4D-Var data assimilation of atmospheric CO$_2$ from infrared satellite sounders

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Thanks to: Soumia Serrar, Yogesh Tiwari, Frédéric Chevallier and many others.
Outline

• COCO project – 1st attempt with a relatively simple data assimilation system

• GEMS project – towards a full 4-dimensional greenhouse gas data assimilation system

• Outlook & Conclusions
COCO (Measuring CO$_2$ from space exploiting planned missions 2001 - 2004) was an European Union funded Integrated Project (IP) within the Fifth Framework Programme.

The purpose of the COCO project was to take advantage of already planned satellite missions to develop, evaluate and apply methods for the estimation of CO$_2$ column inventories from space and subsequently to estimate CO$_2$ emissions and CO$_2$ surface exchange fluxes.
4D-Var Data Assimilation

4-dimensional variational data assimilation is in principle a least-squares fit in 4 dimensions between the predicted state of the atmosphere and the observations.

The adjustment to the predicted state is made at time $T_0$, which ensures that the analysis state (4-dimensional) is a model trajectory.
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$\text{CO}_2$ is added to the state vector as a tropospheric column amount for each AIRS observation.
CO$_2$ column estimates

Mar 2003

Mar 2004

Sep 2003

Mar 2003
Comparison with in-situ observations

Japanese flight data kindly provided by H. Matsueda, MRI/JMA
Comparisons with models

Figure 7: Monthly mean CO₂ (ppm) averaged zonally and over 5° latitudinal bands as retrieved by AIRS and simulated by TM3 and LMDZ.
Comparisons with models

Figure 9: Zonal mean latitudinal variation of CO₂ (ppm) averaged over two months period. (A) over land and ocean, (B) only over land, (C) only over oceans.
GEMS

GEMS (Global and regional Earth-system Monitoring using Satellite and in-situ data) is an European Union funded Integrated Project (IP) within the Sixth Framework Programme.

The project will create a new European operational system for global monitoring of atmospheric chemistry and dynamics and an operational system to produce improved medium-range & short-range air-chemistry forecasts, through much improved exploitation of satellite data.
GEMS organisation

Data input (Assimilation, Evaluation)

Reactive Gases

Greenhouse Gases

Aerosol

GEMS Global System

Validation

Regional Air Quality

Products, User services

Coordination

System Integration

oxidants

GHGs

optical properties

boundary conditions
Greenhouse gas activities

Development of RT models and bias correction methods

Definition of background error covariance matrix

Building of surface flux parameterization/model

AIRS, IASI, CrIS, Sciamachy, OCO, GOSAT observations

CO\textsubscript{2} & CH\textsubscript{4} Flux Inversions

Validation

CO\textsubscript{2} & CH\textsubscript{4} analysis data

4D VAR data assimilation system

4D VAR data assimilation system
In the 4D-Var version, CO$_2$ is added to the state vector $X_0$. This means that only changes to the initial CO$_2$ field can be made to fit the observations within the assimilation window.
CO$_2$ surface fluxes - climatology

Ocean

Takahashi CO2 flux
kg C/m2/second x 10^4 [-9]

January

July

University of Leeds  ECMWF  2 March 2006
CO₂ surface fluxes - climatology

Natural Biosphere

CASA Net Ecosystem Production

December

Global Mean = -1.044

July

Global Mean = 3.913

University of Leeds

ECMWF

2 March 2006
CO₂ surface fluxes - climatology

Anthropogenic

1995 carbon emissions
1000 tonnes C/grid cell

Global Mean = 109
Using climatological fluxes (CASA, Takahashi, and Andres) we have made a 2 year run to test the system at resolution T159 (~ 1.125°).
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**CO₂ in ECMWF forecast model**
Comparisons between CMDL surface flasks and the free-running ECMWF model show good agreement for the north-south gradients.

Southern hemisphere model values are slightly too low (missing biomass burning??)
Comparisons between CMDL surface flasks and the free-running ECMWF model show good agreement for the seasonal cycle. Northern hemisphere summer model values are slightly too high (missing land sink??)
A negative offset and a 15h filtering is applied to observations.
CO$_2$ 4D-Var setup

- T159L60 (1.125° x 1.125° with 60 levels)
- 6-hour assimilation window
- Background covariance:
  - Each layer only correlated with 2 layers directly above and below
  - Horizontal correlation length of 500 km
  - Standard deviation of 2 ppmv
- Operational AIRS bias correction
- Operational AIRS cloud detection
After 31 days of 4D-Var, the analysis has increased the global mean value as well as the spatial gradients.

The increments in any analysis cycle are within ± 3 ppmv.
The effect of assimilating AIRS radiances is mainly to increase CO₂ mixing ratios in the upper troposphere and reduce mixing ratios in the SH stratosphere.

However, a very simple background error matrix was used!!!
CO$_2$ flux inversions

Simulated flux inversions for OCO data show error reductions between 0 and 20% over the ocean and between 10 and 40% over land.

The difference is caused by the small a priori flux errors over ocean compared to the land fluxes.

These estimates assume there are no significant systematic errors.

Thanks to Frédéric Chevallier
Near-future improvements

- Use of diurnal biosphere fluxes
- Possible use of flask optimized fluxes
- Better specification of background covariance matrix
- 12 hour assimilation window
- Different AIRS channel selection
- Use of IASI radiances
- Implement CH$_4$
Conclusions

• First relatively simple implementation of CO$_2$ variable in operational data assimilation system proved successful

• Work in progress to build a full 4D-Var greenhouse gas data assimilation system that can combine observations from various satellite sensors to estimate atmospheric CO$_2$

• These 4D atmospheric fields will then hopefully contribute to a better quantification and understanding of the carbon surface fluxes.