult to explain how an inversion without ABP (CH2010) can fit the ABP data better than the INVSAm case where ABP is included, especially when there is almost no temporal overlap of other Amazonian sites with ABP, so little possibility that the ABP fit is being compromised by fitting other nearby sites. As plotted it appears that the INVSAm case is weakly retaining the seasonality of the prior at ABP while CH2010 manages to almost completely remove it. Were there any inversion settings different between CH2010 and INVSAm which could explain this?

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A) Thanks to this comment of the reviewer, we carefully checked the results for ABP. While there was no switch between the MACCv10.1 and INVSAm time series, we had made a mistake when extracting the time series from INVSAm. The new plot and statistics of the posterior model data misfits are much more consistent with what is expected from the assimilation of the ABP data. We apologize for this mistake and thank the reviewer for having helped us to detect it. We have modified the markers used in Fig. 4 to make the comparisons between observations and modelled estimates easier. We have also updated Fig. 4 and Figure 5, which summarizes the statistics of the misfits between observations and model simulations. The analysis of those figures has been updated accordingly.

Q.13) p 1928, line 12: I'm guessing the correlations are relatively low because you are using daily data but are estimating 8 day mean fluxes. It might be worth calculating the correlations on a monthly timescale as it would be interesting to see if they show a clear improvement between CH2010 and INVSAm because of an improved seasonal cycle.

A) We have now calculated the correlations for monthly mean data at each station and, indeed, in general correlations to the observations are increased for the prior, MACCv10.1 and INVSAm. The corresponding Taylor diagram is provided in figure A.4. We comment these results in the manuscript.

C) In the revised manuscript, in Sect. 3.1, we comment: "The best correlations with the observations are obtained with INVSAm at all sites (Fig. 5). The values of these correlations remain generally low, ranging from 0.23 at GUY to 0.81 at ABP. These correlations are based on comparison of daily CO2 mole fractions while the inversions control 8-day mean fluxes, which strongly limits the ability to impact the mole fractions at higher temporal resolution, and which can thus explain the low correlation values. Correlations between time series of observed and simulated monthly mean mole fractions are higher than those for daily values, ranging from 0.76 at GUY to 0.92 at ABP for INVSAm, with which, again, these correlations are the highest."

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Q.14) p 1929, line 25-27: Perhaps it is also worth reinforcing the limited temporal coverage of the observations as another reason why there isn't a large impact on the seasonality.

A) We have added such a comment in the text. To avoid redundancies between the analysis in Sect. 3 and discussions in Sect. 4, we have updated the Sect. 4.

C) In the revised manuscript, Sect. 4, we state:

"The reliability in the seasonal patterns of the inverted fluxes is thus not high. This seems to confirm that the zonal dipoles of increments from the inversion are artificial patterns, which balance the overall correction in the Southern Hemisphere, and which are not necessarily consistent with the actual NEE in the TSA region. We thus conclude that the confidence in the corrections from MACCv10.1 and INVSAm in the TSA region is rather low. This is directly connected to the lack of CO2 measurements in the TSA region, both in space and time."

Q.15) p 1930, line 3-12 and figure 6b: Am I correct in understanding that for the inversion this is just a regional selection of the data, the inversion itself doesn't do anything differently depending on the pft? If this is right, it might be worth mentioning. In Fig 6b the CH2010 line looks very similar to the CH2010 line in Fig 6a. Is this correct? The other cases all look noticeably different between Fig 6a and Fig 6b.

A) The reviewer is correct about the fact that the PFTs are not accounted for in the inversion configuration and that this analysis for TBE forests is, strictly speaking, just a space selection of the data. Still, we can hope that the spatial patterns of the increments from the inversion could be consistent with the spatial patterns potentially induced by the heterogeneity of the vegetation types in the actual world. This is briefly discussed in the revised manuscript. There was an error in Fig. 6b concerning the fluxes from MACCv10.1 and we thank the reviewer for pointing out this. The referred figure is now Fig. 7. This figure has been updated and shows differences for MACC between Fig. 7a and 7b, as well as for the other flux estimates.

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C) In Sect. 3.3.1 in the revised manuscript, we comment:

"The inland data are prone to bear a stronger signature from fluxes in tropical broadleaf evergreen and raingreen (TBE) forests (Fig. 8), while the mean seasonal behaviour over the whole TSA region could be mainly related to other PFTs. Therefore, we isolate the results for the area of TBE forests, this area being defined by the selection the model grid-cells dominated by this vegetation type. The configuration of the prior uncertainties in the inversion does not account for PFTs, so that the spread of the flux corrections in the inversions is not forced a priori to depend on vegetation type. We still expect that the variations in the measurements, when their footprint covers different distributions of PFTs, reflect differences in NEE of the PFTs."

Q.16) p 1930, line 13-26: The flux tower precipitation and NEE plots (Fig 6c-f) are not really described in the text and need to be more strongly linked with the results presented in the rest of Figure 6.

A) Previous Fig. 6 is now updated (see previous comment) and renumbered as Fig. 7. The flux tower and precipitation data in previous Fig. 6c-f were not fully exploited in the manuscript, as the reviewer observes. The plots depict the seasonal behaviour of both NEE and precipitation at those sites, and the message we meant to convey from these figures, i.e. the spatial variability of the seasonal cycle of NEE across Amazonia, was already well illustrated by the number of studies referred to in the introduction. We have removed that information from the new Fig. 7. The description of the sites is now provided along those data in Fig. S2 in the supplementary material.

C) In the revised manuscript we have removed the information regarding the EC and precipitation data. The text has been updated as follows: "The strong spatial heterogeneity of the time variations of the NEE in TBE forests has been discussed in the introduction. Figure S2 illustrates it with results of local NEE mean seasonal cycle estimated from EC measurements across TSA. This figure also shows the mean seasonal cycle of the precipitation at these sites to illustrate the spatial heterogeneity of

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the drivers of NEE within TSA."

Q.17) p 1931, line 14-18: The change in seasonality in Zone 1 for the INVSAm case might be even clearer if the seasonal cycle was calculated separately for 2002-2005 (when SAN was active) and 2006-2010. A stronger signal in the earlier period would be good confirmation of the influence of SAN data.

A) Following this suggestion, we calculated the seasonal cycle of the four NEE estimates for zone 1 over the two proposed periods: 2002–2005 and 2006–2010 and shown in Figure A.5. The dry season extends September–November on both periods. As anticipated, the strongest changes between MACC and INVSAm take place during the first period, when data from SAN are available, which confirms the critical influence of this site in zone 1. However, there are still significant changes between MACCv10.1 and INVSAm occurring in zone 1 between 2006 and 2010. And, as noticed in answer to major comment 5 of Referee 2, corrections in a zone can be driven by remote measurements and by their difference to South American data as revealed by the large scale structure of the increments shown in the new Fig. 6. So there is no need for having a South American site located in the vicinity of a zone for getting a significant change between MACC and INVSAm in this zone. We comment this in the revised manuscript.

C) In the revised manuscript, in Sect. 3.3.1, we comment: "The influence of SAN over this zone is clearer when splitting the analysis period of the mean seasonal cycles between 2002-2005 and 2006-2010 (not shown). The differences between INVSAm and MACCv10.1 are more accentuated during the period 2002-2005, when SAN is active. However, there are still significant changes between these two estimates during 2006-2010. The changes between MACCv10.1 and INVSAm in Zone 2 (Fig. 7d) are also significant, even though Zone 2 seems hardly observed by the TSA observation network. As analysed in Sect. 3.2, the control of the long-range dipole (of its amplitude and latitudinal position) by the measurements in region TSA explains such an impact of these measurements on the results in Zone 2, as well as that of measurements outside

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South America, which explains the departure of MACCv10.1 from the prior NEE in zone 2."

Q.18) p 1932, line 1-13 (Figure 8): This is an interesting figure but how do the INVSAm flux corrections compare to the CH2010 flux corrections? Are the CH2010 ones more uniform across the region? This is another figure where averaging over 2002-2005 and 2006-2010 separately would be interesting to try and maximise the signal from SAN.

A) As mentioned above, previous Fig. 8 has been updated and is now new Fig. 6, introduced above, and now shows the results for MACCv10.1, as well. The average increments over land from INVSAm and MACCv10.1 and for the periods 2002-2005 and 2006-2010 are also shown in the Fig. S1. This complements the discussions given above in answer to the comment on ocean fluxes and on the corrections applied in zone 1 by the reviewer. The assimilation of data in South America generally shifts the zonal dipole in the increment (with a negative / positive gradient from the South to the North in February / July) to the south and amplifies it. Such a behaviour applies to winter and summer, and for the 2002-2005 and 2006-2010 periods. But it is particularly strong in July and for the period 2002-2005, emphasizing the higher weight of data at the most inland site i.e. SAN. The results of new Fig. 6 and Fig. S1 (provided as supplementary material) have lead us to insert a discussion in a new section 3.2.

C) In the revised manuscript, we have inserted the new Sect. 3.2: "3.2 Characterization of the monthly to annual mean inversion increments to the prior fluxes

Figure 6 shows the spatial distribution of the mean corrections applied during the period 2002-2010 by INVSAm and MACCv10.1 over land and ocean, across an area that covers the TSA area and neighbour regions. In complement, Figure S1 shows the spatial distribution of the corrections over land in the TSA region for the full 2002-2010 period, and for the 2002-2005 and 2006-2010 sub-periods. Both give results for the full years and for the months of February and July. As such, these figures are indicative of the amplitude and spatial extent of the corrections from the inversions, and of the impact of the assimilation of the measurements in South America. Figure S1 even dissociates the impact of assimilating data at SAN and MAX and that of assimilating data at MAX, ABP and GUY by splitting the results between the time periods when these two different sets of data are available. The analysis of the annual mean corrections and of mean corrections for February and July should also give first insights on the significance of the corrections applied to the seasonal cycle and IAV of the NEE in the TSA region. Figure 6 depicts the increments from both inversions, showing large patterns which are nearly zonal (or along the prevailing winds) and which overlap continuously over land and ocean. Since there is no correlation between the uncertainty in ocean and land fluxes in the B matrix, and given the typical length scale of the correlations in this matrix, this can be directly connected to the signature of atmospheric transport. The contiguous zonal patterns have alternate negative and positive flux increments. There is thus an opposition between corrections in the North and in the South of the TSA region. These corrections are rather negative in the North and positive in the South (positive in the North and negative in the South) during the austral summer (winter). As these corrections are stronger during the austral winter, it results in positive (negative) corrections in the North (South) at the annual scale. Such dipoles are a typical behaviour of inverse modelling systems in data-poor regions (Peylin et al., 2002). However, changes in the amplitude and latitudinal position of this zonal dipole appear to be the main impact from the assimilation of data in the TSA region. This dipole structure may thus yield sensible corrections to the NEE in the TSA area. The dipole has a high amplitude for MACCv10.1, and even higher for INVSAm. The increments from INVSAm to the annual fluxes often exceed 150% of the prior estimate in terms of absolute values. The highest increments are obtained during austral winter and when the SAN data are available (during the period 2002-2005, see Fig. S1), which is in line with the fact that this site is located more inland than the others. Such high control of the data in the TSA region (even when checking the SAN and MAX, or the MAX, ABP and GUY datasets only) over the zonal patterns of flux corrections also highlights the very large-extent impact of these data, and of the data in the southern hemisphere in

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general, despite the relatively small spatial correlation length scales in the B matrix, and the limited area in which the station footprints are very high. The inversion also generates patterns of corrections of smaller spatial scale close to the measurement sites in the TSA region when these sites are used by the inversion. This raises hope that the NEE over the whole TSA region is strongly constrained by the observations, but can also raise questions regarding the spatial variations of the corrections applied by the inversion to the NEE within the TSA region, at least when considering areas at more than 500 km from the measurement sites. However, various pieces of evidence (Fig. 5 and 6, the analysis of the decrease in misfits to the observations from the inversion in section 3.1, and the previous analysis of the high increments to the monthly mean and annual mean NEE over the entire TSA region) indicate that the corrections from the inversion are significant."

Q.19) p 1932-1933, section 3.2.2: I assume the FLAT inversion included the 4 Amazonian sites. This should be noted in the text. Fig 10a shows a large difference in flux anomaly between CH2010 and INVSAm for 2008. Any ideas why, since during this year only ABP data is available and it is relatively remote from zone 1? I'm not sure that I am convinced that 'some patterns of the IAV in the NEE from the inversion seem robust and strongly driven by atmospheric measurements' (p1934, line 24) - even for the significant drought/wet years the results seem quite mixed depending on which region is considered and what prior was used.

A) We have clarified in the revised text that FLAT includes the four new surface sites in TSA region. Regarding the interannual anomaly for a specific year such as 2008, anomalies can be modified by increments during other years given that the posterior annual anomalies are calculated against the posterior average of the NEE during 2002-2010 (this will be better explained in the manuscript). This explains why large differences in such anomalies can occur between MACC and INVSAm even during years there are few data in South America. The general behaviour of the inversions illustrated by the new Fig. 6 and Fig. S1 indicates that zones 1 and 2, such as the area of TBE

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forest, are often located at the edge of the zonal dipole controlled by the assimilation of data in south America, leading to varying (depending on which data are assimilated) interannual anomalies in these zones/areas, as discussed for zone 2 and year 2003 in answer to the comment 5 by Referee 2. However, results should be more stable when considering the entire TSA region. When referring to the robustness of some IAV patterns (based on the similarity of the results from the different inversions), we referred more specifically to the anomaly observed in 2009 over TSA region, when considering all PFTs (Fig. 9a). This discussion about the fact that the edge of the dipole, crossing the TBE forest area and zones 1 and 2, may give further insights into why the consistency between the IAV from the different inversions does not apply when restricting the analysis to these areas/zones will be conducted in the new manuscript. We have also modified the text to be more cautious when speaking about the 'robustness' of the results.

C) In the revised manuscript, in Sect. 3.3.2, we state: "FLAT assimilates the data from the four surface sites in TSA in addition to that used by MACCv10.1 such as INVSAm. Of note is that even if increments on the NEE annual budget of a given year from an inversion are weak, the changes in the corresponding annual anomaly from the inversion can be high because the inversion modifies the 2002-2010 average against which the anomaly is computed."

C) In the revised manuscript, the statement referred by Referee 1 has been reformulated: "(...) some patterns of the IAV in the NEE seem consistent between the different inversion estimates when the atmospheric measurements have a strong control on it: across the TSA region, the estimates from the prior fluxes, MACCv10.1, INVSAm and FLAT indicate small positive flux annual anomalies (CO2 release) during the drought in 2005 and a strong negative (CO2 sink) anomaly in 2009, presumably related to lower temperatures and more humid conditions in 2009. However, in 2010 there is a divergence of the results between the FLAT estimate and the others."

————————-

Technical corrections

Q) p 1917, line 13-15: Suggest rewrite start of sentence as ‘We focused on the NEE impact of the strong droughts ...’

C) The sentence has been reformulated as:

”We attempt at assessing the impact on NEE of the strong droughts in 2005 and 2010 (due to severe and longer-than-usual dry seasons), and of the extreme rainfall conditions registered in 2009.”

Q) p 1919, line 14: ‘reversal’ instead of ‘reversion’?

A) We have incorporated this change.

Q) p 1919, line 16: delete ‘)’ at end of sentence

A) We have corrected the error.

Q) p 1920, line 20: ‘the inverted pattern...’ Do you mean the opposite pattern is seen in S and W Amazonia compared to E Amazonia? I would rewrite this sentence and avoid the word ’inverted’ because of the potential confusion with using an inversion method to estimate fluxes.

C) We have reformulated the sentence:

“...that also suggests an opposite pattern...”

Q) p 1921, line 5: Figure 1 could be referenced here

A) We have inserted the reference to Fig 1.

Q) p 1921, line 15-22: I would consider moving this description of the J2011 data until later (maybe have a short section 2.3 for ‘comparison data’) in which case you need to change ‘J2011’ on p1921, line 27 to ‘independent flux estimates’.

A) We have moved that description to the section: Sect. 2.3 Analysis of an alternative estimate of the NEE for the evaluation of the inversions.

Q) p 1921, line 22: replace ‘were’ with ‘where’

A) We have incorporated this change.

Q) p 1925, line 17-21: I think the sampling periods are adequately covered in the figure and it is probably sufficient to reduce these three sentences to ‘The longest records were from ABP and SAN.’

C) We have reformulated the sentence: “The longest records were from ABP (3 years: 2007-2009) and SAN (4 years: 2002-2005).”

Q) p 1926,line 9: Suggest paragraph break before ‘To further ...’. Suggest add ‘designed to remove interannual variations’ following ‘ "flat prior"’.

A) The text in lines 9-24 in the original manuscript has been removed. As mentioned in an answer to Referee 1, this part of the text was not clear for the reader and we decided to convey the message through the discussion in sections 3.1 and 3.2.

Q) p 1926, line 17: insert ‘variability and’ between ‘spatial’ and ‘the temporal’

A) This part of the text has been removed. See previous comment.

Q) p 1928, line 7: ‘amplitude of variations’, on what time scale? Seasonal?

A) We refer to seasonal variations. We have clarified this in sentence.

Q) p 1930, line 26: suggest paragraph break before ‘To examine’

A) We have incorporated the change.

Q) p 1931, line 19: suggest add ‘other’ before ‘sub-regions’

A) We have incorporated the change.

Q) p 1931, line 21: suggest add ‘where the dry season is potentially earlier and more extreme (Fig 6c,f)’ after ‘Amazonia.’ and delete following sentence ‘Both ... (2011)’.

A) We have added the suggested phrase butd ecided to keep the following sentence because it was actually the study of Lewis et al. (2011) that motivated us to inspect areas most affected in terms of water deficit during the extreme climatic events of 2005 and 2010, first to look at impacts on the seasonality and then for interannual variations of NEE predicted by the different inversion estimates.

Q) p 1931,line 23: suggest delete 'here' and add 'any' between 'provide' and 'further'

C) We have reformulated the sentence as follows:

"The results, however, do not provide any further information than Fig. 7c,d and are not shown."

Q) p 1931, line 28: might want to note that the slight modifications to NEE are to be expected since there is not much data in the southern part of the TSA region.

C) At the end of the sentence, we add: "maybe because of insufficient data in the southern part of the TSA region. "

Q) p 1933, line 2: suggest adding to the end of the sentence 'opposite to the response for the whole TSA region.'

A) We have incorporated the suggested change.

Q) Figure 1: It would be helpful to label the red sites, perhaps with their initial letter.

A) We have updated the figure.

Q) Figure 2: The vertical line between 2008 and 2009 appears to be missing

A) We have corrected the figure.

Q) Figure 3 caption: perhaps give local time as well as UT for the sensitivity plots

A) We have incorporated the suggested change.

Q) Figure 6 caption: The caption doesn't actually say that it is a NEE anomaly that is shown.

A) We have clarified this in the caption. Figure 6 in the original manuscript corresponds to Fig. 7 in the revised manuscript.

Q) Figure 7 caption: Replace ‘Dominating PFTs’ with ‘Dominant PFT’

A) We have incorporated the suggested change. Figure 7 in the original manuscript corresponds to Fig. 8 in the revised manuscript.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/15/C3640/2015/acpd-15-C3640-2015-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., 15, 1915, 2015.

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Spatial distribution of 2002–2010 mean flux corrections at the transport model resolution ($3.75° \times 2.50°$) to ORCHIDEE from (left) INVSAm and (right) MACCv10.1 over the study region: mean for **(a,d)** February, **(b,e)** July, and **(c,f)** mean over the full period 2002–2010. Flux increments over land and ocean are represented with two distinct colour scales and units: green–yellow for land, in $gC\,m^{-2}\,hr^{-1}$; blue–red for ocean, in $mgC\,m^{-2}\,hr^{-1}$. Filled circles indicate locations of sites with continuous measurements; open circles indicate locations of sites with discrete air sampling.

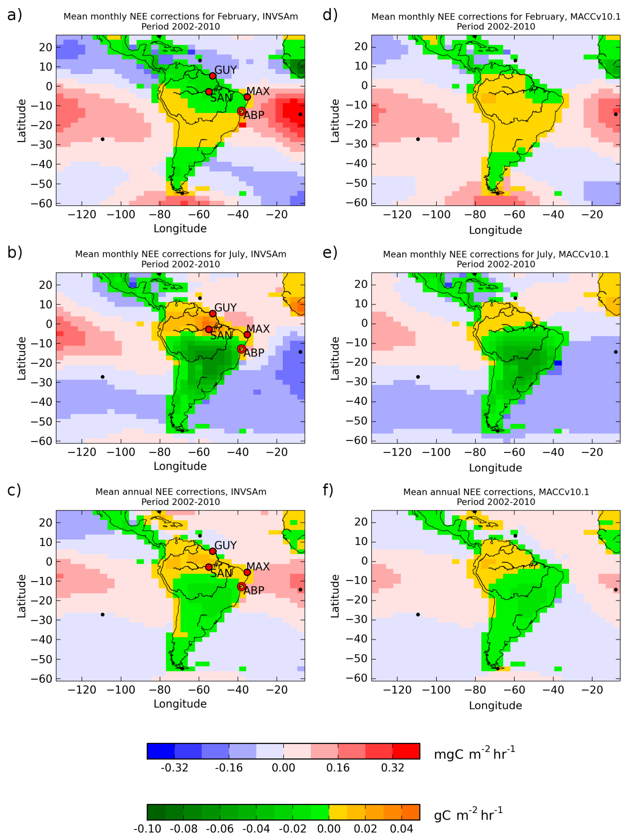

Fig. 1. New Fig. 6 in the revised manuscript

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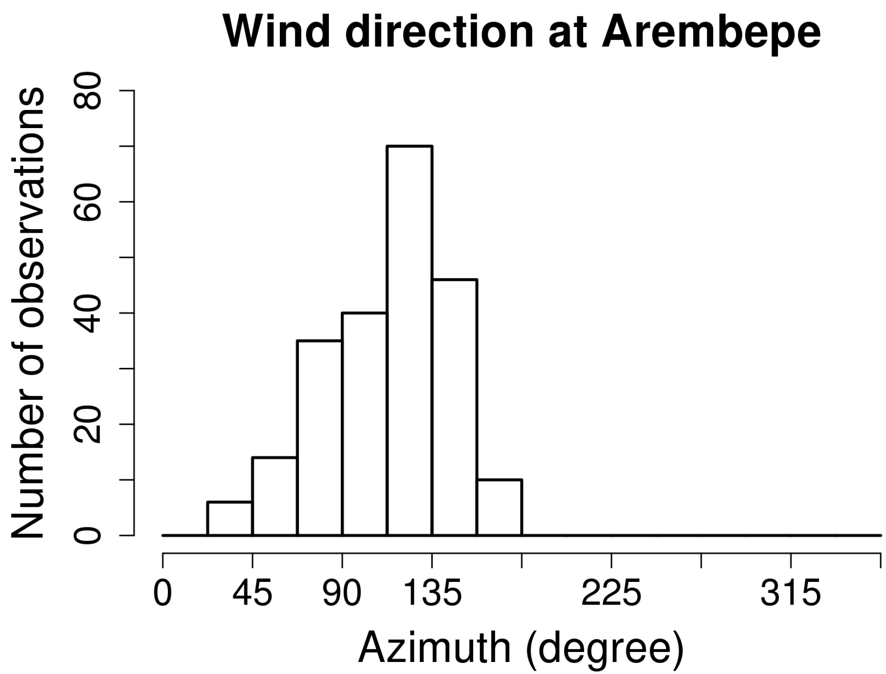
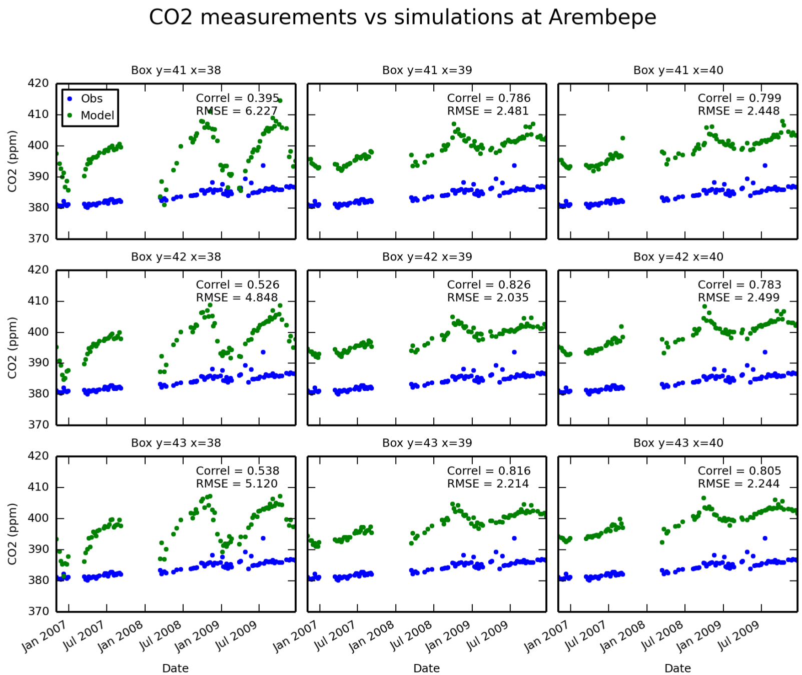


Frequency distribution of ECMWF wind direction at Arembepe, when CO_2 samples area available in the time window 12:00–15:00 local time.

Fig. 2. Fig. A.1



Evaluation of the grid-cell of the transport model that best represents the observations at Arembepe. Observations (blue) are selected within the time window 12:00 to 15:00 LT and have been already filtered for wind speed $>$ 2 m/s. Simulated mole fractions (green) are calculated by transporting the prior surface fluxes described in the model setup (Section 2.1).

Fig. 3. Fig. A.2

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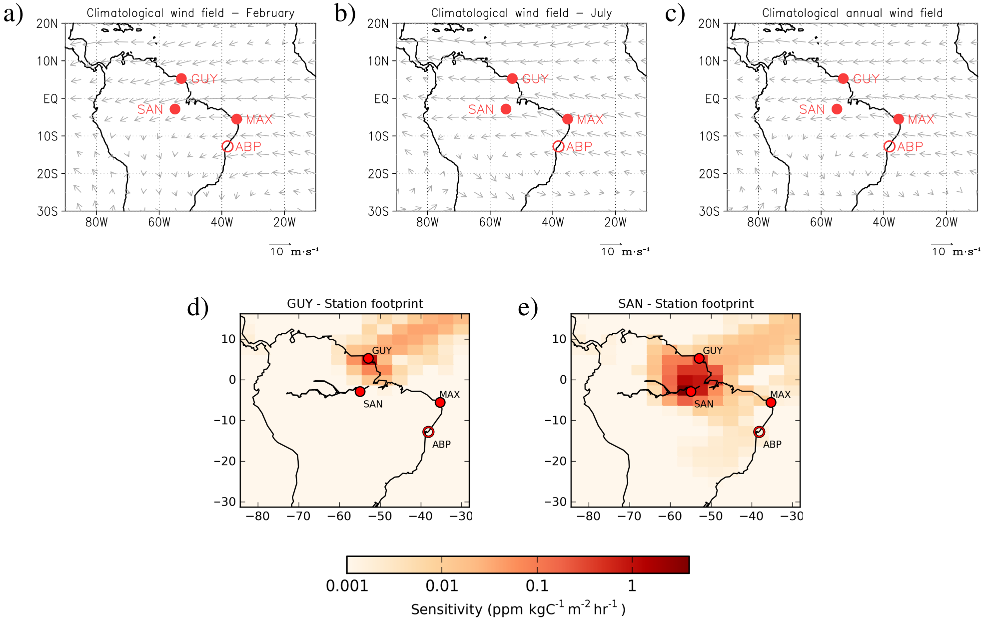

Top: Climatological wind speed and direction for (a) February, (b) July, and (c) annual mean for the period 1981–2010 (from NCEP/NCAR Reanalysis), averaged between the surface and 600 hPa. Bottom: Sensitivity of surface atmospheric CO_2 mole fractions measured on 20 February 2009 at 10:00 UTC, at Guyaflux (d) and Santarém (e), to a constant increment of surface fluxes during the two days prior to the measurement. Sensitivity values are expressed in log-scale. Circles indicate location of surface stations in South America. Open circles: sites with discrete air samplings. Filled circles: measurements taken with continuous analyzers.

Fig. 4. New Fig. 3 in the revised manuscript

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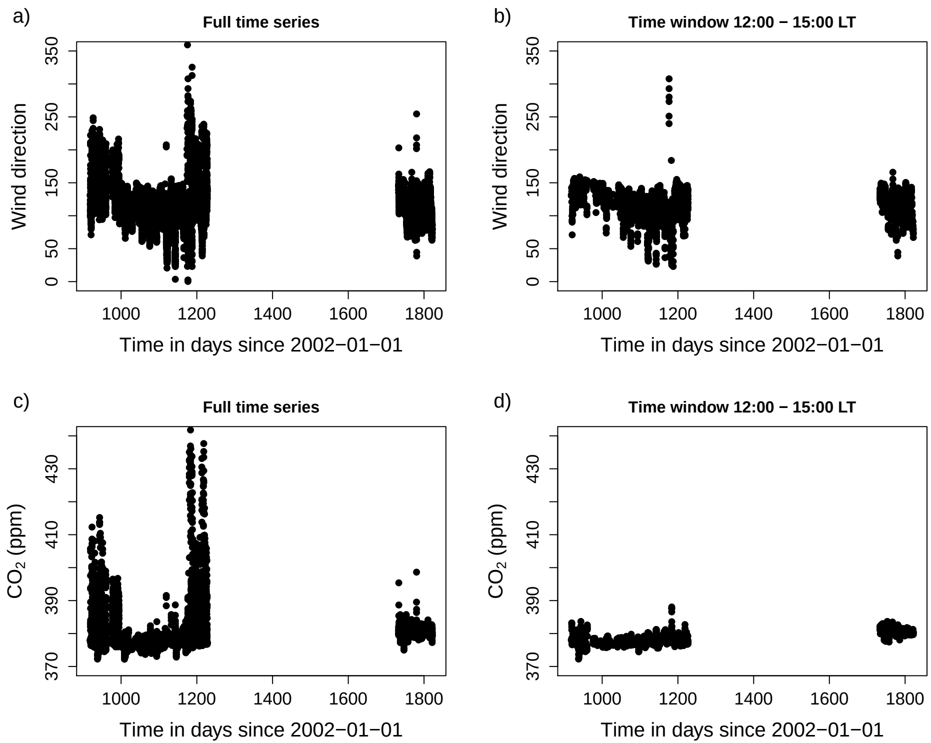

Time series of wind direction and CO_2 mole fraction measured at station Maxaranguape for: all the available observations (a,c) and observations within the time window 12:00 to 15:00 LT (b,d). Wind direction in degrees, measured clockwise from geographic North.

Fig. 5. Fig. A.3

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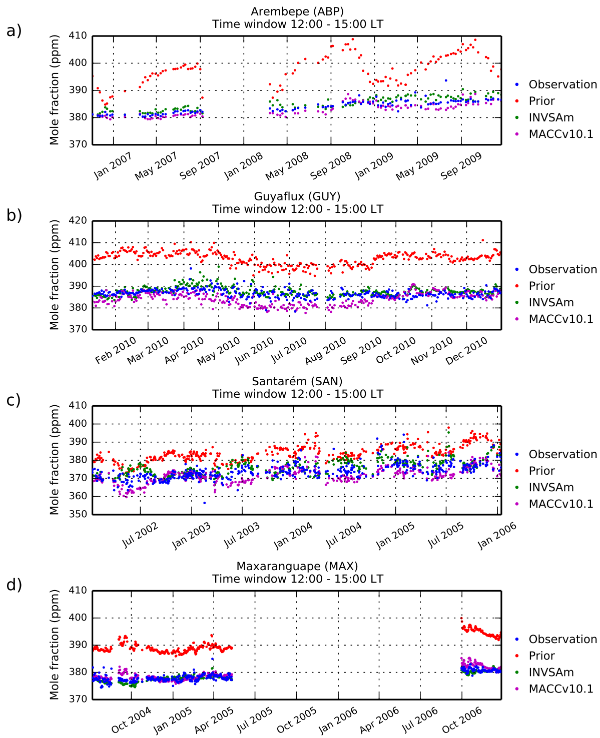
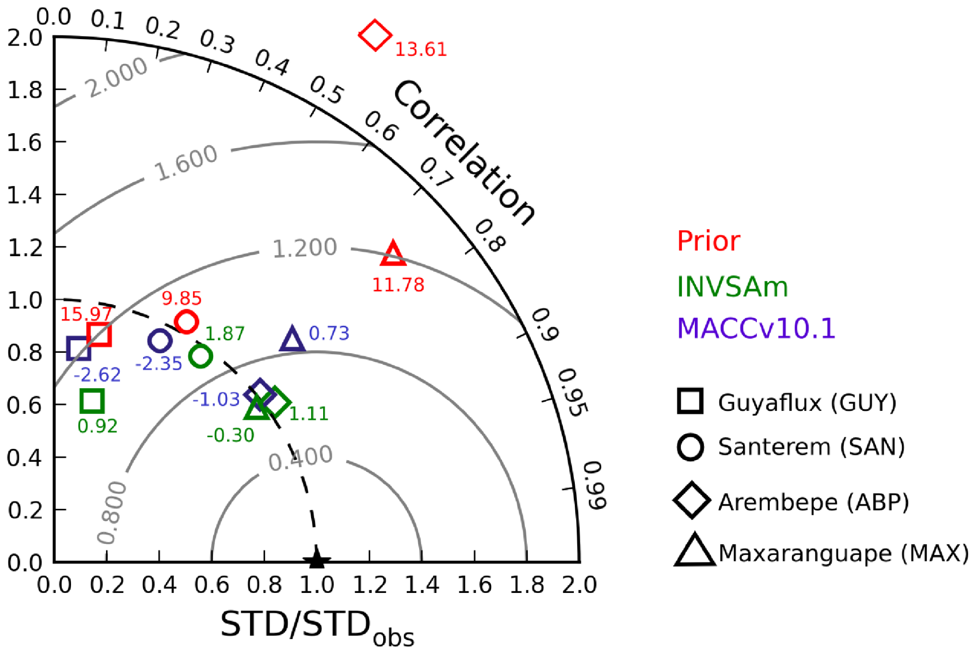


Comparison of assimilated CO_2 observations (blue) and corresponding simulated mole fractions using prior fluxes (red), INVSAm (green) and MACCv10.1 (purple). Measurements were collected at Arembepe **(a)**, Guyaflux **(b)**, Santarém **(c)** and Maxaranguape **(d)**. Data shown here correspond to daily average mole fractions between 12:00 and 15:00 local time (LT), when wind speed 2 m s^{-1}. Note that the time scale differs between plots.

Fig. 6. New Fig. 4 in the revised manuscript



New Fig. 5. Taylor diagram of the statistics of misfits between observations and simulated CO_2 mole fractions between 12:00 and 15:00 LT at Guyaflux (square), Santarm (circle), Arembepe (diamond) and Maxaranguape (triangle), when wind speed $> 2\,m\,s^{-1}$, using prior fluxes (red), INVSAm (green) and MACCv10.1 (purple). Radial distance from the origin: ratio of SD of simulated mole fractions and SD of the observations. Angle measured from the y axis: coefficient of correlation. Numbers next to the symbols: bias (in ppm). Gray circles: SD of the misfits (in ppm).

Fig. 7. New Fig. 5 in the revised manuscript

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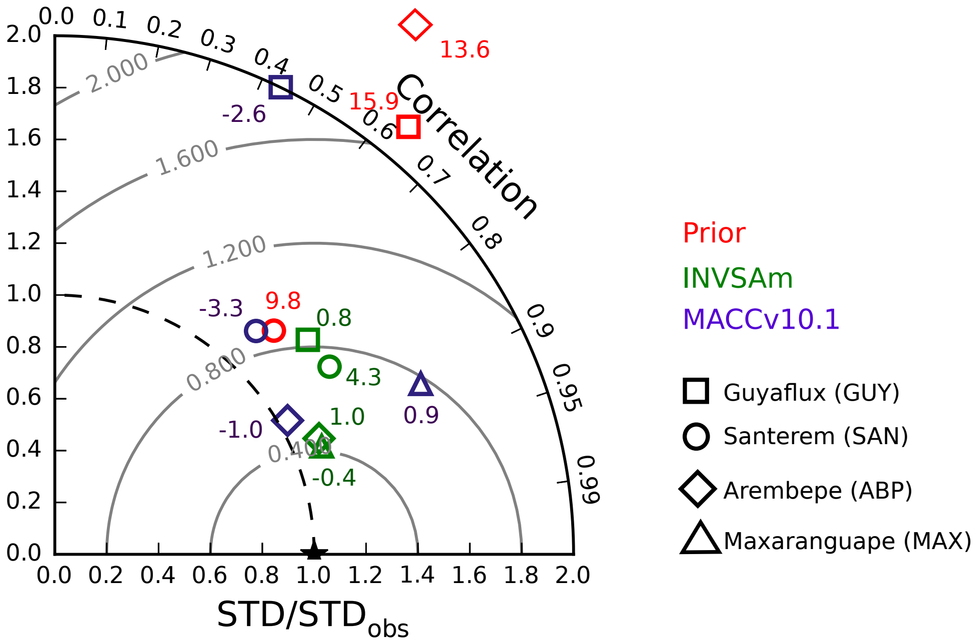

Fig A.4 Taylor diagram of the statistics of misfits between observed and simulated monthly mean CO_2 mole fractions at Guyaflux (square), Santarém (circle), Arembepe (diamond) and Maxaranguape (triangle). Observed monthly means are calculated with observations available between 12:00 and 15:00 LT, and when wind speed $> 2\,\mathrm{m\,s^{-1}}$. Simulated monthly means are calculated from simulated mole fractions between 12:00 and 15:00 LT. Radial distance from the origin: ratio of SD of simulated mole fractions and SD of the observations. Angle measured from the y axis: coefficient of correlation. Numbers next to the symbols: bias (in ppm). Gray circles: SD of the misfits (in ppm).

Fig. 8. Fig. A.4

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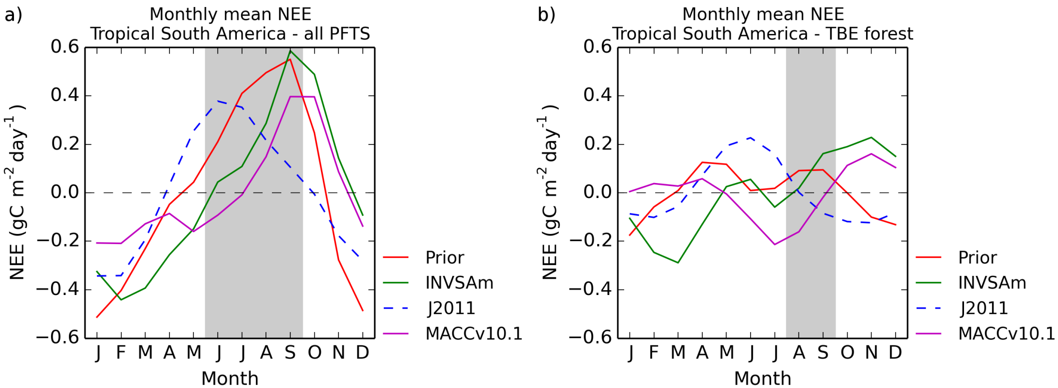

New Fig. 6, panels a,b. Monthly mean NEE integrated over (a) the whole study region and (b) over pixels dominated by TBE forests in ORCHIDEE for 2002–2010. The shaded areas denote dry seasons, defined as months with precipitation < 100 mm, based on monthly totals from TRMM data over 2002–2010. Estimates from prior fluxes (red), INVSAm (green), MACCv10.1 (purple) and J2011 (dashed blue).

Fig. 9. New Fig. 7a and b in the revised manuscript

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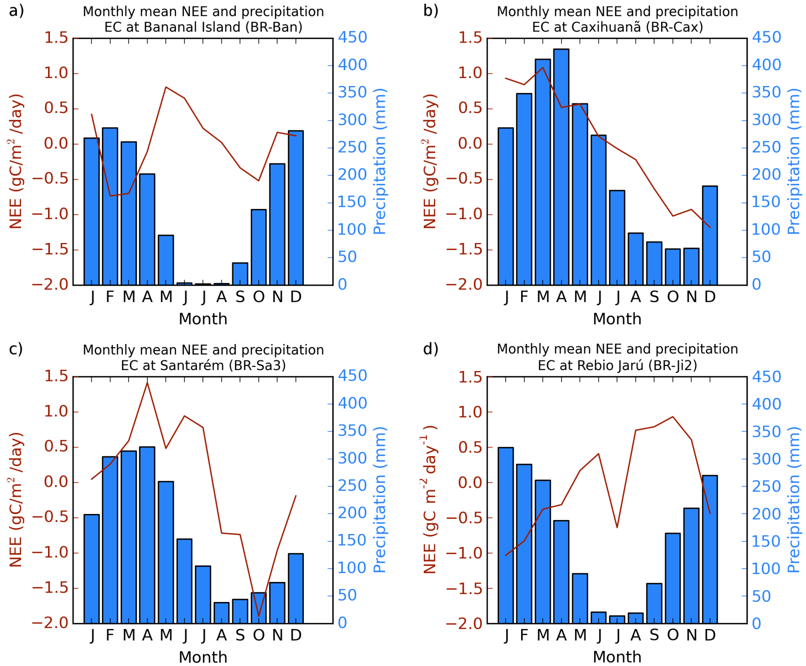

Red: Monthly mean NEE measurements from EC stations at (a) Bananal Island (BR-Ban), (b) Caxihuanã (BR-Cax), (c) Santarém (BR-Sa3) and (d) Rebio Jarú (BR-Ji2). Blue: mean monthly precipitation at the respective station, calculated with data from Tropical Rainfall Measuring Mission (TRMM 3B43 (v6) product) for the same periods for which EC data are available. Location of the EC stations is shown in Fig. S3. For the site at BR-Ban data were available for the period 2000-2002. It is located in a floodplain, in an area of transition between forest and savannah vegetation. A full description is found in Borma et al. (2009). At BR-Cax data were available for 2001-2002. The station is located in an area covered by terra firme humid forest, described by Carswell et al. (2002). At BR-Ji2 data were available for 2000-2002, and is also located in a terra firme humid forest von Randow et al. (2004). At BR-Sa3 data shown were collected at the Tapajós km 83 tower site, an area covered by tropical humid forest, over 2001-2002. A description of the site can be found in Goulden et al. (2004) and Miller et al. (2004).

Fig. 10. Fig. S2

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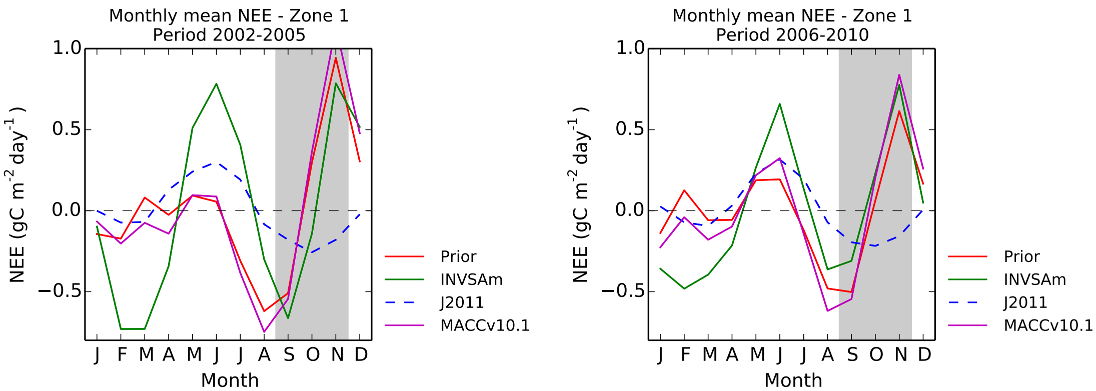
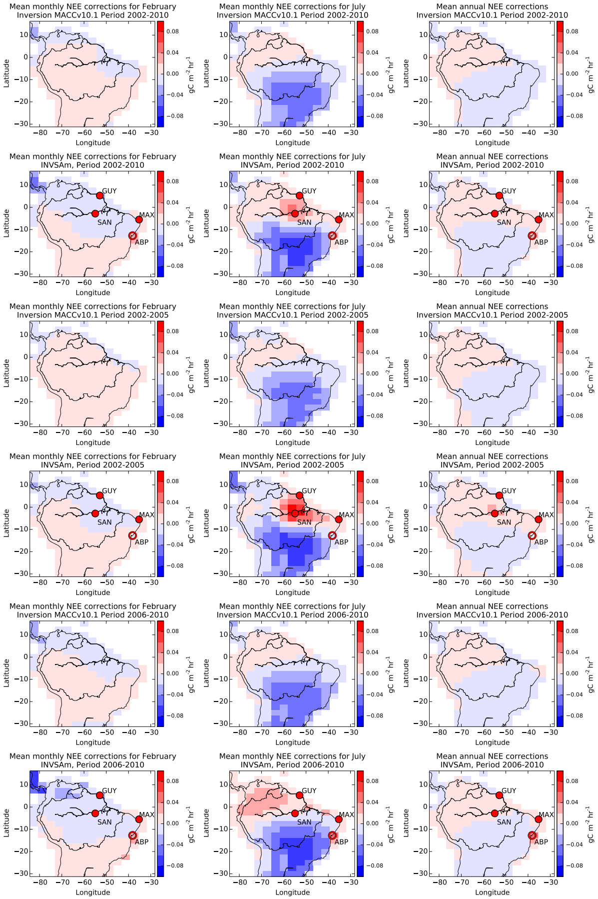


Monthly mean NEE at the Zone 1 predicted by (red) prior fluxes, (dashed blue) J2011, (green) INVSAm and (magenta) MACCv10.1 for two periods: (left) 2002–2005, when SAN is active, and (right) 2006–2010. Shaded area denotes dry season, defined by months with precipitation < 100 mm, using monthly totals from TRMM.

Fig. 11. Fig. A.5



Spatial distribution of mean flux corrections at the transport model resolution (3.75° × 2.5°) to ORCHIDEE from INVSAm and MACCv10.1 over the study region: mean for (left column) February, (middle column) July, and (right column) annual mean for the period 2002–2010 (rows 1,2), for 2002–2005 (rows 3,4), for 2006–2010 (rows 5,6). Filled circles indicate locations of sites with continuous measurements; and open circles indicate locations of sites with discrete air sampling.

Fig. 12. Fig. S1

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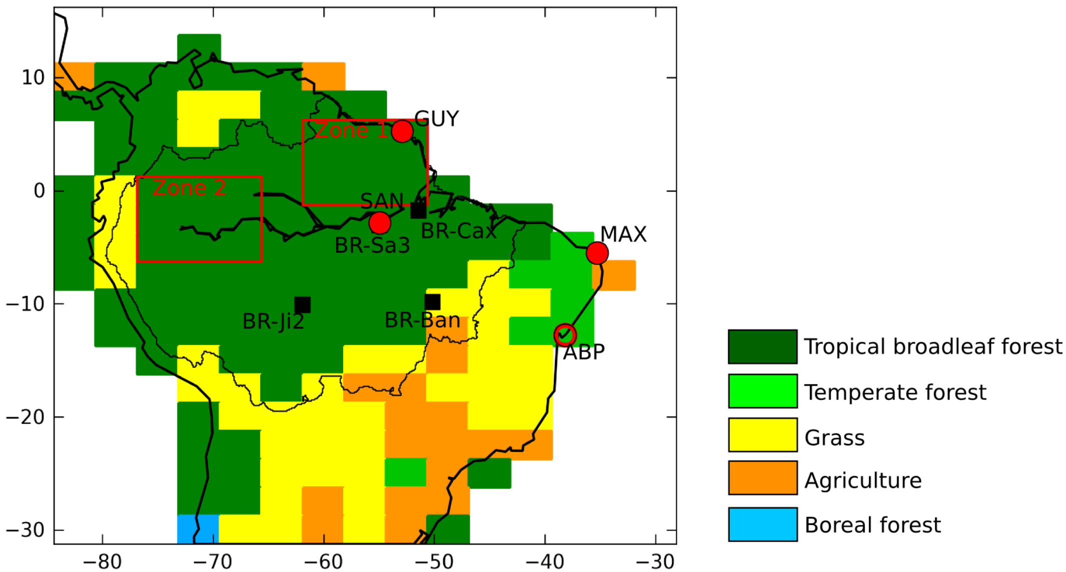

Dominant PFTs for each transport model grid cell (i.e. 3.75 2.50) according to the ORCHIDEE vegetation map over the study region. Circles indicate location of the new four surface sites assimilated in INVSAm: open circles show location of sites with discrete air sampling; filled circles show location of sites with continuous measurements. Squares show locations of the EC measurement stations referred to in Fig. S2. Zones 1 and 2 indicate areas for which the NEE is presented in Figs. 7c and d.

Fig. 13. Fig. S3

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