Supporting the improvement of the carbon observing system by quantitative network design

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ABSTRACT

We use the Carbon Cycle Data Assimilation System in quantitative network design mode and evaluate observational networks consisting of various types of in situ observations as well as a space mission.

INTRODUCTION

For analysing and eventually predicting the behaviour of the global carbon cycle we rely on observational constraints, collected by the global observing system. Ideally, all data streams are interpreted simultaneously to yield a consistent picture of the carbon cycle that balances all the observational constraints, thereby taking the respective uncertainty ranges into account. Data assimilation systems around prognostic models of the carbon cycle are the ideal tools for this integration. In a first step, they use the observations to constrain the model, and in a second step, they use the calibrated model for analysis and prediction. Ideally, both steps include the propagation of uncertainties. This allows to derive uncertainty ranges on diagnostic or prognostic target quantities that are consistent with the uncertainties in the observations and the model. Examples of such target quantities are fluxes of carbon on regional, continental, or global scale, integrated over some period in the past or the future. With regard to a specified target quantity, such an assimilation system can assess the performance of a given observational network. This performance is quantified by the uncertainty range on the target quantity that is consistent with the observational constraint. Quantitative network design is the construction of an observation system with optimal performance (Kaminski and Rayner, 2008). We demonstrate quantitative network design using the Carbon Cycle Data Assimilation System (CCDAS, Rayner et al., 2005). CCDAS is build around the comprehensive terrestrial biosphere model BETHY (Knorr, 2000), coupled to the atmospheric transport models TM2 (Heimann, 1995) and TM3 (Heimann and Körner, 2003). We present two applications, one addresses the ground-based network, the other one is a preparatory study for a space-borne sensor for atmospheric CO2.

METHOD

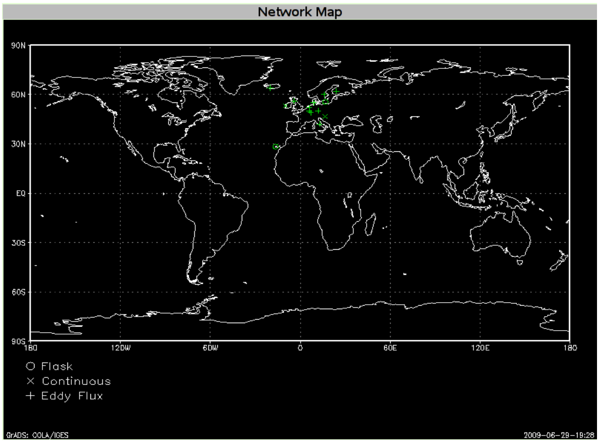

Fig. 1: Base network

CCDAS uses a gradient method to adjust about 60 process parameters in order to minimise a cost function. This cost function quantifies the fit to all observations plus the deviation from prior knowledge on the process parameters. The second derivative of the cost function at the optimum is used to infer uncertainty ranges on the parameters that are consistent with uncertainties in the observations and the model. In a second step, the linearisation (Jacobian) of the model around the optimum is used to propagate the parameter uncertainties forward to uncertainties in diagnostic or prognostic target quantities. All derivative information is provided in efficient form via automatic differentiation of the model code (Giering and Kaminski, 1998). In network design mode, the system is restricted to the uncertainty propagation for candidate networks. It builds on the parameter set estimated from data of the current network for the calculation of the required first and second derivatives, that express the model's sensitivities of target quantities and observations to parameter changes. Candidate networks are defined by a set of observations characterised by observational data type (such as atmospheric flask samples of carbon dioxide or a direct flux measurements), location, and data uncertainty. The data uncertainty reflects observational errors and model errors, including the error from representing a point measurement by a value extracted from a model grid box. In practise for pre-defined target quantities and observational types and locations, model sensitivities can be pre-computed and stored. A network composed of these pre-defined observations, can then be evaluated in terms of the pre-defined target quantities without further model evaluations. Only matrix algebra is required to combine the pre-computed sensitivities with the data uncertainties.

NETWORK DESIGNER

The network designer (see http://imecc.ccdas.org) is an interactive tool that evaluates networks composed of flask and continuous samples of atmospheric CO2 and direct flux measurements. Available target quantities are net primary productivity (NPP) and net flux (NEP) over three regions: Europe, Brazil, and Russia. Model sensitivities have been pre-computed for a list of atmospheric sampling sites. For flux measurements, model sensitivities have been pre-computed for every terrestrial grid cell and up to three plant functional types. For a demonstration, we start from a simple European observing system composed of two flask sampling sites, two sites with continuous CO2 samples and 10 sites with direct flux measurements, all active over 20 years (base network). We evaluate the effect of excluding in turn the flask sites (noflask) the continuous sites (nocont), or the flux sites (noflux). Table 1 shows the performance of the respective networks together with the performance of the case without observations (prior).

Network	NEP Eur	NEP Rus	NEP Bra	NPP Eur	NPP Rus	NPP Bra
prior	0.45	1.45	1.13	0.66	1.08	4.86
base	0.01	0.09	0.08	0.01	0.06	0.19
noflux	0.08	0.19	0.12	0.12	0.24	0.82
noflask	0.02	0.14	0.11	0.01	0.06	0.22
nocont	0.03	0.16	0.28	0.01	0.06	0.29

Table 1: Posterior uncertainties in GTC/yr

ASCOPE

We explore the benefit of the concept for ESA's Earth Explorer candidate mission A-SCOPE, which would use an active LIDAR instrument to observe the column-integrated CO2 concentration. We use the TM3 model to pre-compute observational operators for vertical weighting functions corresponding to two potential wavelengths, namely 1.6 micron and 2.0 micron. We use the same target quantities as the network designer. Within CCDAS, A-SCOPE yields considerably better reductions in posterior uncertainties than the ground-based flask sampling network used by (Scholze et al., 2007). This is true for assimilating monthly mean values and instantaneous values, and it is true for both the 1.6 micron band and the 2.0 micron band vertical weighting function. The strength of the constraint through A-SCOPE observations is high over the range of observational uncertainties from 0.05 to 1.25 ppmv over land and from 0.15 to 3.75 ppmv over ocean. For details we refer to Kaminski et al. (2009).

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