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CO$_2$ from space: estimating atmospheric CO$_2$ within the ECMWF data assimilation system

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In 2001 a report by the Intergovernmental Panel on Climate Change (IPCC) noted that *"the atmospheric concentration of CO$_2$ has increased from 280 ppmv in 1750 to 367 ppmv in 1999 (31%). Today's CO$_2$ concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. The rate of increase over the past century is unprecedented, at least during the past 20,000 years."*

Currently, the global mean atmospheric concentration is about 380 ppmv. Interestingly enough, this is less than could be expected based on anthropogenic emissions. Somehow, the land and ocean take out half the amount of CO$_2$ that is injected in the atmosphere by the anthropogenic emissions. Accurate quantification of the processes responsible for this so-called 'missing sink' is not yet available.

Within the COCO project, funded by the European Commission, ECMWF has implemented a CO$_2$ estimation within the data assimilation system to monitor atmospheric CO$_2$ concentrations. European research groups will use these estimated concentrations to improve their surface flux estimates in order to solve the 'missing sink' problem.

More than a year of satellite data from the Advanced Infrared Sounder (AIRS) has now been processed and results are very promising. Comparisons with independent observations show that the data assimilation system is able to estimate tropospheric column CO$_2$ with an accuracy of better than 1%. Although these estimates are not sensitive to the boundary layer concentrations, the wealth of spatial information will help to improve the flux inversions that are currently based on the surface flask network. Recent comparisons show that for the first time we have a dataset that is able to evaluate differences between CO$_2$ climate model simulations on a global scale. Within the EU-funded GEMS (Global and regional Earth-system Monitoring using Satellite and in-situ data) project the CO$_2$ analysis system will be extended to a full 4D-Var system that will be able to assimilate CO$_2$ information from various instruments. Further information about GEMS can be found in the spring 2005 edition of the ECMWF Newsletter.

Carbon cycle

In 1957 Charles Keeling and colleagues started observing atmospheric CO$_2$ concentrations at Mauna Loa, Hawaii, and at the South Pole. Concentrations have risen from 313 ppmv (parts per million by volume) in 1957 to 380 ppmv in 2004, an increase of about 20% in 50 years. It is now clear that this increase in atmospheric CO$_2$ is largely due to anthropogenic emissions, such as combustion processes, cement production, and biomass burning. Since these early observations, a network of accurate flask measurement sites has been set up to obtain a better idea of the variability of atmospheric CO$_2$. From these observations and from our knowledge of the amount of anthropogenic emissions an interesting result arose: only half the amount of anthropogenic emissions accumulates in the atmosphere. The other half is somehow absorbed by the ocean and/or land biosphere. This phenomenon is now widely known as the missing sink (see Figure 1).

Much of the carbon cycle research has been focused on the possible processes that can account for the missing sink. Bottom-up approaches try to build better flux models for both the ocean and the natural biosphere. At the same time top-down methods have used the flask observations together with atmospheric transport models to infer flux estimates. The main problem with the latter approach, the flux inversions, is the data sparseness. Only about 100 surface flask sites exist today and the inversion problem therefore strongly relies on the atmospheric transport model being used. This has not helped research groups reach consensus as to which processes are responsible for the uptake of anthropogenic emissions. Observing atmospheric CO$_2$ with satellite instruments is therefore regarded as a very promising way forward to improve flux inversions. However, there are currently no satellite instruments that have been specifically designed to observe CO$_2$.

Both the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) are building designated CO$_2$ instruments that will use solar reflection in the near infrared to observe atmospheric CO$_2$ concentrations (Orbital Carbon Observatory, OCO, and GOSAT, respectively). These instruments will potentially provide accurate observations, but they also suffer from poor reflectivity over ocean, aerosol interference, and the need for solar radiation. Meanwhile, the AIRS instrument flying on board of the NASA Aqua satellite observes the infrared part of the spectrum at high spectral resolution.

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Important absorption bands in the infrared part of the spectrum consist of CO_2 absorption lines. Traditionally, these CO_2 absorption lines have been used to infer atmospheric temperatures from the measurements assuming the CO_2 concentration to be fixed. It is possible, though, to estimate both temperature and CO_2 from these observations by either adding other absorption bands (e.g. water vapour) or making assumptions about for instance the vertical profile of CO_2 (e.g. well-mixed profile). Another possibility is to add observations from other instruments that provide information about the temperature profile as is routinely done in a numerical weather prediction (NWP) data assimilation system. However, the amount of independent CO_2 information is small and can easily be obscured by the other signals and/or the noise in the observations and the radiative transfer modelling. Also, measurements in the infrared are generally not sensitive to atmospheric CO_2 in the lower part of the troposphere. This is an important restriction, because most of the variability of CO_2 occurs in the boundary layer. However, the infrared option is attractive because it guarantees continuity in time with instruments such as the European Infrared Atmospheric Sounding Interferometer (IASI) and the American Cross-track Infrared Sounder (CrIS) being launched in the next few years. It also has the advantage over near-infrared observations that there is no restriction to daytime observations.

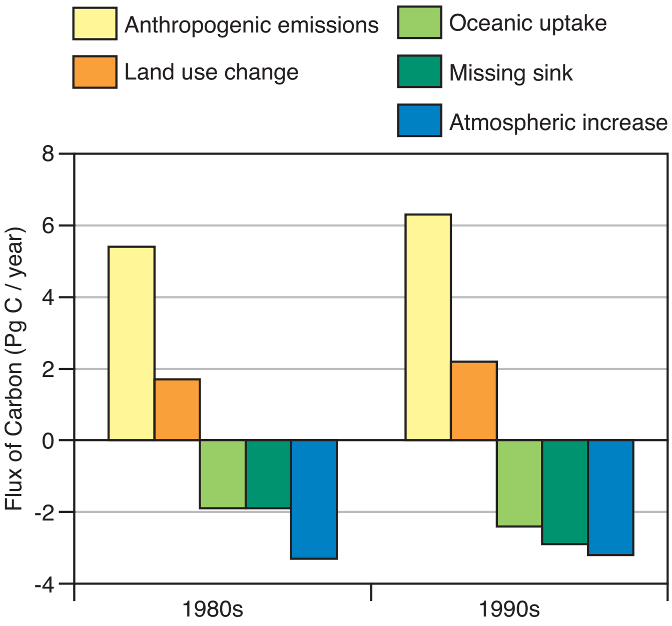

Figure 1 Anthropogenic perturbations to the natural atmospheric carbon cycle in Petagram Carbon per year for the 1980s and 1990s. The missing sink represents the part of the budget that can not be explained with current knowledge about the carbon cycle.

CO_2 estimation set-up

ECMWF has been operationally assimilating observations from the AIRS instrument since October 2003. The measurements constrain temperature and water vapour by assuming constant CO_2 mixing ratios. Within the COCO project we have added CO_2 to the minimization state vector in an experimental configuration to prove the feasibility of this approach. Instead of including CO_2 in the forecast model, which would require extensive coding to transport tracers around as well as defining proper background statistics, CO_2 was added to the state vector as a column variable for each AIRS observation location. Then the output of one analysis cycle consists of all the relevant atmospheric fields (temperature, winds, humidity, etc.) together with CO_2 tropospheric column estimates at all the AIRS observation locations that go into the assimilation. Because CO_2 is not part of the assimilation transport model, there are no forecasts for CO_2. Consequently CO_2 information from one analysis cycle cannot be used in the next analysis cycle. Also, to generate global fields, individual estimates have to be gridded in for instance 5° by 5° boxes for a certain time period.

A set of only 18 AIRS spectral channels (out of 324 available channels) sensitive to tropospheric CO_2 was used to estimate the tropospheric CO_2 columns. These channels were chosen to minimize the effect of water vapour and ozone absorption. Because the signal of CO_2 in the observed radiances is so small, it is easily obscured by uncertainties in the water vapour and ozone distributions. For the background constraint a global mean value of 376 ppmv was chosen with a background error standard deviation of 30 ppmv. The analysis error was estimated based on the background error, the observation error, and the sensitivity of the observations to atmospheric CO_2 . This sensitivity largely depends on the temperature lapse rate and the depth of the tropospheric layer (i.e. the height of the tropopause).

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Results of analysing AIRS data

More than one year of AIRS data has been processed and Figure 2 shows monthly mean results for March 2003, September 2003, and March 2004. The fourth panel shows the monthly mean analysis error for March 2003. White areas represent areas with extensive cloud cover throughout the month.

The largest signal in atmospheric CO$_2$ concentrations comes from the terrestrial biosphere. Vegetation absorbs CO$_2$ by photosynthesis and emits CO$_2$ through respiration. Plant litter on and in the soil releases CO$_2$ as well due to decomposition. A strong seasonal cycle is produced, although the annual net biosphere flux is very close to zero. The terrestrial biosphere also creates a latitudinal gradient in the atmospheric concentrations due to the large amount of land in the northern hemisphere compared to the southern hemisphere. This latitudinal gradient is amplified by the anthropogenic emissions that mainly originate from the northern hemisphere. Both the seasonal cycle and the latitudinal gradient are visible in the results of Figure 2. It is encouraging to see that the assimilation is capable of producing these spatial and temporal variations without having that information in the background.

March 2004 shows generally higher CO$_2$ concentrations than March 2003, representing the upward trend in global atmospheric CO$_2$. The difference between March 2003 and March 2004 at the location of Hawaii is 1.6 ppmv compared to the 1.4 ppmv observed at the Mauna Loa flask station. The monthly mean error shows the clear dependence of the analysis error on the temperature lapse rate as well as the thickness of the tropospheric layer. Errors are smallest in the tropics were the tropopause is high and the temperature lapse rate is large, while they increase at higher latitudes where the tropopause is lower. The relatively low errors over Europe are caused by a higher tropopause (deeper tropospheric layer) in the sub-tropical air mass.

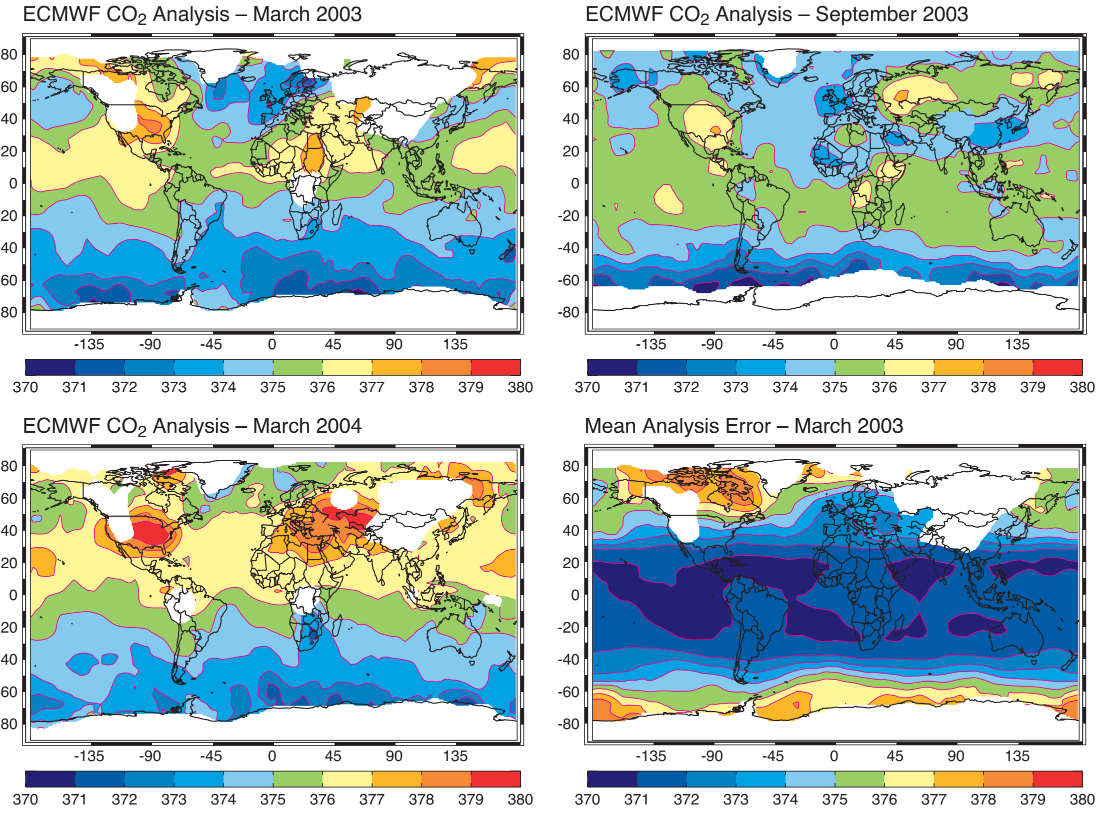

Figure 2 Monthly mean CO$_2$ analysis results for March 2003, September 2003, and March 2004 as well as the monthly mean analysis error for March 2003. Units are ppmv of CO$_2$.

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Validation of the analyses

The presentation of monthly mean results is interesting by itself, but an important check of the validity of our analysis results is by comparing these results to independent observations of atmospheric CO_2. There are only very few data sources for 2003 and we can generally not use the surface flask data. This is because our estimates represent a layer between about 700 hPa and the tropopause, while the surface flasks are sampled in the boundary layer. Only if we are sure that the full tropospheric CO_2 profile is well-mixed would a comparison be useful. However, Dr Hidekazu Matsueda and colleagues at the Japanese Meteorological Agency have been measuring CO_2 on board commercial flights of the Japanese Airlines (JAL) flying between Japan and Australia. These observations consist of automatic flask samples gathered at altitudes between 8 and 13 km on bi-weekly commercial flights. For 2003, there were 21 flights available for our comparisons.

Figure 3 shows the CO_2 annual cycle for both the flight observations and the assimilation estimates. For the full processed period (1 January 2003 to 31 March 2004), CO_2 analysis estimates were sampled in 6° by 6° boxes around the locations of the flight observations and over a period of 5 days around the date of those observations. We then generated three plots that represent the northern hemisphere region, the equatorial region, and the southern hemisphere region, by averaging the respective box averages for each region together. The figure shows that the analysis estimates follow the JAL observed annual cycle quite well. All differences fall within the one standard deviation error bars and are of the order of 1 ppmv in most cases. There is a clear improvement compared to the background, which is 376 ppmv throughout the year. The main anomaly can be seen in both the northern hemisphere and the southern hemisphere in January and February, in which period the analysis estimates are consistently higher than the JAL observations.

Figure 4 shows geographical comparisons with the JAL data for January and May 2003. The figure for 20 January 2003 is an example of a bad match between the JAL observations and the analysis results, while the figure for 20 May 2003 is an example of a good match. We suspect the main problem area in the January plot is affected by undetected thin cirrus clouds. Although the signal of these undetected clouds is negligible in terms of the temperature analysis, it causes the average CO_2 field to be high compared to the surrounding area. This difference in the cloud detection between January 2003 and May 2003 is most likely caused by the effect of the GOES-9 satellite on the moisture fields of the ECMWF analysis. The normal geostationary satellite over the Pacific area was GMS-5, but continuing problems with the onboard imager required a replacement by the GOES-9 satellite in May 2003. Therefore, during the critical (in terms of amount of convection over the Pacific) months of January, February and March the geostationary constraint on the humidity field was lacking. This is a cautionary example showing the impact of seemingly unrelated satellite instrument changes on the CO_2 estimates. Continuous validation of the results is therefore of great importance.

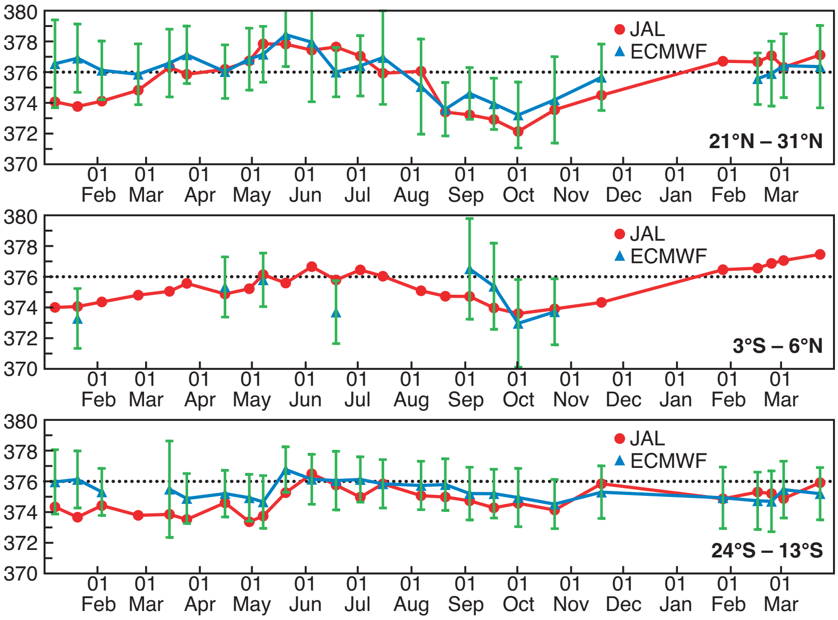

Figure 3 Comparison of ECMWF CO_2 estimates (blue triangles) with JAL observations (red dots) for three different latitude zones from January 2003 to March 2004. The CO_2 background value is denoted by the dotted line. Mean analysis errors are denoted by the green error bars. Missing ECMWF data are caused by extensive cloud cover in the area. Units are ppmv of CO_2.

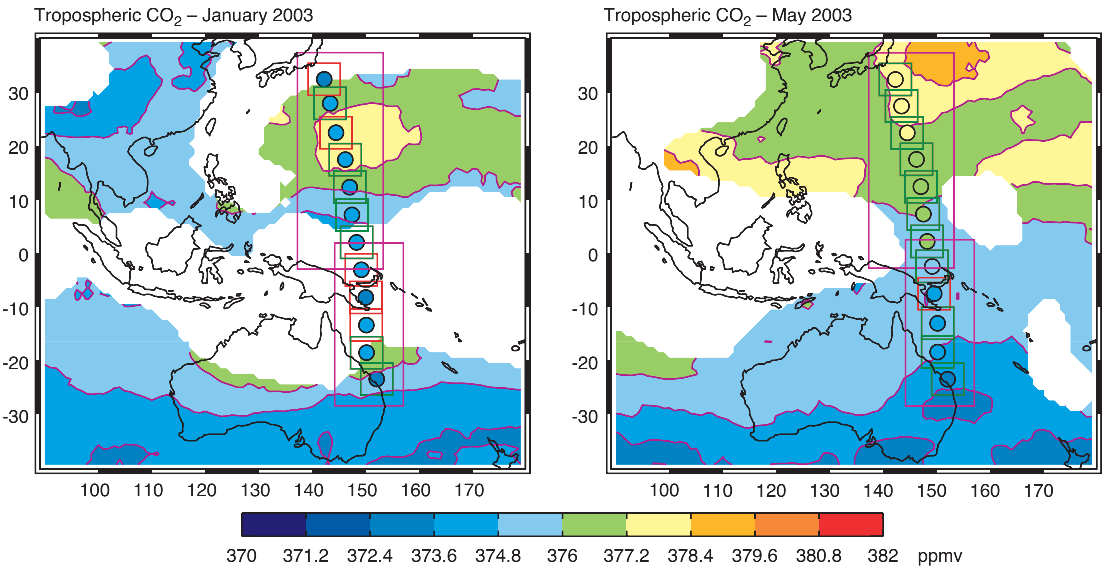

Figure 4 Comparison of ECMWF CO$_2$ estimates with Japanese Airlines (JAL) observations (filled circles in same colour scale) for 20 January and 20 May 2003. Units are ppmv of CO$_2$.

The next phase

On 1 March 2005 the EU-funded GEMS project started with the aim to develop an operational environment monitoring system. Within this project the CO$_2$ data assimilation will be upgraded to a full 4D-Var data assimilation system. Work is now underway to add CO$_2$ as a tracer variable to the forecast model. We are also defining proper background statistics that will be very important for the interpretation of the satellite observations. It is envisaged that this system will provide even better results than the relatively simple assimilation system, here described. The main output will be three-dimensional CO$_2$ fields every 12 hours constrained by observations from AIRS, IASI, CrIS, and possibly OCO and GOSAT. These fields will then be used by some of the partners of the GEMS project to improve their flux estimates and hopefully get a better idea of the processes behind the missing sink.

Further reading

Engelen, R.J., E. Andersson, F. Chevallier, A. Hollingsworth, M. Matricardi, A.P. McNally, J.-N. Thépaut & **P.D. Watts,** 2004: Estimating atmospheric CO$_2$ from advanced infrared satellite radiances within an operational 4D-Var data assimilation system: Methodology and first results. *J. Geophys. Res.,* **109,** D19309, doi:10.1029/2004JD004777.

Engelen, R.J. & **A.P. McNally,** 2005: Estimating atmospheric CO$_2$ from advanced infrared satellite radiances within an operational 4D-Var data assimilation system: Results and validation. *J. Geophys. Res.,* in press, doi:10.1029/2005JD005982.

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