Climate Data Assimilation using inverse modelling: Application to the Carbon Cycle

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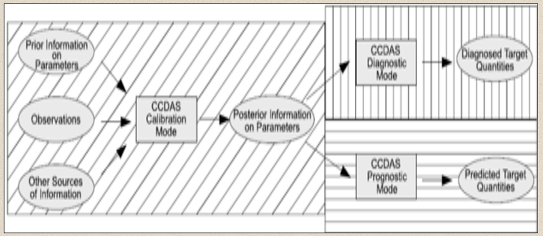
ABSTRACT

Uncertainties of the terrestrial carbon cycle have stimulated the climate research community to build complex observing systems. These observations of many forms are made either at a point or with detailed spatial coverage. In order to incorporate them into underlying modelling frameworks, **assimilation techniques are being developed**, similar to numerical weather forecasting. One main difficulty is that the underlying models of the terrestrial biosphere are much less developed than in meteorology. Thus, there are large uncertainties both on the underlying model and on the observation operators.

An application of the **assimilation system CCDAS** (Carbon Cycle Data Assimilation System) is presented: The observations are atmospheric concentrations and the observation operator is an atmospheric transport model that links carbon fluxes to atmospheric concentrations. Two different representations of the transport model and two different networks are tested. In addition, simulations with a global transport model have been performed to check the sensitivity of the assimilation system to the network.

CCDAS

CCDAS consists of a biosphere model BETHY (Biosphere Energy Transfer Hydrology) [1] and an atmospheric transport model, together with CO_2 fluxes representing ocean flux, land use change and fossil fuel emission [2,3]. CCDAS has two main modes of operation (Figure 1):



Optimization/Calibration mode: This step allows calibrating the physical process parameters of BETHY via a comparison with observed CO_2 concentrations.

Diagnostic/Prognostic mode: Using the optimized parameters of BETHY, CCDAS allows the calculation of diagnostic[2] and prognostic[3] quantities.

Figure 1: The two-steps procedure for inferring diagnostic and prognostic target quantities from CCDAS. Rectangular boxes: processes; Oval boxes: data; Diagonally hatched box: optimization or calibration step; Vertical hatched box: diagnostic step; Horizontally hatched box: prognostic step.

MODEL AND DATA

BETHY

BETHY, the core model of CCDAS, is a process-based model of terrestrial biosphere which simulates carbon assimilation and plant and soil respiration, embedded within a full energy and water balance[2,3]. It uses 13 plant functional vegetation types. It is implemented on a 2°x2° grid box, and is driven by climate and radiation data.

Transport Model

A 'full' atmospheric transport model is not actually used. The pre-computed sensitivities of atmospheric CO_2, at a given observed station, to global CO_2 fluxes are rather considered[2,3,4]. These sensitivities, also called Jacobians, allow the calculation of the change in concentration at a given point in response to a source field. In this study, Jacobians of **two versions of TM with different resolutions**, namely TM2 [5] (8° latitude by 10° longitude) and TM3 [6] (3.75° latitude by 5° longitude), are considered.

Set up

Jacobians for 41 and 68 sites for CO_2 concentration observations from TM2 and TM3 are used, respectively. The CO_2 observations and the Jacobians cover the 1980-2000 period, but TM2 uses only one year of winds. Three sets of optimized parameters of BETHY are computed :

- **TM2**: optimization with TM2 Jacobians with observations at 41 sites
- **TM3^{2*} (TM3^3)** : optimization with TM3 Jacobians with observations at 38 (68) sites

Comparing TM2 to TM3^2 shows the sensitivity of the optimisation to the transport model while comparing TM3^2 to TM3^3 shows the sensitivity to the station network.

SOME RESULTS

Net Ecosystem Production (NEP)

Figure 2 (summarized in Table 1) shows the net CO_2 flux between the biosphere and the atmosphere (NEP), obtained from the atmospheric networks for the 3 simulations:

- Similar NEP distributions are obtained for the 2 TM3 assimilations, which are quite different from TM2 results, particularly in the tropics and southern hemisphere. Thus, the NEP shows a high sensitivity to the transport model, in terms of spatial resolution and meteorology (TM2 has a coarser resolution than TM3 and uses only one year of winds).
- The near-neutral NEP of the TM3 simulations seems more reasonable than the large southern hemisphere source of TM2.

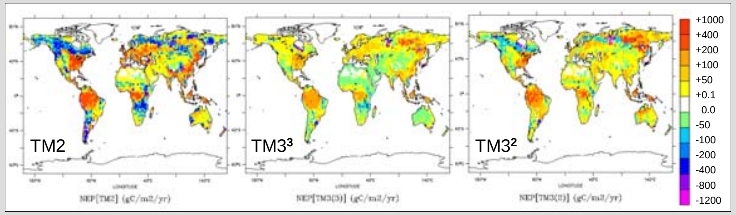


Figure 2: Map of Net Ecosystem Production (NEP in gC/m^2.yr) for simulations using TM2 (left), TM3 with 68 stations (TM3^3: centre) and TM3 using 38 stations (TM3^2: right))

CO_2 fluxes (GtC/yr)	TM2 8° x 10° **41 stations**	TM3^2 3.75° x 5° **38 stations**	TM3^3 3.75° x 5° **68 stations**
NEP	**2.27**	**2.08**	**2.04**
	0.88	**1.07**	**1.11**
	2.40	**1.07**	**1.05**
	-1.01	**-0.06**	**-0.12**
GPP	**115.3**	**123.4**	**94.6**
	35.6	**27.4**	**25.7**
	76.6	**93.2**	**66.2**
	3.9	**2.9**	**2.8**

Table 1:
NEP and GPP derived from the optimized model BETHY by using TM2, TM3 with 38 stations (TM3^2), and TM3 with 68 stations (TM3^3):

- Global (**black**)
- Northern hemisphere [20°N-90°N] (**blue**),
- Tropical [20°S-20°N] (**red**)
- Southern hemisphere [90°S-20°S] (**green**)

Gross Primary Productivity (GPP) [Figure 3 and Table 1]

- Unlike NEP, the greatest differences are between TM3^2 and TM3^3
- Thus, the choice of network seems more important than the choice of the model
- Largest differences are in the tropics, i.e. where more additional stations are considered

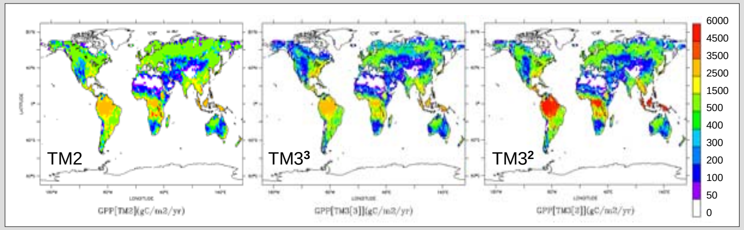


Figure 3: Map of Gross Primary Productivity (GPP in gC/m^2.yr) for simulations using TM2 (left), TM3 with 68 stations (TM3^3: centre) and TM3 using 38 stations (TM3^2: right))

Additional Simulations

CO_2 surface concentrations were simulated with CCDAS at the 30 additional stations of TM3^3 but using parameters from TM3^2

- Results are very close to the simulation using TM3^3 parameters

The 30 extra stations do not bring much extra information on GPP. Is this a property of this specific network, or of atmospheric measurements in general?

CO_2 surface concentrations were simulated with LMDz-INCA(7) global climate model using NEP from TM3^2 and TM3^3

- Only small differences are found at the stations (consistent with the small change in cost function), but large differences elsewhere. Thus the observational network needs to be optimized to observe the primary productivity.

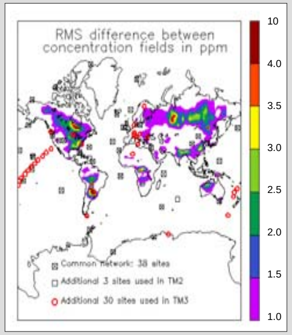


Figure 4: RMS difference (ppm) between CO_2 concentration fields using NEP of TM3 with 68 stations (i.e., TM3^3) and TM3 with 38 stations (TM3^2). Simulations are performed through the transport model LMDz-INCA.

CONCLUSIONS

Our investigations show that:

- The patterns of NEP produced by CCDAS are more sensitive to the behaviour of the transport model while those of GPP depend more on the observing network
- A network that can constrain the NEP is not necessarily optimized to constrain the GPP
- A denser atmospheric network, e.g., satellite CO_2 measurements, may be used to constrain the primary productivity
- The direct measurement of CO_2 fluxes in some sensitive areas such as the Tropics may help to better constrain the primary productivity

* The data for the two models is computed slightly differently but we repeated TM3^2 using an exact subset of the TM2 data and produced very similar results to TM3^2

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