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Can seasonal and interannual variation in landscape CO_2 fluxes be detected by atmospheric observations of CO_2 concentrations made at a tall tower?

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Abstract

The Weather Research and Forecasting (WRF) meteorological model has been coupled to the Soil Plant Atmosphere (SPA) terrestrial ecosystem model, hereafter known as WRF-SPA. SPA generates realistic land-atmosphere exchanges through fully coupled hydrological, carbon and energy cycles. Here we have used WRF-SPA to investigate regional scale observations of atmospheric CO_2 concentrations made over a multi-annual period from a tall tower in Scotland. WRF-SPA realistically models both seasonal and daily cycles, predicting CO_2 at the tall tower (R^2 = 0.67, RMSE = 3.5 ppm, bias = 0.58 ppm), indicating realistic transport, and appropriate source sink distribution and magnitude of CO_2 exchange. We have highlighted a consistent post harvest increase in model-observation residuals in atmospheric CO_2 concentrations. This increase in model-observation residuals post harvest is likely related to a lack of an appropriate representation of uncultivated components (~ 36 % of agricultural holding in Scotland) of agricultural land (e.g., hedgerows and forest patches) which continue to photosynthesise after the crop has been harvested. Through the use of ecosystem specific CO_2 tracers we have shown that tall tower observations here do not detect a representative fraction of Scotland's ecosystem CO_2 uptake. Cropland CO_2 uptake is the dominant ecosystem signal detected at the tall tower, consistent with the dominance of cropland in the area surrounding the tower. However cropland is over-represented in the atmospheric CO_2 concentrations simulated to be at the tall tower, relative to the simulated surface cropland CO_2 uptake. Observations made at the tall tower were able to detect seasonal variation in ecosystem CO_2 uptake, however a majority of variation was only detected for croplands. We have found evidence that interannual variation in weather has a greater impact than interannual variation of the simulated land surface CO_2 exchange on tall tower observations for the simulated years. This highlights the importance of accurately representing atmospheric transport used within atmospheric inversion models used to estimate terrestrial source/sink distribution and magnitude.

1 Introduction

The global climate is changing and these changes are driven by human activities, in particular by anthropogenic emissions of CO_2 (IPCC, 2007). The terrestrial biosphere currently absorbs a significant proportion of anthropogenic emissions of CO_2 (Canadell et al., 2007). However, terrestrial ecosystems are highly complex and dynamic, creating a land surface that can be either a source or sink of CO_2. Furthermore, the magnitude of sources and sinks vary both spatially and temporally resulting in significant seasonal and interannual variation. Changes in weather, climate and plant functional type (e.g., forest or grassland) have a significant impact on net ecosystem exchange of CO_2 (NEE). Moreover, many ecosystems are now under human management adding further complexity to ecosystem processes (IPCC, 2007). A greater understanding of the drivers of variability of surface sources and sinks is needed. To achieve this, increasingly higher spatial and temporal resolution observations over multi-annual periods are required to detect fine scale ecosystem heterogeneity and ecosystem response to drivers. Critical to this objective is an improved understanding of the information contained within observations.

Both forward running and atmospheric inversion models have been used in conjunction with observations of atmospheric CO_2 concentrations to investigate regional scale exchange of CO_2. Forward running models, such as WRF or RAMS, have been used to investigate a wide range of topics including the impact of surface processes on atmospheric transport (e.g., Steeneveld et al., 2011) and how ecosystems contribute to observations made at the regional scale (e.g., Tolk et al., 2009). Inverse atmospheric models infer surface fluxes from measurements of atmospheric CO_2 concentrations made at the regional scale (e.g., at a tall tower) and have been used to successfully constrain the terrestrial carbon balance at global, continental and regional scales (Gurney et al., 2002; Peters et al., 2010; Lauvaux et al., 2012). Inverse models are able to detect large scale, large magnitude interannual variations in CO_2 exchange, such as

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the Europe wide heat wave in 2003 which resulted in a large scale reduction in carbon sequestration across Europe (Ciais et al., 2005; Peters et al., 2010).

There remains uncertainty over the ability of regional scale inversions to detect small magnitude changes in surface CO_2 exchange (Peters et al., 2010; Lauvaux et al., 2012). Peters et al. (2010) suggested two contrasting hypotheses to explain increases in regional estimates of sequestration in the years following the European 2003 heat wave. First, increased sequestration may have been due to interannual variation in plant phenology, i.e. regrowth of leaf area lost due to water stress during the heat wave. Second, changes to atmospheric transport due to interannual variation in weather (e.g., due to turbulent exchange) may have significantly altered the footprint of tall tower observations and consequently sequestration estimates.

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). Observations of atmospheric CO_2 concentrations made at tall towers contain seasonal and interannual phenological information about ecosystems near to the tower (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). Despite a rapid decline in ecosystem contribution, the total footprint of a tall tower observation can cover a large area. For example, an area of ~ 500 km × 700 km has been simulated to contribute up to ~ 50 % of the observed signal at the Cabauw tall tower in the Netherlands (Vermeulen et al., 2011). Therefore, it remains to be investigated whether seasonal or interannual information about more distant vegetation is preserved within observations but obscured by the dominant local signal (< 100 km).

We used a mesoscale model, WRF-SPA, to simulate a 7 yr period between 2002 and 2008 over northern Britain (Fig. 1). The spin up period between 2002 and 2005 allows for differentiation of ecosystem phenology. WRF-SPA simulated atmospheric CO_2 concentrations for the period 2006–2008 were compared to observations made at tall tower Angus on the east coast of Scotland. Tall tower Angus is currently Scotland's

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only tall tower equipped for measurement of atmospheric CO_2 concentrations. WRF-SPA provides a means to upscale land surface exchanges such as photosynthesis and respiration, using atmospheric CO_2 tracers, to observations made mostly within the planetary boundary layer (PBL) of regionally integrated CO_2 concentrations i.e. those made at tall tower Angus.

WRF-SPA uses ecosystem specific CO_2 tracers to represent net release and net uptake of CO_2 by the land surface. Net uptake CO_2 tracers provide information on land surface net uptake detected at tall tower Angus when compared with the net CO_2 uptake of the simulated land surface. Net uptake CO_2 tracers are passive as they represent a depletion of the background atmospheric CO_2 which can be detected within a network of tall towers (e.g., Miles et al., 2012). Net release CO_2 tracers represent a physical mass of CO_2 added to the atmosphere through respiration. Therefore, net release tracers are not passive as they can be removed from the atmosphere by photosynthesis; complicating the interpretation of the modelled results. Despite this added complication allowing net release CO_2 tracers to be removed from the atmosphere by photosynthesis allows us to consider only CO_2 which is released by the land surface which actually reaches the tall tower rather than being consumed on route. For example, if an ecosystem, such as a forest, is simulated to have a NEE that represents a net removal of CO_2 from the atmosphere an equal mass of CO_2 is added to the forest net uptake CO_2 tracer. Conversely, if an ecosystem is simulated to have a NEE that represents a net addition of CO_2 to the atmosphere an equal mass of CO_2 is added to that ecosystem's net release CO_2 tracer pool. Net uptake and net release CO_2 tracers are simulated for forest, cropland, managed grassland and "other" (i.e. all other land cover types not specified) land cover types.

The overall aim of this paper is to use ecosystem specific CO_2 tracers of net uptake and net release of CO_2 to improve our understanding of how different ecosystems contribute to observations of atmospheric CO_2 concentrations and relate these contributions to surface processes. Ecosystem specific net uptake and release CO_2 tracers have been previously used to investigate how ecosystems contribute to observations

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(Tolk et al., 2009). A unique aspect of this study is the multi-annual observation dataset used to consider the detection of both seasonal and interannual variation.

Here we address the following questions:

i. Does tall tower Angus detect a representative fraction of Scotland's land surface ecosystem CO_2 uptake?

ii. Can observations made at tall tower Angus detect seasonality in ecosystem CO_2 uptake?

iii. Can observations made at tall tower Angus detect interannual variation in ecosystem CO_2 uptake?

2 Model description: WRF-SPA

WRF-SPA (Smallman et al., 2013) is a coupling between the high resolution mesoscale model Weather Research and Forecasting (WRF) and the mechanistic land surface model (LSM) Soil Plant Atmosphere (SPA). SPA generates realistic land–atmosphere exchanges through fully coupled hydrological, carbon and energy cycles to drive atmospheric transport.

2.1 WRF

The Weather Research and Forecasting model (WRFv3.2) (http://www.mmm.ucar.edu/wrf/users/, accessed 19 October 2009, 15:00 UTC) is a well supported and rapidly developing high resolution non-hydrostatic meteorological model (Skamarock et al., 2008). WRF is designed to be highly adaptable, with a portable code for use on massively parallel systems and a modular structure to allow for tailoring to specific uses. The model has been extensively validated over a range of locations around the world (e.g., Borge et al., 2008; Zhang, 2008; Ahmadov et al., 2009; Wang et al., 2009) and performs favourably in comparison to other commonly used regional meteorological models (e.g., Sarrat et al., 2007; Steeneveld et al., 2011). Here we use the Advanced Research WRF dynamical solver which uses non-hydrostatic equations, allowing horizontal resolutions of < 1 km.

2.2 SPA

The Soil Plant Atmosphere (SPA) model is a high vertical resolution mechanistic terrestrial ecosystem model (up to 10 canopy layers and 20 soil layers). SPA provides realistic surface fluxes of heat, water and CO_2 in response to meteorological drivers through a close coupling of its hydrological and carbon cycles, based on ecophysiological principles (Williams et al., 1996). A brief description of the SPA model is given below. Detailed descriptions of the major SPA developments can be found in Williams et al. (1996, 1998, 2001, 2005); Sus et al. (2010); Smallman et al. (2013).

WRF provides SPA with meteorological drivers including air temperature, precipitation, vapour pressure deficit (VPD), wind speed, friction velocity, atmospheric CO_2 mixing ratios, air pressure, short and long wave incoming radiation. SPA currently has parameters for 8 vegetation types (evergreen forest, deciduous forest, mixed forest, arable cropland, managed grassland, grassland, upland and urban) suitable for UK application and 13 soil types. Vegetation and soil classifications are from the default WRF land cover maps (Mesoscale and Microscale Meteorology Division, 2011).

The Farquhar model of photosynthesis (Farquhar and von Caemmerer, 1982), the Penman-Monteith model of leaf transpiration (Jones, 1992) and the leaf energy balance are coupled via a mechanistic model of stomatal conductance. Stomatal conductance is modelled by linking atmospheric demand for water and available water supply from the soil through plant hydraulics (Williams et al., 1996, 2001). SPA maximises carbon assimilation per unit nitrogen within a minimum leaf water potential constraint to prevent cavitation (Williams et al., 1996). SPA uses a detailed parameterisation of canopy processes, including multi-layer canopy radiative transfer (Williams et al., 1998), above and within canopy momentum decay and leaf level boundary layer conductance (Smallman et al., 2013).

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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 (foliage, structural/wood carbon, fine roots, labile, soil organic matter (SOM) and surface litter) were "spun-up", in an offline SPA simulation (except for crops) using 3 yr of meteorology (1998–2000) from Griffin Forest. These observations are broadly representative of the Scottish average and are from a period not simulated here. The observations were obtained from the CarboEurope network (www.carboeurope.org/) and looped for a 30 yr period. A 30 yr period was found to be sufficient for carbon pools to reach steady state when SOM was initialised with realistic values for Scotland based on the soil carbon stocks from Bradley et al. (2005). No spin up of cropland above ground carbon stocks was needed as arable systems are annual with complete clearing of the above ground vegetation at harvest and addition of labile carbon in the form of seed at sowing. 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. Crops have two additional C pools; storage organ C (i.e. harvestable C) and dead foliar C (still standing).

2.3 Atmospheric CO_2 tracers

WRF-SPA has been modified with the addition of several CO_2 tracer pools (Table 1). CO_2 tracer transport is simulated within the model domain concurrently with meteorological variables (feedback on atmospheric radiative transfer due to variable CO_2 is neglected).

Atmospheric CO_2 fields (2002–2007) are from Carbon Tracker Europe (CTE, Peters et al., 2010) providing $1^\circ \times 1^\circ$ resolution fields at 3 hourly intervals. Optimised CO_2 fields were not available for 2008 from CTE; instead CO_2 fields for 2008 are from Carbon Tracker (Peters et al., 2007). These are also available at 3 hourly intervals, but at a coarse $3^\circ \times 2^\circ$ resolution. CO_2 initial (IC) and lateral boundary conditions (LBC) were linearly interpolated to the WRF-SPA domain. LBCs for the outer domain have been set with zero inflow and zero-gradient outflow for all CO_2 fields, except total atmospheric

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CO_2 and "forcings only" CO_2 (Table 1). Zero gradient inflow/outflow allow tracers to easily leave the domain and prevent artificial influx to the CO_2 tracer fields.

Global flux maps of anthropogenic CO_2 emissions and ocean absorption were used to provide non-biospheric surface CO_2 exchange. Flux maps were also from CTE at $1^{\circ} \times 1^{\circ}$ resolution with 3 hourly update interval. Fluxes were interpolated using 4 point weighted mean based on latitude and longitude coordinates. Biospheric fluxes of CO_2 are simulated by SPA. All surface CO_2 fluxes were calculated as rates which were added to the lowest model atmospheric layer in each time step.

Total atmospheric CO_2 and "forcings only" CO_2 are used in the initial validation against tall tower Angus observations. "Forcings only" CO_2 tracer contains IC, LBC, anthropogenic emissions and ocean sequestration of CO_2 but no exchange with the SPA simulated biosphere, whereas total CO_2 does include exchange with the SPA simulated biosphere. The difference between these two tracers is the effect of the terrestrial biosphere.

2.4 Model domain

WRF-SPA modelled two domains with two-way nesting; the outer domain has a resolution of 18 km × 18 km and inner domain 6 km × 6 km (Fig. 1). Model output from the inner domain only is presented. Scotland provides a highly complex topography and land use heterogeneity, with a longitudinal gradient from dominantly forested and peatland areas in the north west to pasture in the central and south west and arable cropland in the east.

The main features of the WRF-SPA model set up are presented in Table 2. All meteorological data required e.g., sea surface temperature (SST), soil initialisation, initial conditions and lateral boundary conditions were taken from the Global Forecasting System (GFS) reanalysis product (http://www.emc.ncep.noaa.gov/). GFS data are available at $1^{\circ} \times 1^{\circ}$ longitude/latitude resolution with 6 hourly time steps (available from http://rda.ucar.edu/datasets/ds083.2/).

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3 Tall tower observations

Observations of atmospheric CO_2 concentration are from tall tower Angus (TTA), a 222 m tower (observation height) near Dundee, Scotland (56.56° N, 2.99° W). TTA is equipped for continuous measurement of atmospheric CO_2 concentrations producing half hourly observations which have been averaged to hourly time scales for comparison with WRF-SPA. TTA has been operational since the end of 2005 to the current date. Observations made at TTA have an accuracy limit of 0.1 ppm.

4 Results

4.1 CO_2 time series at TTA

Statistical comparison of hourly observations with the WRF-SPA simulated total atmospheric CO_2 (R^2 = 0.67 and RMSE = 3.5 ppm) and "forcings only" CO_2 (R^2 = 0.71 and RMSE = 3.3 ppm) at TTA suggests minimal or slightly negative impact of including the modelled biosphere. The annual bias for total atmospheric CO_2 (bias = 0.58 ppm) is lower than "forcings only" CO_2 (bias = 0.82 ppm) highlighting the impact of Scotland's biosphere sink (Fig. 2a). Furthermore the addition of biospheric fluxes captures diurnal variation in hourly observations which is otherwise absent in "forcings only" CO_2 (Fig. 2a and b). However, inclusion of biospheric fluxes results in an overestimation of night time atmospheric CO_2 concentrations simulated at the tall tower (Fig. 2b).

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). Monthly mean bias between total atmospheric CO_2 and observations is reduced for the majority of the comparison period. Seasonal bias is reduced in total CO_2 by up to 59 % between March–June and October–December of each year

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compared to "forcings only" CO_2 (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 and 3). During July–September total atmospheric CO_2 has a larger bias than "forcings only" CO_2 compared to observations. A larger 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).

4.2 Representativeness of TTA observations for the whole land surface

The dominant ecosystems simulated are forest, cropland and managed grassland. Over the validation period (2006–2008) WRF-SPA simulated forest ($-2.56 \pm 0.05\,\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$, ±standard error accounting for spatial and temporal uncertainty only) and grassland ($-0.48 \pm 0.02\,\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$) ecosystems to be mean annual sinks of CO_2. Cropland ($0.89 \pm 0.01\,\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$) ecosystems were simulated to be a net mean annual source of CO_2.

CO_2 tracers simulated at TTA suggest that cropland ecosystems have a distinct seasonal cycle from that of forests, managed grassland and "other" land cover types (Fig. 4). Managed grassland and "other" land covers are not included in the figure due to their contribution to atmospheric CO_2 concentrations being small, never exceeding 0.2 ppm. Peak net uptake CO_2 tracer simulated at TTA occurs 2–3 months earlier in crops than forest, while net release CO_2 tracer simulated at TTA for cropland shows a similar seasonality to all other ecosystems. Peak crop respiration coincides with crop harvest, a point in time when plant biomass has undergone senescence and has subsequently either been removed as part of harvest processes or remains after harvest as residue added to the litter pool (mean simulated harvest day of year: 2006 = 225±17.9, 2007 = 229±21.4, 2008 = 229±21.5, standard deviation accounting for spatial variability only). Anthropogenic CO_2 simulated at TTA is comparable in magnitude to that of CO_2 released by the biosphere. Also, anthropogenic CO_2 does not display a strong seasonal trend (Fig. 4).

The representativeness of TTA observations of national scale land surface CO_2 uptake was investigated. To achieve this the fraction of total land surface net CO_2 uptake for each ecosystem type was compared to the fraction of net uptake CO_2 tracer simulated at TTA that each ecosystem contributed. Forest and cropland dominate the net uptake CO_2 tracer simulated at TTA (60–95 % of TTA signal and 72–91 % of surface signal). Managed grassland and "other" ecosystems tend to be under-represented (i.e. the fraction of net uptake CO_2 tracer at TTA, which an ecosystem is responsible for, is less than its fraction of total land surface net CO_2 uptake) (Fig. 5).

Ecosystem fractions of net uptake CO_2 tracers simulated at TTA are largely inconsistent with the fractions of simulated land surface CO_2 uptake, except during August 2007–March 2008 and August 2008–December 2008 (Fig. 5). Fractional forest detection is under-represented at TTA on average by ~22 %, while cropland is over-represented on average by ~33 % at annual time scales. The bias towards cropland is consistent with the spatial distribution of crop and forest covers relative to TTA's location. TTA is located on the east coast of Scotland where surface cover is predominantly cropland. While forest areas are predominately in central and westerly regions (Fig. 1). Forest and cropland show seasonality for which ecosystem is the dominant signal at TTA. Cropland is dominant during the crop growing season, ending with harvest. Correspondingly, all other land cover types show an increase in their fraction after cropland is harvested (Fig. 5).

4.3 Seasonal and interannual variation

Net uptake CO_2 tracers simulated at TTA are able to explain the majority of seasonal variation in surface cropland net CO_2 uptake (R^2 = 0.88, linear regression). Net uptake CO_2 tracers simulated at TTA do not explain the majority of seasonal variation in forest, managed grassland or "other" ecosystem net CO_2 uptake (R^2 = 0.33, 0.43 and 0.32 respectively) (Fig. 6). The seasonal profile for forest, managed grassland and "other" net uptake CO_2 tracer is offset compared to the simulated land surface (Fig. 6). The rank

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order of net uptake CO_2 tracer simulated at TTA from each year does not correspond with the rank order of total surface net CO_2 uptake for forest, managed grassland and "other" (Fig. 6). Incorrect ranks indicate that interannual variation in land surface activity is not reproduced in TTA observations for the years simulated here. However, the rank order of years is correctly predicted for cropland during the majority of months (April, May, July–December) (Fig. 6). Correct detection of cropland interannual variation is consistent with the cropland bias in fractional detection and spatial distribution. Interannual variation in mean annual land surface uptake is ~ 6 % while interannual variation for mean annual net uptake CO_2 tracers simulated at TTA is ~ 16 %.

Seasonal variation in net CO_2 uptake for each land cover type was investigated using regression analysis to determine their environmental drivers. Air temperature and incoming short wave radiation, while closely coupled, both significantly contribute, statistically, to explaining seasonal cycles ($0.88 \leq R^2 \leq 0.97$). This indicates that both direct effects of temperature on metabolic processes (photosynthesis and respiration) and availability of photosynthetically active radiation (PAR) from short wave radiation are important for determining changes in regional scale net CO_2 uptake.

5 Discussion and conclusions

5.1 CO_2 time series

WRF-SPA demonstrated that it can re-create regional scale observations of atmospheric CO_2 concentrations (Fig. 2a and b). 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. The modelled biosphere generates diurnal cycles of realistic magnitude in the modelled CO_2 time series (Fig. 2b) and reduces the seasonal bias seen in "forcings only" CO_2. These results indicate the importance of including Scotland's biosphere and that Scotland's terrestrial ecosystem is likely on average to be a net carbon

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sink for the years simulated here (Fig. 3). 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).

WRF-SPA simulated forest sequestration ($-2.56\,t\,C\,ha^{-1}\,yr^{-1}$) 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 forest sequestration simulated here; Scotland specific estimates range between $\sim 1.8\,t\,C\,ha^{-1}\,yr^{-1}$ (Thomson et al., 2012) and $\sim 2.0\,t\,C\,ha^{-1}\,yr^{-1}$ (Forestry Commission Scotland, 2009). However it remains likely that WRF-SPA's estimate for Scotland's forest sequestration is overestimated. Forest activity is largely under-represented in observations made at TTA (Fig. 5), which likely explains 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 ($-0.48\,t\,C\,ha^{-1}\,yr^{-1}$) while croplands were simulated to be a net carbon source ($0.89\,t\,C\,ha^{-1}\,yr^{-1}$). Estimates of grassland carbon sink are more comparable with other estimates, which range between $-0.69\,t\,C\,ha^{-1}\,yr^{-1}$ (UK average, Janssens et al., 2005) and $-0.15\,t\,C\,ha^{-1}\,yr^{-1}$ (Scotland specific, Thomson et al., 2012). The WRF-SPA estimate of cropland source magnitude is also comparable with other UK wide ($0.53\,t\,C\,ha^{-1}\,yr^{-1}$, Janssens et al., 2005) and Scotland specific estimates ($0.88\,t\,C\,ha^{-1}\,yr^{-1}$, Thomson et al., 2012).

The simulated representation of arable cropland within WRF-SPA is likely to be responsible for the increase in total CO_2 bias between July–September in total atmospheric CO_2 (Fig. 3). Cropland net uptake CO_2 tracer simulated at TTA declines in magnitude concurrently with the increase in total CO_2 bias in July (Figs. 3 and 4). In addition, the total atmospheric CO_2 bias exceeds the "forcings only" CO_2 bias in August as cropland respiration increases due to the input of litter from harvest. Above ground carbon is removed as part of the harvest, leaving a fraction of above ground carbon as surface residue and root carbon within the soil. Both the surface residue and root

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carbon are added to the litter carbon pool, which begin to decompose significantly increasing respiration from cropland. The parameterised harvest processes are broadly realistic.

WRF-SPA does not simulate uncultivated land associated with agriculture. In Scotland on average ~ 36 % of agricultural land is uncultivated, including woodland patches, hedgerows and fallow land (The Scottish Government, 2012). These unmodelled vegetative components are likely to be perennial systems, lacking intensive management and as a result have a longer growing season. For example, forest and grassland ecosystems continue to have a significant level of surface CO_2 uptake for several months after cropland harvest (Fig. 6). Therefore, uncultivated systems represent a significant contribution to the agricultural carbon balance at regional scales (Smith, 2004). Further development in the representation of agricultural land within LSMs is needed. For example, modelling at high spatial resolutions may allow land cover maps to resolve some of this heterogeneity, alternatively a tiling system could be used to represent this sub-grid heterogeneity.

5.2 Representativeness and seasonal variation of TTA observations

WRF-SPA net uptake CO_2 tracers simulated at TTA are not representative of ecosystem specific fractions of total surface net CO_2 uptake (Fig. 5). Cropland is most often the dominant ecosystem detected at TTA and the dominant simulated land surface in terms of net CO_2 uptake (Fig. 6). Cropland is also fractionally over-represented at TTA compared to it's net surface uptake (Fig. 5). Over-representation of crops is expected given the spatial distribution of the land cover types in relation to TTA (Fig. 1). Local dominance is consistent with PBL theory, where during warmer times of the year the PBL deepens with increased sensible heat fluxes enhancing vertical mixing. The effect of enhanced vertical mixing increases dominance of the local signal over regional information. Our results are consistent with other findings of both modelling and observational studies in this regard (Gerbig et al., 2009; Vermeulen et al., 2011; Lauvaux et al., 2012; Miles et al., 2012). Forests dominate the fractional activity after cropland harvest (Fig. 5).

TTA observations do not contain realistic seasonal information on ecosystems that are not adjacent to the tower. Forest fractional dominance of net uptake CO_2 tracer (Fig. 5) at TTA coincides with the seasonal peak in net uptake CO_2 tracer for forest simulated at TTA (Fig. 4). This suggests that peak forest net CO_2 uptake occurs later than cropland. However comparison with forest net surface CO_2 uptake shows that the TTA peak in forest net uptake CO_2 tracer occurs after the peak in forest surface net CO_2 uptake (Fig. 6). A similar delay in the TTA detected peak CO_2 uptake is also present for managed grassland and "other" land cover types (Fig. 6). Crop maturity and harvest results in significant and sudden shifts in surface biogeochemical and biogeophysical processes, resulting in changes to turbulent exchange likely impacting atmospheric mixing (Schomburg et al., 2012). Uptake CO_2 tracers simulated at TTA explain the majority of seasonal variation for cropland net CO_2 uptake (Fig. 6). Good detection of cropland is consistent with the local dominance already discussed. Effective cropland detection is also consistent with the spatial distribution of ecosystems around TTA and the resultant under-representation of all other ecosystems in TTA observations. Only a minority of seasonal variation in total land surface net CO_2 uptake is explained by tracers simulated at TTA for all other ecosystems (Fig. 6).

5.3 Interannual variation

Interannual variation of the simulated seasonal cycles is poorly detected by TTA, except for cropland (Fig. 6). Interannual variation of net uptake CO_2 tracers simulated at TTA is greater than interannual variation in modelled land surface net CO_2 uptake. This suggests that interannual variation in atmospheric transport due to year to year variation in weather, not variation in land surface net CO_2 uptake, is the dominant driver of interannual variation in tall tower observations for the years simulated here. This highlights the need for careful attention to atmospheric transport uncertainties and errors when carrying out atmospheric inversions. To detect a change in land surface activity

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the magnitude of the change must be greater than the variation in detection due to transport. Alternatively, an extended network of tall towers is required to gain spatially explicit information on land surface exchange (Lauvaux et al., 2012).

Net uptake CO_2 tracer concentrations for managed grassland and "other" ecosystems simulated at TTA are less than 0.2 ppm and 0.05 ppm respectively. The accuracy limit for CO_2 detection of the equipment installed at TTA is 0.1 ppm. This suggests that limited real world information is present in TTA observations for managed grassland and "other". Therefore it is also likely that TTA provides limited information in the real world for any ecosystem with limited activity or small spatial extent. Ineffective detection of "other" vegetation is significant as "other" land cover types include Scotland's uplands and peatland areas. Upland and peatland areas are highly important given the significant amount of carbon stored as soil organic matter in these soils, estimated to contain $> 200\,\mathrm{t\,C\,ha^{-1}}$ (Bradley et al., 2005).

5.4 Caveats and future work

WRF-SPA estimates for ecosystem specific mean annual sequestration are broadly reasonable, however they should be considered with caution. First, most ecosystems are under-represented in observations at TTA, therefore validation of exchange from these ecosystems is likely to be less robust. Second, this study does not estimate the LSM parameter uncertainties or uncertainties associated with atmospheric transport that may have a significant impact on the interpretation of sequestration estimates given here. As a result, estimates of ecosystem mean annual carbon sequestration should be considered only as indicators of consistency with other estimates. Therefore future work should involve an appropriate data driven uncertainty analysis of LSM parameters (i.e. data assimilation) and an attempt to assess atmospheric transport uncertainties.

WRF-SPA does not currently include a representation of forest management. Forest ecosystems are initialised with identical conditions that have been "spun up" into steady state. As a result important differences in forest sequestration due to age class

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distribution and lateral transport of carbon due to forest harvest are not included. In future, a more detailed representation of forest processes should be included.

It remains to be investigated whether policy relevant land cover management can be detected at TTA (e.g., afforestation). WRF-SPA simulations presented here indicate that observations made at TTA are unable to reliably detect interannual variation of ecosystems not adjacent to the tall tower. However tall towers are expected to be used for monitoring the effects of land surface management aimed at mitigating climate change (ICOS, 2012). Current Scottish Government policy is to increase Scotland's forest cover by 650 000 ha by 2050 (Forestry Commission Scotland, 2009). Through the use of WRF-SPA the capability of current observations to detect changes in Scotland's regional carbon balance should be investigated.

5.5 Conclusions

Three specific questions were asked of WRF-SPA to investigate atmospheric observations of CO_2 made within the PBL from tall tower Angus, Scotland. (i) Does tall tower Angus detect a representative fraction of Scotland's land surface ecosystem CO_2 uptake? Cropland is over-represented in tall tower Angus observations for much of the annual cycle. Correspondingly forest, managed grassland and "other" land covers are under-represented. (ii) Can tall tower Angus observations detect seasonality in ecosystem CO_2 uptake? Tall tower Angus does not detect the majority of seasonal variation in surface uptake for forests, managed grassland or "other" land covers. Crop seasonality is well detected, consistent with dominance of crop activity in tall tower Angus observations. (iii) Can tall tower Angus observations detect interannual variation in ecosystem CO_2 uptake? Interannual variation is only well detected for croplands. This is consistent with the spatial bias in ecosystem distribution around tall tower Angus and over-representation of cropland uptake in tall tower observations. 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.

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Table 1. Tracer pools and definitions used by WRF-SPA. A passive tracer does not have the potential to be exchanged with the land surface after its initial emission. Whereas a non-passive tracer can be removed from the atmosphere, as it represents a physical mass of CO_2 added to the atmosphere through respiration.

Tracer	Description	Passive tracer
1	Total CO_2concentration, includes all sources and sinks of CO_2, for comparison to observations	Yes
2	Forest net CO_2uptake	No
3	Anthropogenic emissions	No
4	Forcings only, i.e. anthropogenic emissions, ocean sequestration, initial and lateral boundary conditions only	No
5	Crop net CO_2uptake	No
6	Ocean sequestration	No
7	Forest net CO_2release	Yes
8	Crop net CO_2release	Yes
9	Managed grassland net CO_2release	Yes
10	Other vegetation net CO_2release	Yes
11	Managed grassland net CO_2uptake	No
12	Other vegetation net CO_2uptake	No

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Table 2. Parameter and model options used in WRF-SPA.

Basic equations	Non-hydrostatic, compressible Advanced Research WRF (ARW)
Radiative transfer scheme	Rapid Radiative Transfer Model for GCMs (RRTMG) for both long wave and short wave
Planetary boundary layer scheme	Yonsei University
Surface scheme	Monin-Obukov
Microphysics scheme	WSM 3-class simple ice
Cumulus parameterisation	Grell 3-D ensemble scheme (coarse domain only)
Nesting	Two-way nesting
Domain, resolution	44 × 47, 18 km 48 × 54, 6 km 35 vertical levels
Domain centre	56.63° N, 3.35° W

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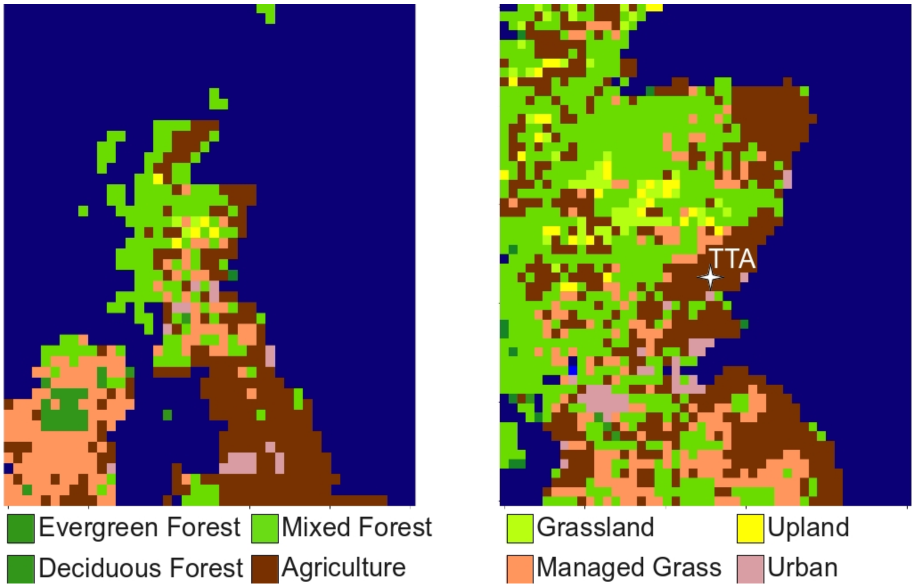

Fig. 1. Land classification map used covering the spatial extent of the model domain. The left panel is the parent domain at 18 km × 18 km, right panel is nested domain at 6 km × 6 km. The star indicates the location of tall tower Angus (TTA). The map used in WRF-SPA is a modified MODIS land cover map provided with the WRF model.

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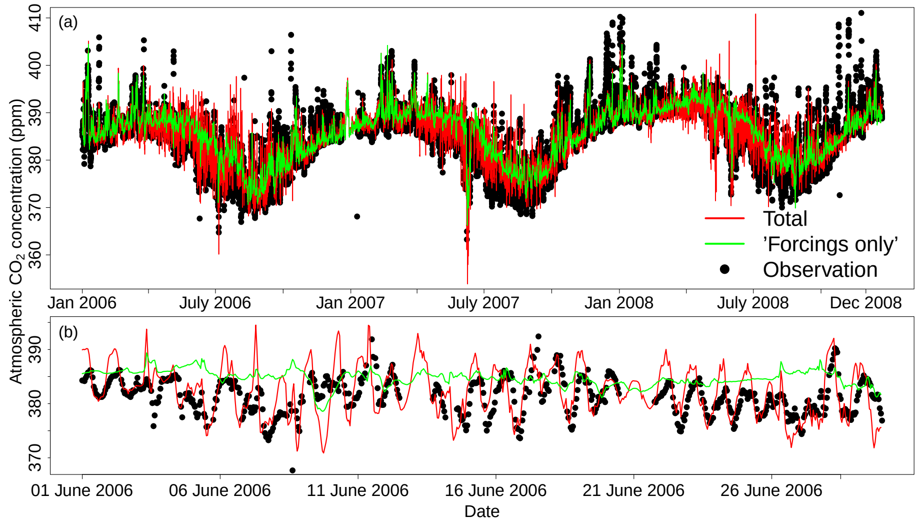

Fig. 2. Time series comparison between hourly observations of atmospheric CO_2 concentrations made at TTA and WRF-SPA simulated total atmospheric CO_2 and "forcings only" CO_2. Panel **(a)** shows realistic seasonality in the simulated CO_2 time series (2006–2008) is driven mostly by forcings originating outside of the model domain as indicated by "forcings only" CO_2. Panel **(b)** shows an hourly 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).

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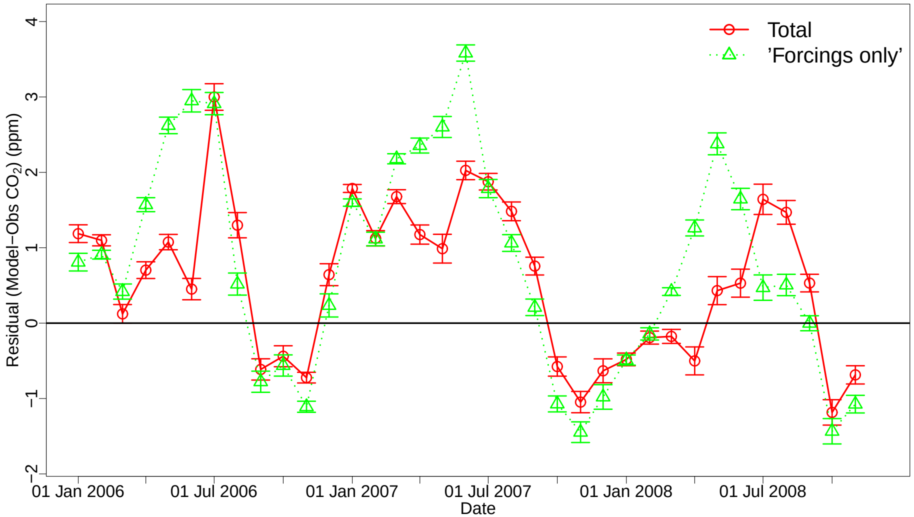

Fig. 3. Monthly mean residual (Model–Obs) between observed and simulated atmospheric CO_2 concentration time series. Highlights time periods during which the inclusion of the simulated biosphere results in a reduction in monthly mean bias. Total CO_2 includes exchange with the simulated biosphere, whereas "forcings only" CO_2 does not include exchange with the simulated biosphere. Error bars are ±1 standard error, accounting of temporal and spatial uncertainty only.

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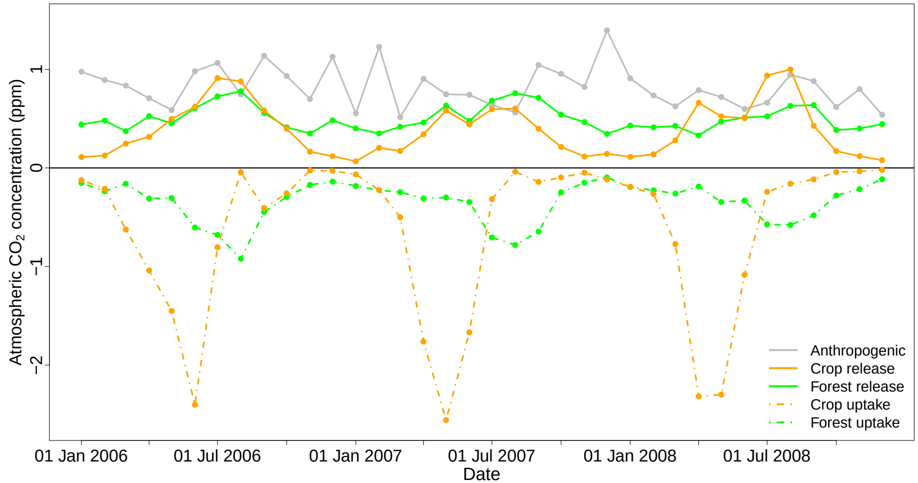

Fig. 4. Monthly mean mixing ratios for net uptake and net release CO_2 tracers, for cropland and forest ecosystem, simulated to be present at TTA. Highlights differences in detection of ecosystem processes at TTA, in particular the distinct seasonal cycle of cropland net CO_2 tracer compared to all other ecosystems. Crop uptake CO_2 tracer shows a decline each year during July/August due to crop maturity and subsequent harvest resulting in increased net release CO_2 tracer present at TTA. Managed grassland and "other" ecosystems are not included due to their small magnitude contributions, never exceeding 0.2 ppm.

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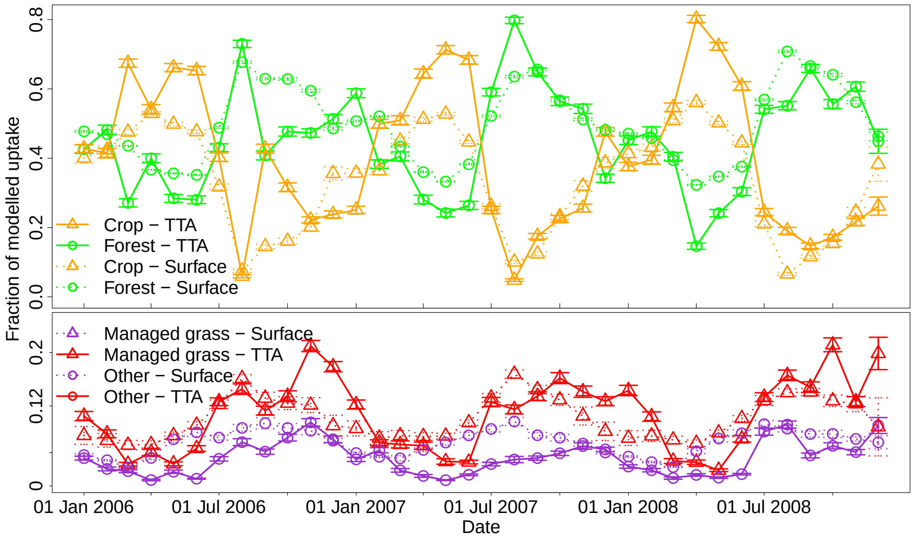

Fig. 5. Fraction of CO_2 tracers at TTA which each ecosystem is responsible for, and fraction of total simulated land surface net CO_2 uptake each ecosystem is responsible for (averaged to monthly mean values) are shown here. Comparison between the fractions of surface CO_2 uptake and the fractions detected at TTA indicate seasonal variation for when ecosystems are over or under-represented in simulated observations at TTA. Fractional cropland uptake tracer at TTA is greater than the fraction cropland surface uptake, indicating that for the majority of the year cropland is over-represented in TTA observations. Error bars are ±1 standard error, accounting of temporal and spatial uncertainty only.

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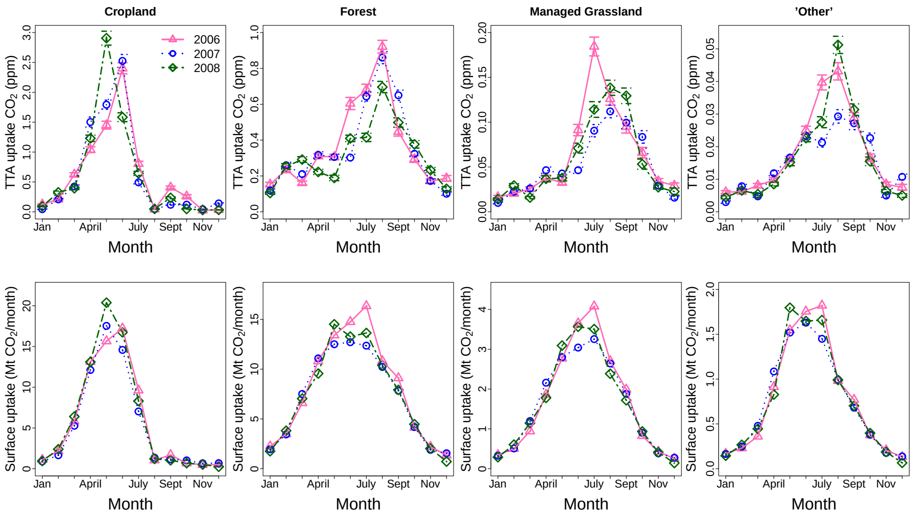

Fig. 6. Interannual comparison of monthly mean net uptake CO_2 tracer at TTA (upper panel) and monthly sum of net CO_2 uptake for the whole simulated land surface (lower panel) for each ecosystem type. TTA detected CO_2 tracers only detects correct monthly rank order between years cropland ecosystem, when comparing with the actual monthly rank order of surface net uptake CO_2. The seasonal cycle in tall tower detected CO_2 tracers does not accurately represent seasonality in ecosystem specific surface uptake, except for crops. Also note the different scales between ecosystem types. Error bars are ±1 standard error, accounting of temporal and spatial uncertainty only.

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