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METEOROLOGY

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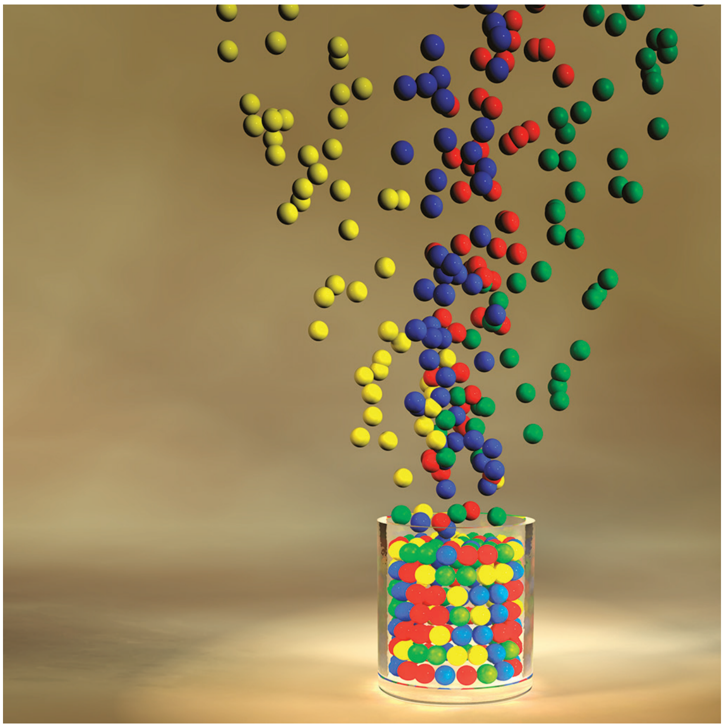

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# GEMS aerosol analyses with the ECMWF Integrated Forecast System

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Environmental monitoring will become an integral part of the ECMWF mission under the new convention that is undergoing ratification by the Member States. One of the major EU-funded projects dedicated to this goal is GEMS which deals with global and regional earth-system (atmosphere) monitoring using satellite and in-situ data. GEMS is being undertaken by thirty-two European partners with expertise in various aspects of atmospheric composition monitoring.

As part of ECMWF's contribution to GEMS, a 4D-Var reanalysis for the years 2003–2007 is currently being run to estimate atmospheric greenhouse gases (carbon dioxide and methane), reactive gases (carbon monoxide, ozone etc.) and aerosols using satellite-based observations. In parallel, an aerosol-only reanalysis is being run for the years 2003–2004. Near real-time forecasts of these tracers are also being performed both on global and on regional (European) scales. Preliminary results for both reanalyses and forecasts can be found at http://gems.ecmwf.int.

This short note focuses on describing the development and implementation of the aerosol component of the 4D-Var assimilation system.

## The aerosol analysis system

The aerosol species included in the analysis are sea salt, desert dust, black carbon, organic matter and sulphates. Stratospheric background aerosol can be also activated. However, the background values for 2003–2004 are so small that it has been decided to run the reanalysis without stratospheric aerosols. Some of the key features of the analysis system are as follows.

- The emission sources for the various aerosol species are defined either using established emission inventories (black carbon, organic matter and sulphates) or through parametrizations (sea salt and desert dust) which involve model variables such as surface winds and soil moisture, amongst others.
- All aerosols species are subject to horizontal and vertical advection, diffusion and aerosol-specific physical processes such as sedimentation and wet/dry deposition.
- For organic matter and black carbon, both the hydrophobic and the hydrophilic components are considered.
- Desert dust and sea salt are represented with three size bins whose limits are chosen to include 10%, 20% and 70% of the total mass.

The analysis is performed on the total aerosol mixing ratio which is calculated as the sum of all species. The background fractional contributions are then used to re-distribute the analysis increments of total mixing ratio into the single species. This is achieved primarily through an aerosol mass adjustment using observations of total aerosol optical depth derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on-board of the NASA Terra and Aqua satellites. The aerosol observations are processed through the operational pathway and ingested in the 4D-Var system where they are processed with an ad hoc observation operator specifically designed for aerosol optical depth. This operator uses pre-computed values of aerosol optical properties, specific to the different aerosol species at the wavelength of interest (at present, 550 nm), in combination with the first-guess values of the aerosol mixing ratios from the model to calculate a profile of extinction. This extinction profile is then vertically integrated to obtain the aerosol total optical depth.

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Initial test analyses showed anomalous increments in total aerosol mixing ratio, and consequently in aerosol optical depth, over the polar regions. The values produced in the analysis were clearly unrealistic, with optical depths reaching values as large as 3 over the north pole, where they should be around 0.1–0.2. Several experiments were conducted to understand the reason for these large increments, including:

- Data denial experiments.
- The implementation of aerosol loss parametrizations in the minimisation.
- The redefinition of the background error statistics.

The last of these proved to be the solution to the problem.

The old background aerosol statistics had been calculated with a preliminary model version which included only sea salt, desert dust and a generic continental background aerosol type; hence they had become outdated for the improved aerosol model. New statistics have been calculated with the current model version. Comparisons with the old set of statistics show dramatic differences both in the standard deviation and in the vertical and horizontal correlations. Specifically the new standard deviation is one order of magnitude smaller than the old one, indicating that the model has a smaller degree of variability in the aerosol forecasts at 24 and 48 hours. This, in turn, translates into a smaller background error, which is more realistic given the improvements implemented in the current aerosol model. With this new background error, the analysis, while still drawing to the observations, takes the model background constraint more into account. This is extremely important, especially in areas that are data-limited such as the polar regions where the aerosol analysis could be severely under-constrained.

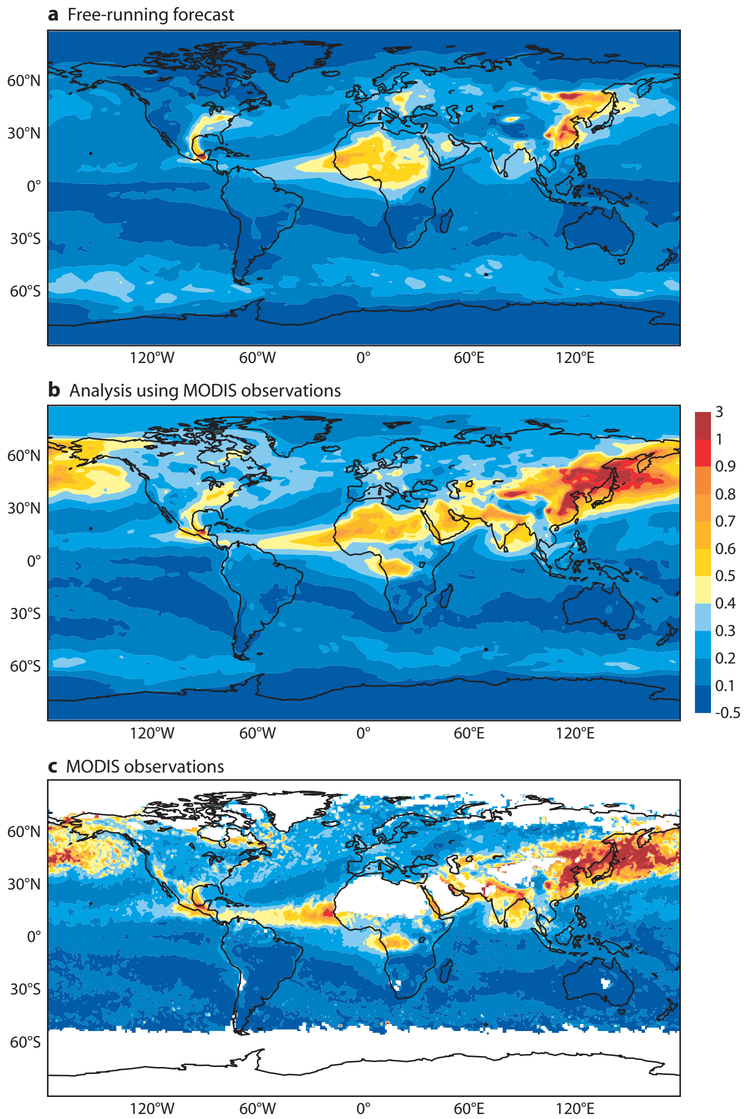


**Figure 1** Comparisons of simulated aerosol optical depths from the new aerosol module implemented in the IFS model: (a) free-running forecast, (b) analysis using MODIS collection 5 observations, and (c) MODIS average optical depth for the month of May 2003.

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## First results

The current analysis configuration includes the new aerosol background statistics. Also it includes the error analysis for MODIS optical depth data over ocean developed at the Laboratoire d'Optique Atmosphérique (LOA), which is a partner in the project. The aerosol data in the analysis come from MODIS collection 5 (see http://modis.gsfc.nasa.gov/).

Figure 1 shows quantitative comparisons between a 'free-running' forecast of aerosol optical depth without any assimilation and the analysis of optical depth from assimilated MODIS observations. The MODIS observations are also shown as reference. Optical depth retrievals are assimilated over both land and ocean. The three-hourly forecasts of optical depth from the free-running model and from the analysis are averaged over May 2003.

Results show that the analysis is very effective in bringing the model aerosol optical depth closer to the observations. The assimilation generally improves the aerosol distribution, especially over areas with extensive biomass burning and other anthropogenic sources. These are not captured as well in the free-running simulation, mainly because of inadequate definition of the sources for these anthropogenic emissions. Note, however, the overall skill of the forecast model in predicting the general distribution of the aerosol fields which provides a good first-guess for the analysis.

Figure 2 shows some preliminary comparisons of the free-running forecast and analysis of aerosol optical depths with AERONET independent data for May 2003. Forty-one sites, as evenly distributed over the globe as possible, were chosen for the comparison. Both plots show that the analysis is closer to the AERONET observations, with the analysis displaying a lower bias and Root Mean Square (RMS) error than the free-running forecast.

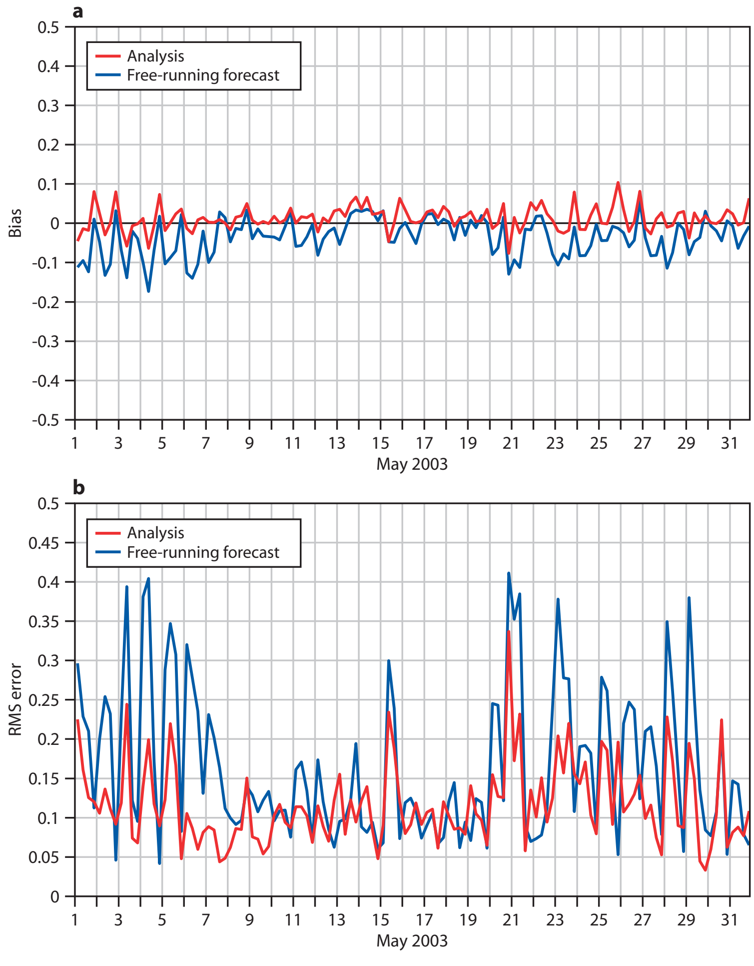


**Figure 2** (a) Bias and (b) RMS error of free-running forecast (blue) and analysis (red) of aerosol optical depths at 550 nm with respect to AERONET ground observations for May 2003.


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As a further example, Figure 3 compares the analysed optical depth at 550 nm with the observed aerosol optical depth over the AERONET sites of Dakhla (Morocco), Solar Village (Saudi Arabia) and Fresno (California). Note that the analysis is able to reproduce the observed variability and intensity of the dust episodes at Dakhla and Solar Village, despite the lack of MODIS data (not available over bright surfaces).

The GEMS aerosol reanalysis for 2003–2004 will be completed in August 2008. An in-depth review of the results and comparisons with yet more independent datasets is needed for a final assessment of the quality of the analysis. This will involve several of the partners in the GEMS project. Preliminary results are, however, encouraging and show a good degree of skill in the analysis to provide initial conditions for improved forecasts of atmospheric aerosol fields.

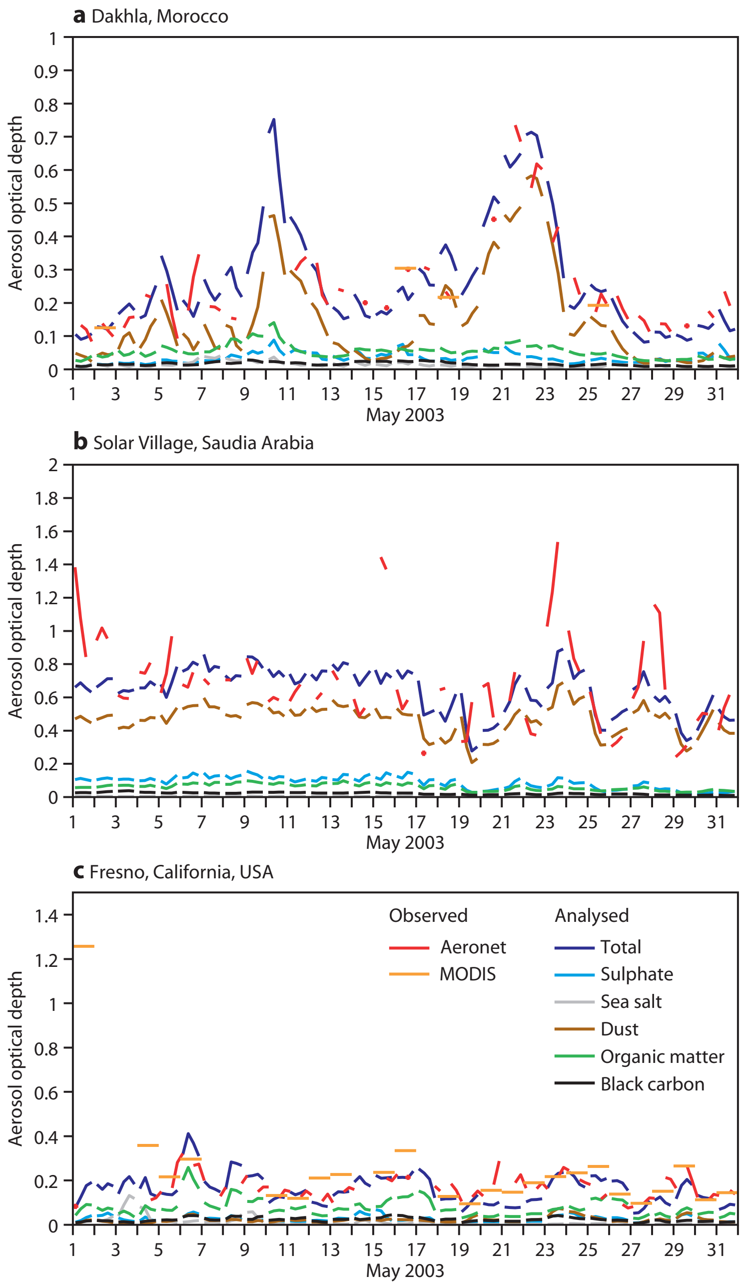


**Figure 3** Comparisons of analysed aerosol optical depths at 550 nm with AERONET and MODIS observations for (a) Dakhla (Morocco), (b) Solar Village (Saudi Arabia) and (c) Fresno (California).

## Further Reading

**Benedetti, A.** & **M. Fisher,** 2007: Background error statistics for aerosols. *Q. J. R. Meteorol. Soc.,* **133,** *391–405.*

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**Morcrette, J.-J., L. Jones, J. W. Kaiser, A. Benedetti** & **O. Boucher,** 2007: Toward a forecast of aerosols with the ECMWF Integrated Forecast System. *ECMWF Newsletter No. 114,* 15–17.



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