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Towards an operational GMES Atmosphere Monitoring Service

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Towards an operational GMES Atmosphere Monitoring Service

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The MACC-II (Monitoring Atmospheric Composition and Climate - Interim Implementation) project delivers the pre-operational atmospheric composition services of GMES (Global Monitoring for Environment and Security, http://www.gmes.info) and strengthen the production chains in order to be in readiness for the operational phase, due to start immediately after the end of the project. MAC-II succeeded the MACC project (see *ECMWF Newsletter No. 123*, 10–13) at the end of 2011 and will run till July 2014. It is funded under the European Union's Seventh Framework Programme as was MACC.

This article provides some insight in the global production chain of MACC-II, focusing on reactive gases, aerosol and then greenhouse gases. These aspects share commonalities for the preparation of the operational phase, but have different level of maturity and face specific scientific and technical challenges. We highlight also that the developments on atmospheric composition performed in the context of MACC-II are also very promising from the point of view of improving numerical weather prediction (NWP) and existing ECMWF products. The vision of ECMWF, supported by its Member States, that atmospheric composition would not only extend the scope of useful products connected with meteorology at large but would also benefit weather forecasts is becoming a reality. Visionary? Maybe not quite so.

"The chemical composition of air, the nature of the particles it transports, provides also its own piece of information. One never has enough enlightening in solving such a difficult and important problem as weather forecasting" H. Marié-Davy (Les mouvements de l'atmosphère et les variations du temps, Masson, Paris, 1877)

Background to GMES and MACC-II

The purpose of GMES is to deliver information about environment and security based on Earth-monitoring data collected from space, air, water or land. The GMES services deal with six areas: marine, atmosphere, land, emergency, security, and climate change.

There are currently discussions at the European level on the sustainable funding scheme for GMES, either through a budget line in the Multi-annual Financial Framework (the main budget of the European Union, EU) or a dedicated intergovernmental fund. However, the full development of GMES, including the space, in-situ and services components, is expected to go forward with the strong backing of cost-benefit analyses (*Pricewaterhouse-Coopers*, 2006; *booz&co.*, 2011). Return on investment ratios of 4 to 10 make GMES an integral part of a successful implementation of the Lisbon strategy of the EU which is concerned with developing a competitive and dynamic knowledge-based economy. But beyond economic aspects, GMES will provide information of unprecedented quality on the environment at large, as well as support European policies on emergencies and security.

MACC-II follows in the track of previous European projects, MACC and GEMS, to deliver information services on atmospheric composition: reactive gases, aerosol, greenhouse gases, European air quality, and solar and ultra-violet radiation. As with its predecessor projects, MACC-II is co-ordinated by ECMWF. It involves a large consortium of 36 partners from 13 countries. Nine National Weather Services (AEMET, DWD, FMI, IM, KNMI, met.no, Météo-France, Met Office and SMHI), as well as a number of National Environment Agencies and academic partners, constitute the bulk of the consortium. The website of MACC-II, http://www.gmes-atmosphere.eu, delivers the portfolio of products in the form of graphics and maps, and also serves as a gateway for access to numerical data.

As in MACC, there are two main production chains: a global one, operated at ECMWF, and a regional one, operated by a network of seven processing centres federated by Météo-France, and delivering European scale air quality services. Most services are forecasts for a few days ahead and delivered in near-real-time, but some of them are also delivered in delayed mode – a few months after time – as this is necessary to acquire the observations, particularly for greenhouse gases.

The MACC project produced a new 'chemical' reanalysis of the period 2003–2010, which supersedes the GEMS one and is now being extended for the years 2011 and 2012 as part of MACC-II. The number of users of this MACC reanalysis is already in excess of six hundred, covering most countries in the world (Figure 1).

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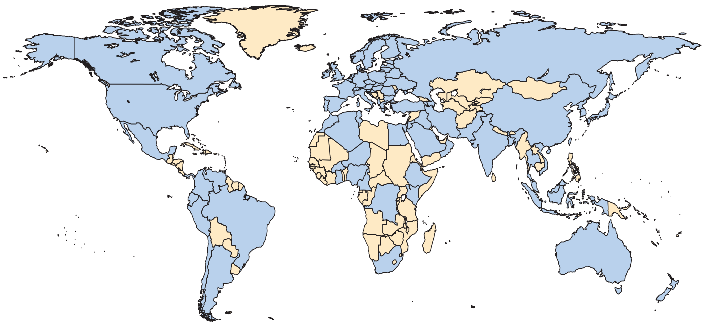

Figure 1 Countries with users of MACC reanalysis data for 2003–2011 are marked in blue (as of May 2012).

Value of comprehensive atmospheric chemistry representation in the IFS

GEMS and MACC have put significant resources into the building of a coupled chemical data assimilation system that allows assimilating satellite data of O_3, CO, NO_2, and SO_2 in the IFS while properly accounting for the full underlying chemistry.

Validation of the MACC reanalysis

The MACC reanalysis, already mentioned, was the occasion to evaluate the skill of the main system used: Integrated Forecasting System (IFS) at a T255 reduced Gaussian grid (approximately 80 km horizontal resolution) resolution and 60 levels, coupled to the Chemistry and Transport Model (CTM) MOZART-3 using the OASIS4 coupling software (*Valcke & Redler*, 2006). This system allows representation of 115 chemical compounds, offering thus a reasonably comprehensive description of atmospheric chemistry.

A detailed report is available on the validation of the reanalysis (*Inness et al.*, 2012, *ECMWF Tech. Memo. No. 671*). Figure 2 highlights one of the results: it is a comparison of ozone profiles at Alert, Canada (82.5°N, 62.3°W, the northernmost permanently inhabited place in the world, only 500 miles from the North Pole) for the MACC reanalysis and for the ERA-Interim reanalysis against ozone sondes for the period 2003 to 2010. The performance of the MACC reanalysis is strikingly better than ERA-Interim regarding tropospheric ozone: errors with the MACC system range between ±30%, while errors reach 100% in ERA-Interim and show marked seasonal variations. This is not unexpected, as the representation of ozone in ECMWF operations and ERA-Interim only accounts for (simplified) stratospheric ozone chemistry, while MACC has a representation of the complex non-linear tropospheric ozone formation from its precursors, nitrogen oxides and volatile organic compounds. The MACC system also allows a better use of the available satellite data with sensitivity to ozone in the troposphere. In the stratosphere the skill of both the MACC reanalysis and ERA-Interim is much better than in the troposphere (±10%), with the MACC reanalysis also being marginally more realistic than ERA-Interim at these altitudes.

The good quality of the MACC ozone reanalysis is not only important for users interested in the full vertical profile of ozone: in the MACC system there are much better prospects for using the actual ozone fields in the computation of radiation as well as in the assimilation of radiances that are sensitive to ozone. A first step has been to use climatologies of key radiative species from the MACC reanalyses in the IFS as a default. Also, *Engelen & Bauer* (2011) have shown the benefit of using MACC's CO_2, rather than a fixed background value, in reducing the bias correction needed for assimilation of IASI and AIRS radiances. Making the MACC-II suite operational will also offer the opportunity to use time-dependent forecast fields, which is a very promising path for weather prediction, considering in particular the sensitivity of surface temperature to ozone content in the upper troposphere/lower stratosphere region.

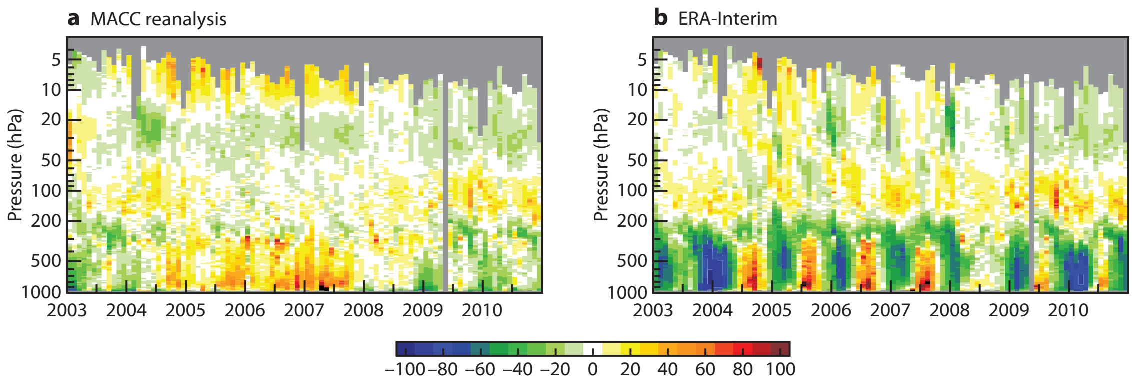

Figure 2 Verification of ozone profiles against ozone sondes at Alert (Canada) for (a) MACC reanalysis and (b) ERA-Interim (bottom) in percent.

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In-line representation of atmospheric chemistry in IFS

Another objective of MACC-II is to be in a position to operate, at the end of the project, a validated version of the IFS augmented with a comprehensive in-line representation of atmospheric chemistry and associated processes, called C-IFS hereafter (*Flemming et al.*, 2009) – a modelling and data assimilation system with little or no equivalent worldwide. C-IFS will replace the current systems based on coupled models, offering increased computational efficiency as well as the option to activate feedback of composition on physical processes at each model time step.

Figure 3 illustrate the capabilities of the MACC-II system, by presenting a map of carbon monoxide (CO), a pollutant emitted by incomplete combustion processes of human (e.g. car traffic, industries, residential heating, energy production) and natural (e.g. wildfires and biomass burning) origins. CO has an atmospheric lifetime of approximately one month. It is represented here with a simplified version of C-IFS, comprising a linear representation of CO chemistry. C-IFS can be run at much higher resolution than the current MACC systems.

Figure 3 shows a zoom over Europe of travelling CO plumes. This is of direct interest for applications such as regional air-quality forecasting, which can now include the effects of long-range transport of pollutants, but it is opening interesting perspectives for NWP as well. CO is one of the tropospheric species which are best observed from space, due to its absorption properties in the short-wave and thermal infra-red, and instruments such as TERRA/MOPITT (NASA) and MetOp/IASI currently provide good monitoring capabilities. The use of the quasi-tracer properties of CO could help improve winds (especially in cloud free areas, where cloud-drift winds cannot be used by design) using data assimilation, in a similar manner as it at been shown successful for ozone and winds in the upper troposphere/lower stratosphere.

C-IFS will initially include three state-of-the-art chemical schemes: TM5 (from KNMI), MOCAGE (from Météo-France) and MOZART-3 (from NCAR, USA, and Research Centre Jülich). However, part of the MACC-II plan is to release C-IFS as a community model, following directly in the steps of open-IFS for the meteorological part. This will allow a wider range of partners to include their chemical parametrizations in C-IFS – for the benefit of research activities and to improve the GMES atmospheric services delivered to users.

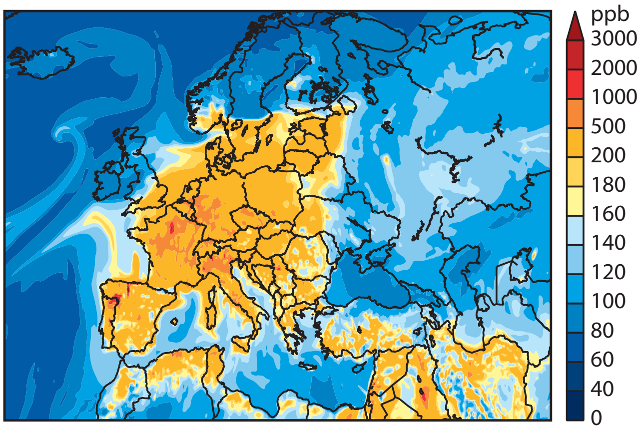

Figure 3 Example of surface CO distribution at high resolution over Europe using linear CO as part of C-IFS developments.

Forecasting dust, smoke and other aerosol

Contrary to the path chosen for reactive gases, which necessarily involves addition of the order of 100 tracers or more to represent complex non-linear chemical processes in the troposphere, aerosol representation has been directly introduced in-line in the IFS since the GEMS project. The initial 'compact' representation of aerosol in the IFS modelling and assimilation suite has already been the topic of articles in the winter 2007/08, summer 2008 and spring 2009 editions of the ECMWF Newsletter. Since then, developments have carried on both internally at ECWMF, especially to improve incrementally the representation of dust and volcanic ash, and externally to test a much more detailed representation of tropospheric (University of Leeds, UK, based on the GLOMAP model) and stratospheric (LATMOS, France, based on the REPROBUS model) aerosols. Integration of these advanced modules is on-going during MACC-II and the evaluation of relative performance will guide the next steps towards operational use.

Aerosol assimilation/forecasting system

Already, the new version of the aerosol scheme implemented in May 2012 produced a significant improvement in the skill of products, both analyses and forecasts. This is illustrated by Figure 4 showing the mean bias of the aerosol optical depth (AOD) relative to observations from the AERONET network (*Holben et al.*, 1998) as a function of forecast lead time (panel a) and day of the month (panel b).

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Global aerosol products have been among the most widely used in MACC and MACC-II. Support to Volcanic Ash Advisory Centres during volcanic eruptions has already been documented (e.g. *ECMWF Newsletter No. 123*, 9). Aerosols affect visibility and radiation, and thus are of significant interest for meteorological forecasters in ECMWF Member States. GEMS and MACC have allowed development of one of the more advanced aerosol assimilation and forecasting systems, and ECMWF is now playing an important role in international initiatives such as the International Cooperative for Aerosol Prediction (*Benedetti et al.*, 2011).

Long-range transport of natural aerosols

The interaction with users in MACC and MACC-II, particularly in the air quality policy sector, has confirmed a major interest of these communities for accurate estimates of long-range transported natural aerosol, in particular soil dust and aerosol from large wildfires. Indeed, European Directives require EU Member States to take action when the PM10 (particulate matter of diameter smaller than 10 μm) regulatory threshold is exceeded. Local sources in general dominate, but the contribution of remote sources can be significant for some exceptional events.

In a meeting in May 2011, the European Commission confirmed interest on its behalf and of its Member States for natural aerosol estimates from MACC-II and, later, the GMES atmospheric service as an input to the air quality reporting process. Figure 5 provides an example of very high surface PM10 measured in Virolati (Finland) as a consequence of the Russian fire events of July and early August 2010. In real-time, the MACC system predicted that only Southern Finland out of the 27 EU countries would be significantly affected by the transport of fire aerosol from the sources near Moscow; this was useful information, in particular for the European Environmental Agency (EEA).

Figure 5 shows that the skill of the system is due both to the assimilation of aerosol optical depth data (in this case from the MODIS sensors on board the Terra and Aqua satellites), allowing to capture the travelling plumes of pollutants, and to the prescription of fire sources depending on satellite-detected 'Fire Radiative Power' (FRP, also a MODIS product) of the actual fires (*Kaiser et al.*, 2011). A system based on climatological fire emissions and no data assimilation completely fails, as expected, to predict the observed extreme levels observed in Virolati (Finland) in excess of 100 μg m^{-3}.

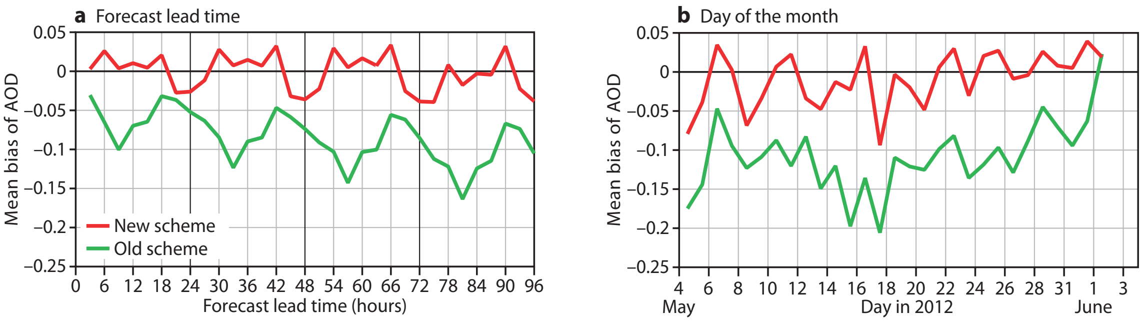

Figure 4 Verification of the aerosol forecasts for the new and old aerosol representation in MACC/IFS in terms of the mean bias of the aerosol optical depth (AOD) relative to observations from the AERONET network as a function of (a) forecast lead time and (b) day of the month for May 2012.

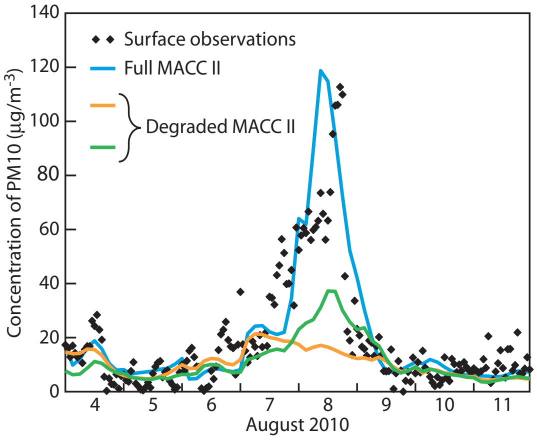

Figure 5 Concentrations of PM10 (see text) at Virolati, Southern Finland, during the period 4–11 August caused by the Russian fires near Moscow. Surface observations are black dots and the lines represent the full MACC-II system (blue) and two degraded versions: no assimilation and FRP-based 'dynamical' fire emissions (green) and no assimilation and climatological fire emissions (yellow).

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Extending headline skill scores for atmospheric composition

A

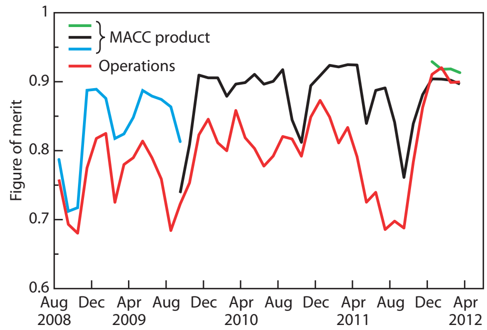
Headline Skill Scores (HSS) have been defined to monitor progress over time of ECMWF's main products and implementation of our strategy. These skill scores use long-standing and widely recognised metrics for skill forecasts (anomaly correlation at 500 hPa) as well as a range of additional indicators specifically suited for following up the forecast skill on extreme events, as well as the EPS products at the different time horizons.

With the approaching operational phase of GMES atmosphere, it has been decided to look into the extension of HSS into atmospheric composition. Though MACC-II has a very comprehensive validation sub-project looking in detail at all aspects of our products, making use as far as possible of independent satellite and in-situ composition data, the definition of HSS is a specific target to reflect overall performance of the global atmospheric composition system operated at ECMWF by only a few synthetic indicators. The 'chemical' HSS will comprise four indicators to sample the main aspects of the system:

- Vertical ozone profile (as a proxy for stratospheric composition)
- Surface carbon monoxide (as a representative of tropospheric chemistry and of boundary conditions used for air quality application)
- Aerosol optical depth (AOD)
- Surface in-situ CO_2 and CH_4

We illustrate here the indicator for the skill of the ozone profile. It is based upon a figure of merit (a quantity characterising the performance of a system relative to its alternatives) comparing the modelled profile (forecast, analysis or reanalysis) with an observed profile from an independent ozone sonde, a perfect match of the two being 1. This unique indicator captures not only differences in the vertically integrated content of ozone (total column), but also if there are issues with the vertical structure of the modelled profile – which could be due to dynamical and/or chemical processes.

Though in principle this skill score can be computed for any ozone sonde regular launch site, we have selected Neumayer in Antarctica, which witnesses in particular the representation of dynamical and chemical processes associated with the ozone hole. The figure shows that the MACC near-real-time main product (three successive system evolutions) has clearly outperformed the skill of ECMWF operational ozone, while improving over the first year of routine production.



Skill of ozone profile. Figure of merit for monthly-mean profiles of ozone over Neumayer (Antarctica) from August 2008 to May 2012.

Benefits of including aerosols for NWP

The inclusion of aerosols in atmospheric models has a large potential to improve NWP forecasts. Aerosol effects on cloudiness and the hydrological cycle are the topic of acute scientific debate, in particular concerning the indirect effects. Initial tests at ECMWF indicate that, though neutral overall on main global skill scores, taking into account the direct effect of aerosols brings local/regional benefits – these can be marked during strong episodes such as large dust outbreaks. It is less the load of aerosol than its physical properties, size distribution and spatio-temporal variability that matters really and in-line integration in the IFS makes it possible to be a pioneer in this direction.

Monitoring methane and carbon dioxide

While the global MACC-II system generally has been focusing on assimilating satellite observations, different solutions had to be found for the greenhouse gases due to a lack of accurate satellite observations for carbon dioxide (CO_2) and methane (CH_4).

Observations of greenhouse gases from space

The SCIAMACHY instrument has provided a long record of methane observations, but the recent loss of the ENVISAT satellite has ended this time series. The European IASI and Japanese GOSAT instruments also provide information on methane, but their retrieval algorithms are not yet fully mature.

For CO_2 the situation is even more problematic with the AIRS and IASI instruments providing some information about the global growth rate of CO_2 but without any significant regional information. Retrieval algorithms for the Japanese GOSAT instrument are not mature enough to fully constrain atmospheric CO_2 concentrations and surface fluxes.

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MACC-II greenhouse gas products

This situation has forced the MACC-II project to explore other directions to provide useful greenhouse gas services resulting in three main products.

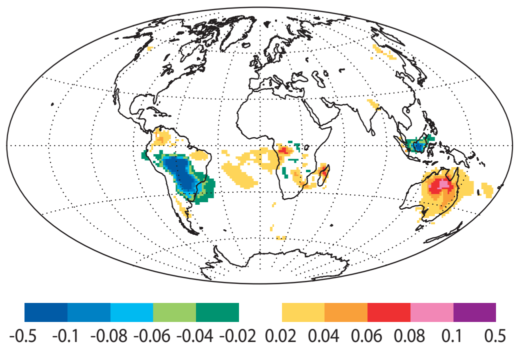
- ***Fluxes of CO_2 and CH_4 using flux inversion.*** Estimation of surface fluxes from atmospheric concentration observations remains a key component of MACC-II. These flux inversions are provided by our partners LSCE (Laboratoire des Sciences du Climat et l'Environnement) and JRC (European Commission's Joint Research Centre) for CO_2 and CH_4, respectively. For CO_2, the flux inversions are currently based on surface flask observations only, but trials with the slowly-maturing GOSAT retrievals are starting to look promising. For CH_4, the flux inversions were based on a combination of surface flask observations and SCIAMACHY retrievals. With the loss of ENVISAT, a transition to the use of GOSAT retrievals is currently under way.
- ***Fields of CO2 and CH4 using fluxes from flux inversion.*** The optimized fluxes from the flux inversions are used in the IFS model to produce atmospheric CO2 and CH4 fields at relatively high resolution (currently T255L60). Validation has shown that these atmospheric concentrations are quite realistic and therefore very useful to produce boundary conditions for regional greenhouse gas models or to test new satellite retrieval data, such as from GOSAT or the upcoming Sentinel-5p satellite.
- ***Fields of CO_2 using fluxes from C-TESSEL.*** The above two products are produced in delayed (six months to one year behind near-real-time) and reanalysis modes because of the very limited availability of surface observations and greenhouse gas satellite data in near-real-time. Therefore, the third product makes use of the land-surface modelling developments at ECMWF. The work in the MACC-II and GEOLAND2 projects at ECMWF has been very collaborative on the development and use of the C-TESSEL land carbon model. With the implementation of the C-TESSEL model in the IFS, CO_2 fluxes can be modelled on-line allowing a realistic forecast capability for the MACC-II CO_2 system. Observations are used to regularly update some key C-TESSEL model parameters as well as to constrain the global CO_2 growth rate providing reasonably accurate forecasts of CO_2 that can be used for boundary conditions, flight campaign planning, and near-real-time monitoring and processing of satellite data.

Figure 6 shows the validation of modelled CO_2 using fluxes from flux inversion (panel b) and C-TESSEL (panel c) against observations from *GLOBALVIEW-CO2* (2011) (panel a) as a function of time and latitude. While some differences between the observations and the model runs remain, it is clear that the main variability of CO_2 is well-captured, which is confirmed by other independent observations as well.

Contribution to the annual report on the State of the Climate

B

MACC and now MACC-II is a regular contributor to the annual supplement of the Bulletin of the American Meteorological Society on the '*State of the Climate*'. Anomalies in emissions due to biomass burning and in aerosol distributions (distinguishing between sea salt, dust, biomass burning and sulphate components) are provided to this international reference publication, which aims at regrouping best accurate estimates on the different component of the Earth's climate system.



Example of MACC information included in 'State of the Climate' report. Anomolous distribution of carbonaceous aerosol optical depth for September to November 2011 with respect to MACC reanalysis average (2003–2010) indicating a quiet season in South America and a highly active season in Australia.

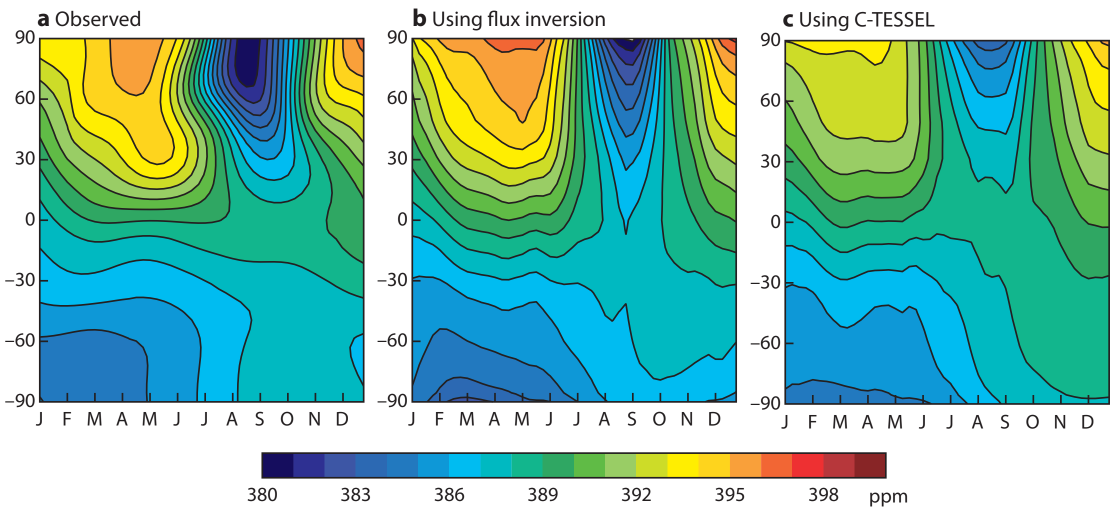


Figure 6 Validation of modelled CO_2 against observations: (a) the processed marine boundary layer surface flask observations from GLOBALVIEW-CO2, (b) the results using optimized fluxes from a flux inversion, and (c) the results using C-TESSEL CO_2 fluxes.

Looking ahead

Based on GEMS and MACC, MACC-II delivers a wide range of services on atmospheric composition. As a result, its user base is growing and MACC-II is attracting worldwide attention both on the products available and on the associated research conducted at ECMWF and at partners' organisations. While MACC-II is consolidating the production chains in preparation of the GMES operational phase in the second half of 2014, there are significant challenges ahead such as making the move to an in-line representation of chemistry in the IFS or evolving towards a more detailed aerosol representation that is linked with clouds and precipitation. Finally, MACC-II has begun to illustrate how atmospheric composition developments can benefit NWP and the meteorological reanalysis by developing the IFS in such a way that the representation of Earth-system processes are more integrated and comprehensive.

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Further reading

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