ENVIRONMENTAL MONITORING OF THE ATMOSPHERE USING A 4-DIMENSIONAL VARIATIONAL (4D-VAR) DATA ASSIMILATION SYSTEM AT ECMWF

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Abstract

Within the EU-funded GEMS project (Global Earth-system Modelling using Satellite and in-situ data) the European Centre for Medium-range Weather Forecasts (ECMWF) has been building a 4-dimensional variational data assimilation system that will be capable of assimilating data from various satellite sensors as well as in-situ observations to model and constrain global fields of greenhouse gases, reactive gases, and aerosol. These fields will then be used to monitor the environmental aspect of the atmosphere, to infer surface fluxes for several species, and to provide boundary conditions for regional air quality models. This paper presents the background and aims of the project as well as the current status illustrated with some initial results.

THE GEMS PROJECT

The GEMS project (Global Earth-system Modelling using Space and in-situ data) is an Integrated Project funded under the EU's initiative for Global Monitoring for Environment and Security (GMES). The aim of the project is to extend the modelling, forecasting and data assimilation capabilities used in numerical prediction to problems of atmospheric composition. This will deliver improved services and products in near-real time (e.g. global air quality forecasts to provide boundary conditions for more detailed regional air-quality forecasts). In addition the operational analyses and retrospective reanalyses will support treaty assessments (e.g. the Kyoto protocol on greenhouse gases and the Montreal protocol on the ozone layer) while the joint use of satellite and in-situ data will enable sources, sinks and transports of atmospheric constituents to be estimated. The project involves about thirty institutes in fourteen European countries. It will run for four years from spring 2005 to spring 2009 with coordination carried out by ECMWF.

The GEMS forecast capabilities will require sophisticated operational models. In addition global and regional data assimilation systems will be needed to exploit satellite and in-situ data so as to provide initial data ('status assessments') for the forecasts. These operational ‘status assessments’ are also invaluable for documenting sources, sinks and transports of atmospheric trace constituents. The specific objectives of the GEMS Project are to:

• Develop and implement at ECMWF a validated, comprehensive, and operational global data assimilation/forecast system for atmospheric composition and dynamics, which combines all available remotely sensed and in-situ data. Operational deliverables will include current and forecast three-dimensional global distributions (four times daily with a horizontal resolution of 50–100 km, and vertical resolution of 60 levels between the surface and 65 km) of key atmospheric trace constituents including greenhouse gases, reactive gases and aerosols.

• Provide initial and boundary conditions for operational regional air-quality and ‘chemical weather’ forecast systems across Europe. This will provide a methodology for assessing the impact of global climate changes on regional air quality. It will also provide improved operational real-time air-quality forecasts.
• Provide a retrospective analysis of all accessible in-situ and remotely sensed data on atmospheric dynamics and composition as validation material for the ENVISAT-EOS era (1999–2007).
• Develop state-of-the-art variational estimates of the sources/sinks, plus inter-continental transports, of many trace gases and aerosols. These estimates will be designed to meet policy-makers’ key information requirements relevant to the Kyoto and Montreal Protocols and to the UN Convention on Long-Range Trans-boundary Air Pollution.

The GEMS consortium consists of four categories of participants.
• Sixteen research institutes in seven countries providing expertise in satellite and in-situ observations for assessing/validating models, expertise in developing models and assimilations of tropospheric and stratospheric chemistry and aerosol, and expertise in inversion methods to estimate sources, sinks and transports.
• Ten regional modelling centres in nine countries, most with operational responsibilities for national or regional air-quality forecasts.
• Two environmental protection agencies.
• Two international bodies: ECMWF with extensive experience in exploiting satellite and in-situ data to produce forecasts, and the Institute for Environment and Sustainability of the EU’s Joint Research Centre.

Figure 1 illustrates the main strands of the GEMS strategy to build an integrated operational system for monitoring and forecasting the atmospheric chemistry environment. The building blocks of the separate elements of the system already exist. The schematic also illustrates the scientific interactions between the strands of development, which will develop and mature as the integration of the system proceeds. In formulating the strategy, both scientific and practical considerations were taken into account. The primary scientific goal is to create an architecture which will provide a fully integrated treatment of all aspects of atmospheric composition and dynamics when it becomes operational in the first half of 2009. In doing this full use will be made of the existing infrastructure provided by WMO’s World Weather Watch and European resources in information technology.

The GEMS strategy is based on a step-wise approach.
• Establish in parallel, and validate, individual elements of the system in the first half of the period.
• Merge the individual components in an integrated system, and validate the integrated system. The operational system for greenhouse gases and for the inference of surface fluxes will be the first such operational system. It will considerably strengthen the already strong European position in international negotiations, because of its transparency and sophistication.

Research systems for assimilation of reactive gases and aerosol have been developed in recent years, but none has the comprehensive use of satellite data, the comprehensive validation mechanisms and the high spatial resolution of the system proposed here. Again the operational global system will be a first, and will maintain and strengthen European leadership in these areas. The GEMS assessments of the impact of the global composition changes on regional air quality will be based on a range of regional air-quality models using similar assessment protocols. The resulting assessments will be comprehensive and extensive, examining impacts on mean fields and on extreme events.
PROGRESS ON GLOBAL MODELLING AND DATA ASSIMILATION

Substantial efforts have been devoted to extending the modelling needs of the project. ECMWF’s Integrated Forecast System (IFS) has introduced the generic capability to advect many trace species by the model’s dynamics, and to transport them in the parameterisations, such as the convection parameterisation. In-line parameterisations have been implemented for greenhouse gases and aerosols, with surface fluxes specified climatologically (CO₂) or dynamically (aerosols). Year-long test runs with specified meteorology and free-running chemistry have provided valuable checks on the models. A considerable effort has also been made to gather data from the various satellite sensors and put them in consistent data formats. Tools to distribute the data and analysis fields have also been built.

For reactive gases it is essential that the assimilating model has the benefit of an advanced chemistry scheme. Since it is believed premature to introduce a full-blown chemistry representation into the IFS, the IFS model is being coupled to three participating Chemistry Transport Models (CTMs).

A key requirement of the GEMS modelling and assimilation capability is an accurate representation of the stratospheric Brewer-Dobson circulation, which is involved in the control of the stratospheric distribution of many stratospheric constituents, and in key aspects of tropospheric-stratospheric exchange. There is evidence that there have been important improvements in this regard since the completion of the ERA-40 reanalyses in 2002. Consequently the meteorological components of the preliminary GEMS system have been used to reanalyse 2003–2004. Preliminary results are encouraging.
The IFS’s 4D-Var system has been adapted to provide three separate data assimilation systems for greenhouse gases, reactive gases and aerosols. Depending on which of the domains is addressed, the assimilation systems will use radiances via fast forward models and their adjoints (greenhouse gases initially, aerosols later), or retrieved profiles (aerosols, reactive gases) or total column amounts. The specification of natural and anthropogenic emissions is a key issue for both the global and regional elements of the GEMS project. Agreement has been reached on the use by GEMS of the global anthropogenic emissions calculated by the RETRO project of the Fifth Framework Programme. Emissions by wildfires and biomass burning are a key issue for the GEMS project. A proposed approach to the issue was developed recently through discussions between the HALO, GEMS, GEOLAND and ACCENT projects. Efforts will be made to include the issue in the Work Programme of the Seventh Framework Programme.

EXAMPLES OF CURRENT MODELLING AND ASSIMILATION CAPABILITIES

As described in the previous section, GEMS has now achieved the capability to model greenhouse gases, reactive gases, and aerosol, and to constrain these modelled fields through the assimilation of various sources of satellite data. Work has now started on defining the background statistics (describing the errors and correlations of the modelled background), tuning the bias correction for the various sensors, and finalizing the coupling of the 4D-Var system to the off-line chemistry transport models. In the meantime, first tests show good performance of both the modelling and the assimilation as is shown in a few examples below.

The CO$_2$ modelling is using prescribed surface fluxes based on Andres et al. [1996] for the anthropogenic sources, Takahashi et al. [1999] for the ocean exchange, and the CASA model [Randerson et al., 1997] for the natural biosphere. Good agreement between the modelled seasonal cycle for both hemispheres and ground-based surface flask measurements [GLOBALVIEW-CO$_2$, 2000] is shown in Figure 2.

![Figure 2: Comparisons between NOAA/CMDL surface flask measurements of CO2 and a year-long run of the ECMWF model where the meteorology is corrected every 12 hours and the CO2 is free-running with specified climatological surface fluxes. The figure shows good qualitative agreement for the seasonal cycle.](image)

When we assimilate radiance observations from the Atmospheric Infrared Sounder (AIRS) we see an increase of CO$_2$ in the middle and upper troposphere and a decrease in the stratosphere compared to a free-running CO$_2$ forecast. Zonal mean CO$_2$ distributions of the free-running CO$_2$ model and zonal mean results after one month of assimilating AIRS data are shown in Figure 3. A more extensive description can be found in Engelen [2005].
Figure 3: Results of 1 month of assimilating radiance observations from the AIRS instrument constraining atmospheric CO₂. The left panel shows the zonal mean CO₂ distribution from a free-running CO₂ forecast and the right panel shows the same field when 1 month of AIRS data has been assimilated.

The aerosol modelling is also progressing well. The physical package for aerosols was taken from the Laboratoire d'Optique Atmosphérique (LOA)/Laboratoire de Météorologie Dynamique (LMD) model of Boucher et al. [2002] and Reddy et al. [2005]. It includes sources for sea salt and desert dust and a representation of sedimentation, and wet and dry deposition processes. Wet and dry deposition schemes were adapted directly from the LMD model (also known as LMDz model) whereas the sedimentation follows recent developments by Tompkins [2005].

Figure 4: Plume of Saharan dust on 5 May 2006 as modelled by the ECMWF aerosol model.

All aerosol species are treated as tracers in the ECMWF vertical diffusion and convection schemes and are advected by the semi-lagrangian scheme, consistently with all other dynamical fields. In the current model configuration, a bin representation is used to treat various aerosol species and improved emission sources have been implemented [Morcrette et al., 2005]. This aerosol
configuration might change in the near future to achieve a better representation of the aerosol distribution. Figure 4 shows the modelling results of the dust plume over Western Europe in May 2006. The results are very similar to modelling results from other research groups (not shown here) and agree quite well with observations.

Figure 5 shows preliminary results from early aerosol assimilation trials. Aerosol optical depth retrievals from the MODIS instrument were used in a single analysis cycle and the figure shows the first-guess departures (observation minus model first-guess) in the top panel and analysis departures (observations minus analysis) in the bottom panel.

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Figure 5: Aerosol first-guess departures (top) and analysis departures (bottom) from an initial aerosol data assimilation experiment using aerosol optical depth retrievals from the MODIS instrument.
The analysis is able to use the information from the observations to un-bias the model forecast and diminish the standard deviation of the differences between the observations and the model fields, as is also illustrated by the histograms below the two panels.

For the reactive gases work is underway to fully couple the 4D-Var system with off-line chemical transport models (CTMs). The idea is to treat the chemistry in a very detailed way and feed the concentration tendencies to the data assimilation system. This then assimilates data from various satellite sensors to constrain O₃, CO, NOₓ, SO₂, and HCHO. The concentration increments together with the meteorology are then fed back to the off-line CTM. Figure 6 shows results from some initial tests of the assimilation system. Total CO retrievals from the MOPITT instrument were assimilated using a background field produced by one of the off-line CTMs. While in this test the background field and the observations were not for the same date, the results show a working system with the observations changing the background field (left panel) to produce an analysis field (right panel) that is closer to the observations. When the coupling has been fully established, this information would then be fed back to the off-line CTM.

![Figure 6](image)

**Figure 6:** CO first-guess field (left) and analysis field (right) in 10⁻¹⁸ molecules/cm² illustrating the effect of assimilating 6 hours of MOPITT total column CO retrievals.

### SATELLITE DATA PROVISION IN 2009-2019

The availability of adequate satellite data provision is a key issue in planning the first decade of operational GEMS activity. In terms of security and adequacy of satellite provision, the greenhouse gas project probably has the most secure provision with operational advanced sounders (IASI plus GOME-2 on METOP in 2006, CrIS on NPP in 2009) for upper-tropospheric measurements and the research missions OCO and GOSAT from 2009 onwards. The least secure provision is probably the air quality (lower-tropospheric chemistry), as no missions are planned beyond the demise of ENVISAT and AQUA/AURA. The satellite provision for aerosols and UTLS (upper troposphere-lower stratosphere) are comparable, with aerosols relying mainly on the VIIRS instrument on NPP and NPOESS and the UTLS chemistry relying on GOME-2 on METOP and OMPS on NPOESS (from 2012).

### REFERENCES


