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1. Introduction

1.1 Short summary

The report outlines the rational for defining the accuracy for an carbon observing system, based on a review of the size of the fluxes expected at a particular time and space scale. It concludes that ath regional scale specific network design studies need to be executed to consolidate the views and estimates derived in this report.

1.2 Rationale for this deliverable

This deliverable reflects only on the atmospheric concentration observations accuracy. While it fulfills the requirements as set out in the DoW (14.1), it is evolving into a work in progress, addressing more than just the atmospheric concentration observations. This will yield an update of this deliverable towards the end of the project.

1.3 Problems encountered and envisaged solutions

The actual delivery took longer. The report will be reviewed in the second reporting period, and updated when network design studies are being undertaken. One of the questions still to be resolved is how to extend the report along lines of the other observation systems. This was not originally foreseen in the DoW.

2 Full description

Accuracy requirements for an Integrated Carbon observing system

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Preamble

This deliverable reflects only on the atmospheric concentration observations accuracy. While it fulfills the requirements as set out in the DoW, it is evolving into a work in progress, addressing more than just the atmospheric concentration observations. This will yield an update of this deliverable towards the end of the project.

Introduction

Understanding the dynamics of current CO_2 levels requires better quantification and process-level understanding of the state of the global carbon cycle, including both the natural components and anthropogenic contributions. The current state of the science can neither confidently account for the processes governing the CO_2 average growth rate nor for the interannual variations. Similarly, needs for independent verification of greenhouse gas emissions at levels relevant to policy and UNFCC require more precise determination and observation. However, limitations in our current understanding and observation capability prevent the precise location of key sink or source regions and its associated dynamics. In addition, fossil fuel emissions estimated from energy use statistics cannot be validated by independent observations, hindering a transparent monitoring of efficacy of policy from climate treaties. To be able to support these issues with observations a monitoring system for carbon and non-GHG needs to be developed. Questions that will need to be addressed by the science based on such an observing system are (Ciais et al., 2013):

- What are the magnitude, distribution, and trends of anthropogenic CO_2 and CH_4 emissions that impact the global carbon cycle?
- What are the magnitude, distribution, variability, trends, and processes controlling present-day terrestrial and marine CO_2 and CH4 sources and sinks~~,~~
- How effective will national, regional and city- scale policy interventions be in reducing greenhouse gas emissions and increasing carbon sequestration?
- How are CO_2 and CH_4 sources and sinks likely to behave in the future under higher atmospheric CO_2 concentrations and altered patterns of climate, land vegetation, and ocean circulation?
- How soon might feedbacks that may enhance natural CO_2 and CH_4 emissions or reduce sinks, possibly associated with thresholds, come into play over different sensitive regions, and how could these feedbacks be detected and quantified by observations?

This non-exhaustive list presents questions at a range of space and temporal scales. How to deal with these scales in a single observing network is a key question. Arguably, each scales and question poses a different demand on the accuracy of the observing system. As an example if we need to be able to determine synoptic scale disturbances, the network needs to be spaced in such a way that the synoptic scale can be resolved. Typically this would be L/2, with L being the scale under interest, in the case of synoptic scale disturbances about 200-500 km. In contrast if we need to determine the mean annual atmospheric XCO2, we can assume that the atmosphere mixes well over a year, and in principle, a single measurement station, like Mauna Loa would suffice. In that case, assuming a 1-2 ppm global increase per year (Canadell, et al., 2010) would require an accuracy of 0.1-0.2 ppm if we aim for an error of 10%. On another note, impacts of sea-breezes, or power plants (Bovensmann et al., 2011) on XCO2 may easily lead to variability of the order of a few ppm regionally (Ahmadov et al., 2009) and thus would call for a high density (L<10 km) but low accuracy network.

The above examples make it clear that a single design for an observation network that covers all relevant scales does not exist, unless we are able to observe at global scale at very high density and accuracy. A more pragmatic approach would involve defining the needs to observe specific signals that are associated with the carbon cycle, both the natural as well as the human perturbation. This is the approach followed here. By briefly reviewing the main important signals, and aligning them in a matrix of space versus time, we can then determine the accuracy of the network that is required to observe them. Specific network design studies (Kaminsky et al, 2012) are then needed to develop the optimum spatial arrangements of the observing stations that make up the system.

	Synoptic	Seasonal	Annual budgets	Interannual trends
Global		FF Emissions 10 PgC/yr 2 ppm/yr	Global growth rate 2-3 ppm/yr	Variability in lobal growth rate 0.5-1 ppm/yr
Continental 1000*3000 km	Fossil fuel emissions of China 5 ppm	Drought, LUC 0.5-1 PgC/yr 1-2 ppm/yr	Budgets 1 PgC/yr 2 ppm	El-Nino, AMO response, Permafrost melt, Amazon die back, 0.2 ppm/yr
Country 500*500 km		LUC, extreme weather 0.5 PgC/yr 10 ppm/yr	Kyoto Budgets 0.1 PgC-1 PgC/yr 5 ppm	Kyoto budgets 0.05-0.1 PgC/yr 5 ppm
Point sources	Forest fire, powerplants 1-10 ppm (column)	Forest fire 0.2 TgC/yr 1 ppm	Powerplant, cities 0.5TgC/yr 1 ppm	Cities 0.5 TgC/yr 1ppm/yr

Table 1 - Signal strengths in the atmosphere

Global

Table 1 provides a matrix of space and time scales relevant to the carbon cycle. Below we discuss the relevant background for these signal strengths. The best known curve is the global growth curve of XCO2. The current global growth rate is around 2-3 ppm yr^{-1}, representing roughly 50% of the 10 Pg C yr^{-1} that are emitted as a result of fossil fuel burning and cement production (Peters et al., 2012). The network accuracy of this global mean average is of the order 0.5 ppm (~ 10% error): this is currently much higher than the actual performance of WMO Global Atmospheric Watch which states as the Data Quality Objectives (DQO) for CO2
as ±0.1 ppm in the Northern Hemisphere, and ±0.05 ppm in the Southern Hemisphere (Technical Report of Global Analysis Method for Major Greenhouse Gases by the World Data Center for Greenhouse Gases (WMO TD No. 1473), 29 pp, June 2009). Note that with increasing emissions the accuracy as estimated here in fact goes down. To determine the interannual variability in this number, we need a better accuracy, as typically this is of the order of 1-2 Pg C yr^{-1}. To accurately determine these variations with an error of 10% requires a network able to operate at an accuracy of 0.1 ppm or even smaller, which is commensurate with the DQO as quoted earlier. It is important to stress that we deal here with annual global averages, that can be based on the assumption of the atmosphere as a perfect mixer. The spatial aspect implies that relative few undisturbed location can manage determination of these components, as in fact is practice since Keeling started the

measurements in 1958 at Mauna Loa. Similarly specific stations, i.e. Cape Grim or other, may be sampling large areas

Continental

The observation requirements become more complicated when we move towards smaller spatial and temporal scales and the determination of sources and sinks. While the emission of fossil fuels is estimated at a current 10 pG C yr^{-1}, determining the fossil fuel emission of for instance China poses stronger problems. China's emissions are currently estimated at 3.5 Pg C yr^{-1} over an area of 9.6 10^{6} km^{2}, i.e. 360 g Cm^{-2}. This amount of carbon released in the atmosphere would cause an increase globally of about 2-3 ppm. Now this emission is concentrated at only 2% of the Earth's surface area into the overlying atmosphere. Determining the emission at 10% of its value requires an accuracy of 0.35 Pg C yr^{-1} or 36 Cm^{-2}. Translating this into a ppm requirement is even more complicated as the atmosphere mixes well and the emissions are effectively spread out. Even more importantly, we are now not interested in solely the atmospheric XCO2, but want to determine a sink or source against the "natural" background of biospheric fluxes that may be as large as the fossil fuel flux. There are two ways to determine then the flux of $CO2_{ff}$: 1) using other trace gasses, such as ^{14}CO2 or CO, SF6 assuming that these trace gasses are advected together (Levin, 2003), or 2) using inverse models, which prescribe the a priori value of the biospheric flux and are in need of adequate transport descriptions. In the first case, observations at a single site are in principle sufficient. The key question here is whether the required accuracy can be met.

Turnbull et al. (2011) show that $CO2_{ff}$ of China varies with synoptic conditions, with a mean of 4.1 ppm and 10th, and 90th percentiles of 0.4, and 15.8 ppm. This is the signal strength quoted in Table 1. Note that other measurements than just XCO2 are used to derive this value. The XCO2 requirement of 0.1 ppm is sufficiently adequate to determine the XCO2 variability. The network design is here an important issue.

At the continental scale, large scale droughts can lead to substantially modified emissions or uptake patterns (Cias et al, 2005, Peters et al., 2010). The detection of these is important and we try here to derive the required accuracy of the observing systems. Drought typically occurs at synoptic scales, of order a few hundred to thousand kilometers. Ciais et al. (2005), using eddy covariance observations and modeling estimate the reduction in uptake led to a loss of 0.5 pG C in 2003.

A sink of that order requires (Ramonet et al., 2010) a consistent change of the order of 1 ppm over Europe in the mixed layer. Ramonet et al (2010) noticed a small (0.5-0.75 ppm yr-1) trend in land station over Europe that they later Aulagnier et al. (2010) attributed to changes in atmospheric transport. The corresponding difference between the lowest and highest values (winter-summer) is of the order of 10 ppm. These are all quantities that can be observed by the current accuracy of the WMO network. Note that the spatial representation of these observation sites is a totally different matter. If the interest is in synoptic scale phenomena, obviously the spacing needs to be such that these can be resolved at order 200-500 km.

Local, poweplants

There is considerable interest to be able to determine emission rates of powerplants. Large plants typially emit 5-10 Mton C yr-1. Bovensmann et al (2010) suggest that this leads to an increase of 2-3% in the column, nearby the plant. This poses considerable detection problems, that appear only solvable by airborne or satellite remote sensing techniques. The detection of forest fires and similar sources poses the same set of problems.

Network design

The issues listed above can only be fully resolved when network design studies are made (e.g. Kaminsky and Rayner, 2008). This requires setting a target quantity, the overall net exchange of an area, the exchange per land use type, or other and evaluating for several candidate networks, the posterior uncertainty. The target quantities as listed in Table 1 can serve this purpose.

The accuracy required of a network designed to observe the target quantities listed in Table 1 can be calculated if multiplied by the required uncertainty. In the case of observing the consequences of a synoptic scale drought to 10% this requires 0.05 PG C to be detected with a network that is sufficiently well spaced and accurate to achieve this. Note that uncertainty of a priori values and transport also play a role here. These questions can only be addressed by specific network design studies. And, even then, do we wish to know the overall flux or that from the land use components, individual pixels, of what length ?

Next steps

Agree on a set of network design studies at the spatial and temporal scales defined in Table 1. Set the required accuracy (i.e. as a percentage of the required signal strength) and run the studies.

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