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Validation of reactive gases and aerosols in the MACC global analysis and forecast system

H. Eskes[1], V. Huijnen[1], A. Arola[2], A. Benedictow[3], A.-M. Blechschmidt[4], E. Botek[5], O. Boucher[6], I. Bouarar[7], S. Chabrillat[5], E. Cuevas[8], R. Engelen[11], H. Flentje[9], A. Gaudel[10], J. Griesfeller[3], L. Jones[11], J. Kapsomenakis[12], E. Katragkou[13], S. Kinne[7], B. Langerock[5], M. Razinger[11], A. Richter[4], M. Schultz[14], M. Schulz[3], N. Sudarchikova[7], V. Thouret[10], M. Vrekoussis[12,15], A. Wagner[9], and C. Zerefos[12]

[1]Royal Netherlands Meteorological Institute, De Bilt, the Netherlands
[2]Finnish Meteorological Institute, Helsinki, Finland
[3]Norwegian Meteorological Institute, Oslo, Norway
[4]Institute of Environmental Physics, University of Bremen, Bremen, Germany
[5]Belgian Institute for Space Aeronomy, BIRA-IASB, Brussels, 1180, Belgium
[6]Laboratoire de Météorologie Dynamique, IPSL/CNRS, Université Pierre et Marie Curie, Paris, France
[7]Max Planck Institute for Meteorology, Hamburg, Germany
[8]Izaña Atmospheric Research Center, AEMET, S/C Tenerife, Spain

[9]Deutscher Wetterdienst, Meteorologisches Observatorium Hohenpeissenberg, Oberpfaffenhofen, Germany
[10]CNRS and Université Paul Sabatier, Laboratoire d'Aérologie, Toulouse, France
[11]European Centre for Medium-Range Weather Forecasts, Reading, UK
[12]Academy of Athens, Athens, Greece
[13]Department of Meteorology and Climatology, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece
[14]Institute for Energy and Climate Research, Forschungszentrum Jülich, Jülich, Germany
[15]EEWRC, The Cyprus Institute, Nicosia, Cyprus

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Correspondence to: H. Eskes (eskes@knmi.nl)

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Abstract

The European MACC (Monitoring Atmospheric Composition and Climate) project is preparing the operational Copernicus Atmosphere Monitoring Service (CAMS), one of the services of the European Copernicus Programme on Earth observation and environmental services. MACC uses data assimilation to combine in-situ and remote sensing observations with global and regional models of atmospheric reactive gases, aerosols and greenhouse gases, and is based on the Integrated Forecast System of the ECMWF. The global component of the MACC service has a dedicated validation activity to document the quality of the atmospheric composition products. In this paper we discuss the approach to validation that has been developed over the past three years. Topics discussed are the validation requirements, the operational aspects, the measurement data sets used, the structure of the validation reports, the models and assimilation systems validated, the procedure to introduce new upgrades, and the scoring methods. One specific target of the MACC system concerns forecasting special events with high pollution concentrations. Such events receive extra attention in the validation process. Finally, a summary is provided of the results from the validation of the latest set of daily global analysis and forecast products from the MACC system reported in November 2014.

1 Introduction

Air pollution is a major issue worldwide, and evidence is accruing on its adverse effects on human health (e.g. WHO, 2013) and ecosystems (e.g. Krupa et al., 2006). Because some air pollutants are also radiatively active, climate change and air pollution are tightly linked problems (IPCC, 2013; Alapaty et al., 2012). Air pollutant concentrations are influenced by very local sources (traffic, industry, local heating) but also contain a long-range component (HTAP, 2010; Schere et al., 2012). Greenhouse gases and certain pollutants like carbon monoxide (CO) and ozone (O_3) have long residence

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times and can easily travel around the globe, while chlorofluorocarbons can even enter the stratosphere, harming the ozone layer (WMO, 2014). Desert dust, volcanic ash and sulfur dioxide (SO_2), or pollution plumes from major fires often travel far, even between continents, and long-range transported air masses can have a major influence on pollution concentrations at the surface. The day-to-day variability of pollution levels is large, and is strongly influenced by local and large-scale weather patterns.

The European Copernicus programme (http://www.copernicus.eu) is focusing on earth observation activities in the field of Land, Marine, Atmosphere, Emergency Monitoring, Climate Change and Security. This programme includes a series of satellite missions, the so-called sentinels. Sentinel 5-precursor (Veefkind et al., 2012; launch planned in 2016), Sentinel 4 and Sentinel 5 are missions dedicated to the atmosphere.

The atmospheric component of the Copernicus programme is the Copernicus Atmosphere Monitoring Service (CAMS). This service has been established to help Europe to respond to air quality problems and a changing climate. The purpose of the CAMS and the precursor project MACC is to combine satellite and other observations into a data assimilation modelling system in order to provide daily analyses and forecasts of the variability in atmospheric pollutant concentrations. CAMS covers global and regional scales, providing boundary conditions to finer-scale air quality models.

The CAMS system will provide operational services for the composition of the atmosphere from 2015 onward, and was developed in the past ten years by a series of European projects including GEMS (Hollingsworth et al., 2008), MACC-I, MACC-II and the current MACC-III (Monitoring Atmospheric Composition and Climate, http://www.copernicus-atmosphere.eu). For the global component of MACC, the numerical weather prediction forecasting system of ECMWF (IFS) was extended to provide daily forecasts, analyses and reanalyses of atmospheric composition, by combining satellite observations of atmospheric composition with state-of-the-art atmospheric modelling. Modules for aerosols (Morcrette et al., 2009; Benedetti et al., 2009) and greenhouse gases (Agustí-Panareda et al., 2014) were added to the IFS model code. Originally, atmospheric chemistry was not included online in the IFS, rather the chemistry transport

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models were run alongside the meteorological analysis system IFS with meteorological fields and chemical tendencies exchanged by a coupler (Flemming et al., 2009). Two such systems were developed, coupling the IFS to the chemical transport models (CTMs) MOZART (Kinnison et al., 2007) or TM5 (Huijnen et al., 2010). More recently, this reactive chemistry component has been integrated in the IFS (Flemming et al., 2014), creating the Composition-IFS (C-IFS) system.

Through continued quantitative validation of forecasts and analyses, the performance of the MACC model and data assimilation system is documented. Awareness of issues relating to the uncertainties and representativeness of observations is crucial for interpreting the comparisons between the analysis and the independent measurements. In MACC the validation work is conducted by groups directly involved in the measurements or with strong links to the measurement teams. Verification and validation starts with direct comparisons of model results with independent measurements, followed by the evaluation of a set of accuracy measures and/or skill scores (Wilks, 2006). For users of the MACC products it is important to present the skill of the system in a way which is intuitively easy to understand and which documents the improvements of the system over time. Standard practices in the evaluation of meteorological forecasts, and the use of headline scores (e.g. Haiden et al., 2014) serves as inspiration for the MACC validation activity.

The validation (VAL) sub-project in MACC has the task to evaluate the quality of the global service products on aerosol and reactive trace gases, including the daily forecasts but also the 2003–2012 MACC reanalysis. This paper provides an overview of the VAL approach to the evaluation of the MACC global modelling system developed over the past three years. Topics addressed are the validation reports, the procedure for model upgrades, and scoring methods. The models evaluated, and the measurements used for these evaluations are listed. A summary is provided of the main validation results for the daily global forecasts, but it is not the purpose of this paper to describe these results in detail. Finally we discuss current developments and future aspects.

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More detailed validation results have been (and will be) described in several scientific papers from the individual partners of VAL (Lefever et al., 2014; Cuevas et al., 2014; Wagner et al., 2014; Langerock et al., 2014; Katragkou et al., 2014) or contributions to papers led by partners from other sub-projects of MACC (Huijnen et al., 2012; Inness et al., 2013; Flemming et al., 2014; Pérez García-Pando et al., 2014; Stein et al., 2014; Cesnulyte et al., 2014). Several of these papers are submitted to the MACC special issue of the Copernicus journals ACP, AMT, ESSD and GMD.

2 Validation of the global MACC services

Quality assurance is an essential element of a pre-operational monitoring service such as MACC. Validation information needs to be supplied regularly and accompany the data products and services provided on the MACC website. The main purpose of the MACC validation effort is to provide the users of the future CAMS with appropriate information to judge the quality of the datasets. A secondary aim of the validation work is to provide feedback to the MACC modelling teams so as to guide model improvement and further development and to contribute to scientific studies and the evaluation of new model versions (Flemming et al., 2014; Inness et al., 2014).

In MACC it was decided to provide 3-monthly updates of the validation reports of the near real-time analysis and forecasts services. This high update frequency of the validation is implemented both for the global production of daily aerosol and trace gas analyses (et al., 2014b), as well as for the regional air quality forecast service, which is based on a de-centralised ensemble of 7 models (Marécal et al., 2014). In this paper we discuss the activities for the global aerosol and reactive gas services. The greenhouse gas sub-project of MACC (Bergamaschi et al., 2013; Chevallier et al., 2014; Massard et al., 2014) has its own validation activity, which will not be discussed in this paper.

For the other global services the update frequency of validation reports depends on the product. During the production of the MACC reanalysis (Inness et al., 2013) in MACC-II, the corresponding validation report was updated roughly

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each half year, corresponding to one more year added to the reanalysis data record. These reports (Eskes et al., 2014a) are available on the MACC website at http://www.copernicus-atmosphere.eu/services/aqac/global_verification/validation_reports/. The VAL sub-project provided also a validation report for the MACC 30 year ozone column reanalysis (the Multi-Sensor Reanalysis; van der A et al., 2010), which is available on the MACC website.

The VAL subproject is maintaining a set of web pages with more detailed verification plots for individual seasons, months or days (http://www.copernicus-atmosphere.eu/services/aqac/global_verification/). Some of these pages are based on near-real time data, and they are complemented by the NRT monitoring information from the data assimilation system.

For a good understanding of the quality of the MACC system it is important to consider which aspects of the global assimilation system are constrained by the observations, and which aspects are covered by the validation datasets used. This is summarized in Table 1. The MACC aerosol and reactive gas models contain on the order of 100 species with global coverage and ranging from the surface into the mesosphere. Clearly, only a small fraction of this is observed and constrained by the available observations. First, the MACC assimilation is focusing on aerosol optical depth (AOD), ozone, CO, NO_2 and SO_2. Note that the species are treated in a univariate way and correlations in background errors of different species are neglected (Inness et al., 2014). An analysis update of one trace gas will nevertheless influence others through the chemical reactions. Second, the validation is also constrained by the limited amount of trace gas and aerosol properties for which validation data is available. Furthermore, validation is limited by the amount of external data that is available in real time or at least within a few weeks after measurement, and with a reasonable global coverage.

For the validation work MACC has the following requirements:

– for near-real time verification of the analyses the independent measurements should become available within a few days.

- For the evaluation of the daily analyses and forecasts service – through the 3 monthly validation reports – data can be used that becomes available within 6 weeks.

- For the 10 year reanalysis produced by MACC (or planned reanalyses in the future CAMS) the requirements are more relaxed and observations several years old can also be accommodated.

Because of these requirements, the MACC consortium is keeping close contacts with major world-wide networks. In the case of the Network for the Detection of Atmospheric Composition Change (NDACC; http://www.ndsc.ncep.noaa.gov), the European project NORS (Demonstration Network Of ground-based Remote Sensing Observations in support of the Copernicus Atmospheric Service; http://nors.aeronomie.be) has set up a validation server to provide real-time access to the validation data and to produce verification plots. In the case of the IAGOS routine aircraft observation infrastructure (http://www.iagos.org), the European project IGAS (IAGOS for the GMES Atmospheric Service) is improving the real-time data delivery and is harmonizing the data quality. The ICOS-INWIRE project (http://www.icos-inwire.lsce.ipsl.fr/) provides a harmonized access to the ICOS infrastructure in Europe for the Copernicus atmosphere service. MACC maintains close links with WMO-GAW (http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html) to improve the use of the measurements performed at the numerous stations worldwide, contributing to this programme, and some stations have begun to submit datasets with weekly or monthly update frequencies for use in the MACC validation. Regarding aerosols, MACC has negotiated access to level 1.5 AERONET (AErosol RObotic NETwork; http://aeronet.gsfc.nasa.gov) data as level 2.0 data only becomes available after re-calibration of the instruments which have been in the field.

We note that Table 1 represents the current status of the system. In collaboration with networks like GAW and NDACC, other datasets are investigated for inclusion in the future CAMS validation activity. For instance, in the coming years the IAGOS aircraft

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will provide observations of aerosols, NO_x, NO_y, CO_2 and CH_4, in addition to O_3 and CO that are currently used.

3 Validation reports for the atmosphere composition forecast and analysis service

The main aim of the 3-monthly validation reports (e.g. Eskes et al., 2014a, b) is to provide the users of the services with up-to-date information on the quality of the products through comparison with independent observations. The reports contain the following sections:

- an extended summary – typically 7 pages – of the main findings of the validation work. This summary is targeting the different user areas, which are defined in the reports as: climate forcing, regional air quality, ozone layer and UV.
- A system summary section. This section contains an overview of the model configurations; description of the models and assimilation; overview of the assimilated datasets; evolution of the system and overview of major model changes; MACC products overview; availability and timing of the daily MACC analyses/forecasts. The document refers to the detailed change logs and model information that are available on the MACC website.
- A detailed section on the validation results obtained for the different species in troposphere and stratosphere. This is the bulk of the document.
- A section to discuss a number of high concentration events and the ability of the MACC forecast and analysis to capture these events.
- An annex providing traceability information on the validation methodology used.

4 New updates: e-suite reports

The MACC project follows a well defined procedure to introduce model upgrades of the operational data assimilation and model system, which is called the "o-suite". First, model changes that are developed by ECMWF's research department or the scientific partner institutions in the MACC project are tested off-line, and quick checks are performed to test the improvement of the model or assimilation aspects targeted by the update. Once these tests are satisfactory, a new model version is earmarked for operational use. At this point, a series of hindcasts for a period between 3 to 6 months are generated in a set-up which closely mimics the o-suite. This parallel assimilation system is called the "e-suite", or experimental suite. A change log for this e-suite is provided on the MACC website. Near the end of the e-suite production phase, VAL performs an evaluation, comparing the performance of the operational o-suite and the new e-suite against the independent observations. If this test shows improved (or at least comparable) scores, a positive advice is given to replace the o-suite, but if problems are identified the VAL results may also lead to a delayed installment of the new model version after the weaknesses have been corrected for.

In the period January 2012–November 2014 four upgrades of the o-suite have been introduced, and for each of them an "upgrade verification note" was produced. These reports are part of the production system description pages that can be found on the "operational info" section of the MACC website. In one case a negative upgrade advice was given, because the e-suite showed a strong loss of aerosol mass during the forecast (see Fig. 1).

5 Accuracy measures and scoring methods

The VAL subproject is maintaining a living document on the evaluation methodology with project-wide recommendations on scoring approaches (Eskes and Huijnen, 2012). The aims of this report are:

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- to “harmonize” the scoring methods by proposing a “default” set of accuracy measures for VAL as well as the other subprojects in MACC.
- To develop a set of “headline scores” which may be used in the future to document the improvements of the Copernicus Atmosphere Monitoring Service products over time. This point is discussed in the Discussion and Future Perspectives section.
- To introduce uniform graphics styles and a uniform presentation of validation results on the MACC II website.
- To briefly discuss the value of alternative scoring approaches (e.g. threshold scores, ranking scores).

The main scoring recommendations are:

- initial evaluation: verification/validation starts with basic evaluation of the model results against individual independent observations. This includes time series plots and scatter plots. For large number of points (> 200) it is recommended to replace the scatter plot by scatter density plots.
- Accuracy measures: it is recommended to use a minimal set of accuracy measures to evaluate and compare model results. These are the modified normalized mean bias, the fractional gross error and the correlation coefficient.
- Data stratification: it is recommended to apply a baseline temporal aggregation of the individual model-observation comparisons on a (three-monthly) seasonal basis. For the global models and for the troposphere it is recommended to apply a baseline spatial data stratification using pre-defined regions. It is recommended that verification is done both against (a) gridded observations (model-oriented verification) on common latitude/longitude grid, and, (b) station observations (user-oriented verification) whenever possible.

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– Presentation: within VAL we adopted a uniform presentation in the figures. The colors of the curves are reserved for the different model configurations. Black is generally used for the independent data.

The scoring recommendations are used in VAL, but also for instance for the evaluation of the MACC European ensemble air quality forecasts (Marécal et al., 2014). Representativity issues should be taken into account, given that model predictions represent averaged concentrations over a grid box, whereas observed values are either taken at individual locations that are un-equally distributed over the globe, in case of in-situ observations, or integrated over space, in case of observations from remote sensing instruments.

The modified normalized mean bias (MNMB) B'_n, fractional gross error (FGE) E_f and correlation coefficient r are computed using the following formulas:

$$B'_n = \frac{2}{N}\sum_i \frac{f_i - o_i}{f_i + o_i}, \tag{1}$$

$$E_\mathrm{f} = \frac{2}{N}\sum_i \left|\frac{f_i - o_i}{f_i + o_i}\right|, \tag{2}$$

$$r = \frac{\frac{1}{N}\sum_i \left(f_i - \overline{f}\right)\left(o_i - \overline{o}\right)}{\sigma_f \sigma_o} \tag{3}$$

where $\overline{f}$ and $\overline{o}$ are the mean values of the forecast and observed values and σ_f and σ_o are the corresponding SDs. The B'_n can have values between −2 and 2, and is symmetric around zero. E_f ranges from 0 to 2, where 0 is perfect agreement, and values close to 1 or larger indicate a very poor agreement. r ranges between −1 and 1, where −1 means perfect anti-correlation, 0 means uncorrelated, and 1 indicates perfect correlation.

The normalised approach provides errors in a relative sense, which is easier to comprehend by users not very familiar with the concentration ranges and their units. The

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fractional gross error is a linear measure, and has the advantage compared to the more common root-mean-square measure that it is not dominated by outliers.

6 Model configurations

6.1 Before September 2014: coupled systems

During the projects GEMS and MACC three modelling systems were developed and used to describe reactive gases in troposphere and stratosphere (Hollingsworth et al., 2008). These were constructed by coupling the ECMWF IFS system to a CTM. The CTM can be MOZART, TM5 or MOCAGE, resulting in a small ensemble of models. In this coupled system the IFS simulates only the transport of a limited number of chemical species (O_3, CO, NO_x, SO_2, HCHO), and the CTM provides concentration tendencies due to emissions, deposition and chemical conversion to IFS. Satellite observations of these species (apart from HCHO) are assimilated into the IFS using the 4-D-VAR analysis system, together with the full suite of meteorological observations. The resulting analyses for the five species are subsequently passed to the CTM. The CTMs maintain their own transport schemes and are driven by meteorological data at hourly resolution from the IFS. More details on the coupled systems can be found in Flemming et al. (2009).

During MACC, the MOZART and TM5 based systems have been used to produce daily forecasts. Because of the computing costs of running the MACC 4-D-Var system, and in order to provide one single pre-operational product, it was decided to have only one operational analysis. This MACC o-suite was based on the IFS-MOZART coupled system. This system was used both for the daily analyses and forecasts, and for the production of the MACC 2003–2012 reanalysis (Inness et al., 2013). Apart from the analysis runs, the two coupled systems are operated without data assimilation to produce daily forecasts. The IFS-MOZART runs apply the same settings as the o-suite, except that data assimilation is not switched on and the spatial resolution is lower:

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T159L60 (where "T" is the spectral resolution and "L" is the number of vertical layers) compared to T255L60 for the IFS part, and this model version does not contain aerosol. The IFS-TM5 runs apply similar emissions as IFS-MOZART, but chemical reactions, deposition and transport are described by the TM5 model (Huijnen et al., 2010). More details on the model configuration and the change log can be found on the MACC website or in the validation report (Eskes et al., 2014a).

The aerosol model is integrated in the IFS and includes 12 prognostic variables, which are 3 bins each for sea salt and desert dust, hydrophobic and hydrophilic organic matter and black carbon, sulphate aerosols and its precursor trace gas SO_2 (Morcrette et al., 2009). Satellite AOD measurements from MODIS are assimilated in this system (Benedetti et al., 2009). Changes of the operational system compared to the aerosol model described in the above papers can be found on the MACC website or in the VAL reports. The aerosol system is based on one model (Morcrette et al., 2009), and there is no stand-alone version of the model operated without data assimilation.

The reactive gas and aerosol modelling systems use real-time aerosol fire emissions from the Global Fire Assimilation System (GFASv1; Kaiser et al., 2012) developed within GEMS and MACC.

The daily stratospheric analyses from the three model configurations are compared with three offline stratospheric analysis systems: BASCOE (Errera et al., 2008; Viscardy et al., 2010), SACADA (Elbern et al., 2010) and TM3DAM (van der A et al., 2010). Lefever et al. (2014) compared the analyses of stratospheric ozone by the o-suite (IFS-MOZART) with the results of these three offline systems and showed that its quality is primarily determined by the availablity and vertical range of Aura-MLS observations.

The VAL project evaluates all these model configurations. For the near-real time reports (Eskes et al., 2014a) three model configurations are considered: the o-suite, the free-running IFS-MOZART and free-running IFS-TM5 coupled systems. The aerosol model is only switched on in the o-suite. The comparison between the o-suite simulated gas concentrations and the free running model provides important information on

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the impact of the observations through the assimilation. The comparison between the MOZART and TM5 configurations provides information on the variability between the CTMs.

6.2 After September 2014: C-IFS

A major change occurred in September 2014 when the o-suite based on the coupled system was replaced by an o-suite based on a version of IFS with in-line chemistry (Composition-IFS, or C-IFS). Currently the chemistry modules from the TM5 model are used, which are based on a modified CB05 chemical mechanism. This C-IFS (CB05) model is described in detail in Flemming et al. (2014) and the reactive gas data assimilation results with C-IFS (CB05) are reported in Inness et al. (2014). The aerosol scheme is basically unchanged, and was already fully integrated into the IFS code.

The daily production of the analyses and forecasts consists of operating the full system with 4-D-Var assimilation (the o-suite). In parallel, daily forecasts are produced by running the same model without assimilation. Both model configurations are evaluated by the VAL team. A precursor of the C-IFS (CB05) system without data assimilation was producing daily forecasts from December 2012 to September 2014. This version was also evaluated by the VAL team, and results for this version are shown below.

7 Measurements used for validation

The following independent datasets are presently used (year 2014) to produce the validation reports:

- profiles of CO and O_3 from MOZAIC/IAGOS (http://www.iagos.fr/macc). IAGOS is a new European Research Infrastructure conducting longterm observations of atmospheric composition (reactive and greenhouse gases) aerosol and cloud particles on a global scale from commercial aircraft of internationally operating airlines (http://www.iagos.org; and http://www.iagos.fr for the map of network cov-

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erage). IAGOS builds on the scientific and technological experience of MOZAIC and CARIBIC. For 10 years, GEMS/MACC validation activities are using ozone and CO from MOZAIC/IAGOS to evaluate the different model runs on a regular/operational basis for profiles and UTLS region (cruise part of the flights at northern mid-latitudes) or on special events such as the summer 2003 heat wave over Europe (Ordóñez et al., 2010) and summer 2004 Canadian boreal forest fires (Elguindi et al., 2010). Two versions of IAGOS data are used to assess the model. The first one is the validated data used to assess the NRT model runs qualitatively in terms of vertical, daily and regional O_3 variability. The second and final version of IAGOS data is fully calibrated and hence more reliable for an accurate model evaluation. This is usually available within 6 to 12 months after recording.

- Surface observations of CO and O_3 from GAW stations, including ESRL stations as available from http://www.esrl.noaa.gov/gmd/ (Oltmans and Levy, 1994; Novelli et al., 2014). Detailed information on GAW and GAW related O_3 and CO measurements can be found in GAW report No. 209 (2013) and No. 192 (2010), available from http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html. Near-real time monitoring of the global forecasts is based on NRT observations of ozone and carbon monoxide from WMO GAW surface stations.

- Ozone sondes, used to validate stratospheric and tropospheric ozone. This data is taken from a variety of data centres: World Ozone and Ultraviolet radiation Data Centre (WOUDC), Southern Hemisphere ADditional OZonesondes (SHADOZ) and Network for the Detection of Atmospheric Composition Change (NDACC).

- Assimilation O_3 results from the independent BASCOE, SACADA, and TM3DAM data assimilation systems (http://www.copernicus-stratosphere.eu/; http://www.knmi.nl/goa/ozone/tm3dam_webdocu/tm3dam.html). BASCOE assimilates ozone profiles from Aura-MLS retrievals, while SACADA and TM3DAM assimilate ozone columns from GOME-2 (Lefever et al., 2014).

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- Independent satellite data from the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS; Dupuy et al., 2009), the OSIRIS instrument onboard satellited Odin (Degenstein et al., 2009) and the limb module of the Ozone Mapping and Profiler Suite (OMPS; Kramarova et al., 2014), used to evaluate stratospheric ozone.

- NDACC data, automatically collected by means of an online validation server which was developed in the EU FP7 research project NORS, see http://nors.aeronomie.be, de Mazière et al. (2012), Langerock et al. (2014). Presently the NORS server validates O_3 using FTIR, MWR, UVVIS DOAS and LIDAR measurements, CO and CH_4 using FTIR measurements, H_2CO and aerosol using UVVIS DOAS and NO_2 using FTIR and UVVIS measurements. The number of sites is continuously expanding as more sites start submitting data in rapid delivery and in GEOMS format.

- MOPITT and IASI CO observations (Emmons et al., 2009; Deeter et al., 2010; Clerbaux et al., 2009).

- Independent DOAS (Differential Optical Absorption Spectroscopy) based retrievals of NO_2 and HCHO columns (Richter et al., 2005, 2011; Wittrock et al., 2006) from the UV-vis sensors SCIAMACHY (Scanning Imaging Absorption spectroMeter for Atmospheric ChartographY; Bovensmann et al., 1999) onboard ENVISAT and GOME-2 (Global Ozone Monitoring Experiment-2A; Callies et al., 2000) onboard MetOp-A. These global data sets provide a large number of comparison points at all latitudes and seasons, but do not offer vertical resolution and have larger uncertainties than many in-situ observations. As the European Space Agency lost contact to the ENVISAT satellite in April 2012, SCIAMACHY is used for model validation up to March 2012, while model results are compared to GOME-2 from April 2012 onwards.

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- AOD and Ångström Exponent (AE) datasets from the AERONET sun photometer network. Near-real time (NRT) level 1.5 data is made available on a monthly basis by NASA Goddard (Holben et al., 2001; Smirnov et al., 2000) and is used for a real-time verification of the analyses and forecasts. Supporting graphs were generated with the AeroCom tools, http://aerocom.met.no/cgi-bin/aerocom/surfobs_annualrs.pl?Project=MACC.
- AOD, AE and dust aerosol optical depth (DOD) from thirty six AERONET stations, combined with AOD from MODIS (Aqua) and with lidar vertical extinction profiles at Tenerife station. These datasets are used for the quarterly assessments of mineral dust content, and analyses of outstanding dust events over Northern Africa, Middle East and Europe. This is a relevant geographical region where two of the most important mineral dust sources of the world (the Sahara–Sahel and Middle East) are present. Previous dust evaluations have extensively used AERONET and ground based and space-borne lidars data to assess the column dust content provided by dust models (i.e., Pérez et al., 2006; Schmechtig et al., 2011; Tegen et al., 2013; Cesnulyte et al., 2014), and PM_{10} for surface dust concentration validation (Schmechtig et al., 2006; Cuevas et al., 2014).
- Greenhouse gas observations provided by ICOS (Integrated Carbon Observation System, http://www.icos-infrastructure.eu) through a special agreement between ICOS and MACC, and by TCCON (Total Carbon Column Observing Network, http://tccon.ornl.gov/, Wunch et al., 2011).

The teams involved in MACC maintain close links with many of the observation networks from which the above mentioned observational data is obtained.

8 Case studies

One prominent application of MACC is the description and forecasting of the variability of trace gas and aerosol concentrations and the occurrence of high concentra-

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tion events. These events include dust storms (Cuevas et al., 2014), major wildfire or biomass burning events (Elguindi et al., 2010; Huijnen et al., 2012), ozone and aerosol pollution episodes (Ordóñez et al., 2010), ash and SO_2 from volcanic eruptions (Flemming and Inness, 2013), and the rapid depletion of ozone over the Antarctic and Arctic (Lefever et al., 2014). The VAL group studied more than 10 events in the period 2013–2014, and the results have been included in the validation reports.

A first example of a case study is shown in Fig. 2. In June 2014 a huge desert dust plume occurred that originated in the Sahara and, out through the Sahel, traveled more than 6000 km over the North Atlantic impacting the Amazon and the Caribbean. The path travelled by the plume was well captured by the MACC global system, as is shown by the comparison with MODIS. The correct timing of the dust event in the MACC o-suite is further confirmed by the time series at the available AERONET sites (black dots), although the modelled optical depth has a moderate low bias compared to the observations.

A second example is the observation of a prominent biomass burning plume from Canada by Ceilometer instruments in Germany. Active fires in Canada in June/July 2013 produced a large amount of biomass-burning aerosols which were transported to Europe. The features of this biomass plume were observed by German ceilometers.

In Fig. 3 measured and modelled 2-D time-height sections of biomass burning plumes at the station Soltau (Northern Germany) are compared. Though total extinction is displayed, the plumes are only made of smoke particles. The uncertainty of the ceilometer extinction coefficients is estimated to be ±50 %. Areas with noisy or missing ceilometer data, e.g. above clouds, are masked to prevent missinterpretations. During this period, which is characterised by fast transport of the air-masses across the Atlantic, the heights of individual plumes and even their internal structure (7 and 9 July, early 10 July) are reproduced with remarkable detail by the model. This indicates that injection heights and plume dispersion are realistic. The plume observed on 8 July at Soltau appears too weak in the model, because it had a meridional extent of about

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100 km only and was displaced southward with respect to the model grid cell. Absolute extinctions, however, are about a factor of 2 too small in the model due to the much coarser resolution (in order to prevent artifacts due to averaging the ceilometer data over regions with low signal/noise ratios a high resolution is maintained). Representativity issues, which are admittedly significant in this test evaluation will be improved in the future CAMS.

The widespread use of ceilometers and their capability to measure the backscatter coefficient offers a level of information content which is well suited for the evaluation of aerosol models. Their uncertainty of extinction coefficients can be below 30 %, depending on the instrument used, see e.g. Heese et al. (2010) or Wiegner and Geiß (2012). The adequate representation of sources and dispersion of different aerosol types is still a challenge for aerosol models. The evaluation of the MACC analyses with ceilometer observations from the German Weather Service (DWD – http://www.dwd.de/ceilomap) showed the usefulness of the ceilometer data to track fire plumes, (Sahara) dust plumes and to validate the modeled boundary layer heights.

Data from major international measurement campaigns are also used to evaluate if the MACC system is able to describe mean concentrations, transport of pollutants and observed variability. Examples are ACCESS (Roiger et al., 2014) and POLARCAT/POLMIP (Emmons et al., 2014). Note that MACC is providing support to flight planning during field campaigns like e.g. ACCESS.

9 Validation of the MACC o-suite

Below we give a summary of the results from the latest (November 2014) validation update for the MACC o-suite. This provides an overview of the extent of the validation work and validation methodology for the global aerosol and reactive gas service, and at the same time it serves to document the performance status of the recent MACC system against independent observations for the period up to August 2014. More detailed validation results and plots can be found in the validation report (Eskes et al., 2014a), on the MACC website and in the papers mentioned in the introduction.

The runs discussed here contain the o-suite, for this period based on analyses and forecasts from the coupled IFS-MOZART assimilation system including the MACC prognostic aerosol module. The impact of other chemistry schemes and of the use of data assimilation is furthermore assessed by comparing the validation results from the o-suite to those of the two other MACC model configurations, both without assimilation. These are the coupled IFS-MOZART system, and C-IFS (CB05), which is an earlier version of the model described in Flemming et al. (2014).

9.1 Tropospheric ozone

Model tropospheric ozone is validated with respect to surface and free tropospheric ozone observations from the GAW network, IAGOS airborne data and ozone sondes, hence covering the model performance at the surface, in the boundary layer and in the free troposphere. For the free troposphere MNMBs for ozone are on a global scale between ±0.4 for the o-suite, as displayed in Fig. 4. Best performance is generally achieved over the northern mid-latitudes, with MNMB often less than 0.1. This is also the region with the largest coverage of ozone sonde data. In the northern mid-latitudes and tropics, the coupled IFS-MOZART system shows in most cases larger positive MNMBs: in the northern Mid-latitudes a positive offset of up to 0.2, in the Tropics of up to 0.3 which appears mostly during November to March. This demonstrates that the ozone data assimilation, using stratospheric profiles (MLS) and ozone column observations, on average has a positive impact on the tropospheric ozone profile (Inness et al., 2013, 2014). For high latitude regions, where data assimilation is less effective, larger biases (±0.4) are observed (Fig. 4) and the o-suite partly shows larger biases than the version without assimilation.

At the surface, the o-suite evaluation against GAW stations is generally slightly positive, especially during the Summer months for European stations, which is broadly

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in line with the evaluation against ozone sondes, and also discussed in Inness et al. (2014).

For tropical stations biases are generally larger than over the northern mid-latitudes. The model is scarcely evaluated over the Southern Hemisphere. Both for Arctic and Antarctic stations the variability between the three model versions is generally larger than for mid-latitude and tropical stations, while biases with respect to observations are significant. This indicates the poorer constraints from data assimilation and also the larger uncertainty arising from the chemistry model.

9.2 Tropospheric nitrogen dioxide (NO_2)

Retrievals of tropospheric NO_2 columns from SCIAMACHY and GOME-2 observations are used for the validation of the three MACC systems. Nitrogen dioxide satellite observations from the OMI instrument are assimilated (Inness et al., 2014), but this is based on a different retrieval scheme and data from the OMI instrument which has a later overpass time. The comparisons with SCIAMACHY/GOME-2 show that spatial distributions of tropospheric NO_2 columns are well reproduced by all three NRT model runs throughout all seasons, indicating that emission patterns and NO_x photochemistry are generally well represented. A general feature is the underestimation of NO_2 columns over the continents in general and particularly in China (see Fig. 5), which may point to an underestimation of anthropogenic NO_2 emissions in the inventories. Unresolved non-linearities in NO_x photochemistry at the coarse model-resolution might also play a role, as well as larger retrieval uncertainties in the winter months. Another observation is the occurrence of localized high bias regions of NO_2 in the Northern high latitudes during Summer, which indicates that the NO_2 produced by boreal fires in Siberia, Canada and Alaska, as derived from the GFAS system (Kaiser et al., 2012) may be overestimated.

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9.3 Tropospheric carbon monoxide (CO)

Carbon monoxide is validated using GAW network surface observations, IAGOS airborne data, FTIR observations and satellite retrievals, hence providing good coverage both horizontally and vertically. This evaluation consistently shows that – even though the seasonality of CO can be reproduced well – there is a systematic underestimation of CO surface mixing ratios by all model versions in the Northern Hemisphere, with seasonal MNMBs up to −0.3 in comparison with GAW observations. The biases are largest during winter and early spring. During take-off and landing the IAGOS in-flight profile observations are frequently capturing layers with elevated levels of CO, and have been used to evaluate the model ability to describe the magnitude and transport of plumes originating from biomass burning (Elguindi et al., 2010).

We note that MOPITT and IASI satellite retrievals of CO are assimilated in the o-suite (Inness et al., 2014), so such evaluation is not an independent source of information. Nevertheless, these retrievals provide a good reference for the ability of the models to capture spatial patterns and seasonal cycles in free tropospheric CO and also clearly quantify the effect of the bias correction applied in the o-suite.

During the fire season over Siberia and Alaska an under-estimation up to 10 % is observed with respect to MOPITT, in contrast to the significant overestimate in NO_2 and a positive bias in aerosol. It should be noted that MOPITT and IASI show significant differences in this region.

A clear improvement in performance of the o-suite against the free running IFS-MOZART coupled system was found, especially during summer seasons, indicating that data assimilation is more effective in summer compared to the winter season. This is confirmed by validation with FTIR profile observations. The GAW surface observations with high temporal resolution are used to evaluate the small-scale model variability. For instance, a rather remarkable improvement of the temporal correlation between the o-suite and C-IFS (CB05) is found for most stations. This is illustrated by the time series of CO at Hohenpeissenberg station for March–May 2014 shown in

Fig. 6. In this example the temporal correlation coefficients (r) are 0.59, 0.62 and 0.71 for the o-suite, IFS-MOZART and C-IFS (CB05) respectively.

9.4 Formaldehyde

Model validation based on SCIAMACHY and GOME-2 HCHO satellite observations shows that overall, mean concentrations and spatial patterns show a good match, see, e.g., Flemming et al. (2014). A more detailed comparison reveals differences between satellite data and models, particularly over the emission regions Central Africa, South America, South-Eastern US as well as South-East Asia, indicating the significant modelling uncertainties associated with this trace gas. For instance, time series over East-Asia and the Eastern US, which are both regions where HCHO columns are likely dominated by biogenic emissions, show that the MOZART-based model versions are well in line with satellite retrievals in terms of magnitude and seasonality, whereas the C-IFS (CB05) shows larger biases. In the African regions, dominated by biogenic and biomass burning HCHO (precursor) emissions, model performance is reasonable although the C-IFS (CB05) chemistry run overestimates satellite values. In contrast to NO_2, the HCHO columns for boreal fire regions are well reproduced by all models. It should be noted that no formaldehyde observations are assimilated, and these results reflect the performance of the unconstrained models.

9.5 Aerosol

Bulk optical properties of the MACC aerosol model are validated against NRT level 1.5 AERONET observations, see Fig. 7. This reveals that the latest model version has on average a positive bias of about +20 % for AOD. The positive bias is smaller in winter (+5 %) but increases in spring. A month-to-month variation is observed in the correlation, ranging from 0.65 to 0.8. On average, approximately 50 % of the day to day AOD variability is predicted by the o-suite. Also the +3 day forecast aerosol distributions are routinely evaluated and show 5–10 % less AOD than the initial day.

This indicates that the model AOD at equilibrium between emissions and removal is somewhat lower in optical depth than the IFS analysis, possibly implying a bias in the MODIS observations used in the assimilation. These forecasts additionally show slightly lower correlation, as a consequence of imperfect forecasted meteorology and a fading impact of the initial assimilation of MODIS AOD and MODIS fire information on model performance.

The model Ångström exponent (AE) is evaluated with the AERONET data, and proved to be a good indicator of aerosol size changes as a consequence of aerosol parameterisation changes. The current model version shows a positive global bias indicating too fine particles in the model. A significant variation of Ångström exponent was seen over the last three years, which is a result of changes in the contributions from fine and coarse aerosol components to total AOD. The latter being constrained through the assimilation method.

The NRT aerosol model evaluation remains limited. One limitation is the quality of the NRT Aeronet data, which have a preliminary nature. Retrospective analysis of the year 2011 shows that this level 1.5 NRT AOD AERONET data, due to undetected cloud contamination and any uncorrected instrumental drift, are on global average 20 % higher than quality assured level 2.0 AERONET data, see Fig. 8. This suggests that the o-suite bias in AOD is likely to be larger than suggested by the comparison with the NRT observations. Another limitation is that little information on the aerosol composition is available, and this can only be assessed indirectly, e.g. through the AE.

MACC o-suite dust parameters have been routinely assessed over Northern Africa, Middle East and the Mediterranean basin and southern Europe, using AERONET, MODIS (Aqua) and lidar observations. A specific evaluation has been performed, as well, for the MACC-II short (2007–2008) reanalysis with improved dust parameterizations (Cuevas et al., 2014). The spatial agreement between MACC o-suite AOD and MODIS AOD is very good, confirming that MACC o-suite captures almost all dust outbreaks tracking fairly well their spatiotemporal evolution over the North Atlantic and the Mediterranean. The results of the comparisons of the o-suite AOD/DOD

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with AERONET AOD/DOD, MODIS AOD, and the WMO Sand and Dust Storm Warning Advisory System (SDS-WAS) multi-model DOD median (http://sds-was.aemet.es/forecast-products/forecast-evaluation/model-evaluation-metrics), formed with seven to nine models, indicate and excellent agreement in all regions, except over the Sahara. In this region the o-suite tends to overestimate, showing an averaged seasonal MB (with AERONET) ranging from 0.08 to 0.24 in winter and spring, respectively. The o-suite behaves quite well compared with other regional and global dust models, providing similar results to those of the SDS-WAS multi-model median.

9.6 Stratospheric ozone

Ozone profiles are routinely evaluated with vertical profiles from balloon borne ozone sondes, ozone profile retrievals from the MLS, OMPS and OSIRIS satellite instruments, ground-based remote-sensing observations at a selection of stations from NDACC, including microwave, FTIR and LIDAR observations. The MACC system is further compared to analyses from the BASCOE, TM3DAM and SACADA assimilation systems. This implies that the performance of the modeled stratospheric ozone is well characterized.

Relative monthly mean biases of the o-suite are on average between −5 and 17 % compared with ozone sondes. The Antarctic ozone hole 2013 was reproduced by the o-suite with relative biases less than 10 %. The validation results of the o-suite in comparison to other model versions clearly reveal that data assimilation, and especially the use of profile observations by limb-sounding instruments such as MLS, is essential for a correct representation of the vertical distribution of ozone in the stratosphere (Inness et al., 2013, 2014; Lefever et al., 2014). The impact of data assimilation at other locations is confirmed by the evaluations based on NDACC stations, for example at Izaña, Fig. 9.

Total ozone columns in the o-suite show always good agreement compared with TM3DAM (Lefever et al., 2014). This system can serve as a reference for the ground-

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truth since it applies bias corrections to GOME-2 data based on the surface Brewer–Dobson measurements.

Ozone daily mean time series from the o-suite are further compared to BASCOE assimilation system and to OMPS, OSIRIS and MLS satellite data for different latitudes at 20 km (lower stratosphere), which is relevant for future validation and operation of forecast models, see Fig. 10. This evaluation illustrates that o-suite and BASCOE are usually very close (> 5 %). There are in fact significant biases between satellite instruments, with an ozone abundance in OMPS that is in general 25–30 % lower than MLS data for all latitudes at 20 km. A similar behaviour is found for OSIRIS in the tropics, while the agreement with MLS is much better at the poles. It should be noted that the product from OMPS is relatively new, and the comparisons may improve with future retrieval algorithm updates.

10 Discussion and future perspectives

In this paper we provided an overview of the validation approach for the global MACC service products. The principle behind this work is that every product in the catalogue of MACC should be accompanied by validation information based on independent observations, and summarised in validation reports, which is essential for the users. For the global forecast/analysis service this validation report is updated on a very regular 3 monthly basis to provide up-to-date information on the product quality. The validation team is operating largely independently from the modelling teams. The VAL activity is targeted to users, but it also provides feedback to the modelling and data assimilation teams in MACC concerning new model test versions.

The assimilation and validation activity within MACC is clearly limited by the finite amount of high-quality observations available for comparison in NRT. The model contains a large number of trace gases and aerosol components simulated with global coverage at as high resolution as practically feasible. Only a small amount of these variables is constrained, as was indicated in Table 1. Additional constraints can oc-

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casionally be obtained from an in-depth analyses of field campaigns, e.g., Emmons et al. (2014). The focus in VAL is mainly on those modelling aspects that are strongly influenced by the assimilation process: tropospheric and stratospheric ozone, tropospheric CO, aerosol optical properties, and, to a lesser extent, NO_2, SO_2 and HCHO. Apart from this, the availability of observations in near-real time is crucial for the assimilation. For the validation reports the requirements are somewhat more relaxed: observations should be available within one month to 6 weeks.

In the near future more focus will be given to the evaluation of the MACC system in terms of trace gas and aerosol boundary conditions to regional air quality models. Suitable evaluation datasets and good quality metrics are currently under investigation. Another aspect not yet well covered in the VAL activity is the evaluation of the aerosol composition and vertical distribution, in particular because no, or very limited NRT observations are available. More research and technical work is needed to use e.g. the climatological aerosol composition and variation as used for AeroCom model evaluations to obtain relevant information on the actual quality of the IFS forecast system. Validation of vertical distribution of some components, such as aerosols, could be improved in future, incorporating observations from networks of ceilometers and micropulse lidars functioning operationally. However, for these measures to be truly useful in MACC validation, calibration constraints must be first overcome.

Apart from the observational datasets listed in Sect. 7, which are currently used for the validation of the MACC system, VAL is also expanding its scope by looking at new promising datasets. Previous (e.g. ACCESS) and future field campaign data provide interesting case studies and allow for a more extensive evaluation in the free troposphere. A dataset that was considered in MACC are Ceilometer observations, and the use of ceilometer networks was discussed in Sect. 8.

A second type of new observations studied in MACC involves ground-based MAX-DOAS instruments. These instruments are well suited to probe the amount of pollutants in the boundary layer above urban areas. Because several of the instruments are located close to large cities, these observations are especially valuable to test regional air quality models with enough spatial resolution to simulate fine-scale variability (see, e.g., Vlemmix et al., 2011). The models can be tested on an hourly basis during daytime, which offers the possibility to investigate diurnal, weekly and seasonal dependencies, as well as dependencies on the meteorological conditions. For a continuous validation, a mix of stations at background locations in polluted and unpolluted regions as well as close to emission hot-spots such as cities or industrial areas would be ideal.

The near-future C-IFS system is foreseen to include a set of three different chemistry modules for tropospheric and stratospheric chemistry (Flemming et al., 2014), and a more comprehensive aerosol model based on the GLObal Model of Aerosol Processes model (Mann et al., 2010). These independent model configurations will be employed routinely to provide a small ensemble of forecasts (without assimilation) to complement the o-suite. This ensemble will be evaluated by the validation team. This intercomparison between the model configurations will provide a better interpretation of the validation results, identifying model related aspects and quantifying the improvement brought by the assimilation.

In the long-term there are several more generic aspects which are of concern for the validation activity in CAMS:

1. There is a clear need for a set of summary skill scores which can be used to document the performance, and monitor the improvements of the MACC system over time. This is related to the concept of "headline scores", which are used by meteorological centers to monitor and intercompare the performance evolution of the forecast system in time. A prominent example is the 500 hPa height anomaly score. In MACC we are developing a methodology to arrive at a set of skill scores. The application of this approach is work in progress.

2. The validation reports are written first of all for the users of the services. The information should be digestible by those user groups, should be presented in a friendly way, e.g. through intuitively meaningful skill scores. Interaction with the users is facilitated by a dedicated "Interface" sub-project in MACC through user

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surveys and workshops, and VAL is responding to the validation-related user feedback. One example is the provision of information on how well the global model is able to simulate surface ozone observations in Europe, which is currently being implemented. It is recommended that the interaction with the users will be intensified in CAMS, for instance by asking for feedback to specific users on a more detailed level.

3. The CAMS validation work done should be tested for compliance against general quality assurance principles. During MACC a "Validation Protocol" was developed (Lambert, 2013). In part this is based on principles developed in the Quality Assurance Framework for Earth Observation (QA4EO, http://www.qa4eo.org) activity of the Group on Earth Observations (GEO). Some aspects have been incorporated in the VAL practice, but a regular testing against these principles is foreseen.

4. The user driven future service evolution has been the topic of the EU project GMES-Pure (http://www.gmes-pure.eu). The definition of service data requirements (SDRs) was found to be a crucial intermediate step in the systematic approach on service evolution. The validation activity in the future CAMS forms an essential element for the translation of (i) the end-user requirements into SDRs and of (ii) the SDRs into observational requirements for both space and non-space components for assimilation as well as validation purposes.

5. Surface and airborne observations are crucial for CAMS, but the funding of these observations is not covered by Copernicus. Strong links with the major global networks and data providers will be maintained to ensure NRT access and data quality standards. We note that various MACC management team members and partners are strongly involved in observational network activities, in particular those coordinated by WMO.

The operational CAMS will start in 2015. It is foreseen that the validation of CAMS will proceed in a similar way as was developed in MACC, with, e.g., regular three monthly

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reports. These regular updates allow the validation teams to continuously improve the presentation of the information, taking into account the more long-term aspects mentioned above.

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Validation of reactive gases and aerosols in the MACC global analysis and forecast system

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Table 1. Overview of the trace gas species and aerosol aspects relevant for the real-time global atmospheric composition service. Shown are the datasets assimilated (second column) and the datasets used for validation (third column). Green colors indicate that substantial data is available to either constrain the species in the analysis, or substantial data is available to assess the quality of the analysis. Yellow boxes indicate that measurements are available, but that the impact on the analysis is not very strong or indirect (second column), or that only certain aspects are validated (third column).

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Aerosol, optical properties	MODIS Aqua/Terra AOD	AOD, Ångströ; <A=>O?=T, @AA , SBCnet, MIS>, OMI, liDar
OE, stratospFere	MGS, @OM=HI A, @OM=HI J, OMI, SJKLHI	SonDe, liDar, MA >, MTI>, OSI>IS, OMNS, JASCO= anD MS> analCses
OE, KT/GS	InDirectlCconstraineD PCli; P anD naDir sounDers	IA@OS, sonDe
OE, Qee tropospFere	InDirectlCconstraineD PCli; P anD naDir sounDers	IA@OS, sonDe
OE, NJG/ surQace	H	SurQace oRone<A MO/@AA , ?OAA/=S>G, IA@OS
CO, KT/GS	H	IA@OS
CO, Qee tropospFere	IASI, MONITT	IA@OS, MONITT, IASI
CO, NJG/ surQace	InDirectlCconstraineD PC satellite I> sounDers	SurQace CO<A MO/@AA , ?OAA/=S>G, IA@OS
?OI , tropospFere	OMI, partiallCconstraineD Due to sFort liQeti; e	SOIAMACST, @OM=HI , KLHLis DOAS
SOSO	H	@OM=HI , KLHLis DOAS
SOI	OMI UnDiViDual Volcanic eruptions anD strong sourcesW	H
StratospFere, otFer tFan OE	H	?OI colu; n onlC< SOIAMACST, @OM=HI
KLHInDeX	ConstraineD PC assi; ilation oQ oRone anD aerosol AOD	COST KL InDeX DataPase

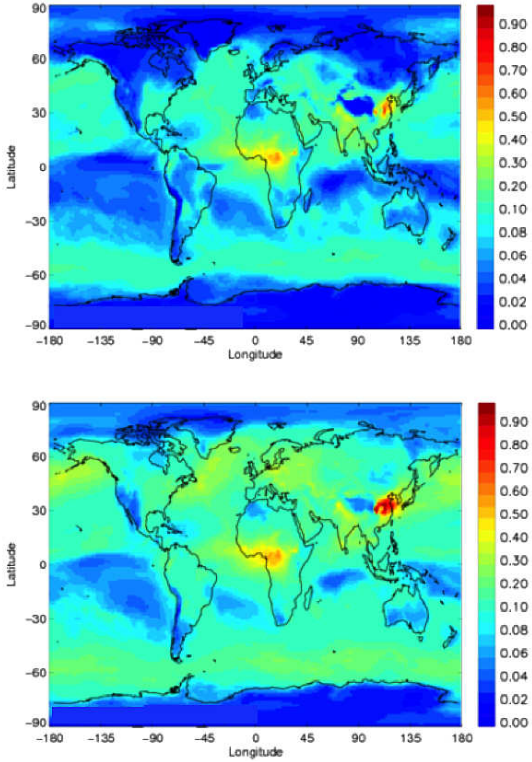

Figure 1. E-suite verification example. Total AOD plots showed that there was a considerable loss of aerosol of 30 %, from a mean AOD of 0.14 to 0.094, after a 96 h forecast in the e-suite (top panel) compared to the o-suite (bottom panel). The Ångström exponent showed considerably smaller particles in the e-suite as compared to the o-suite. Because of this the o-suite upgrade of April 2013 was postponed. The problem was solved and a new e-suite run was tested positively in August 2013. Example taken from the e-suite report of April 2013 (Eskes et al., 2013).

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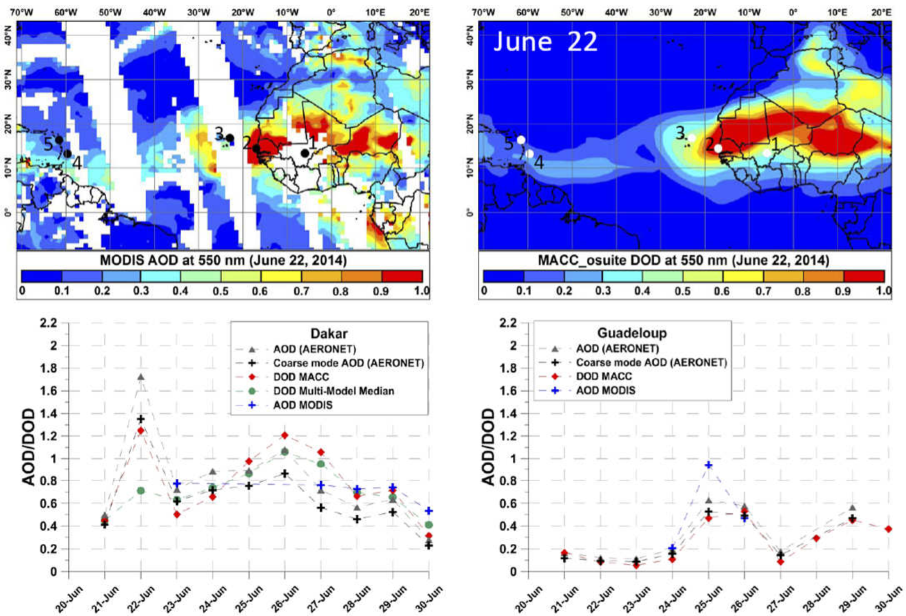

Figure 2. Top: daily averaged DOD from MACC o-suite (top-right, with the AERONET sites marked with white dots: 1 – IER Cinzana; 2 – Dakar; 3 – Capo Verde; 4 – Barbados Saltrace; 5 – Guadeloup) and daily AOD from MODIS-AQUA (AOD Ocean + DeepBlue) (top-left, with the AERONET sites marked with black dots) for 25 June 2014. Bottom: coarse mode AOD at 500 nm (DOD) (black crosses) and AOD at 550 nm (grey triangles) from AERONET, DOD from MACC o-suite (red diamonds), and AOD retrieved from MODIS-AQUA (blue crosses) at Dakar and Guadeloup AERONET sites during the case analysis from 21 to 30 June 2014.

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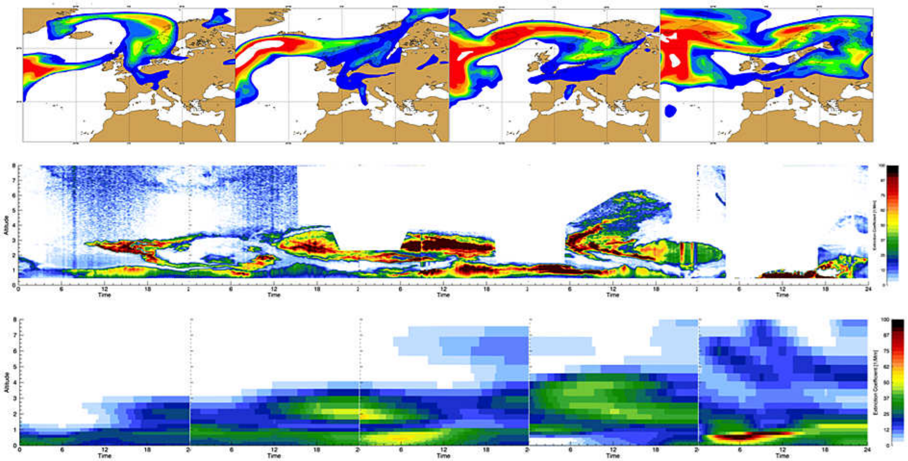

Figure 3. Example from the Ceilometer study. Top panel: MACC o-suite biomass burning AOD over Europe from 6–9 July 2013. Middle panel: time-height plot of extinction-coefficient above Soltau from 6–9 July 2013 from Ceilometer. Bottom panel: vertical profiles from the operational MACC o-suite at Soltau.

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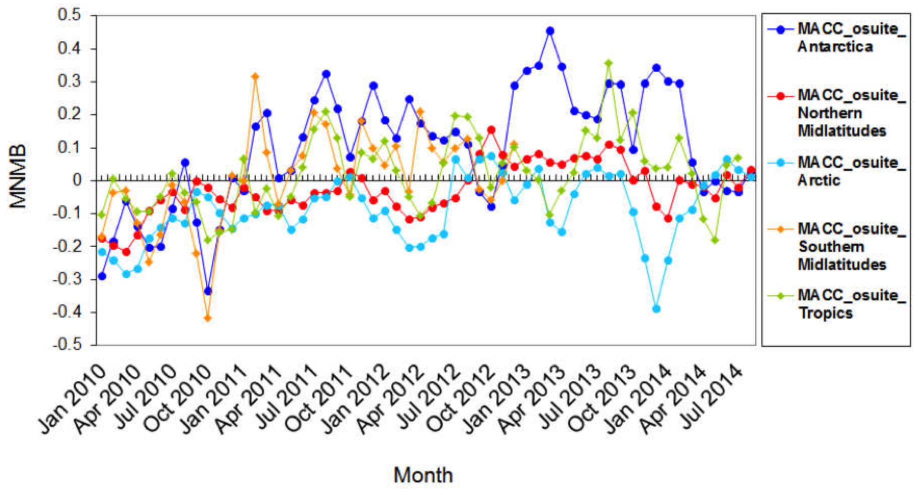

Figure 4. MNMB of ozone in the free troposphere (750–200 hPa in the tropics and 750–300 hPa elsewhere) of MACC o-suite against aggregated sonde data in 4 different regions.

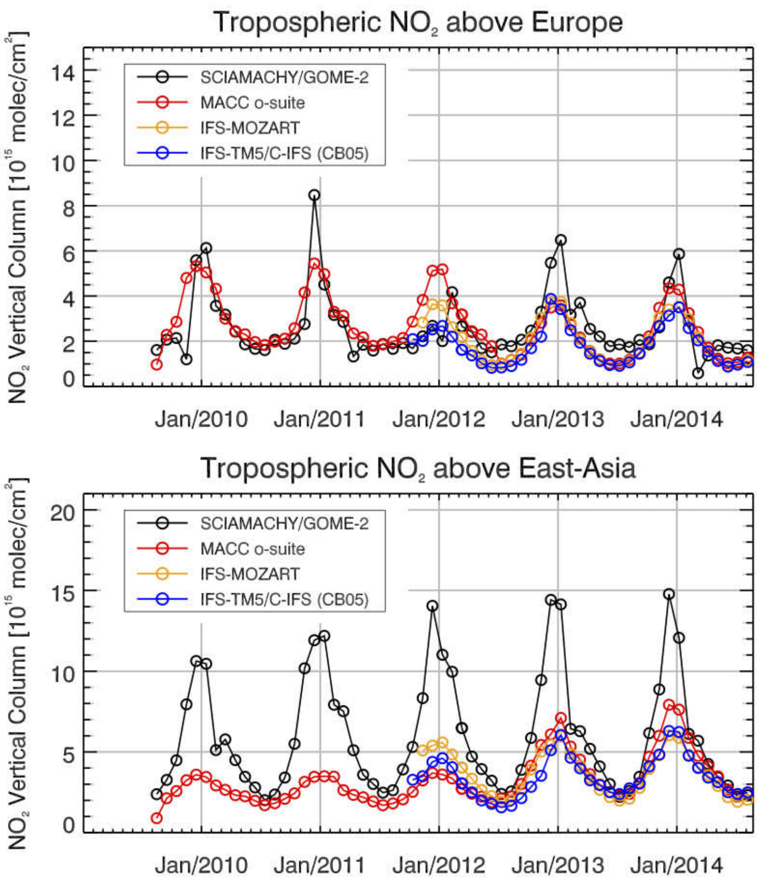

Figure 5. Time series of tropospheric NO_2 columns from SCIAMACHY (up to March 2012), GOME-2 (from April 2012 onwards) compared to the o-suite (red) and the coupled IFS-MOZART model (orange) results for Europe and East-Asia. The blue line shows C-IFS (CB05) results from December 2012 onwards.

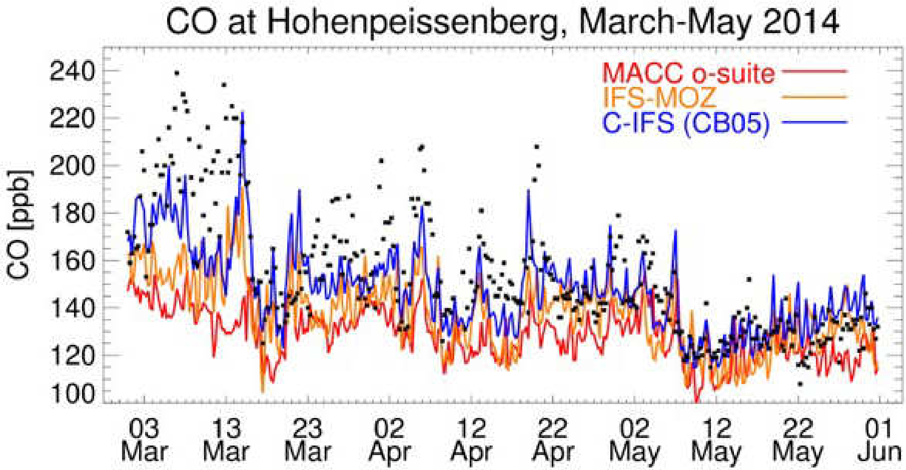

Figure 6. O-suite (red), stand-alone IFS-MOZART (orange) and C-IFS (CB05) (blue) compared to GAW observations (black dots) at Hohenpeissenberg station (47.80° N, 11.02° E) for the period March–May 2014.

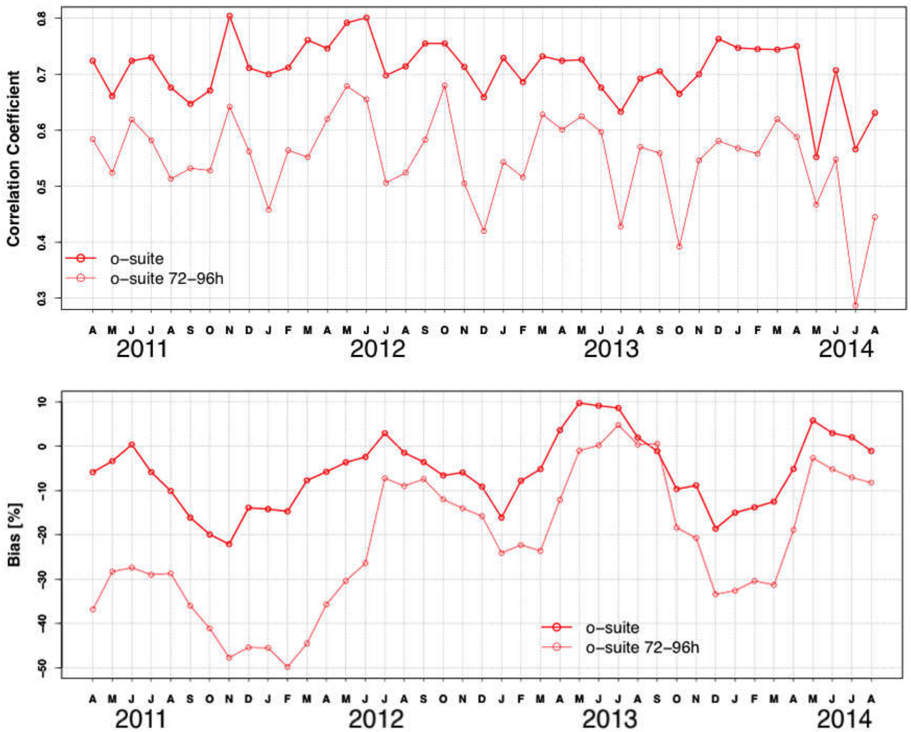

Figure 7. AOD at 550 nm **(a)** correlation coefficient MACC o-suite model simulation against Aeronet NRT level 1.5 data for April 2011–August 2014 (thick red curve); last forecast day is shown separately (light red curve); **(b)** corresponding normalized mean bias (%). Note that our best estimate of the o-suite bias is 20 % more positive, because the reference (AERONET NRT data) itself has a positive 20 % bias against level 2.0 AERONET data.

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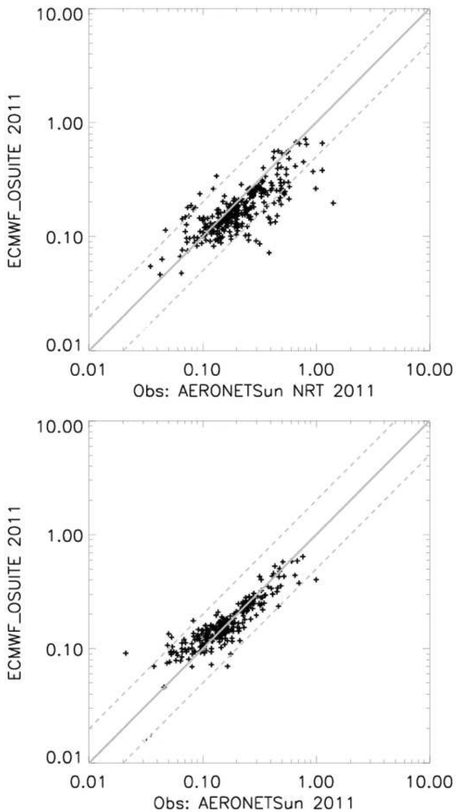

Figure 8. Retrospective evaluation of MACC o-suite for 2011, using NRT Aeronet level 1.5 data (top) and quality assured Aeronet level 2.0 data (bottom).

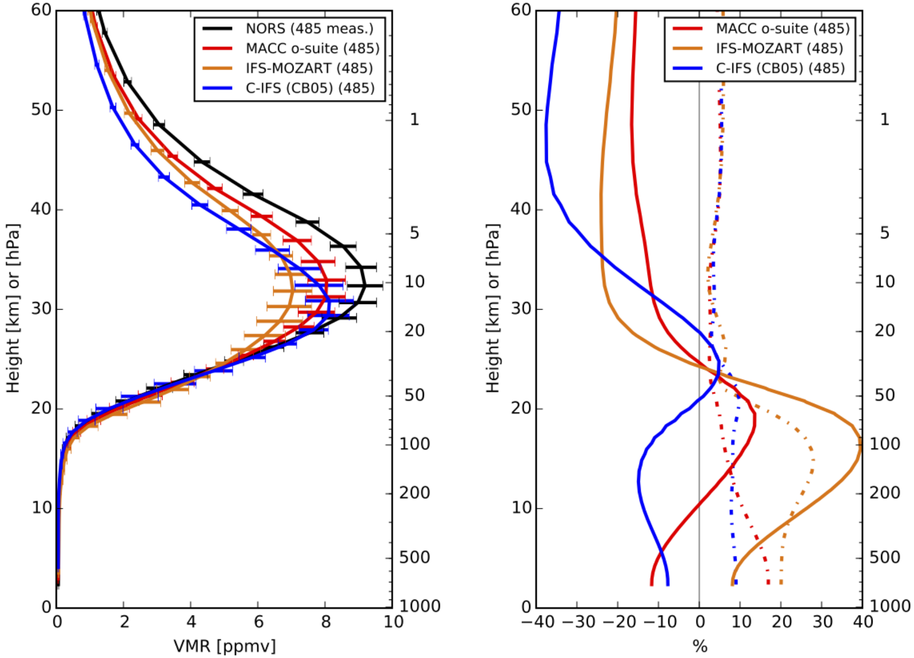

Figure 9. Comparison of the average O_3 mixing ratios of MACC o-suite (red), IFS-MOZART (orange) and C-IFS (CB05) (blue) with the average NDACC FTIR profiles (black) observed at Izaña (28.3° N, 16.5° W) for the period September 2013–September 2014. Left: O_3 profiles, right: profiles of the bias and SD of the differences centered on the bias. The number of available O_3 profiles and the number of collocated model profiles are indicated in between brackets.

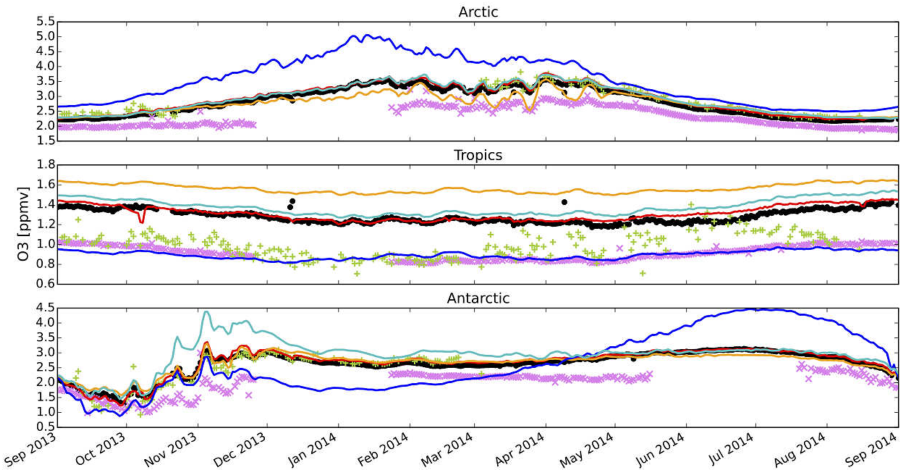

Figure 10. Daily mean time series comparing ozone abundances from the o-suite (red line), the IFS-MOZART coupled system (orange line), C-IFS (CB05) (blue line), and BASCOE (cyan line) with MLS (black dot), OMPS (pink cross) and OSIRIS (green plus) observations for the period 1 September 2013–1 September 2014 at 20 km altitude.

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