Authors reply for manuscript: Can seasonal and interannual variation variation in landscape CO_2 fluxes be detected by observations made at a tall tower?

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* Reviewer comments and italics

- Indicates authors reply, newly inserted text is coloured blue

Page and line numbers refer to those in the original discussion manuscript

Short comment by Ed Dellwik:

** The overestimation of model CO2 concentration relative to the TTA measurements during night-time in Figure 2 could be due to a bug in the YSU scheme in version 3.2 of the WRF model. For the versions 3.0 to 3.4, excessive mixing during stable night time conditions can be attributed to a coding error [Hu et al., 2013]. The impact of correcting this error is also documented in this study.*

- We thank Ed Dellwik for his comment on our paper. We agree that the error in the YSU PBL scheme likely contributes to the overestimation of atmospheric CO_2 concentrations simulated at tall tower Angus by WRF-SPA. Hu et al. [2013] showed an error in the YSU scheme, prior to WRFv3.4.1, results in an overestimation of eddy diffusivity under stable conditions such as those which occur at night. The correction of this error caused the simulated nocturnal PBL height to decrease by $\sim$500 m. As a result the inversion of concentration profiles of scalars, such as ozone, also shifted closer to the surface resulting in free troposphere concentrations being present at lower altitudes.

- If we were to assume that the nocturnal PBL simulated here were also to decrease by $\sim$500 m the free troposphere would extend down to the height of the tower. Simulated free tropospheric nocturnal atmospheric CO_2 concentrations are up to 9 ppm lower (mean = 3 ppm lower) than currently simulated by WRF-SPA. Such a reduction would correct a significant fraction of the simulated overestimation shown in this study.

- However, the meteorological conditions simulated over Scotland will be different to those present in Hu et al (2013), therefore the actual magnitude of impact due to the correction for this study remains unknown. Future simulations using WRF-SPA will incorporate the correction to the YSU PBL scheme.

- Despite the error in the PBL scheme we do not expect the underlying conclusions of the study to be altered. The majority of CO_2 exchange between the surface and atmosphere occurs during turbulent day time conditions which remain well simulated by the YSU scheme. Moreover the atmosphere within the simulated domain is subject to nudging from the lateral boundary conditions and the small spatial domain results in rapid turnover of atmospheric CO_2 diminishing the long term effects of the error in the YSU scheme. Furthermore, an assessment of the impact of the YSU error has been made on simulated atmospheric CO_2 concentrations in the well mixed boundary layer during the following day and found no significant impact (*pers comm* Wouter Peters).

- The discussion will be updated to include:

"In contrast CTE-CT continues to overestimate atmospheric CO_2 until late in the year (November / December) indicating that the inversion analysis continues to underestimate Scotland's carbon sink / overestimate carbon source during this period (Fig. 3). The WRF-SPA modelled biosphere generates diurnal cycles of realistic magnitude in the modelled CO_2 time series (Fig. 2b) and reduces the seasonal bias seen in "forcing only" CO_2 (Fig. 3), however nocturnal atmospheric

CO_2 concentrations are overestimated. The nocturnal overestimation of atmospheric CO_2 concentrations is likely due to an error in the YSU PBL scheme used in WRF-SPA. The error results in an overestimation of atmospheric eddy diffusivity under stable conditions, ultimately leading to a higher PBL [Hu et al., 2013]. However, given that day time CO_2 concentrations remain well simulated it is unlikely that the nocturnal error persists into the well mixed boundary layer due to rapid turnover of the atmosphere through nudging by LBCs. Moreover, WRF-SPA has been previously assessed against surface fluxes of heat, water and CO_2, and daytime vertical profiles of atmospheric CO_2 concentrations where profile structure was well simulated, from which we can infer appropriate atmospheric transport [Smallman et al., 2013]. Furthermore WRF-SPA's performance is comparable with several studies which have compared observations of atmospheric CO_2 concentrations made at tall towers to high resolution mesoscale model simulations [e.g., Ahmadov et al., 2009, Tolk et al., 2009, Pillai et al., 2011]."

Response to anonymous Referee 1:

** The study evaluates the performance of a coupled atmospheric-biospheric model WRF-SPA with CO2 observations made from a tall tower in Scotland. Based on the model performance, the study is further extended to assess the representativeness of tall tower measurements in detecting seasonal and inter-annual variation of regional ecosystem CO2 uptake. The model evaluation part in this paper is largely as a followup of Smallman et al., 2013. The paper holds scientifically relevant topic which is necessary for Carbon community; hence lies within the scope of BG. The paper is organized well; however some parts are not concise enough. I have a serious concern on the analysis described in sections 4.2 and 5.2 (See Specific Comments).This strongly needs to be revised or clarified to support the conclusions. In the present form, it is not adequate to reach the conclusion. Additionally, I suggest authors to consider avoiding line-by-line repetition of sentences here and there from their previous published paper, Smallman et al. [2013]. For example, see the whole section 2.1, which is exactly identical to the section 2 of Smallman et al., 2013 - authors can consider revising it or reducing the text by giving reference. Besides on these, I ask authors to kindly work on language fluency for enhancing the clarity of their statements, especially the introduction part. I recommend the paper to be published after minor revision, considering the above and following comments*

- We thank referee 1 for their comments on our paper and agree that it is of interest to researchers in the carbon community. In reply to the general comments we recognise that the paper needs to be made more concise and to have a clearer description of the analysis and introduction to ensure the reader can more easily understand the analysis undertaken. Further we will produce a simpler description of the WRF-SPA model by relying on directing the reader to the WRF-SPA description paper [Smallman et al., 2013].

- Below we detail each comment by the reviewer followed by an explanation of how we intend to accommodate the reviewers recommendations.

Specific Comments:

** p. 14312: The representativeness of TTA total land surface net CO2 uptake (Fig.5) -¿ Please indicate what you meant by land surface CO2 uptake- Is it tracer concentration or flux? If it is flux, I may follow the basis of your analysis to some extent. But in the referred figure (Fig. 5), the plotted variables are all seem to be concentrations.*

- We recognise that the description of the ecosystem specific CO_2 tracers and the associated analysis are poorly explained. A new section describing both the CO_2 tracers and the analysis using the CO_2 tracers is to be included in the methods. In reply to the specific comment the surface net CO_2 uptake is a flux while net uptake CO_2 is a tracer.

- We also appreciate that the choice of describing these tracers as passive and / or non-passive could be confused with definitions used in atmospheric chemistry. Therefore we will rename these tracers such that passive = non-interacting and non-passive = interactive, to indicate their ability to interact or not with the land surface.

- The new section will state:

"The ecosystem specific tracers of net uptake and net release of CO_2 are used to investigate the information content on these processes contained within the total atmospheric CO_2 concentrations simulated at TTA. We investigate how representative observations at TTA are of the underlying surface fluxes of CO_2. Note that LBCs for the outer domain have been set with zero inflow and zero-gradient outflow for ecosystem specific net uptake and net release CO_2 tracers. Zero gradient inflow / outflow allow tracers to easily leave the domain and prevent artificial influx to the CO_2 tracer fields.

The land surface can be either a net source or net sink of atmospheric CO_2, varying both spatially and temporally. Whether the land surface is a net sink or source of CO_2 is determined by the net result of photosynthetic and respiratory processes. Atmospheric CO_2 concentrations represent a spatial and temporal integration of the net flux of CO_2 between the land surface and the lower atmosphere. Therefore, when the simulated surface flux of CO_2 represents a net removal of CO_2 from the atmosphere, an ecosystem specific 'net uptake CO_2 tracer' is released into the simulated atmosphere at the same rate as the 'surface net CO_2 uptake flux' (i.e. rate of NEE). Correspondingly, when the surface net CO_2 uptake flux represents a net addition of CO_2 to the atmosphere an ecosystem specific 'net release CO_2 tracer' is released.

The net uptake CO_2 tracers are considered to be non-interacting / non-interactive, while the net release CO_2 tracers are interacting / interactive. The net uptake CO_2 tracers are non-interacting as they represent a removal of atmospheric CO_2 and as such cannot interact with the land surface. After their emission from the surface the net uptake CO_2 tracers are transported through the model atmosphere. Conversely, net release CO_2 tracers represent an addition of a physical mass of CO_2 to the atmosphere via respiration, which can therefore be subsequently removed from the atmosphere by photosynthesis after its initial release. Allowing the removal of a net release CO_2 tracer prevents a respiratory signal from being simulated at TTA which in reality does not reach TTA due to being consumed en route in a physically consistent manor.

Net release CO_2 tracers are removed from the atmosphere if they are present in the lowest model atmospheric level and the land surface below represents a net removal of CO_2. If there are multiple ecosystem specific net release CO_2 tracers present in the same model atmosphere grid box, then removal is determined by the relative fraction of each ecosystem specific tracer. For example, to determine the removal of crop net release CO_2 tracer

$$\gamma \uparrow t_{crop} rm = \frac{\uparrow t_{crop}}{\uparrow t_{crop} + \uparrow t_{forest} + \uparrow t_{grass} + \uparrow t_{other}} \tag{1}$$

where $\gamma \uparrow t_{crop} rm$ is the fraction of surface CO_2 flux (i.e. NEE) to be applied to the crop net release CO_2 tracer. $\uparrow t_{crop}$ is the crop net release (as indicated by the direction of the arrow and t indicates it being a tracer) CO_2 tracer concentration, similarly for forest, managed grassland and 'other' land cover types.

0.0.1 Investigating representivity and detection of seasonal and interannual variation using CO_2 tracers

Ecosystem specific CO_2 tracers are used to infer representativeness of the simulated atmospheric CO_2 concentrations at TTA of surface CO_2 flux and to investigate how much seasonal and interannual information is contained within these atmospheric CO_2 concentrations. We assumed that the simulated atmospheric CO_2 tracers are driven by the simulated surface CO_2 fluxes (from which they originate) and that atmospheric transport determines how much information on surface fluxes is represented within atmospheric CO_2 concentrations at any given location within the simulated atmosphere. To minimise the effects of short term transport and to focus only on large seasonal variations, we conducted these analyses using monthly mean values.

We investigated the representativeness of atmospheric CO_2 concentrations simulated at TTA of surface CO_2 flux. We compared the fraction of each ecosystem specific net uptake CO_2 tracer (e.g. for crop $\downarrow t_{crop}$) simulated at TTA to the fraction of ecosystem specific surface net CO_2 uptake flux (e.g. for crop $\downarrow f_{crop}$, where f indicates this is a flux).

$$\gamma \downarrow t_{crop} = \frac{\downarrow t_{crop}}{\downarrow t_{crop} + \downarrow t_{forest} + \downarrow t_{grass} + \downarrow t_{other}} \tag{2}$$

$$\gamma \downarrow f_{crop} = \frac{\downarrow f_{crop}}{\downarrow f_{crop} + \downarrow f_{forest} + \downarrow f_{grass} + \downarrow f_{other}} \tag{3}$$

Representativeness for any given ecosystem type is assumed to be when

$$\gamma \downarrow t_{crop} \approx \gamma \downarrow f_{crop} \tag{4}$$

Moreover, this comparison provides an indication of whether the activity of a given ecosystem is over-represented (i.e. $\gamma \downarrow t_{crop} > \gamma \downarrow f_{crop}$) or under-represented (i.e. $\gamma \downarrow t_{crop} < \gamma \downarrow f_{crop}$) in simulated atmospheric CO_2 concentrations. Such information can help the interpretation of results from comparing ecosystem specific CO_2 tracers and the simulated atmospheric CO_2 concentrations.

Investigation of seasonal variation is achieved through linear regression analysis between the surface net CO_2 uptake flux and net uptake CO_2 tracer concentration, for a given land cover type. As net uptake CO_2 tracers originate from the simulated surface net CO_2 uptake flux, differences between seasonal variation of tracer concentrations and surface fluxes are due to how atmospheric transport relays variations in flux to TTA. To investigate interannual variation simulated to be detected at TTA, we assume that a change in surface net CO_2 uptake flux for a given ecosystem should be reflected in the net uptake CO_2 tracers simulated at TTA."

** Please specify the unit here (Y-axis).*

- The y-axis description states that the information contained are fractional, we will correct the legend to clearly describe the variables as ecosystem specific fraction of either surface CO_2 flux or atmospheric CO_2 tracer concentration. An updated legend can be found at the end of this reply.

** How can you assess representativeness of the measurements at national scale by just comparing concentration fractions (e.g. crop uptake) for two levels (surface and tower level)? If surface CO2 concentration (e.g. crop uptake) is less than upper level CO2, you may vaguely say that there may be some influence from far-field fluxes (but not necessarily at national scale).*

- We accept that inferring representativeness of national scale net CO_2 uptake is incorrect. Rather, the comparison between ecosystem specific CO_2 tracer concentration and simulated surface CO_2 fluxes (surface fluxes are the source of the atmospheric tracers) informs on representativeness of the model domain. Moreover, we appreciate that we have not sufficiently discussed the footprint of TTA. This is further discussed in the response to Thomas Lauvaux.

** However, a serious caution should be made for the (local) transport patterns both horizontally and vertically which affect the concentrations in different levels. You can check this with your simulated meteorological fields. Now there comes another issue: the uncertainty in simulated tracer transport (e.g. issues with vertical mixing). So you have to take into account that. Thus, in short, by comparing two levels of concentrations, one cannot say about the ecosystem representativeness at national scale. Another possibility is to do some tests by changing local biosphere (perhaps topography also) + meteorological drivers (e.g. local wind direction) and analyze the impact. Based on results (e.g. dominance of boundary effect), one can say about the representativeness at national scale.*

- The comparison was carried out against monthly mean values to attempt to average out short terms effects due to local transport. As a result our comparison should only be responsive to large spatial scale / long duration signals. A new section, described earlier, will be added to describe the ecosystem specific tracers and the analysis of representativeness and detection of seasonal and interannual variation.

** p.14313: Seasonal variation in net CO2 uptake .. regional scale net CO2 uptake -¿ This analysis does not seem to be interesting. These are simulated results (not observations!) and are based on parameterization. The regression will give you the results based on how you parameterize the fluxes.*

- We accept that this analysis does not convey any significant information as these results are indeed dependent on the model parameterisation and structure. This analysis will be removed from the manuscript.

** p. 14303: . . resulting in significant seasonal and interannual.. -¿ Add also spatial*

- The text will be altered to include significant spatial, seasonal and interannual variations.

** p. 14303: ..made at the regional scale (e.g. at a tall tower).. -¿ It is misleading Did you mean the representativeness of measurements? Please remove it or make it clear otherwise.*

- We recognise that tall tower observations are not made at the regional scale, rather they can contain spatially and temporally integrated information on surface CO_2 fluxes which when used in conjunction with atmospheric inversion models con inform on surface fluxes. To avoid confusion the text will be altered "...atmospheric CO_2 concentrations (e.g. at a tall tower)...."

** P.14307: ..frictional velocity, atmospheric CO2 mixing ratios .. -¿ a bit lost here. As far as I understood, the coupled model WRF-SPA simulates atmospheric CO2, using met. drivers provided by WRF and associated fluxes calculated by SPA. Then again why do you need atmos. CO2 concentrations to be passed to SPA? Please clarify.*

- The listed meteorological drivers and atmospheric CO_2 mixing ratios are required as input drivers for SPA. Atmospheric CO_2 mixing ratios are passed to SPA as SPA's representation of photosynthesis is sensitive to variation in atmospheric CO_2 via changes in leaf internal CO_2 concentrations.

- The WRF-SPA description will be modified to make the close coupling between WRF and SPA explicit

" Model description: WRF-SPA

WRF-SPA [Smallman et al., 2013] is a coupling between the high resolution non-hydrostatic mesoscale model Weather Research and Forecasting (WRF) and the mechanistic land surface model (LSM) Soil Plant Atmosphere (SPA). SPA is fully integrated into the WRF model framework where WRF simulates meteorological fields and atmospheric transport of the CO_2 fields. SPA in return provides WRF with surface temperature, roughness length, albedo, and exchanges of energy, heat, water and CO_2. A brief description of the WRF and SPA models are given below."

** p. 14308: Atmospheric CO2 fields (20022007) are from Carbon Tracker Europe-¿ Please indicate that it is initial fields of atm. CO2*

- The text will be modified to make clear that Carbon Tracker Europe atmospheric CO_2 fields were used to provide initial atmospheric CO_2 conditions and nudging to the atmosphere via lateral boundary condition.

"Initial conditions (IC) and lateral boundary conditions (LBC) for atmospheric CO_2 (except 2008) are from Carbon Tracker Europe [CTE, Peters et al., 2010] providing 1°x 1° resolution fields at 3 hourly intervals."

** p. 14310: Statistical comparison of hourly observations with the WRF-SPA simulated The annual bias for total atmospheric CO2 .. -¿ How did you do the statistical comparison? What is the period of data you used for this? What makes it different from your annual bias calculation?*

- The text will be updated to include both the time period and statistical method used.

"We compared hourly observations of atmospheric CO_2 concentrations from TTA (2006-2008) with both the WRF-SPA simulated total atmospheric CO_2 (R^2 = 0.67, rmse = 3.5 ppm, bias = 0.58 ppm, linear regression) and "forcings only" CO_2 (R^2 = 0.71, rmse = 3.3 ppm, bias = 0.82 ppm)."

and

"The impact of the biosphere is more clearly seen at seasonal time scales using monthly means (Fig. 3). Total atmospheric CO_2 (R^2 = 0.96, rmse = 1.2 ppm, bias = 0.54 ppm), which includes biospheric exchange, shows improved statistical agreement with observations compared to "forcings only" CO_2 (R^2 = 0.91, rmse = 1.6 ppm, bias = 0.71 ppm) and CTE-CT atmospheric CO_2 concentrations (R^2 = 0.94, rmse = 1.5 ppm, bias = 0.94 ppm)."

** p. 14310: ..suggests minimal or slightly negative..-¿ please remove minimal. Though it is not clear how you did your statistics (see above comments), another possible reason for this negative impact is the variability. CO2 variability is well captured in the Total CO2 for active biosphere months when compared to the less variable forcing only CO2. However, positive fluxes (ecosystem release) are underestimated for winter months.*

- The text will be modified to remove "...minimal or...". Also, the discussion will be modified to include reference to the underestimation of winter CO_2 release.

"Atmospheric CO_2 concentrations are underestimated during the winter, however the bias is of a smaller magnitude in total atmospheric CO_2 than in "forcings only" CO_2 (Fig. 3). The underestimation during winter likely indicates that SPA underestimates net release of CO_2 flux (i.e. respiration) from the land surface. WRF-SPA has previously been validated against eddy covariance observations of NEE at forest, managed grassland and cropland sites, where forest and managed grassland NEE was overestimated during winter while cropland was underestimated [Smallman et al., 2013]. Given that net release CO_2 tracers simulated at TTA for crops is half the magnitude for forests, crops are a plausible candidate to explain the winter time underestimate in simulated atmospheric CO_2 concentrations (Fig. 4). Smallman et al. [2013] hypothesised that the underestimate in crop could be related to an underestimation of soil organic matter or the rate of soil organic matter turnover within the carbon model, however there remain several possibilities to be explored (e.g. ploughing)."

** p. 14310: an overestimation of night time atmospheric CO2 concentrations simulated -¿ it could also be very well related to the misrepresentation of nocturnal boundary layer. Which model level do you use for your comparison? Also comment on the bug report of YSU scheme as indicated in the interactive comment by ED Dellwik.*

- please see the response to Ed Dellwik.

** p. 14310: reduced in total CO2 by up to 59% between MarchJune and October December of each year -¿ I dont see any significant bias reduction for October December in terms of forcing-only and total co2 residuals by including biospheric fluxes. Please clarify.*

- We recognise that the reduction in the seasonal bias between October and December is of a smaller magnitude than March-June and is only significant in 2007. The text will be modified to remove the reference to the winter bias.

"The impact of the biosphere is more clearly seen at seasonal time scales using monthly means (Fig. 3). Total atmospheric CO_2 (R^2 = 0.96, rmse = 1.2 ppm, bias = 0.54 ppm), which includes biospheric exchange, shows improved statistical agreement with observations compared to "forcings only" CO_2 (R^2 = 0.91, rmse = 1.6 ppm, bias = 0.71 ppm) and CTE-CT atmospheric CO_2 concentrations (R^2 = 0.94, rmse = 1.5 ppm, bias = 0.94 ppm). The monthly mean bias between total atmospheric CO_2 and observations is reduced for the majority of the comparison period relative to "forcings only" CO_2 and CTE-CT. The seasonal bias is reduced in total atmospheric CO_2 by up to 2.8 ppm and 1.9 ppm between March and June of each year compared to "forcings only" CO_2 and CTE-CT respectively (Fig. 3). However, the modelled biosphere does not capture the observed seasonal minimum in atmospheric CO_2 concentrations which occurs in July - August of each year (Figs. 2,3). During July - September total atmospheric CO_2 has a larger bias than both "forcings only" CO_2 and CTE-CT, compared to observations. A larger positive bias in total atmospheric CO_2 than "forcings only" CO_2 indicates that modelled ecosystems within the footprint of the tall tower have become a net source of CO_2 at a time when they should remain a net sink (Fig. 3)."

** p. 14312: ..while cropland is overrepresented on average by 33%.. -¿ What do you mean by over-represented well represented?*

- We accept that the terminology used is confusing. A new section, described above, detailing the CO_2 tracers will be added in the methods section including a definition of both over- and under-representation.

** p.14312: The seasonal profile for forest, managed grassland ..surface -¿ not clear*

- We apologise that we have not been clear, we are referring to the seasonality in the time series presented in Figure 6. The text will be altered to make this explicit.

"Net uptake CO_2 tracers simulated at TTA are able to explain the majority of seasonal variation in surface net CO_2 uptake for crops, forest, managed grassland and 'other' land covers (Table 3). The seasonal cycles in net uptake CO_2 tracers are more variable during the growing season (i.e. May - August), such that there is a mismatch between peak net uptake CO_2 tracers and surface net CO_2 uptake flux by $\pm$ one month (Fig. 6). Moreover the amount of variation in surface net CO_2 flux explained by net uptake CO_2 tracers simulated at TTA varied between years (e.g. forest 2006 R^2 = 0.79 and 2008 R^2 = 0.58). The rank order of net uptake CO_2 tracers simulated at TTA from each year does not correspond with the rank order of surface net CO_2 uptake flux for any ecosystem (Fig. 6). Interannual variation in mean annual surface net CO_2 uptake flux was $\sim$9 % while interannual variation for mean annual net uptake CO_2 tracer at TTA was $\sim$19 %.

The annual prevailing wind direction over Scotland varied between years; in 2006 and 2008 the prevailing wind direction was broadly south / south west, while in 2007 the prevailing wind direction was westerly. Moreover, the prevailing wind direction varied at seasonal time scales. During the peak growing season (May to August) there was considerable variation (Fig. 7). In 2006 prevailing wind direction during the growing season varied between southerly and westerly. While in 2007 and 2008 there were periods of northerly and easterly winds, particularly during June; returning to more south westerly directions by August in each year. This interannual and seasonal variation in wind direction will have impacted the detected footprint by TTA."

** p. 14313-14314: ..that Scotlands terrestrial ecosystem is likely on average to be a net carbon sink .. -¿This is not clear from Fig.3 as you plotted only TTA observations. If you rely on SPA for this estimate, please indicate it explicitly and give numbers.*

- We use the good agreement with TTA atmospheric CO2 concentrations (and with aircraft profiles of atmospheric CO_2 concentrations from Smallman et al. [2013]) to infer that SPA simulated surface exchange is broadly realistic for most of the year. Therefore, we conservatively infer that as WRF-SPA's simulated land surface is a net CO_2 sink that Scotland's real world biosphere is also likely to be a sink. We will alter the text to make this explicit. Furthermore we will include a comparison with the official estimates of Scotland's carbon balance from the UK's National Atmospheric Emissions Inventory (NAEI).

In the results section:

"The dominant ecosystems simulated within the footprint are forest, crop and managed grassland (Fig. 1). Over the validation period WRF-SPA simulated forest (-2.56$\pm$0.05 tC ha^{-1} yr^{-1}, $\pm$ standard error accounting for spatial and temporal uncertainty only) and managed grassland (-0.48$\pm$0.02 tC ha^{-1} yr^{-1}) ecosystems to be mean annual sinks of CO_2. Crop ecosystems (0.89$\pm$0.01 tC ha^{-1} yr^{-1}) were simulated to be a mean annual source of CO_2. WRF-SPA estimates Scotland to be on average a carbon sink of -0.99$\pm$0.04 tC ha^{-1} yr^{-1}. CTE-CT estimate Scotland to be a carbon source of +0.65 tC ha^{-1} yr^{-1}."

and in the discussion:

"WRF-SPA's estimate of sink magnitude is $\sim$4 fold greater than the official estimate of Scotland's carbon sink by the UK National Atmospheric Emissions Inventory (NAEI), which estimates Scotland's carbon balance to be -0.20 tC ha^{-1} yr^{-1} [Thomson et al., 2012]. WRF-SPA does not account for a number of management impacts such as biomass burning and land cover change. Excluding these fluxes the NAEI estimate for Scotland's carbon sink is -0.44 tC ha^{-1} yr^{-1}. While WRF-SPA agrees with the NAEI that Scotland is a net sink of carbon, there appears to be a large discrepancy in the magnitude of the sink strength, the causes of which remain to be identified. However as we currently lack an error analysis of atmospheric CO_2 concentrations simulated by WRF-SPA it remains unknown whether the discrepancy shown here is within errors.

WRF-SPA simulated mean forest sequestration (-2.56 tC ha^{-1} yr^{-1}) is approximately double estimates for UK wide [Cannell et al., 1999] and average European forest sequestration [Janssens et al., 2005, Luyssaert et al., 2010]. Scotland specific estimates of forest sequestration are more similar to the simulations; Scotland specific estimates range between ∼1.8 tC ha^{-1} yr^{-1} [Thomson et al., 2012] and ∼2.0 tC ha^{-1} yr^{-1} [Forestry Commission Scotland, 2009]. Forest activity is under-represented in atmospheric CO_2 concentrations simulated at TTA as indicated by the lower fraction of net uptake CO_2 tracer simulated at TTA compared to the fraction of surface net CO_2 uptake flux originating from forest land cover. This under-representation of forest cover may explain why there is no apparent overestimation of Scotland's net carbon sink in the comparison between simulated CO_2 at TTA and observations. Grasslands were simulated to be a net carbon sink (-0.48 tC ha^{-1} yr^{-1}) while croplands were simulated to be a net carbon source (0.89 tC ha^{-1} yr^{-1}). Estimates of grassland carbon sink are more comparable with other estimates, which range between -0.69 tC ha yr^{-1} [UK average, Janssens et al., 2005] and -0.15 tC ha yr^{-1} [Scotland specific, Thomson et al., 2012]. The WRF-SPA estimate of cropland source magnitude is also comparable with other UK wide [0.53 tC ha^{-1} yr^{-1}, Janssens et al., 2005] and Scotland specific estimates [0.88 tC ha^{-1} yr^{-1}, Thomson et al., 2012]."

** p. 14314: WRF-SPAs estimate for Scotlands forest sequestration is overestimated. Forest activity is largely under-represented in observations made at TTA (Fig. 5) -¿ I cant see this information from Fig.5. Please explain it clearly.*

- We infer that forests are under-represented in observations made at TTA as the fraction of net uptake CO_2 tracer simulated at TTA, which originated from forest land covers, is less than the fraction of surface net CO_2 uptake flux which originated from forests. We infer that the reason no underestimate in atmospheric CO_2 concentrations is apparent during the growing season is due to overestimating forest net carbon sink is due to forest CO_2 fluxes being under-represented in atmospheric CO_2 concentrations at TTA.

** p. 14315: The parameterised harvest processes are broadly realistic -¿ Do you have a reference for this?*

- A relevant reference Sus et al. [2010] will be added

** p. 14318: Cropland is over-represented in tall tower Angus observations for much of the annual cycle -¿ over-represented? Please clarify.*

- A detailed description of the CO_2 tracers will be added to the methods section, including a description of terminology.

** Fig 6: I see a shift in maxima for cropland tracer for the year 2007 when compared to flux. Do have an explanation for this?*

- The prevailing wind direction varies between years and during the growing season. Therefore, it is likely that the shift in maxima is due to changes in transport of net uptake CO_2 tracers as a result of variations in the footprint of TTA. The text will be altered and a figure added to add a comment to the differences in mean annual and interannual variation in seasonal wind direction.

"The annual prevailing wind direction over Scotland varied between years; in 2006 and 2008 the prevailing wind direction was broadly south / south west, while in 2007 the prevailing wind direction was westerly. Moreover, the prevailing wind direction varied at seasonal time scales. During the peak growing season (May to August) there was considerable variation (Fig. 7). In 2006 prevailing wind direction during the growing season varied between southerly and westerly. While in 2007 and 2008 there were periods of northerly and easterly winds, particularly during June; returning to more south westerly directions by August in each year. This interannual and seasonal variation in wind direction will have impacted the detected footprint by TTA."

Response to anonymous Referee 2:

** The manuscript tackles with two issues relevant for use of high tower greenhouse gas concentration data: the representativeness of a single tower to the surrounding landscape, on one hand, and the ability of the tower to detect temporal variability of the surface flux signal, on the other. The manuscript fits to the scope of the journal and its title reflects the contents. However, reading the paper I had a feeling that there were assumptions made that were neither thoroughly explained nor demonstrated in the paper. For instance, it seemed to me that most of the main conclusions were based on the assumption that the modeled ecosystem signal at the surface is without any potential error sources even though the modeled region is in fact quite large and heterogeneous, not only from land cover, but certainly also from soil property and topography points of view. One would expect such a heterogeneous surface to introduce uncertainty to the modeled surface signal. If that is my misinterpretation rather than an assumption made, please, restructure and rephrase the text so that the main aims, assumptions and limitations are acknowledged from the beginning on. Many of the following specific* *comments may in fact, be similar misinterpretations and the recommendation given above will hold for tackling with them too. Furthermore, some of the specific comments reflect the fact that it was not always clear which modelled or measured variables were referred to in each occasion of terms simulated and detected.*

- We thank anonymous reviewer 2 for their comments on our manuscript. We apologise that we have not been clear with the assumptions we have made and which causes of surface variability are taken account of. The WRF model comes with topographical, soil cover and land cover classification maps which are used in the WRF-SPA model. We will modify the manuscript to be explicit when referring to observations and simulated results and provide a full description of the nature of the coupling between WRF and SPA and how these represent the heterogeneous land surface. We shall indicate how we address these issues below.

Specific comments:

** In the abstract as well as in the description of the model framework it has been stated that the models are coupled, furthermore it has been explained that the hydrological, carbon and energy cycles in SPA model are fully coupled but the actual way of coupling between the two models has not been explained. It seems to me that a one-way coupling among WRF and SPA takes places, where there is no feedback from SPA to the driving model, except for the inclusion of tracers in each time step (what was the time step, by the way?). If this is the case, its implications are worth of explaining and discussing more thoroughly.*

- The WRF-SPA model is a direct coupling between the models, where SPA is fully integrated into the source code of the WRF model. SPA calculates surface albedo, sensible and latent heat exchange in addition to CO_2 flux are passed to WRF, driving near surface turbulent mixing. WRF-SPA uses the MODIS land cover and default soil maps available in WRF, allowing for variation of ecosystem type and soil hydraulic parameters within SPA. WRF also contains a topographic map which will impact air flow over the surface. The model time step are 90 and 30 seconds for domain 1 and 2 respectively; this information will be added to Table 1.

- WRF-SPA model description:

"WRF-SPA [Smallman et al., 2013] is a coupling between the high resolution non-hydrostatic mesoscale model Weather Research and Forecasting (WRF) and the mechanistic land surface model (LSM) Soil Plant Atmosphere (SPA). SPA is fully integrated into the WRF model framework where WRF simulates meteorological fields and atmospheric transport of the CO_2 fields. SPA in return provides WRF with surface temperature, roughness length, albedo, and exchanges of energy, heat, water and CO_2. A brief description of the WRF and SPA models are given below."

and in WRF description:

"WRFv3.2 includes a number of land surface maps including vegetation type and soil classification used by SPA, but also orography which impacts simulation of air flow within the model [Mesoscale and Microscale Meteorology Division, 2011]."

** Having a background in flux observations and their source area problematics I find some parts of the motivation in the introduction slightly confusing. It is stated for instance that: Despite a rapid decline in ecosystem contribution, the total footprint of a tall tower observation can cover a large area. Isnt the rapid decline of contribution an implication of a large footprint rather than a contradiction? Related to this I wonder where the range of dominant signal of ¡100 km derives from. Above there is given a measure with a reference that area of 500km x 700km contribute up to 50%. Can you give similar approximate fraction of the signal originating from within ¡100 km as a measure of its dominance?*

- We accept that a rapid decline of the source contributions is an implication of a large footprint rather than a contradiction. We will alter the text to better reflect our intent, i.e. that while most of the information in an observation of atmospheric CO_2 concentrations comes from the near field, the observation does still contain information from a greater distance, but to a lesser degree.

- In the introduction:

"Observations of atmospheric CO_2 concentrations made at tall towers contain seasonal and interannual phenological information about ecosystems near the tower [Miles et al., 2012]. However the correlation between surface NEE and observed profiles of atmospheric CO_2 concentration declines with increasing distance from the observing tower [Gerbig et al., 2009, Miles et al., 2012]. A reduction in correlation between tall tower observations and ecosystem activity is consistent with signal dilution due to atmospheric transport [Gerbig et al., 2009, Miles et al., 2012]. The dominant influence on observations of atmospheric CO_2 concentrations are from the near field, although the total footprint can cover a large area. For example, an area of $\sim$ 500 km x 700 km has been simulated to contribute up to $\sim$ 50 % of the observed signal at the Cabauw tall tower in the Netherlands, while the land surface at the edge of this area contributes $\sim$10 time less than the land surface directly beneath the Cabauw tower [Vermeulen et al., 2011]. Similarly Gerbig et al.

[2009] investigated the Harvard forest tower, USA, estimating that the land surface fluxes within 20-60 km of the tower contributed a similar amount to observations as all other areas within their simulated domain combined (5000 km x 5000 km). Furthermore, atmospheric inversions are unable to attribute variation and / or anomalies in atmospheric CO_2 concentrations to a specific ecosystem process (e.g. respiration or photosynthesis). A forward model has the advantage that processes and source area contributing to the atmospheric CO_2 signal can be directly investigated."

** Please, explain in more detailed manner how the concept of non-passive and passive tracers accounting for carbon sources and sinks, respectively, preserves the mass balance. Is the fraction of the absorbed non-passive tracers taken into account in the contribution of the passive tracers from the area of absorption? A mathematical formulation would help the reader. Under which conditions and how frequently an absorption of a non-passive tracer took place in the simulations?*

- A more detailed explanation of the interacting and non-interacting CO_2 tracers will be added to the methods section, described in response to anonymous reply #1. Our intention is to use the tracers to simulate physically consistent tracers where net release CO_2 tracers are a physical mass added to the atmosphere and can therefore be removed consumed by the land surface subsequent to its initial emission. Net uptake CO_2 tracer does not represent a physical mass in the atmosphere (i.e. in the real world) and is not allowed to interact with the land surface after its emissions.

** Please, mention the number of years used for the analysis instead of multi-annual as the expression is a bit misleading.*

- The text will be modified to state the number of years to prevent confusion with the spin-up period.

** It has been stated that spin-up period from 2002 to 2005 allows for differentiation of ecosystem phenology but that was not presented in this paper and thus the statement is redundant.*

- The statement regarding ecosystem spin-up is part of the description of the model set up and as such we feel it is relevant. However we do recognise that in its current form the statement is potentially confusing and the text will be modified to simply state that the model ecosystem phenology were spun up as described in [Smallman et al., 2013].

** Give the abbreviation TTA at the first occasion of tall tower Angus and use it from the first occasion on.*

- The text will be modified to ensure that TTA is defined on first mention of tall tower Angus and will then be used there after.

** Please specify how the Griffin Forest meteorological data is suited for the carbon store spin-up the location of the site in relation to the study region would among other specifications be a very helpful piece of information for a reader. How well does the data represent the regional variability within the domain? It is stated in the manuscript that the topography is complex, which may introduce local variability in the meteorological fields. There is on the other hand a re-analysis data used in the study the representativeness of the site meteorological data could for instance be validated against this data.*

- Griffin forest is located at the centre of the model domain (56.61 N, 3.80 W, 340 m a.s.l.). Griffins location places it approximately half way along the east-west precipitation gradient found in Scotland (Scotland mean annual precipitation gradient $\sim$ 600 mm to $\sim$ 2000 mm, Griffin = $\sim$1152 mm). The mean annual temperature at Griffin is also approximately equal to the median mean annual temperature for Scotland (Scotland mean annual air temperature $\sim 4^oC$ to $\sim 10^oC$, Griffin = 6.6^oC). However it is worth noting that mountain regions of Scotland have mean annual precipitation for in excess (up to 3500 mm) of the regional average. We will remove the description of the SPA model spin-up and direct the reader to [Smallman et al., 2013] which contains a full description of the WRF-SPA model.

- The description of spin up will read

"Plant phenology is described by a box carbon model to simulate the main ecosystem carbon (C) pools [Williams et al., 2005, Sus et al., 2010]. C pools are foliage, structural wood carbon, fine roots, labile, soil organic matter (SOM) and surface litter. Crops have two additional C pools; storage organ C (i.e. harvestable C) and dead foliar C (still standing). The C pools within WRF-SPA are 'spun-up' as described in Smallman et al. [2013], using meteorology which is broadly representative of the median meteorological conditions in Scotland. The carbon model provides a direct coupling between the plant carbon cycle and plant phenology, specifically foliar and fine root C. Foliar C determines the leaf area index (LAI) while fine root C impacts water uptake potential."

** Is it typical to call the tracers excluding land biosphere forcings only? In what sense those tracers are forcings as opposed to the total?*

- The use of the term "forcings only" is not typical, however it is common practice to distinguish between the origin of different components of atmospheric CO_2 in atmospheric modelling studies [e.g. Ahmadov et al., 2007, Tolk et al., 2009]. In this case we are primarily interested in isolating variation in simulated atmospheric CO_2 due to CO_2 exchange between the atmosphere and biosphere, particularly for validation (Fig. 2ab, 3). All exchanges of CO_2 between the model domain and its boundaries are provided by external forcing fields (IC and LBC) or flux maps (ocean and anthropogenic exchange).

** In the beginning of Results there are statistical values R2, RMSE and bias given as measures of performance of total signal in comparison to forcings only for different temporal averaging periods. Confusingly the set of given statistical values varies from time scale to time scale. Please, always give the same set of statistics so that the reader can see herself in which time scales the performance improves because of the inclusion of the ecosystem signal.*

- The statistics will be provided identically for each time period.

"We compared hourly observations of atmospheric CO_2 concentrations from TTA (2006-2008) with both the WRF-SPA simulated total atmospheric CO_2 (R^2 = 0.67, rmse = 3.5 ppm, bias = 0.58 ppm, linear regression) and "forcings only" CO_2 (R^2 = 0.71, rmse = 3.3 ppm, bias = 0.82 ppm)."

and

"Total atmospheric CO_2 (R^2 = 0.96, rmse = 1.2 ppm, bias = 0.54 ppm), which includes biospheric exchange, shows improved statistical agreement with observations compared to "forcings only" CO_2 (R^2 = 0.91, rmse = 1.6 ppm, bias = 0.71 ppm) and CTE-CT atmospheric CO_2 concentrations (R^2 = 0.94, rmse = 1.5 ppm, bias = 0.94 ppm)."

* In the end of 4.2 there are couple of sentences that need to be rephrased. Especially, I do not understand the sentence: Forest and cropland show seasonality for which ecosystem is the dominant signal at TTA.

- We recognise that the description at the end of section 4.2 is not as clear as it should be. The paragraph will be re-written to improve the written English.

- The end of section 4.2 will be rewritten to

"Forest and crops dominate the net uptake CO_2 tracer simulated at TTA (65 - 93 % of TTA tracer concentration and 72 - 91 % of surface flux) (Fig. 5). On average crop and managed grassland are over-represented in net uptake CO_2 tracers simulated at TTA by 3 % and 3.4 % respectively. Managed grassland represents on average just ~13 % of surface net CO_2 uptake flux compared to ~40 % for crops. Forest and 'other' ecosystems are under-represented by 5 % and 1.2 % respectively. However the over / under-representation varies at seasonal time scales, e.g. the largest under-representation of forests at TTA occurs between August 2006 and January 2007 (max = 21 %) while at other times atmospheric CO_2 simulated at TTA is more representative. The bias towards crops is consistent with the spatial distribution of crops and forest cover in relation to TTA's location (Fig. 1). Crops is the dominant ecosystem, both in terms of net uptake CO_2 tracer and surface net CO_2 uptake flux during the growing season (Fig. 5). After harvest (July of each year) forest becomes the dominant land cover for driving CO_2 exchange, as crop surface net CO_2 uptake flux declines due to senescence and removal of plants."

** It is not clear from the text (throughout the manuscript) and from figure captions of figures 5 and 6 what is referred to with surface or total surface in the context of simulated net uptake. I guess that is the inner domain of the model area but this should be clearly defined and named and consistently referred to throughout the text and figure captions.*

- A new section (described in reply to annonymous reviewer # 1) in the methods will be added to further describe the ecosystem specific CO_2 tracers, including a definition of their relevant terms. These terms will then be consistently used throughout the manuscript. We state in the description of the model domain that results from the inner domain only are presented.

** What is meant by the statement that the observations do not contain realistic information on ecosystems not adjacent to the tower? I do not think that it contains somehow false information about those distant ecosystems either, uncertain surely but realistic as long as their contribution is above the detection limit. Please, rephrase to clarify the point.*

- Here we are inferring that as the ecosystem specific CO_2 tracers simulated at TTA do not significantly inform on seasonal variation of forest, managed grassland and 'other'. We recognise that the choice of "realistic information" is miss leading and will rephrase this sentence to better express our intention. Furthermore, since reanalysis of the simulations we have show that appropriate seasonal variation is detected at TTA. However we do accept that in the context of atmospheric inversion modelling, the lack of a seasonal cycle may still serve to reduce the uncertainty in the posterior estimate of surface flux.

- "Atmospheric CO_2 concentrations simulated at TTA contains significant seasonal information on ecosystems that are not adjacent to the tower (i.e. forest, managed grassland and 'other'). Forest dominance of the fraction of net uptake CO_2 tracer (Fig. 5) at TTA coincides with crop senescence and harvest (Fig. 4). The relatively small mismatches shown here seem likely to be explained by seasonal variation in tower footprint as indicated by seasonal and interannual variation in prevailing wind direction (Fig. 7). Cropland is best represented by net uptake CO_2 flux tracers (Table 3) which is expected given the local dominance already discussed."

** The following sentence is even more confusing: Interannual variation of the simulated seasonal cycles is poorly detected by TTA . How come can one expect that the simulated seasonal cycles would be detected in the first place? Doesnt the poor detection of simulated signal rather imply that some part of the model system fails to produce the correct seasonal cycle than that the tall tower fails to detect it? I probably misinterpreted the message here as well, please clarify.*

- We apologise for the misunderstanding regarding this statement. Here we are considering the ability of the simulated TTA atmospheric concentrations to detect seasonal variations of the simulated land surface as indicated by comparison between the net uptake CO_2 tracers and surface net CO_2 uptake flux from which the tracers originated. The text will be modified to make this explicit.

- "Interannual variation of the simulated seasonal cycles in surface net CO_2 uptake flux is poorly represented by net uptake CO_2 tracers simulated at TTA (Fig. 6)."

** There is some text in the figure captions (see especially the Figures 4, 5 and 6) that would rather belong to the Results than to the captions. Please, explain in the caption what is shown in the figure and the interpretation in the Results and Discussion*

- We will rewrite the figure legends to move information best placed in the results and discussion to the relevant sections. Please see the end of this reply for updated figure legends.

Response to Thomas Lauvaux:

** The paper entitled can seasonal and interannual variation in landscape CO2 fluxes be detected by atmospheric observations of CO2 concentrations made at a tall tower by Smallman et al. presents a comparison of a multi-tracer mesoscale simulation over several years to observed concentrations from the Angus tower. The subject is highly relevant for current regional carbon budget estimates produced by inverse methods, and more specifically the study of the inter-annual variability which, to the extent of my knowledge, has not been simulated over such a long time period at such resolution (6km). However, there are three major issues requiring significant changes in this study, and have to be addressed before considering the paper for publication. One of them is related to the simulation of tracers. The second is related to the comparison of national scale flux signals to the atmospheric signals observed at the tower which is not related to any scientific questions. The last one is addressing the questions in the introduction, which are confusing and somehow incomplete.*

- We thank Thomas Lauvaux for his comments on our manuscript. Dr Lauvaux has identified a number of mistakes in the manuscript and areas for improvement, in particular our description of the model experiment and the need for considering the source of surface fluxes which impact observations of atmospheric CO_2 concentrations. We will address the errors and concerns raised in the following ways.

** Major issues: 1. The tracers, as defined in Table 1, tell a confusing story of the different fluxes and their corresponding atmospheric signals. More specifically, some tracers are representing the uptake from the surface. These tracers are listed in Table 1 as nonpassive tracers, which means that these tracers can be removed from the atmosphere. In other terms, the tracer representing the uptake from a given ecosystem/place/time can be removed from the simulation. This doesnt make much sense. The description is somehow very confusing and what I try to describe here may not be true (in this case you need to correct the table 1 and explain the time lag in Figure 6). But the Figure 6 shows that this seems to be true. The explanation in Table 1 states that a nonpassive tracer can be removed from the atmosphere, as it represents a physical mass of CO2. I dont understand how a tracer representing the uptake (which is a process and not a physical mass of carbon) can have a mass and therefore be removed from the atmosphere.*

** Related to this problem, in Figure 6, the fact that the maximums in concentrations are delayed compared to the maximums in the surface fluxes for all the ecosystems except the crops is very surprising. There is no reason at the regional scale to observe a time lag between the surface flux uptake maximum and its corresponding maximum in atmospheric mixing ratios (unless the air has to travel a long time across hemispheres for example). I think it indicates that the uptake from other ecosystems is removed from the simulation by the crop surface uptake. Here, it seems that the crops remove the uptake tracers from other ecosystems, until harvest. Then, once the area around the tower is free of crop uptake (=after harvest), the uptake tracers from the forest, grassland, and other types can finally reach the tower location. Removing the uptake tracer is not physically realistic. The uptake tracers should all be added and conserved during the simulation. Or you release CO2 molecules, which are then affected by surface uptake and respiration, or you represent uptake and respiration by individual tracers which will be always conserved in the simulation, but will partly cancel each other at the end (one being positive and the other negative). But if your tracers represent different processes (uptake for example), you cant remove this process from the atmosphere. Otherwise it means that the uptake from crops can absorb the uptake signals from the forest, which is not what happens in the atmosphere. The crops will remove CO2 from the atmosphere, as well as the forest and other ecosystems.*

- We apologise for the confusion caused by the errors in Table 1. The net uptake CO_2 tracers are not intended to interact with the land surface after their initial emission from the surface. Table 1 will be corrected to detail that net uptake CO_2 tracers are non-interacting tracers and net release CO_2 are interacting or interactive tracers. We will deal with the issue of delayed peak detection in Figure 6 below.

** Concerning the time lag in the maximums, here is another way to look at the problem: how can a maximum in forest uptake happening less than 100km away from the tower be observed with a time lag of 2 months at the tower? Even though there is no forest in a 5km radius around the tower, these signals will still be observed at the tower, attenuated by the diffusion of the atmosphere, and potentially super imposed with larger uptake signals. But in any case, the extremes should happen at the same time. This is independent of the amplitude of the signals from the forest. A parcel of air in the domain is mixed vertically through the PBL in few minutes, and transported to the tower in few hours. Even if the TTA tower is mostly surrounded by crops, the seasonal maximum for other ecosystems should be identical in the mixing ratios and in the fluxes within a 50km radius. The travel time is too short to generate a difference of 2 months.*

- We recognise that the delay in peak forest net uptake CO_2 tracer simulated at TTA, compared to the forest surface net CO_2 uptake flux is unexpected. We have as requested investigated this further and discovered an error in the WRF-SPA source code which allowed for net uptake CO_2 tracers to sometimes be consumed by the land surface. This problem has been resolved.

** 2. The comparison of the national scale land surface uptake to the observed uptake at TTA (comparison of fractions) is missing a scientific justification. This comparison should include the influence of the tower footprint at the surface. Assuming that TTA observes surface flux signals from the entire domain does not make sense (which is explained in the introduction but surprisingly not considered later on). The tower has a specific footprint (which can vary significantly as a function of time) and this footprint is clearly not as large as the UK (or the simulation domain). This question has been addressed in several papers (some of them being cited in the introduction) and the analyses here do not provide much insights.*

** The analysis (sections 4.2 and 4.3) should be modified to include some information about the footprint of the tower (i.e. backward plume simulations) or at least should approach the footprint by considering the climatology of the wind across seasons, or use some existing calculated footprints for similar towers (Mace Head?) and apply it as a mask on the surface fluxes. But the analysis as presented here does not bring any relevant information. An atmospheric mixing ratio corresponds to a specific footprint at the surface at a given time multiplied by the corresponding fluxes.*

** In addition, the analysis is also affected by the uptake of non-passive tracers as explained in 1. Your conclusions may change once you solve the issue of the uptake of the uptake. Forests and other ecosystems may show a larger contribution.*

** I would recommend to perform some additional simulations to evaluate the spatial extent of the tower footprint, which can be used to understand the contributions from the different ecosystems. The footprints could also be used to correct the problem described in 1., without re-running WRF. By combining the surface fluxes with the tower footprints, the contributions of each ecosystem to the observed atmospheric signals can be calculated. But if this suggestion represents too much work for this paper, the climatology of winds and the use of similar footprints from other tall towers would suffice, as long as some information about the tower footprint is introduced in the analysis.*

- We apologise for the confusion here. Our intention is the consider whether the land surface within TTA's footprint is representative of Scotland as a whole. By which we define representative to be appropriate fractions of land cover activity (not area) and whether the land surface in TTA's footprint varies at seasonal and interannual time scales that accurately reflect the changes of the whole of Scotland, as simulated within the inner domain. Furthermore, we understand that while the vast majority of the land surface influence on TTA will come from an area far smaller than the inner model domain, there will be small contributions from a much larger area. Our analysis attempts to consider whether these small contributions still contain information on seasonal variability of the simulated land surface which of a detectable level.

- We accept that we have not appropriately addressed the issue of tall tower Angus' footprint. We will implement Dr Lauvauux's suggestion of using a published assessment of the Mace Head tower as a mask for the simulated land surface around TTA. Mace Head is located on the west coast of Ireland, therefore both Mace Head and TTA are exposed to similar large scale weather systems. Using 12 hour backtrajectory analysis as a mask, the footprint of TTA is estimated to cover $\sim$98 % of the simulated land surface [Henne et al., 2010].

The text will be updated to state

"Currently there are no published assessment of TTA's observation footprint, however the footprint of Mace Head, located on the west coast of Ireland has been assessed in multiple studies [e.g. Henne et al., 2010, Rigby et al., 2011, Brunner et al., 2012]. Mace Head is exposed to similar meteorological conditions in north west Europe, and therefore we expect a similar footprint. Henne et al. [2010] calculated a 12 hour inversion, estimating the footprint of Mace Head to be the land surface within ∼195 km of the tower. Therefore, if a similar footprint is assumed for TTA ∼98 % of the inner domain's land surface is within the footprint of TTA. We use this estimate of footprint to mask the area of the land surface which is presented throughout this study."

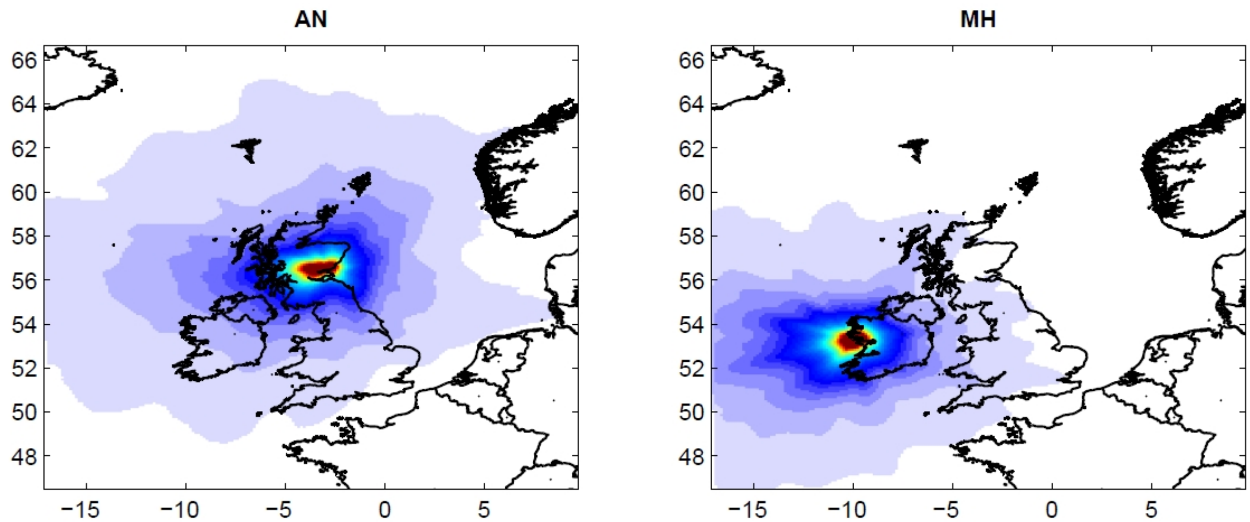

Figure 1: Estimated annual footprints of TTA (left) and Mace Head (right) for 2007 using the NAME Lagrangian particle dispersion model. This figure is from an unpublished University of Edinburgh PhD thesis by James Howie.

The use of a published Mace Head footprint as an appropriate mask is supported by unpublished works carried out at the University of Edinburgh. An unpublished comparison of TTA and Mace Head footprints (footprint estimated as described in Manning et al. [2011]) indicates that the footprints are similar (Figure 1). A comparison of the unpublished footprint of Mace Head and several published examples ([Rigby et al., 2011, Brunner et al., 2012]) indicate that the unpublished estmates are consistent with published footprints (Figure 2 and 3).

** 3. The questions 2 and 3 of the introduction are not correctly stated. The TTA will detect some seasonality and some IAV. The question is to define the area covered by the tower. In addition, I dont think you need to run WRF over 3 years to answer this question. If the average surface footprint of TTA over one month is not covering your domain, you can argue that TTA cannot capture the seasonality and IAV of Scotlands terrestrial ecosystems. Re-phrase your questions to explain more clearly your objectives.*

** General comment about this study: You should consider additional questions, which could greatly improve your study, and not very demanding considering the large amount of results at hands. I recommend that you extract additional information from your simulations. More statistics would be very informative.*

- The research questions will be modified to correctly consider spatial extent. We will also add an addition question to addresses whether relevant ecosystem process information can be extracted through the use of the ecosystem specific tracers (i.e. the post harvest bias) and the compare between carbon tracker simulated atmospheric CO_2 concentrations at TTA and the WRF-SPA model.

- Research questions will be:

"

i. Does WRF-SPA more accurately simulated observed atmospheric CO_2 concentrations compared to a coarse resolution global atmospheric inversion model?

ii. Can ecosystem specific CO_2 tracers be used to inform on which ecosystem processes and land covers are responsible for observed variations in atmospheric CO_2 concentrations?

iii. Can observations made at TTA detect variation in ecosystem carbon uptake, for ecosystems within the footprint of TTA, at seasonal and interannual time scales?

"

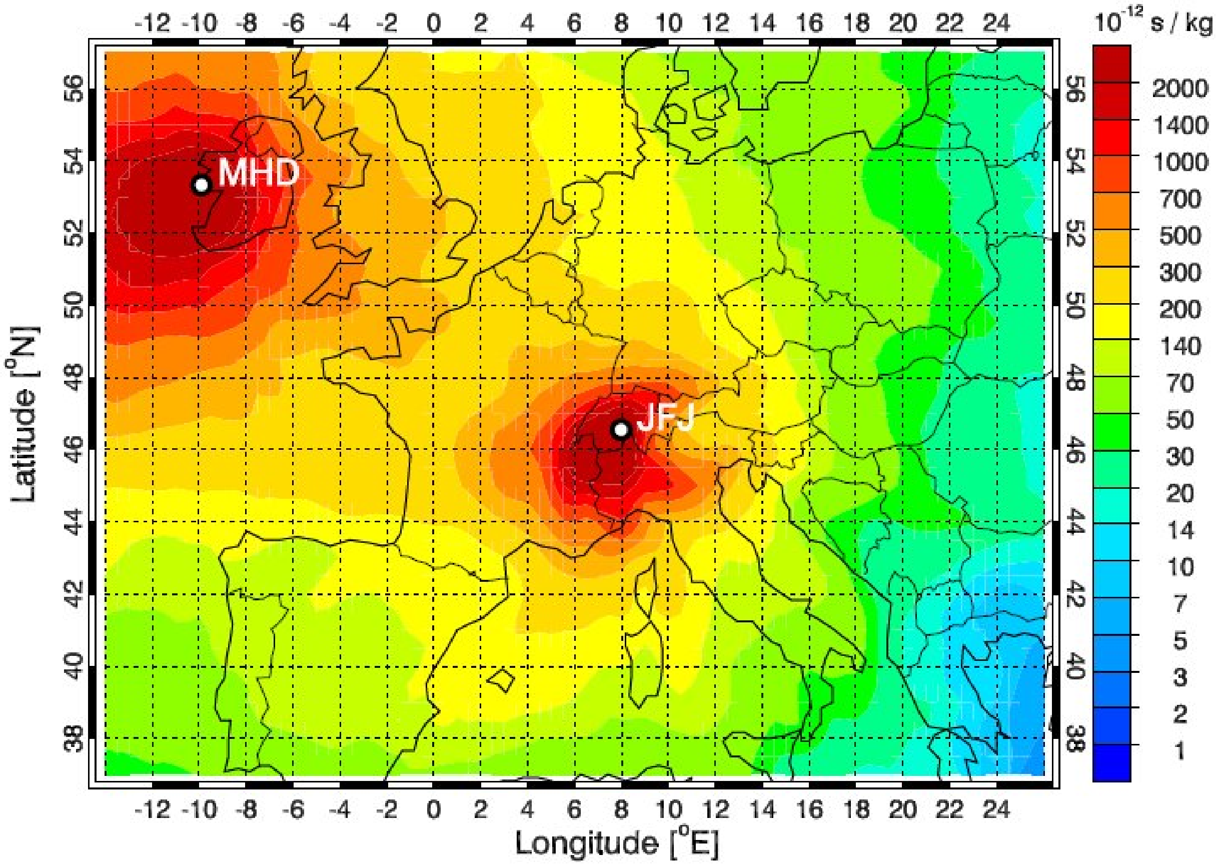

Fig. 2. Footprint emission sensitivity (in picoseconds per kilogram) averaged over all air masses arriving at Jungfraujoch (JFJ) and Mace Head (MHD) between February 2006 and December 2010.

Figure 2: Estimated annual footprint of Mace Head between February 2006 and December 2010 [Brunner et al., 2012].

** Specific wind climatology could be used to evaluate the boundary inflow from CT (when the wind blows from the East), or at night when the measurements are above the stable PBL.*

** The paper would really benefit from more analysis of the WRF-SPA results, e.g. detection of flux anomalies, or specific events (droughts?): : : The current analysis is limited mostly to monthly means and correlations. Comparison to CT results would be relevant for the evaluation of the atmospheric model resolution and its impact on the mixing ratios. These short analyses do not require any additional model runs, and would be more relevant than comparing the tower signals to an artificial domain which is not scientifically relevant.*

- CTE and CT will be assessed against TTA observations of atmospheric CO_2 concentrations. This analysis will consider how well CTE & CT predict observations made at TTA (which was not part of the inversion analysis) compared to towers which were included. The mean bias for towers within the inversion ranges between +1.59 to -3.10 ppm, although typically the bias is < 1 ppm [Peters et al., 2010]. CTE & CT mean annual bias is +0.92 ppm at TTA compared to +0.58 ppm achieved by WRF-SPA. At sub daily time scales CTE & CT also underestimates daily variations in atmospheric CO_2 concentrations compared to observations made at TTA. CTE & CT has been assessed at seasonal time scales (monthly means) highlighting periods where WRF-SPA adds the greatest improvement but also that CTE & CT does not show the post harvest bias which occurs in WRF-SPA.

A comparison between atmospheric CO_2 concentrations observed at TTA and CTE & CT atmospheric inversion model ($R^2 = 0.69$, rmse = 3.5 ppm, bias = 0.92 ppm). As CTE & CT are available at 3 hourly intervals the analysis was conducted against TTA observations averaged to 3 hourly time step.

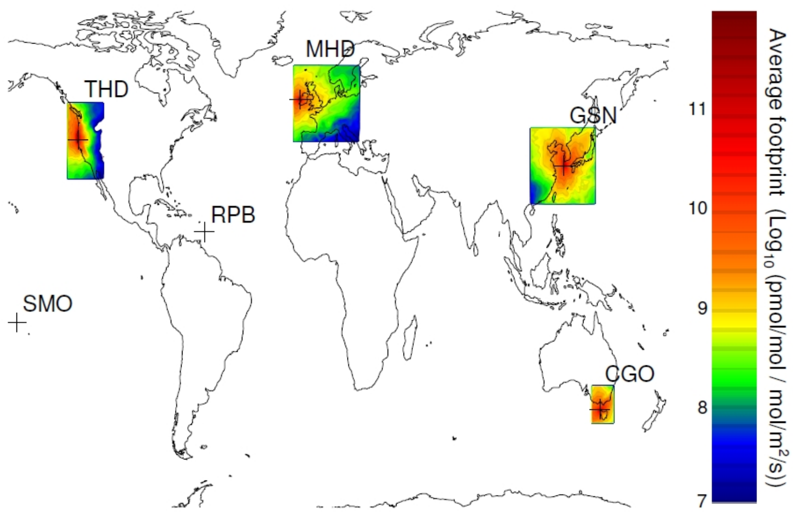

Fig. 4. Average footprints at four AGAGE sites (THD=Trinidad Head, California, MHD = Mace Head, Ireland, GSN = Gosan, South Korea, CGO = Cape Grim, Tasmania) for the year 2008. Also shown are the locations of two sites (RPB = Ragged Point, Barbados, SMO = Cape Matatula, Samoa) used to constrain background emissions. The boxes show the extent of the "local" regions in which the LPDM was used to estimate sensitivities.

Figure 3: Estimated annual footprint of Mace Head 2008 [Rigby et al., 2011].

Additional text to the results section:

"The impact of the biosphere is more clearly seen at seasonal time scales using monthly means (Fig. 3). Total atmospheric CO_2 (R^2 = 0.96, rmse = 1.2 ppm, bias = 0.54 ppm), which includes biospheric exchange, shows improved statistical agreement with observations compared to "forcings only" CO_2 (R^2 = 0.91, rmse = 1.6 ppm, bias = 0.71 ppm) and CTE-CT atmospheric CO_2 concentrations (R^2 = 0.94, rmse = 1.5 ppm, bias = 0.94 ppm). The monthly mean bias between total atmospheric CO_2 and observations is reduced for the majority of the comparison period relative to "forcings only" CO_2 and CTE-CT. The seasonal bias is reduced in total atmospheric CO_2 by up to 2.8 ppm and 1.9 ppm between March and June of each year compared to "forcings only" CO_2 and CTE-CT respectively (Fig. 3). However, the modelled biosphere does not capture the observed seasonal minimum in atmospheric CO_2 concentrations which occurs in July - August of each year (Figs. 2,3). During July - September total atmospheric CO_2 has a larger bias than both "forcings only" CO_2 and CTE-CT, compared to observations. A larger positive bias in total atmospheric CO_2 than "forcings only" CO_2 indicates that modelled ecosystems within the footprint of the tall tower have become a net source of CO_2 at a time when they should remain a net sink (Fig. 3)."

Additional text to the discussion section:

"Atmospheric CO_2 concentrations from CTE-CT were also compared to observation made at TTA, at both 3 hourly averaged (Fig. 2b) and monthly mean time scales (Fig. 3). The statistical comparison suggests little impact of high resolution simulation using WRF-SPA, which contrasts with similar comparisons between high and coarse horizontal resolution models [e.g. Ahmadov et al., 2009]. However, CTE-CT do not capture the observed diurnal cycle seen in TTA observation as well as WRF-SPA (Fig. 2b). The mean bias between observations of atmospheric CO_2 concentrations from TTA (which are not included in the CTE-CT atmospheric inversion) and CTE-CT is comparable to towers which were included in the inverse model [Peters et al., 2010]. At seasonal time scales CTE-CT tends to show a reduced bias compared with "forcings only" CO_2, however the growing season bias remains larger than in total atmospheric CO_2 concentrations simulated by WRF-SPA (Fig. 3).

The prevailing wind direction over the UK is south westerly allowing the tower at Mace Head, Ireland to provide an estimate of the background CO_2 concentration and to act as a boundary condition upwind of the air which passes over Scotland. Mace Head is used to provide a boundary condition in the CTE-CT atmospheric inversion [Peters et al., 2010]. Importantly the bias between observations made at Mace Head and CTE-CT is small at +0.05 ppm [Peters et al., 2010]. Therefore, it can be inferred that the errors between modelled estimates of atmospheric CO_2 concentrations and observations is largely due to the simulation of surface exchanges within the model domain presented here."

* *Is there no flux tower available in the area that could support your analysis? 3 years of simulated atmospheric signals*

offer a lot of possible avenues.

- Smallman et al. [2013] shows a comparison between WRF-SPA and surface NEE for forest, cropland and managed grassland as part of the development and validation of WRF-SPA. The text will be modified to make reference to this previous work. We also include a comparison between our simulated mean annual carbon balance for forest, cropland and grassland against other estimates for Scotland, UK and pan European scales for comparison.

"WRF-SPA demonstrated that it can recreate observations of atmospheric CO_2 concentrations (Fig. 2ab). The dominant seasonal cycle reproduced by WRF-SPA is largely driven by forcings external to the modelled domain, i.e. the global signal from lateral boundary conditions (Fig. 2a) as indicated by the "forcings only" CO_2 tracer. Atmospheric CO_2 concentrations are underestimated during the winter, however the bias is of a smaller magnitude in total atmospheric CO_2 than in "forcings only" CO_2 (Fig. 3). The underestimation during winter likely indicates that SPA underestimates net release of CO_2 flux (i.e. respiration) from the land surface. WRF-SPA has previously been validated against eddy covariance observations of NEE at forest, managed grassland and cropland sites, where forest and managed grassland NEE was overestimated during winter while cropland was underestimated [Smallman et al., 2013]. Given that net release CO_2 tracers simulated at TTA for crops is half the magnitude for forests, crops are a plausible candidate to explain the winter time underestimate in simulated atmospheric CO_2 concentrations (Fig. 4). Smallman et al. [2013] hypothesised that the underestimate in crop could be related to an underestimation of soil organic matter or the rate of soil organic matter turnover within the carbon model, however there remain several possibilities to be explored (e.g. ploughing)."

Technical comments:

** 14302-4: realistic is unclear. Re-phrase.*

- "realistic" will be removed

** 14302-9: realistic transport The CO2 mixing ratios do not provide any information about the accuracy of the transport, or the source/sink distribution and magnitude. Both could be wrong and produce reasonable mixing ratios.*

- This statement is made in conjunction with previously published works using WRF-SPA [Smallman et al., 2013]. Reference will be made to this in the discussion of this statement and the specific statement in the abstract will be removed.

"In contrast CTE-CT continues to overestimate atmospheric CO_2 until late in the year (November / December) indicating that the inversion analysis continues to underestimate Scotland's carbon sink / overestimate carbon source during this period (Fig. 3). The WRF-SPA modelled biosphere generates diurnal cycles of realistic magnitude in the modelled CO_2 time series (Fig. 2b) and reduces the seasonal bias seen in "forcing only" CO_2 (Fig. 3), however nocturnal atmospheric CO_2 concentrations are overestimated. The nocturnal overestimation of atmospheric CO_2 concentrations is likely due to an error in the YSU PBL scheme used in WRF-SPA. The error results in an overestimation of atmospheric eddy diffusivity under stable conditions, ultimately leading to a higher PBL [Hu et al., 2013]. However, given that day time CO_2 concentrations remain well simulated it is unlikely that the nocturnal error persists into the well mixed boundary layer due to rapid turnover of the atmosphere through nudging by LBCs. Moreover, WRF-SPA has been previously assessed against surface fluxes of heat, water and CO_2, and daytime vertical profiles of atmospheric CO_2 concentrations where profile structure was well simulated, from which we can infer appropriate atmospheric transport [Smallman et al., 2013]. Furthermore WRF-SPA's performance is comparable with several studies which have compared observations of atmospheric CO_2 concentrations made at tall towers to high resolution mesoscale model simulations [e.g., Ahmadov et al., 2009, Tolk et al., 2009, Pillai et al., 2011]."

** 14302-12:13: Contradict the earlier statement that fluxes are appropriate. Harvest is a critical component of the regional carbon budget in the area.*

- The earlier statement regarding surface fluxes will be removed to avoid the specific conflict with crops simulations.

** 14302-15:17: This simply implies that these ecosystems are out of the tower footprint. You could have found that with a simple footprint model.*

- Here we intend to consider whether the tower 'detects' a representative fraction of cropland activity not specifically a land cover fraction. However we recognise that we have not been clear with our intention. We will remove this statement from the abstract and clarify our objects within the main text.

** 14302-20: confusing. You mean over-represented compared to the national fraction of cropland*

- We apologise for the confusion, we will describe in greater detail that we consider over- or under-represented in the main text, please see response to anonymous reviewer #1 for further detail. Due to the complexities of describing the use of the ecosystem tracers this statement will be removed from the abstract.

** 14303-4: fraction instead of proportion*

- We will change the text.

** 14303-6: : : : a net land-atmosphere surface exchange: : :. And do you mean that the terrestrial models are not able to constrain the regional carbon budget due to large uncertainties?*

- Here we are inferring that the complex nature of the real ecosystems due to spatial heterogeneity and non-linear responses to environmental drivers. The change will be made to the text.

** 14303-8: plant functional type is not a driver. They represent a set of model parameters. 14303-11: : : :further complexity to simulate/represent the ecosystem processes.*

- The text will be modified to state.

"...impacted by changes in weather, climate and human management adding further complexity to ecosystem processes..."

** 14303-16: what type of observations? GHGs?*

- Here we are referring to observations of atmospheric greenhouse gas emissions. The text will be modified to reflect this.

"...information contained within observations of atmospheric greenhouse gas concentrations."

** 14303-23:26: re-phrase*

- We will rephrase the sentence to:

"Inverse atmospheric models which infer surface fluxes from measurements of atmospheric CO_2 concentrations (e.g., made at a tall tower), have been used to constrain the terrestrial carbon balance at global, continental and regional scales [Gurney et al., 2002, Peters et al., 2010, Lauvaux et al., 2012]."

** 14304-2: They can detect anomalies, but are these systems able to quantify accurately the fluxes?*

- We recognise that the fluxes remain highly uncertain and dependent on uncertainties of the atmospheric drivers, surface flux prior and accuracy of observations. We will modify to the text to include to the remaining uncertainty in flux estimates rather than detection.

"Inverse models are able to detect large scale, large magnitude interannual variations in CO_2 exchange. For example the Europe wide heat wave in 2003 has been linked to a large scale reduction in carbon sequestration across Europe [Ciais et al., 2005, Peters et al., 2010]. However, there remains uncertainty over the ability of regional scale inversions to successfully quantify small magnitude changes in surface fluxes."

** 14304-16: remove to*

- The text will be modified.

** 14305-6:24: this paragraph is not part of the introduction. This should be moved to the method section.*

- We accept that this information is best placed in the methods section. The paragraph will be removed from the introduction. The information will form part of a new section on the experimental design and CO_2 tracers. This section has already been described in a reply to anonymous reviewer # 1.

** 14306-questions ii and iii: these questions are incomplete. Which ecosystems are you referring to? Many papers have shown the seasonality observed at tall towers. What do you mean by interannual variability? Same question for seasonality.*

- We accept that seasonality in observations made at tall towers has previously been observed and correlated with landscape scale variations in photosynthetic activity [e.g., Miles et al., 2012]. However these studies are less able to attribute directly how each ecosystem contributes to variations in observed atmospheric CO_2 concentrations. Attributing specific variations in observed CO_2 concentrations can be inferred through use of ecosystem specific tracers of surface CO_2 flux, or as done here the comparison can be used to infer weaknesses in our current parameterisations of surface processes (i.e. the post harvest bias).

- By seasonal variation we are referring to the representation of the seasonal cycle of surface CO_2 fluxes within ecosystem specific CO_2 tracers simulated at TTA (or any other location in the domain). Equally, for interannual variation we are interested in how changes in the seasonal cycle between years is relayed to observations made at TTA through use of the ecosystem specific CO_2 tracers.

** 14307-3: Mesoscale models cannot be used below 1km resolution during daytime without breaking some of the assumptions made in the turbulence schemes. The parameterization of the turbulence assumes that the turbulence is smaller than the grid dimensions. During daytime, an eddy can easily grow beyond 1km of diameter. The model would simulate well-mixed conditions within an eddy, which is physically unrealistic.*

- We will correct the statement.

** 14307-18: isnt the default land cover map from USGS? MODIS has been recently implemented. What version are you using?*

- The USGS map is the default option map, however a MODIS map is provided with WRFv3.2. We will alter the text to correctly specify that we are using the MODIS map and the default soil classification map.

"Vegetation cover is specified by the MODIS land cover map provided with WRFv3.2, while soil classifications are from the default WRF soil cover maps [Mesoscale and Microscale Meteorology Division, 2011]."

** 14308-5: please add a reference for this dataset.*

- The model spin up for WRF-SPA here is used identically to that carried out in Smallman et al. [2013]. We will instead direct the reader to this paper.

"The C pools within WRF-SPA are 'spun-up' as described in Smallman et al. [2013], using meteorology which is broadly representative of the median meteorological conditions in Scotland."

** 14309-1:2: Why should the inflow/outflow be zero? CO2 is not a conservative physical quantity within your domain. You could have more or less CO2 depending on the inflow/outflow. Your domain is an opened box connected with large scale conditions.*

- We apologise that we have not been clear in our description here. Lateral boundary conditions are provided for forcings only and total atmospheric CO_2 concentrations. However, the ecosystem specific net uptake and net release CO_2 tracers originate from the simulated land surface only, therefore no boundary conditions are provided for the ecosystem specific tracers. This allows for the tracers to freely leave the domain while preventing an influx of ecosystem specific tracers into the model domain for which we cannot know the ecosystem type from which the CO_2 originates.

Therefore we will modify the text to make this explicit:

"Note that LBCs for the outer domain have been set with zero inflow and zero-gradient outflow for ecosystem specific net uptake and net release CO_2 tracers. Zero gradient inflow / outflow allow tracers to easily leave the domain and prevent artificial influx to the CO_2 tracer fields."

** 14309-16: The WRFSPA simulation is comprised of two grids in two-way nesting mode:: : :*

-The text will be corrected

** 14309-26: the driver data are at 1 degree resolution whereas the coarse grid of WRF is at 18km. This is more than a factor of 5 between the two, which is the maximum for grid nesting. An intermediate grid would have been preferable (52km resolution for example).*

- We recognise that the step between the driving data and the WRF-SPA model is greater than is preferable. However we have extensively validated WRF-SPA against both surface and atmospheric observations with good results [Smallman et al., 2013].

** 14310-7: please add a reference or if not available, explain more precisely how the measurements were calibrated.*

- The measurement standards at TTA meet World Meteorological Organisation standards

** 14311-5: A larger positive bias: : :*

- The correction will be included

** 14311-7: This means that the seasonality in SPA is incorrect then. The abstract should highlight this problem which is not unique but important for future studies using the SPA model.*

- This statement is discussed later in the manuscript where we hypotheses that the bias is related to the representation of agriculture in the SPA model. However we recognise the need to be clear that this is an error in the representation of seasonality in SPA and needs to be made explicit in the abstract.

"WRF-SPA realistically models both seasonal (except post harvest) and daily cycles, predicting CO_2 at the tall tower (R^2

= 0.67, rmse = 3.5 ppm, bias = 0.58 ppm). Moreover we compared WRF-SPA simulated atmospheric CO_2 concentrations with those from the coarse resolution global atmospheric inversion models Carbon Tracker and Carbon Tracker Europe (CT-CTE) to investigate the improvement of using a high resolution forward running model. WRF-SPA more accurately simulates observed atmospheric CO_2 concentrations at the tall tower compared to CTE-CT. WRF-SPA better represents diurnal variation and a reduced bias (up to 1.9 ppm) between simulated atmospheric CO_2 concentrations and observations, particularly during the growing season. However we have highlighted a consistent post harvest increase in WRF-SPA - observation residuals in atmospheric CO_2 concentrations."

** 14311-14: could you confirm this result with some data? Flux towers could be used to evaluate the performances of the SPA model. This evaluation is subjective and does not provide much information.*

- The WRF-SPA model has been validated against surface eddy covariance [Smallman et al., 2013]. The discussion will make reference to this previous surface validation.

** 14312-1:20: why do you compare to the national land cover fractions? Is this tower supposed to represent the entire country? This question has been already treated in several studies. Comparing the ecosystem contributions at the tower and over the country will certainly lead to different fluxes and atmospheric signals. State your question more clearly and explain why this comparison is scientifically relevant. Section 4.3: Is it still a comparison between TTA signals and surface fluxes at the national scale?*

** Comparing the ecosystem contributions at the tower and over the country will certainly lead to different fluxes and atmospheric signals. State your question more clearly and explain why this comparison is scientifically relevant*

- We apologise for the misunderstanding here, we do not compare to the national land cover fraction but with the domain total fraction of surface uptake flux activity. Our interest here is in whether TTA detects a representative fraction land surface activity as indicated by ecosystem specific CO_2 tracers simulated at tall tower Angus. We will be making our experimental design explicit in a new section in the methods, already detailed in the response to anonymous reviewer # 1.

- The use of the fractional analysis allows us to consider how well the land surface's activity is represented at TTA but critically it provides a diagnostic when investigating the ecosystem specific seasonal information contained in atmospheric CO_2 concentrations simulated at TTA. In the discussion we consider why WRF-SPA estimates forest sequestration to be considerable larger than other estimates while at TTA atmospheric CO_2 concentrations are overestimated not underestimated as we might expect. The fractional analysis allows for us to hypothesis that the overestimate in forest uptake is not detected in TTA observations as forest uptake is under-represented (in terms of its activity) within TTA observations. Therefore indicating that additional atmospheric observations are required.

** 14312-24: : : :in forest at the national scale: : :*

- The manuscript will be modified to include

"A majority of seasonal variation in surface net CO_2 uptake flux is explained by net uptake CO_2 tracers for each ecosystem within the footprint of the tall tower, however the amount of variation explained varies between years."

** 14313-1:3: Why should the two be the same? Are you comparing national scale to TTA?*

- We would expect that if the footprint of observations made at TTA is representative of the land surface activity at the domain scale, then if for example forests increases its surface net CO_2 uptake flux (either through increased photosynthesis or decreased respiration) that an increase in forest net uptake CO_2 tracer would be simulated at TTA. If changes in surface net CO_2 uptake flux are not simulated to be 'detected' at TTA we can infer that the footprint of TTA is not representative of land surface activity or that there is a significant interannual variation in the areas of greatest influence for the tall tower footprint..

** 14313-4:9: Unclear. Please re-phrase.*

- We apologise that we have not been clear, the text will be modified to statement

"Net uptake CO_2 tracers simulated at TTA are able to explain the majority of seasonal variation in surface net CO_2 uptake for crops, forest, managed grassland and 'other' land covers (Table 3). The seasonal cycles in net uptake CO_2 tracers are more variable during the growing season (i.e. May - August), such that there is a mismatch between peak net uptake CO_2 tracers and surface net CO_2 uptake flux by $\pm$ one month (Fig. 6). Moreover the amount of variation in surface net CO_2 flux explained by net uptake CO_2 tracers simulated at TTA varied between years (e.g. forest 2006 R^2 = 0.79 and 2008 R^2 = 0.58). The rank order of net uptake CO_2 tracers simulated at TTA from each year does not correspond with the rank order of surface net CO_2 uptake flux for any ecosystem (Fig. 6). Interannual variation in mean annual surface net CO_2 uptake flux was ∼9 % while interannual variation for mean annual net uptake CO_2 tracer at TTA was ∼19 %."

** 14313-13:16: How are these two quantities (temperature and PAR) used in SPA? Are the correlations not due to the formulation of photosynthesis and respiration? Explain more.*

- These variables are linked to how the description of photosynthesis used in SPA. As such it is not informative and we will remove it form the manuscript.

** 14314-1: You havent evaluated your transport errors, the boundary inflow, and the anthropogenic emissions which could significantly affect your results. This conclusion uses likely which assumes that the uncertainty has been evaluated. You didnt assess the performance of WRF-SPA, but only the capability of the model to represent the observed variability. WRF and SPA could be both incorrect.*

- We recognise that we have not accounted for transport errors uncertainties of the drivers. This study is not intended as an investigation into uncertainty of the simulation models themselves therefore this statement

"Therefore it is likely that Scotland's biosphere was a net sink of CO_2 over the simulated period."

will be removed from the manuscript.

- Further we will provide greater detail regarding the context of WRF-SPA's performance compared to other systems and address issues highlights by Ed Dellwik and anonymous reviewer #1.

This analysis will include additional comparison with CTE & CT atmospheric CO_2 concentrations as well as directly the reader to Smallman et al. [2013] which includes a comparison with vertical profiles of atmospheric CO_2 concentrations from aircraft observations. These vertical profiles of atmospheric CO_2 concentrations are more informative of atmospheric transport within the profiles vertical structure.

** 14315-1:3: You should evaluate the results using flux towers over similar ecosystems. Broadly realistic doesnt mean anything. Please provide numbers and quantify the errors.*

- We will include a relevant reference which simulated the crop SPA model over a number of European sites in comparison to several other land surface models.

** 14315-21: its net surface uptake*

- we will correct the text

** 14315-24:26: The sentence is confusing. At night for example, the footprint of the tower can be much smaller because of the low wind speed. In this case, the strength of the vertical mixing is very low whereas the influence is very local. There is no direct relationship between vertical mixing and the extent of the footprint, but instead a combination of wind speed, stability conditions, and vertical exchanges (if the PBL grows for example, the air from the Troposphere is entrained in the PBL and dilutes the signals at the surface). Section 5.3: the conclusions are likely to change once the uptake tracer is conserved.*

- We accept that this statement is always true due to dependencies with wind speed and stability conditions and will remove it from the manuscript.

** 14317-14: Caveats = discussion?*

- We recognise that this sections contains material which is part of the discussion however we wanted to highlight the need for further work. We will change the sub-heading to 'Future work' as this is a more accurate representation of our aim to draw the readers attention to further work.

** Conclusions: The questions should be re-formulated. Keywords are missing as national scale fluxes.*

** Qiii There is no bias in ecosystem. I guess you mean that the distribution of ecosystems within the footprint of the tower is different than the distribution of ecosystems at larger scales (national?). This question is not scientifically justified. Instead, you can compute the footprint of the tower directly and define the spatial extent of the footprints across seasons.*

- We recognise that we have not been clear here. We will reform the questions and be clear that we are referring to the difference between the footprint of TTA and the national scale.

"Three specific questions were asked of WRF-SPA to investigate atmospheric observations of CO_2 made mostly within the PBL from TTA, Scotland.

(i) Does WRF-SPA more accurately simulated observed atmospheric CO_2 concentrations compared to a coarse resolution global atmospheric inversion model? WRF-SPA does more accurately simulate observed atmospheric CO_2 concentrations at TTA compared to CTE-CT. WRF-SPA better represents diurnal variation and a reduced bias between simulated atmospheric CO_2 concentrations and observations, particularly during the growing season. (ii) Can ecosystem specific CO_2 tracers be used to inform on which ecosystem processes and land covers are responsible for observed variations in atmospheric CO_2 concentrations? Ecosystem specific tracers have been successfully used to infer crops as responsible for a increase in the bias between WRF-SPA simulated atmospheric CO_2 concentrations at observations post harvest each year. Furthermore we have hypothesised that the cause of the error is the lack of a representation of uncultivated components of agricultural land not currently parameterised for in WRF-SPA. (iii) Can observations made at TTA detect variation in ecosystem carbon uptake, for ecosystems within the footprint of TTA, at seasonal and interannual time scales? A majority of seasonal variation in surface net CO_2 uptake flux is explained by net uptake CO_2 tracers for each ecosystem. However the amount of variation explained varied considerably between years. Moreover interannual variation was not well captured, potentially due to seasonal and inter annual variation in the prevailing wind direction. However for all other ecosystems interannual variation in atmospheric transport due to year to year variation in weather had a large impact on tall tower observations than interannual variation in surface uptake. "

** Table1: A passive tracer has a common definition which is different than the definition used here. This term needs to be changed. interacting tracer could be an option. Passive means that the tracer does not react with other atmospheric components. This term means chemically non-reactive.*

- We will change the terms "passive" and "non-passive" to "non-interacting tracer" and "interacting tracer" respectively to avoid confusion with the atmospheric chemistry terms.

** Figure 2 (caption): Panel (a) shows: : :is driven mostly by: : :*

- We will correct this in the text.

** re-phrase Figure 5 (caption): over- or under-represented compared to national scale fluxes? Explain in the text.*

-The terms over- and under-represented will be defined in a new section in the methods. Please see earlier response to anonymous reviewer # 1.

** Figure 6: This figure illustrates the physical problem with your non-passive tracers. The forest signals are visible once the crops have been harvested, creating a time lag in the maximum. This would mean that the depletion of CO2 due to forest uptake is removed by the crop uptake. Whereas the signals from the forest can be much smaller and so difficult to observe at TTA, there are still observed. Removing the forest removal of CO2 (uptake) is not physically consistent.*

- We apologise for the confusion over the net uptake CO_2 tracers. These tracers are intended to be non-interacting and should not be consumed by the land surface. We have corrected this error and new figures will be generated.

- Updated figure legends:

- Figure 1: "Land classification map used covering the spatial extent of the model domain. The left panel is the parent domain at 18 x 18 km, right panel is nested domain at 6 x 6 km. The star indicates the location of tall tower Angus. The map used in WRF-SPA is a modified MODIS land cover map provided with the WRF model. The fractions of each land cover within the nested domain are crop = 36 %, evergreen forest = 1 %, mixed forest = 42 %, grassland = 2 %, managed grassland = 13 %, upland = 3 %, urban = 3 %."

- Figure 2: "Time series comparison between hourly observations of atmospheric CO_2 concentrations made at TTA and WRF-SPA simulated total atmospheric CO_2 and "forcings only" CO_2. Atmospheric CO_2 concentrations at 3 hourly time step from CTE-CT are also included in panel (b). Panel (a) shows that the simulated CO_2 time series (2006-2008) is mostly driven by forcings originating outside of the model domain as indicated by "forcings only" CO_2. Panel (b) shows an hourly (3 hourly for CTE-CT) time series for June 2006 highlighting that diurnal variation in simulated CO_2 is due to exchange with the biosphere within the simulated domain, as total atmospheric CO_2 captures this variation. WRF-SPA modelled total atmospheric CO_2 contains all model forcings and exchange with the simulated biosphere while "forcings only" CO_2 does not include biospheric exchange (i.e. total - biospheric fluxes)."

- Figure 3: "Time series of monthly mean residual (Model-Obs) between observed, CTE-CT and WRF-SPA simulated total atmospheric CO_2 and "forcings only" concentrations. Highlights time periods during which the inclusion of the simulated biosphere results in a reduction in monthly mean bias. Error bars are $\pm$ 1 standard error, accounting of temporal and spatial uncertainty only."

- Figure 4: "Monthly mean mixing ratios for net uptake and net release CO_2 tracers, for crop and forest ecosystems, simulated at TTA. Highlights differences in detection of ecosystem processes at TTA, in particular the distinct seasonal cycle of cropland net uptake and net release CO_2 tracers compared to all other ecosystems. Managed grassland and 'other' ecosystems are not included due to their small magnitude contributions, never exceeding 0.7 ppm."

- Figure 5: "Comparison between monthly mean ecosystem specific fraction of net uptake CO_2 tracers simulated at TTA and fraction of surface net CO_2 uptake flux. Where an ecosystems fraction of net uptake CO_2 tracer greater than the corresponding fraction of surface net CO_2 uptake flux, it would indicate that the ecosystem is over-represented in total atmospheric CO_2 concentrations. Where the reverse would indicate that the ecosystem was under-represented. Error bars are $\pm$ 1 standard error, accounting of temporal and spatial uncertainty only."

- Figure 6: "Seasonal and interannual comparison between monthly mean net uptake CO_2 tracer simulated at TTA for crop, forest, managed grassland and 'other' (upper panel), and monthly sum surface net CO_2 uptake flux. Note the different scales between ecosystem types. Error bars are $\pm$ 1 standard error, accounting of temporal and spatial uncertainty only."

- Figure 7: " Interannual comparison of growing season (May, June, July and August) prevailing wind direction at TTA. The wind rose shows the count of hourly wind directions simulated by WRF-SPA, where the direction indicated is the direction from which the wind is coming."

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