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On observational and modelling strategies targeted at regional carbon exchange over continents

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Abstract

Estimating carbon exchange at regional scales is paramount to understanding feedbacks between climate and the carbon cycle, but also to verifying climate change mitigation such as emission reductions and strategies compensating for emissions such as carbon sequestration. This paper discusses evidence for a number of important shortcomings of current generation modelling frameworks designed to provide regional scale budgets. Current top-down and bottom-up approaches targeted at deriving consistent regional scale carbon exchange estimates for biospheric and anthropogenic sources and sinks are hampered by a number of issues: We show that top-down constraints using point measurements made from tall towers, although sensitive to larger spatial scales, are however influenced by local areas much stronger than previously thought. On the other hand, classical bottom-up approaches using process information collected at the local scale, such as from eddy covariance data, need up-scaling and validation on larger scales. We therefore argue for a combination of both approaches, implicitly providing the important local scale information for the top-down constraint, and providing the atmospheric constraint for up-scaling of flux measurements. Combining these data streams necessitates quantifying their respective representation errors, which are discussed. The impact of these findings on future network design is highlighted, and some recommendations are given.

1 Introduction

Rising atmospheric CO_2 due to fossil fuel combustion and deforestation represents the major cause for global warming (IPCC, 2007). Only about 45% of the emitted CO_2 remains in the atmosphere, while the rest is taken up by the ocean and land biosphere (Canadell et al., 2007). This so called "airborne fraction" shows large interannual variability ranging from 0% to 80%, mostly due to the varying land sinks (Canadell et al., 2007). Quantifying land biosphere CO_2 fluxes and understanding their behaviour in a

changing climate has therefore high research priority.

Measurements of atmospheric CO_2 from a global network of stations in combination with global inverse transport modelling have been an important source of information on biosphere-atmosphere exchange at coarse spatial resolution ranging from global, hemispheric to continental scales down to regional scales of several hundreds of kilometres (Tans et al., 1990; Gurney et al., 2002). This allows partially resolving scales at which climate anomalies (droughts and rainfall anomalies, heat waves) interact with the biosphere. However, in order to better resolve the responses of various vegetation types and the impact of human interventions (land use change and land management) on land-atmosphere fluxes, inversions increasingly focus on smaller scales. The need to utilize non-background measurements of CO_2 to retain information on fluxes on those scales has already been discussed since more than a decade (Ramonet and Monfray, 1996). The increased availability of new continuous concentration data with high temporal resolution at land based stations from tall (>200 m) towers in principle supports this trend and suggests that in the near future it may indeed be possible to monitor the success or failure of emission reduction or sequestration efforts in the context of climate change mitigation. As a consequence of this trend, estimating regional scale carbon budgets has become a major focus (Dolman et al., 2006; Lin et al., 2006; Wofsy and Harriss, 2002).

Attempts to retrieve information on biosphere-atmosphere exchange at regional scales from continuous concentration measurements made by networks of tall towers implemented in the US and Europe (Peylin et al., 2005; Gerbig et al., 2006; Matross et al., 2006; Lauvaux et al., 2008) have recently started. However, atmospheric forward and inverse modelling at these scales is non trivial, and mesoscale circulations have the potential to dramatically complicate the interpretation of these measurements (Pérez-Landa et al., 2007; van der Molen and Dolman, 2007; Ahmadov et al., 2007; Sarrat et al., 2007). The large heterogeneity of land-atmosphere fluxes requires also transport models with much higher spatial resolution (meso-gamma, 2–20 km) than those currently used. Furthermore, performing inversions at this scale requires im-

proved knowledge of a priori fluxes that represent this variability, together with appropriate estimates of the associated a priori uncertainties and their spatial and temporal correlations. Gerbig et al. (2006) showed that incorrect assumptions about the degree to which the uncertainties in the a priori fluxes are spatially or temporally correlated will either lead to biased flux estimates, or to an overestimation of posterior uncertainties resulting in a weaker constraint on fluxes.

Difficulties in accurately representing atmospheric transport are not simpler at regional scales compared to global transport models. Indeed they may in fact be more complex: modelling vertical mixing, most prominently mixing within the planetary boundary layer (PBL), is associated with uncertainties that cause problems in estimating fluxes from boundary layer CO_2 measurements at large scales (Stephens et al., 2007) as well as at regional scales (Gerbig et al., 2008). However, over continents, the close proximity of measurement sites to spatially variable sources and sinks imply that uncertainties in advection due to slight errors in assimilated winds will significantly affect modelled mixing ratios (Lin and Gerbig, 2005). Although these issues have been recognized for some time now, implementation of strategies to mitigate the impact has proven difficult.

In contrast to "top-down" inversions, "bottom-up" estimates of carbon budgets that start with process information from leaf-level measurements and eddy covariance measurements at the scale of a few square kilometres, require up-scaling to provide information at regional scales. We argue for an approach to combine the data streams from flux and concentration measurements in a model-data fusion system (Matross et al., 2006), similar to the approach recently taken with CarbonTracker (Peters et al., 2007), but now targeted at regional scales. We strongly belief that such a data fusion system would finally be able close the gap between eddy covariance footprints and concentration footprints.

In a model-data fusion system it is paramount to take into account the uncertainties of the various data streams, as they provide a natural and objective statistical weight. Uncertainties in this context include experimental uncertainties, but also uncertainties

of the modelling framework itself. This view has important implications for the design of a carbon observing network, several of which are now planned or being implemented (Dolman et al., 2008). Thus the overall error, including the model uncertainties, needs to be taken into account for network design. Only this will provide an objective measure for the information content provided by a specific network element. This is one of the key arguments of this paper.

This paper is organized as follows. In Sect. 2.1 we investigate the effect of near field variability on the observed concentrations of atmospheric CO_2, which is of fundamental importance for utilizing the information from the top-down constraint imposed by the observations. In Sect. 2.2 we emphasize the need for increased attention to treatment of model uncertainty. In Sect. 2.3 review the implications of this on the treatment of uncertainties in model-data fusion systems, while, in Sect. 3 we discuss the implication for network design.

2 Addressing increasingly smaller scales: the issues

2.1 The near-field versus far field impact of atmospheric observations

Observations made within the continental boundary layer are strongest influenced by sources and sinks in the proximity of the measurement locations. This is related to the nature of atmospheric mixing: tracers emitted from a small patch of surface are dispersed rapidly by the combination of vertical motion through the combined effect of turbulent eddies and wind-shear, causing a fast decrease in concentration with distance. Combined with the strong spatial variability in surface fluxes of CO_2 this causes a corresponding variability in concentrations, which poses difficulties for simulations of atmospheric CO_2 based on transport models (Geels et al., 2007). Various attempts have been made to quantify the scales of variability of atmospheric CO_2 and the related representation error in coarse resolution models, starting with statistical analysis of spatially distributed aircraft data (Gerbig et al., 2003a; Lin et al., 2004) over sensitiv-

ity analysis using different scales of variability of surface fluxes (Gerbig et al., 2003b) to statistical analysis of high resolution simulations of atmospheric CO_2 (Corbin et al., 2008; van der Molen and Dolman, 2007; Tolk et al., 2008).

Increasingly tall towers are being proposed and set up to provide complementary observations over land (Bakwin et al., 1995; Haszpra et al., 2001; Tans et al., 1996), in addition to the mountain top stations that predominantly sample the free tropospheric concentration of CO_2. They are generally conceived as being able to bridge the gap between surface flux stations and tropospheric observations. This observation system raises a number of questions, with respect to the design of a network. In a network of tall towers, the most important one is to ask: what is it that the individual tower observes?

We rephrase this question as: given that a typical atmospheric observation station such as a tall tower is surrounded by vegetation with spatially varying fluxes, what is the relative impact of near-field (~50 km distance) vs. far field fluxes on the measured concentrations? If the far field is dominant they are useful for large scale application, if they are primarily reflecting near field effects, they effectively sample only the small scales. To investigate this question we combine a simple biospheric flux model with atmospheric transport at high resolution. We use the same modelling framework as in Gerbig et al. (2006), further on referred to as G06, which links GEE (gross ecosystem exchange fluxes) for different vegetation types from a light use efficiency (LUE) model and respiration fluxes scaled with near-surface temperature to the STILT (Stochastic Time Inverted Lagrangian Transport) model driven by analysed winds from EDAS (Eta data assimilation system). The model was run for one month during the growing season (August 2002) for the Harvard Forest tower (MA, USA). Observed synoptic and diurnal variability was captured by this model reasonably well (G06).

Formally, the CO_2 mixing ratio at the measurement site can be formulated as a sum of individual contributions from all surface elements of the domain using a polar

coordinate grid with the measurement location at the center of the grid:

$$C(t_r) = \sum_{i,j} c(t_r|\varphi_i, r_j) + \sum_i C_0(t_r|\varphi_i) \quad (1)$$

Here $c(t_r|\phi_i, r_j)$ is the contribution to the mixing ratio at time t_r at the tower from past biospheric fluxes of the grid element i and j in the polar grid, and $C_0(t_r|\phi_i)$ is the contribution from the lateral boundary condition of the regional model domain. The individual contributions from each grid element can be expressed as a product of past surface fluxes and the surface influence (or footprint):

$$c(t_r|\varphi_i, r_j) = \sum_m f(t_r|\varphi_i, r_j, t_m) \cdot \Delta A(r_j) \cdot F(\varphi_i, r_j, t_m) \quad (2)$$

The footprint $f(t_r|\phi_i, r_j, t_m)$ relates the surface flux $F(\phi_i, r_j, t_m)$ (in units of μmoles/m^2/s) at location ϕ_i, r_j, (averaged over the grid cell) and time t_m to mixing ratios at time t_r at the tower located in the origin of the coordinate system. The grid cell area $\Delta A(r_j)$ depends only on the radial index. It is important to mention that in the chosen setup the different distances correspond to areas that strongly increase with distance from the measurement location. This is the result of using a spatially variable grid size that increases with squared distance, and thus is adapted to the spread of surface influence caused by atmospheric mixing (for details see G06). This dependence of $\Delta A(r_j)$ on r_j is chosen so that the contributions from spatially homogeneous surface fluxes are on average independent of the distance from the grid cell to the measurement location. Note that when using a grid with constant grid size, the contributions from distances larger than 100 km would become virtually negligible compared to the local influence. However, since atmospheric mixing does integrate spatially, we regard the chosen representation as adequate. Equation (2) defines footprints as a property of transport only, independent of the surface fluxes; in our case the footprints have been calculated using the STILT model (Lin et al., 2003). The product of footprint and surface flux can be regarded as the instantaneous influence from upstream surface fluxes.

We analysed the contributions to CO_2 originating from surface elements with a certain distance to the measurement site, obtained by summing Eq. (2) over the different sectors ϕ_i. $c(t_r|r_j) = \sum_i c(t_r|\varphi_i, r_j)$, and shown in Fig. 1. These contributions can be positive in case of respired CO_2, and negative in case of CO_2 taken up by biospheric activity. Overall, uptake dominated during this month due to active photosynthesis during the growing season. The dominant influence on the tower observations is caused by the fluxes from the first 20 km annulus, and drops down rapidly for larger distances (Fig. 1). Note that only contributions related to afternoon measurements (15:00 local time) are shown, when mixing is deep and transport models are assumed to be able to accurately represent the measurements (Geels et al., 2007). When analysing monthly averaged contributions to CO_2 signals in the afternoon (15:00 local time), the sharp drop for distances larger than about 20 km can be seen more quantitatively (Fig. 2). The change from negative to positive contributions at a distance of about 50 km is related to the fact that air parcels arriving at 15:00 local time are on average influenced by night time fluxes in the region between 50–200 km upstream of the measurement location. When separating the contributions from respiration and photosynthesis (solid and dashed grey lines in Fig. 2b), this reason becomes obvious. The contribution from photosynthesis fluxes shows a distinct minimum around 50–200 km, while contributions from respiration are more or less constant apart from the 3-fold higher near-field contribution. This suggests an important interplay of spatial and temporal variations in fluxes: the measurements are highly sensitive to the spatial distribution of the different components of the biosphere-atmosphere exchange fluxes, in particular ecosystem respiration and gross exchange due to photosynthesis. For other trace gases without a strong diurnal cycle in sources or sinks, such as e.g. CH_4, the area that the tower measurements are sensitive to is essentially much larger, as can be seen from the contributions from respiration. For CO_2, the day-to-day variance drops by more than a factor of four at distances larger than 100 km (Fig. 2a, grey lines), indicating that the near field also dominates the variability on time scales between diurnal and monthly, most prominently synoptic scales.

Gloor et al. (2001) have estimated footprints using a somewhat different approach, which combines measurements of C_2Cl_4 (tetrachloroethene), a tracer with known spatial emission pattern, with simple trajectory transport simulations. Note that their definition of a footprint is not solely as a transport property as defined in Eqs. (1) and (2), since in their approach the footprint also depends on the emission pattern and on the model-measurement agreement. They find a surprisingly large area of 10^6 km^2 contributing to short term variability of C_2Cl_4, an area corresponding to distances of more than 500 km in Fig. 2. Our different conclusion for the size of the area contributing to variability of CO_2 is partially related to the finer representation of the near-field influence (a 20 km circular area compared to $1\times1^\circ$), but mainly related to the fact that CO_2 is subject to fluxes with a strong diurnal cycle, unlike the tracer (C_2Cl_4).

The important consequence of this dominance of the near field contributions to daytime mixing ratios of CO_2 for inversion studies is that a small bias in the assumed flux in the near field can cause a large bias in the modelled mixing ratio. Thus, a 10% flux bias (assumed constant over the month) in the nearest 20 km is equivalent to a similar flux bias in all other areas combined, i.e. on regional to continental scales between 20 km and several hundred of km. In this sense, the fluxes from the nearest 20 km have the same impact on measurements as from the rest of the domain. It is important to note that this dominance is occurring not only on daily time scales, but on synoptic and monthly time scales. Periods during the dormant season are substantially less affected by this effect due to the absence of photosynthesis which causes the diurnal cycle. However, biases during the growing season will have an impact on annual or decadal budgets.

A compensating effect rises when using multiple towers in a network: since a local bias in fluxes at one tower location is a far-field small scale bias for other tower locations, resulting errors are expected to be uncorrelated between different sites. Thus for large spatial scales the error resulting from local biases should be less for a sufficiently large network than described above for a single site. The exact impact of local effects in case of a network needs to be assessed in a more sophisticated simulation.

2.2 Accounting for uncertainties in models

Most top-down inversions studies performed so far have focused on specifying the a priori uncertainty in fluxes, with other sources of error been mostly treated in a lumped approach. This combines all uncertainties into a single measurement error that is often assumed constant in time and space with the exception of land-ocean differences. However, combining the different data streams in a model-data-fusion requires an appropriate way of weighting their influence on the targeted flux estimates. In principle, the representativeness of the data in the context of the model's capability can provide this weight: instrumental noise which reduces the representativeness of data should be taken into account, but also any possible error of the model such as a too coarse temporal or spatial resolution, or processes that are not represented or only represented in a crude way.

Some of these errors and their impact on the uncertainty of simulated CO_2 in the atmosphere are listed in Table 1. Note that the lower range of prior uncertainties listed in Table 1 is actually smaller than some of the transport related uncertainties, which indicates the importance of improving the capabilities of transport models in order to be able to actually reduce the uncertainties in fluxes.

Transport uncertainties due to advection (Lin and Gerbig, 2005) as well as vertical mixing (Stephens et al., 2007; Gerbig et al., 2008; Denning et al., 2008) significantly affect modelled mixing ratios. These uncertainties need to be addressed by improving the modelling systems. This can be achieved by improved algorithms for boundary layer schemes. A further approach is to assimilate additional information related to transport, such as meteorological observations made at the network elements; Gerbig et al. (2008) for example suggested adding Lidar measurements to monitor mixing heights at the tall tower locations, which when assimilated into the meteorological transport fields are likely to improve the representation of the measurements. However, it is unlikely that within the next decades those transport related issues are completely solved. Therefore an important part of treating these uncertainties is by error propaga-

tion, so that measurements made under conditions that are more difficult to represent are given a lower statistical weight. This approach has been successfully applied in case of transport errors (Lin and Gerbig, 2005; Gerbig et al., 2008)

Spatial representation errors have been assessed using statistical analysis of observations (Gerbig et al., 2003a; Lin et al., 2004), but also using high resolution models (Gerbig et al., 2003b; van der Molen and Dolman, 2007; Tolk et al., 2008; Corbin et al., 2008). These observations and model results could be used to derive parameterizations for representation errors, but they apply so far only to a limited set of conditions, and maybe hard to generalize. The way forward here would be to develop nested modelling systems where it is hoped that the model error would be reduced because of higher resolution near observation stations, and where in less dense observational areas the model resolution becomes less. The development of such systems still requires considerable research.

2.3 Near field versus far field in data assimilation systems

Classical top-down approaches that use atmospheric observations and atmospheric transport models to derive continental or regional scale surface-to-atmosphere exchange fluxes use prior flux estimates and their associated prior uncertainties. These priors are usually based on relatively coarse biosphere models, either of process models (Peylin et al., 2005) or of statistical flux models (Rödenbeck et al., 2003), and the inversion targets corrections to these prior fluxes on relatively coarse scales (from grid cells the size of several hundreds of kilometres to regions the size of continents) within the assumed prior uncertainties. A certain spatial and temporal aggregation of the fluxes to be optimized in the inversions is required for regularization. This avoids that the lack of information in the measurements leads to an under-constrained problem. For instance, assuming inversions will use daily measurements (afternoon only) from a dozen of tall towers within a continent such as Europe, a maximum of 12 pieces of information per day are available. On the other hand, the specification of fluxes at daily resolutions requires on the order of several hundred to thousands pieces of informa-

tion at spatial resolutions of 50–200 km every day. However, the specified spatial and temporal aggregations are likely to cause errors as found by Kaminski et al. (2001).

In the light of the dominance of near-field fluxes on observed mixing ratios on timescales from hourly to monthly (see Sect. 2.1), the current approach of top-down estimation of fluxes can cause substantial aggregation errors. A simple misrepresentation of vegetation cover within the near field (first 20 km) will cause a substantial aggregation error for the smallest pixel resolved by the model ($\sim$ hundreds of km). On these scales the flux patterns are dominated by variation in vegetation type (Gerbig et al., 2003b). This type of variation is quite common in Europe (and probably not only in Europe), with small patches of different crop changing with pasture or forested patches.

There are two basic approaches to deal with this issue. One can a) allow for a corresponding uncertainty that accounts for the potential errors in representing the local scale fluxes on the various time scales, or b) improve the way fluxes are represented at high spatiotemporal resolution in the a priori flux estimates and thus attempt to largely reduce the required uncertainties. In case a) the inversion will use most of the information to adjust the fluxes within the near field, thus leaving little information on large-scale fluxes. In fact, in this case the inversions would mostly tell us whether the near-field flux is consistent with our prior; discrepancies might be e.g. due to a wrongly specified local vegetation cover in the prior. In the case b) significantly more quantitative information on spatial flux patterns is required, which can only be provided through a combination with bottom-up approaches. An intermediate way would be to use a more detailed description of the covariance structure within a statistical flux model (Rödenbeck et al., 2003), however this also involves more information from bottom-up approaches.

Classical bottom-up approaches use process information collected at the local scale, such as from eddy covariance data (Baldocchi et al., 2001). This information is strictly representative only for small scales (e.g. eddy flux footprints ranging from hectares to about 1 km^2 (Schmid, 2002; Vesala et al., 2008). Even with the large number of about 100 flux towers in Europe, by far the majority of the area covered by terrestrial biosphere is not represented. To estimate fluxes on continental to global scales in the

bottom-up approach, this information is scaled up using process oriented or diagnostic models (Papale and Valentini, 2003; Heimann et al., 2008), partially supported by remote sensing information (Running et al., 2004), gridded weather/climate driver data as well as other GIS information (e.g. soil maps, land use/management data etc.). This up-scaling is associated with uncertainties that are linked with the capability of these models to resolve the local conditions, for instance how to represent the land use history of carbon pools, but also how representative the measurements are for wider areas. Validation of the up-scaled product is therefore essential.

Mixing ratio measurements from a network of atmospheric monitoring stations can in principle provide the required large scale constraint to validate the methods used for up-scaling of process level information. A direct comparison of top-down with bottom-up estimates remains impractical, at least when taking the full uncertainties into account including their temporal and spatial error covariances (Heimann et al., 2008). Comparisons can be made on agreed on spatial and temporal scales such as done in CarboEurope (Heimann et al., 2008), but a comprehensive comparison at high spatiotemporal resolution would require covariance matrices that cover spatial scales ranging from about a few km to account for the near-field constraint from the atmosphere to thousands of km for the large-scale far-field constraint, and temporal scales ranging from hours to multiple years, which would result in a prohibitive size. Taking into account the full covariance is however required in order to quantitatively combine the two estimates to a consistent product. The way out of this dilemma is a merging of the data streams into a model-data-fusion system (see Fig. 3). Such a system that will ultimately use in a quantitative way information from atmospheric mixing ratios measured by tall towers, satellites, and aircraft, as well as information from eddy covariance towers, inventories, and remotely sensed vegetation properties, all providing local to regional information on biosphere-atmosphere fluxes. Our model-data-fusion system basically resembles a global carbon cycle data assimilation system (CCDAS) (Kaminski et al., 2002; Rayner et al., 2005), however it uses a much higher resolution to properly represent transport and fluxes over the continents, with higher resolution nested grids around atmospheric

observation sites that allow for representing the near-field. These high resolution nests are a key element of the data-model-fusion in that they bridge the gap between data and model.

Existing efforts in comparing top down and bottom up fluxes yield a complicated picture (e.g. Heimann et al., 2008). This is due to the difference in scales with inversion estimates still being at considerable larger scale, the lack of detailed information to validate the bottom up surface fluxes (see above), the lack of information on several "small" carbon fluxes (Ciais et al., 2007, 2008), and adequate fossil fuel estimates that may contaminate the concentration data on which the inversion is based. There is also the lack of process representation in the bottom up models that are largely parameterized with regard to their key physiological and ecological processes.

3 Impact on network design

Network design is meant to optimize an observational network for maximum information gain about the targeted product, in this case the surface-atmosphere exchange of CO_2 at high spatiotemporal resolution. The gain in information is equivalent to the reduction in uncertainty, and can in fact only be properly treated in a framework that accounts for the uncertainty in the different parts of the modelling system designed to convert the observations (e.g. point observations of concentrations and fluxes) into the targeted product. Previous attempts to optimize networks have considered mostly a-priori uncertainties, and representation errors and errors in transport were treated only in a very simplistic way (Gloor et al., 2000), or by using an ensemble of different transport models of similar coarse resolution (Rayner, 2004). The resulting optimal networks thus were optimal only in a very limited way, not accounting for many of the problems of models to capture the spatiotemporal variations of CO_2 (see Sect. 3). In the following we discuss a number of implications for network design that we can already anticipate from the findings in Sect. 2, without having the model-data-fusion system in place.

The assessment of the relative importance of the near-field compared to the far-

field, which appears directly related to the properties of atmospheric mixing processes, calls for a good characterization of the surface fluxes in the immediate proximity of tall tower observatories measuring atmospheric concentrations (Sect. 2.1). That way the a-priori uncertainty would be largely reduced in the near-field, allowing for atmospheric concentration measurements to be used as a constraint on the larger scales. Possible approaches for this near-field characterization are the deployment of additional eddy covariance systems, the use of additional shorter (and less costly) towers measuring concentrations, deployment of aircraft measuring fluxes and concentrations operationally or in campaign mode, but also enhanced use of high resolution remote sensing information on surface-atmosphere exchange such as airborne spectral reflectance measurements (Eiden et al., 2007).

A further implication is related to the imperfect representation of vertical mixing in the transport models: taking uncertainty in vertical mixing (or simply in mixing heights) into account has a significant impact on the relative value of column observations compared to a network consisting of surface stations or tall towers. Modelled column integrated concentrations are to first order conserved when the mixing height is changed, while modelled mixing ratios within the mixed layer (where ground-based in-situ measurements are made) directly respond to changes in mixing height. This has a corresponding effect on retrieved fluxes. In fact this is a main reason for designing airborne experiments with multiple vertical profiles that allows a direct assessment of the mixing heights (Ahmadov et al., 2007; Dolman et al., 2006). Thus using column or profile information directly reduces the impact of vertical transport errors. This should be taken into account when comparing the impact of different components of the observing system, such as the e.g. future remote sensing of column CO_2 from space (Crisp et al., 2004), ground based FTIR column measurements (Washenfelder et al., 2006), or operational profile measurements from commercial airliners (Machida et al., 2008) with the ground based observational network.

Another implication of accounting for model uncertainty is that areas that are difficult to simulate, such as complex terrain or mountain stations (Geels et al., 2007) and

land-sea breeze circulations (Ahmadov et al., 2008), need to be associated with a correspondingly large uncertainty. A similar situation arises for complicated synoptic conditions, such as during the time of frontal passages. A way out could be to avoid complex situations entirely (i.e. by data selection), but since on the other hand most continental stations in operation are likely to be influenced by mesoscale flows due to terrain effects (van der Molen and Dolman, 2007), it seems desirable to invest into model development.

4 Conclusions

Network design is intrinsically linked with the capabilities of the tools envisioned to utilize the information produced by the network of observations. This paper has highlighted current shortcomings of these tools, with specific attention to atmospheric transport modelling. A crucial conclusion is that we will always be faced with the issue of limited spatial representativeness of any atmospheric measurement station. We show that for a single tall tower during the growing season the fluxes in the nearest 20–60 km contribute as much as the fluxes from all other areas combined. Given the current development towards high resolution information in top-down inversions, this paper calls for a specific model-data-fusion approach that combines top-down and bottom-up approaches. In this approach it is vitally important to reduce the errors that are associated with current low-resolution transport models used in the inversions. The suggested way forward is to develop nested modelling systems that optimally take into account the need for high resolution models near observation sites. Although this paper has not proven that this approach of high resolution model-data-fusion will solve the problems of the near-field representativeness, it seems obvious to us that it will.

A specific recommendation for network design is made based on the, as yet, inherent limitations of current modelling frameworks. We suggest that the near field of towers should receive special attention with additional information provided by flux towers, allowing for atmospheric constraints to have more impact on the large scales inacces-

sible to direct flux measurements. This calls for studies that specifically address the interaction between small and large scale and the dilution of information content when moving away from the observation site. Further, measurements of vertical profiles and/or meteorological measurements allowing the determination of mixing heights are highly recommended at the atmospheric monitoring sites to help reduce the uncertainties in simulated vertical mixing.

Only an adequate treatment of the associated uncertainties of the different components of the system will allow optimal use of resources in assessing surface-atmosphere exchange of greenhouse gases. Such treatment of all involved uncertainties provides the direct incentive to improving the modelling capabilities, either by using models with higher resolution, or by using additional data to constrain them. We thus envision using local meteorological observations made at the tall towers such as winds and temperature, but also mixing height information from nearby radiosondes or from ceilometers to improve the transport simulation where it matters most, in the near-field of the stations measuring concentrations.

A fundamental question that arises is whether a model-data-fusion system such as proposed in this paper can be validated. One might argue that a model-data-fusion approach with many data streams as input, specifically when bringing together the bottom-up and the top-down approach, leaves no source of information for validation or falsification of the results. However, bringing together the different data streams in one model-data-fusion system, allows in fact for a much better validation of the system as compared to the classical top-down and bottom-up comparison: given that each data stream is associated with uncertainties resulting from experimental and model errors, one can in the simplest case use statistical tests such as chi-square tests. Thus by comparing remaining residuals between observations and simulations, one can identify if certain parts or aspects of the model are biased. Alternatively, the model-data-fusion system permits to leave out individual constraints and compare the resulting fluxes on specific spatiotemporal scales. This would for example allow for, but is not limited to, a classical comparison of the top-down constraint from the atmosphere with the

constraint from bottom-up information (e.g. flux towers data).

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Table 1. Uncertainties involved in model-data-fusion using mixing ratio measurements to derive regional fluxes of CO_2, and impact on the observational strategy when attempting to minimize their impact on flux estimates.

Source of uncertainty	Type or error	Size	Impact on observational strategy	Reference
Transport Model	Advection	~5 ppm (summertime)	avoid regions with complex flows	Lin and Gerbig (2005)
	PBL mixing	~3.5 ppm (summertime)	Vertical profiling, column observations	Gerbig et al. (2008)
	Convection	No estimate		–
	Mesoscale processes	~2–3 ppm (summertime)	Avoid regions with mesoscale flows	Van der Molen and Dolman (2007), Tolk et al. (2008)
Transport and Flux Model	Grid resolution	~1 ppm @ 200 km (summertime)	Choice of representative stations	Gerbig et al. (2003)
Flux Model	Prior uncertainty	2–8 ppm*** (summertime)	network elements distributed according to prior uncertainties	P. Peylin, personal communication (2008)
	Aggregation	Depending on Aggregation and Model		Gerbig et al. (2006)
Measurement	Precision, accuracy	0.1 ppm (targeted)	WMO	WMO

*** using different biosphere models coupled to the same transport model

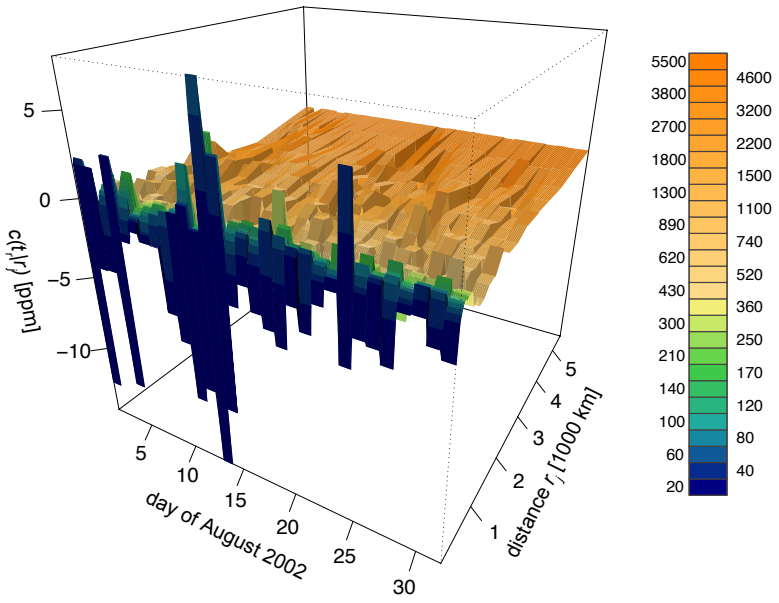

Fig. 1. Contribution to the afternoon signal (15:00 local time) due to biosphere-atmosphere exchange at different distances from the measurement location for the period of August 2002, shown as contributions from the individual annuli. The color legend indicates the radius of the outer boundary of each annulus.

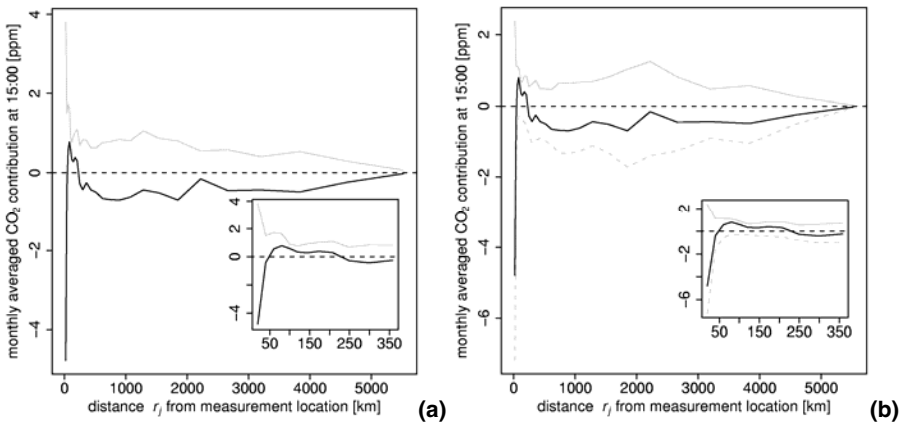

Fig. 2. Monthly-averaged contributions to the signal at 15:00 local time due to biosphere-atmosphere exchange at different distances from the measurement location, shown as contributions from the individual annuli with grey lines indicating monthly standard deviations **(a)**, and together with contributions from respiration and photosynthesis fluxes (grey solid and dashed line, respectively) **(b)**.

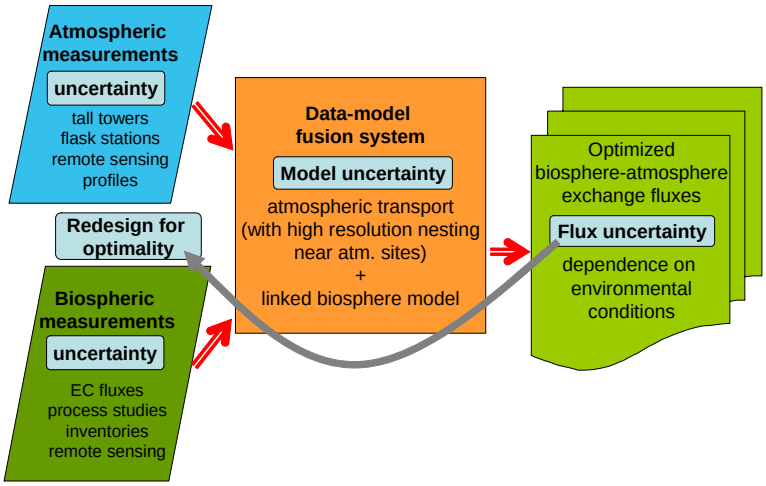

Fig. 3. Simplified schematics of a Model-Data-Fusion system using multiple data streams to derive information on surface-atmosphere fluxes.