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Atmospheric Chemistry and Physics
Discussions

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 3

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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Q.1) Tropical South America is a geographical region where we know very little about the carbon balance on a large scale, with implications for quantifying the carbon balance over other regions. This paper examines the ability of using CO2 mole fraction measurements from four additional sites on the eastern coast of South America, relative to a control calculation that has used all other available mole fraction data. I have a few comments but none of them are sufficiently negative to prevent this work being published – they can be addressed quickly.

A) We thank the reviewer for his analysis of our paper and for his very useful comments, which have certainly improved the revised manuscript through new analysis and discussions that have been incorporated.

Q.2) To some extent this is (yet) another paper that highlights the many difficulties using measurements that represent constraints on spatial scales and temporal scales that are not described well by current models. In this experiment, the model resolution is very coarse that could easily compromise its ability to capture reliably observed variations on certain time scales. It would be good to learn a bit more about the model error that takes this into account because it plays an important role in determining the results.

A) Values of the configuration of the model uncertainty assinged in the inversion system are provided in the revised manuscript (see Table A1 in response to Comment Q.9) but they cannot fully reflect the actual values of the model errors given the modest confidence in this configuration, further to the limited experience acquired for the representation of ground-based in situ measurements in this area using global transport models.

Q.3) The new sites look great but there is precious little information to judge whether they are actual useful.

A) Based on figures 6 (previous Fig. 8, now updated), 7 and 9 in the revised manuscript, we discuss (see also our answer to Comment Q.6 of Referee #3 and General Comment Q.1.2 of Referee #2) the fact that the impact of these new sites on the increments from the inversion is large and spread over a large area (at the transport grid scale, the increments from INVSAM to the annual fluxes generally exceed 150% of the prior estimate in terms of absolute values). Still, the analysis of the increments demonstrates that the reliability of this impact is quite low.

Q.4) I assume they have been calibrated on a scale that is common to the data assimilated as part of the MACC project, but this point needs to be confirmed. More details would be helpful for this reader.

A) This information is now provided in the revised manuscript.

C) In Sect. 2.2 Assimilated data, at the end of the fourth paragraph, we state:

"Data from the four new sites in TSA have been calibrated on the WMO-X2007 CO2 scale, managed by the ESRL/NOAA."

Q.5) I appreciate that these measurements are difficult to sustain over long periods but I am left concerned about the role of sampling frequency on the results. A simple simulation could be used to determine the ability of each site to constrain estimates of NEE and ocean fluxes. This would strengthen the ultimate message of the paper.

A) We are not sure about the kind of simulation that the reviewer had in mind. However, given the relatively short correlation length scales in B, and despite the long-range (in time) corrections associated with the data in global inversions, we assume that corrections applied in response to data assimilation at a given site and over given years does not spread to the other years when there is no data available at this site. Therefore we do not think that we should verify it by conducting separate inversions on each 2/3-year periods when one South American site only is available. Still, we now provide analysis of the results for 4/5-year periods in response to General Comment Q.18 of Referee #1 (see the Fig. S1 in the corresponding document) which shows the influence of SAN and MAX on the one hand, and of GUY and ABP on the other hand.

Q.6) Incidentally, what about the ocean fluxes?

A) Thanks to the comments from the three referees, we now provide an analysis of the increments to the ocean fluxes, which brings new insights on the general patterns of the inversion over land, and in particular on the so-called dipole. However, we still keep our focus on the land fluxes to avoid a digression with a deeper analysis of corrections to the ocean fluxes. The new Fig. 6 below depicts corrections for both the ocean and land fluxes (with different colour scales and units due to the different order of magnitude between increments over land and ocean) and over an area larger than that shown originally. Based on this figure, the revised manuscript explains that the increments from both the inversions have large patterns which are nearly zonal (or along the prevailing winds) and which overlap continuously the ocean and the land. The zonal positions and strength (i.e. the amplitude of the zonal gradient) of these zonal increments are modified by the inclusion in the inversion of the data from the new stations in the Tropical South America region. These effects are more visible when focusing on specific months, while the annual averages smoothens the patterns.

C) We have inserted a discussion on the flux increments applied by the inversion in a new section: "Sect. 3.2 Characterization of the monthly to annual mean inversion increments to the prior fluxes". In this new section 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) Regarding the footprints that are shown for a day in February 2009. Are these representative of the season, year? Either a more comprehensive discussion of the site footprints or a climatology of wind fields would help to explain to the reader why these sites were chosen and potentially why that can add to what we know about NEE over the geographical region.

A) In the revised manuscript, we have updated Fig. 3 (below), which now depicts a climatology of wind fields from NCEP/NCAR reanalysis (1981-2010), averaged between the surface and a level of 600 hPa, in tropical South America (TSA), during (a) the austral summer (February), (b) austral winter (July), and (c) annual mean. According the Fig. 3, the seasonal changes in the atmospheric circulation across region TSA are, in general, not critical. The dominant circulation patterns in the lower troposphere over TSA is that of winds entering Amazonia from the north-east, and as they reach the Andes they turn south back into the Atlantic ocean south of 20°S. With the network configuration in TSA, coastal stations ABP and MAX receive information from background CO2 incoming from the Atlantic Ocean. GUY and SAN, subject to the influence of vegetation, on the other hand, help establish a gradient between the coast and north-eastern Amazonia; this information is used by the inversion system to constrain surface fluxes for the area between those stations. The analysis of the new Fig. 6 (see response to Comment Q.6) also reveals that the inversion relies on the long-range extent of the station footprints to apply corrections at very large scale over South America. The inversion uses data from the South American sites and their long-range gradients to other sites in the Southern Hemisphere to control the fluxes with large zonal patterns of corrections (in the direction of the long-range prevailing winds). We

comment this in the revised manuscript.

C) In Section 2.2, the text from line 22, p1925, to line 9, p1926, in the original manuscript has been reformulated:

"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 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 1981âĂŤ2010) for February, July and annual mean, shown in Fig. 3, illustrates this circulation pattern. This confirms that the variations of CO2 at coastal stations (ABP, MAX) are mainly influenced by air–ocean exchanges and fluxes in distant lands. These stations should thus provide more information on the atmospheric CO2 content upwind of TSA, than on the fluxes within Amazonia. Fig. 3 also shows that GUY and SAN receive a signal from the ecosystems of the north-eastern Amazon Basin. Despite GUY being not far from the coast considering the Amazon-wide scale, this site is still located inland, in an area covered by undisturbed, tropical wet forest. SAN is located considerably further inland than GUY. 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."

Q.8) The authors mention a comment on page 1928 line 20: "...results at ABP may reveal some local issues." What are they?

A) The phrase made reference to the analysis of a version of figures 4a and 5, where the results shown for ABP were wrong. We made a mistake when extracting the time series from INVSAm at this site. Figures 4 and 5 have been updated. The true results are much more in line with what is expected from the inversion after assimilating the new sites in TSA.

Q.9) Perhaps my most serious concern is the absence of a discussion about uncertainties. How well did the model fit these new data? Can you give the reader a sense of the ratio of posterior and prior uncertainties associated with the NEE and ocean fluxes? What about the spatial correlated associated with the posterior NEE fluxes shown in Figure 8? For some of the estimates how does this reader know whether these new data have improved our knowledge of NEE? I expect the authors will respond by saying that the assimilation approach does not easily provide posterior uncertainties but I would argue that these results are difficult to interpret without this information.

A) With the high spatial and temporal resolution of our inversion framework, the computation of the theoretical posterior uncertainties is highly expensive (it should be based on a Monte Carlo estimate with ensemble experiments that are not affordable in the framework of this study). Furthermore, due to their huge computational cost, such computations are generally made for typical years, while here, since the reviewers ask for checking the impact of 4 specific sites and for the critical quantities analyzed in this study i.e., the mean seasonal cycle and the inter-annual variability, this would have required the computation of uncertainty reduction for a large number of years (see our response to General Comments Q.1 and Q.2 from Referee #2).

Furthermore:

- We believe that Fig. 6, Fig. 7 and Fig. 9 demonstrate the high impact on the inversion increments from the data in South America. If the error statistics assigned in the inversion configuration are consistent with actual errors, large increments when using

real data should demonstrate that the theoretical uncertainty reduction is high (for the inversion, statistically, corrections to the prior decrease the uncertainty). In response to reviewer #2 (General Comment Q.1.3), we have also compared the prior and posterior misfits between simulated and measured mole fractions, to the setup of the observation errors in the inversion configuration. Such comparisons indicate a decrease of the misfits due to the inversion, and in particular when assimilating the data in South America, which is significant compared to the theoretical observation errors (Table A1, below). These different results indicate that significant improvements of the fluxes in Amazonia could be, in principle, expected from the large increments from INVSAm, which are strongly driven by the sites in South America. The theoretical computation of uncertainty reduction would thus quantify this qualitative indication.

- The theoretical computation of uncertainty reduction and posterior uncertainties strongly relies on the configuration of the prior uncertainties and observation errors in the inversion system. However, as detailed in the answer to the reviewer #2 (General Comment Q.2), this configuration has been derived and evaluated at very large scale using global datasets (eddy covariance flux measurements in Chevallier et al. [2012] and atmospheric mole fraction measurements in CH2010) that mainly sample the Northern hemisphere. There are reasons to think that it is not so robust at higher resolution and for a particular region, especially in the Amazon area, which is poorly sampled by these datasets. Actually, the results and discussion from this study question the inversion configuration for the Amazon region. This does not give confidence in the theoretical computation of posterior uncertainties and uncertainty reduction. Therefore, we do not really agree that such theoretical computation can give useful insights on the results in this study. We comment the points above in the revised manuscript. We hope this clarifies our choice of not performing the uncertainty analysis.

C) In Sect. 2.1 in the revised manuscript we comment:

"There is a moderate confidence in the adequacy of these error statistics assigned in the global inversion system for the specific TSA area studied here, both because B was designed mostly with statistics gathered in the Northern Hemisphere, and because R may not well account for the uncertainty in the atmospheric convection model, while this could be high in Amazonia (Parazoo et al., 2008). We also investigate here variations of the fluxes within TSA at spatial scales that are not much larger than the e-folding correlation length in B, and these variations in the inversion results may be affected by our simple hypothesis of isotropic correlations in the prior uncertainty. This lack of confidence in the input error statistics weakens our confidence in the posterior error statistics that can be derived based on the inversion system, even though they may be realistic at zonal scale for the Tropics (Chevallier and O'Dell, 2013). In this context, and given the relatively high computational burden of the posterior uncertainty computations for grid-point inversion systems (using Monte Carlo approaches with ensembles of inversions, Chevallier et al. 2007), we do not derive these posterior uncertainties for our domain and its sub-domains."

C) In the revised manuscript, Sect. 3.1, we comment:

"The significance of the reduction of the misfits between the mole fractions observed and simulated from the inversion is seen from the comparison between the standard deviations of these misfits and the estimate of the standard deviation of the observation errors (i.e. of the transport model errors) for hourly values in the configuration of the R matrix (Table A1, in supplementary material).According to this comparison, the prior misfits are much larger than the observation errors at ABP, MAX, and GUY, but are slightly smaller than these at SAN. Misfits between MACCv10.1 and the observations are similar to the prior misfits at SAN and GUY and are much smaller than the prior misfits (and smaller than the 95% confidence interval of the observations) at the coastal ABP and MAX sites. Misfits are further decreased when assimilating the data from the South American sites: they are about the standard deviation of the observation errors at all sites but GUY (where they are twice as large)."

Please also note the supplement to this comment:

http://www.atmos-chem-phys-discuss.net/15/C3709/2015/acpd-15-C3709-2015-supplement.pdf

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

Spatial distribution of 2002–2010 mean flux corrections at the transport model resolution ($3.75^{\circ} \times 2.50^{\circ}$) 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.

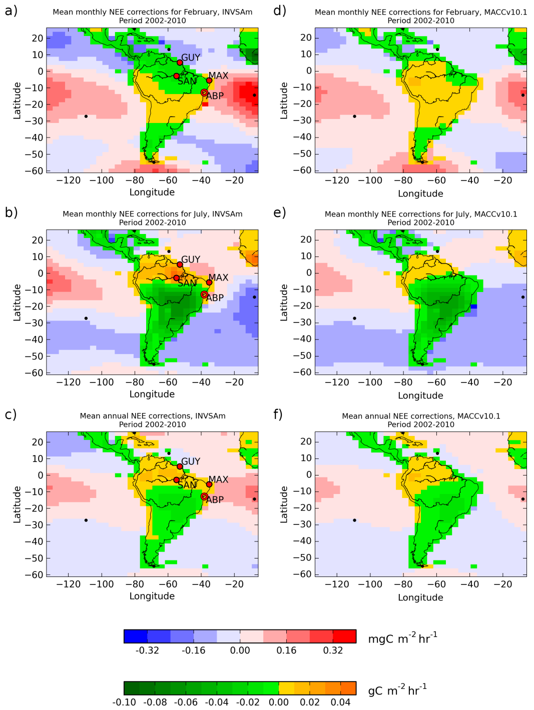
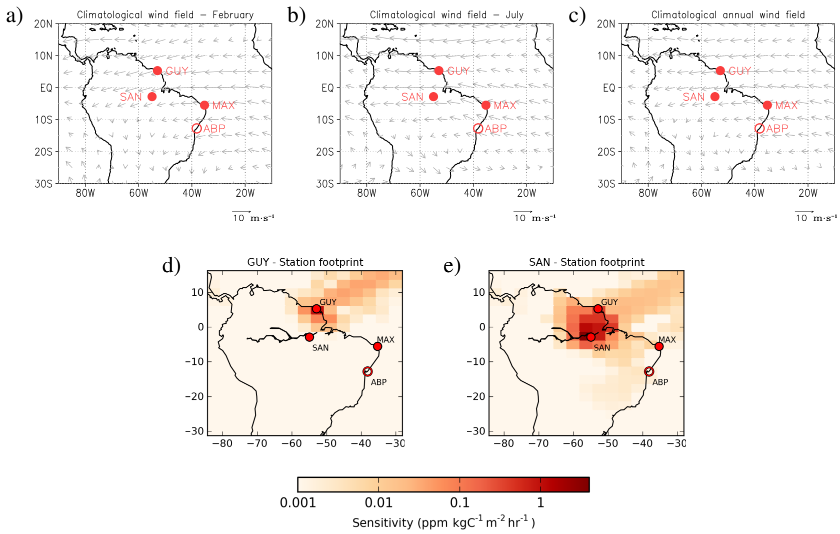


Fig. 1. New Fig. 6 in the revised manuscript



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. 2. New Fig. 3 in the revised manuscript

	Standard deviation of the misfits			
Station	Prior	INSAm	MACCv10.1	2 × (Standard deviation of the model error)
ABP	4.4	1.5	1.6	2.2
MAX	2.1	1.1	1.5	2.0
SAN	4.6	4.0	4.6	9.6
GUY	4.0	3.5	4.1	3.3

Comparison of standard deviation of the misfits between the mole fractions observed and simulated from the inversions prior and the estimate of the standard deviation of the observation errors (i.e. of the transport model errors) for hourly values in the configuration of the **R** matrix.

Fig. 3. Table A1