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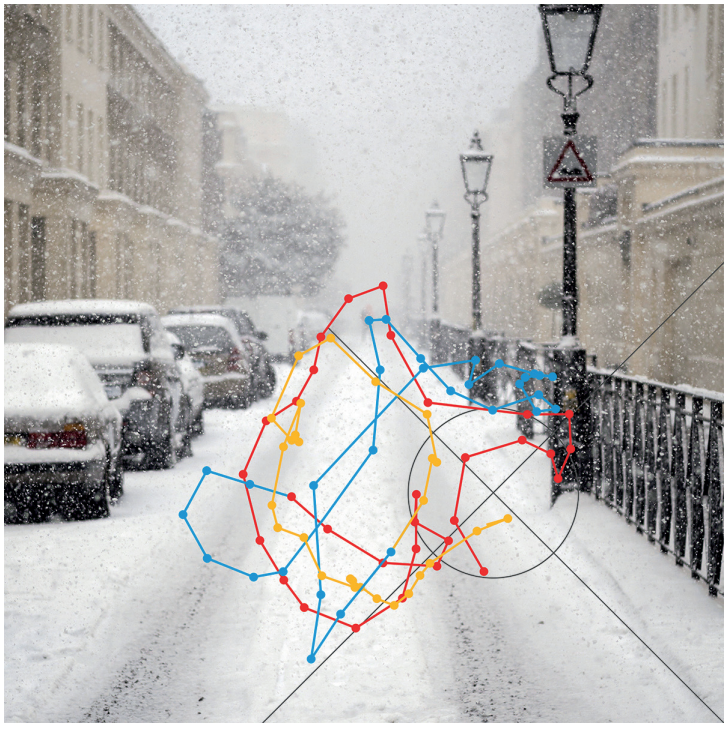
METEOROLOGY

The new CAMS global reanalysis of atmospheric composition



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The new CAMS global reanalysis of atmospheric composition

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ECMWF has a long history of providing global meteorological reanalyses, the latest of which is ERA5. Meteorological reanalyses are datasets providing a complete and consistent record of meteorological conditions for recent decades. They are produced by combining model information with observations through data assimilation. This ensures that the resulting gridded datasets are comprehensive and consistent over time. Over the last decade, reanalysis activities have been extended to include other components of the Earth system, such as the land surface, the ocean and the chemical composition of the atmosphere. This is in line with the emphasis in ECMWF's current ten-year Strategy on the need to account for all relevant interactions between different components of the Earth system in ECMWF's Integrated Forecasting System (IFS). In the framework of the Copernicus Atmosphere Monitoring Service (CAMS), implemented by ECMWF on behalf of the EU, ECMWF released a new reanalysis of atmospheric composition in September 2018. This 'CAMS reanalysis' (CAMSRA) covers the period from 2003 to 2016 and will be extended to subsequent years by adding one year each year. It provides consistent information on aerosols and reactive gases, such as ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2) and many more chemical species, using a fully integrated atmospheric composition modelling and data assimilation system based on the IFS.

Comparison with previous reanalyses

CAMSRA follows in the footsteps of the earlier GEMS, MACC (MACCRA) and CAMS interim (CIRA) reanalyses (see Table 1). It has a greater horizontal resolution (T255 or about 80 km) than CIRA (T159 or about 125 km). It also provides data on more chemical species at a better temporal resolution than the previous reanalyses. Great care was taken to ensure that the emission datasets used in CAMSRA were consistent in time and that consistent anthropogenic, biogenic and biomass burning emissions were used in the aerosol and chemistry schemes. Furthermore, a more recent, improved IFS model cycle was used to produce the CAMS reanalysis, and more and newly reprocessed satellite datasets were assimilated. These include satellite retrievals of CO, NO_2, O_3 and aerosol optical depth (AOD). A step towards the coupling between composition and weather is that in CAMSRA prognostic ozone and aerosol fields from CAMSRA are used in the IFS radiation scheme, while the previous atmospheric composition reanalyses used ozone and aerosol climatologies in the radiation scheme.

As shown in more detail in the section on evaluation results, the CAMS reanalysis performs better than the previous atmospheric composition reanalyses: it has smaller biases compared to independent O_3, CO, NO_2 and AOD observations and is more consistent in time, especially compared to the MACC reanalysis.

Period	Name	EXP	Class	IFS Cycle	Resolution	Model	Production Period
01/01/2003 – 24/05/2009	GEMS reanalysis	eac1	MC	32r3	T159/L60	IFS/MOZART 3.5 coupled system	Mar 2008 – Sep 2009
01/01/2003 – 31/12/2012	MACC reanalysis (MACCRA)	rean	MC	36r1	T255/L60	IFS/MOZART 3.5 coupled system	Mar 2010 – Feb 2012
01/01/2003 – near real time	CAMS interim reanalysis (CIRA)	eac3	MC	40r2/41r1	T159/L60	IFS(CB05)	Dec 2014 – Dec 2016, then continued in near real time
01/01/2003 – near real time	CAMS reanalysis (CAMSRA)	eac4	MC	42r1	T255/L60	IFS(CB05)	Jan 2017 onwards

Table 1 Reanalyses of atmospheric composition produced with the GEMS, MACC and CAMS systems. EXP and CLASS information is needed to retrieve the data from ECMWF's meteorological archive (MARS).

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Ensuring consistency

ECMWF has been producing atmospheric composition forecasts and analyses for over a decade (Flemming et al., 2017a). The model and data assimilation system used for this was developed as a European effort by a consortium of partners in the EU-funded GEMS and MACC projects. Operated by CAMS, the forecasting system has been fully operational at ECMWF since January 2015. Since the model, the data assimilation system, and the observations and emissions used have changed considerably over time, it is difficult if not impossible to compare operational forecast data from a recent period with earlier data in a meaningful way (e.g. to determine trends or seasonal anomalies). This is why reanalyses are produced: they analyse atmospheric composition over a long period of time using a single version of the modelling and data assimilation system, while taking care to minimise changes in the versions of the emissions used or satellite retrievals assimilated. Such a system provides the temporal consistency needed to identify trends or to provide maps of annual or seasonal anomalies.

To illustrate the advantage a reanalysis has over analysis data produced by a continuously evolving operational model, Figure 1 shows the 'Figure of Merit in Space' (FMS) ozone score at the Antarctic Neumayer station for the CAMS operational analysis and the CAMS reanalysis. The FMS score is a measure of the fit between model ozone profiles and ozonesonde profiles (here calculated from the surface to 3 hPa) and has a score between 1 (perfect fit) and 0. Figure 1 illustrates the improvements in the CAMS operational analysis over the years. For instance, in the earlier years the CAMS system did not adequately reproduce the low values and vertical distribution of the Antarctic ozone hole, which is reflected by the low scores in the austral spring from 2008 to 2012. Model improvements and the assimilation of improved O_3 retrievals led to better O_3 scores in more recent years. In contrast, CAMSRA, which uses a model version introduced as recently as 2015, has much better scores than the operational analysis during the earlier years and a better consistency in performance throughout the period.

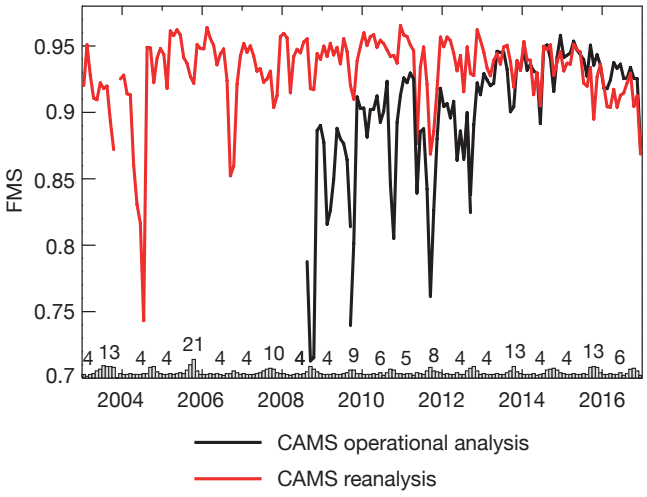

Figure 1 Time series from 2003 to 2016 of the FMS score for ozone profiles (1,000–3 hPa) at the Antarctic Neumayer station from the CAMS operational analysis and the CAMS reanalysis. The bar chart at the bottom shows the number of ozonesonde profiles per month used for validation.

Key features

The chemistry scheme of the IFS used in CAMSRA is an extended version of the Carbon Bond Mechanism 5 (CB05) as implemented in the Chemical Transport Model (CTM) Transport Model 5 (TM5) and is documented in Flemming et al. (2017b). This is a tropospheric chemistry scheme. For stratospheric ozone, the chemical tendencies above the tropopause are computed by a parametrization based on Cariolle & Teyssèdre (2007). The CAMS aerosol model component of the IFS is a hybrid bulk/bin scheme with 12 prognostic tracers, consisting of three bins for sea salt depending on size (0.03–0.5, 0.5–5 and 5–20 μm), three bins for dust (0.030–0.55, 0.55–0.9 and 0.9–20 μm), hydrophilic and hydrophobic organic matter (OM) and black carbon (BC), plus sulphate aerosol and a gas-phase sulphur dioxide (SO_2) precursor (Morcrette et al., 2009). Updates to the chemistry and aerosol schemes that are specific to CAMSRA are given in Inness et al. (2018).

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The CAMS system uses MACCity anthropogenic emissions, biomass burning emissions from the CAMS Global Fire Assimilation System and biogenic emissions from the MEGAN model. Great care was taken to ensure that the emission datasets for CAMSRA were consistent in time and that consistent anthropogenic and biomass burning emissions were used for the aerosol and chemistry fields.

The data assimilation system for the atmospheric composition fields remains unchanged from the one described by Inness et al. (2015). CAMSRA uses 4-dimensional variational data assimilation (4D-Var) with 12-hour assimilation windows. The atmospheric composition fields for O_3, CO, NO_2 and AOD are included in the 4D-Var minimisation, which is carried out together with the meteorological variables.

Figure 2 shows a time series of the observations of atmospheric composition data that were assimilated in the CAMS reanalysis. These include O_3 retrievals from a range of satellite sensors (SCIAMACHY, OMI, GOME-2, MIPAS, MLS, SBUV/2); total column CO (TCCO) retrievals from MOPITT; tropospheric column NO_2 retrievals from SCIAMACHY, OMI and GOME-2; and retrievals of total AOD at 550 nm from MODIS and AATSR. Variational bias correction is applied to the total column O_3, NO_2 and AOD data to ensure good time consistency when blending the various datasets. More details about the model, the emission datasets, the data assimilation system and the assimilated satellite data used in CAMSRA, as well as references for the datasets and time series that show the quality of the datasets, can be found in Inness et al. (2018).

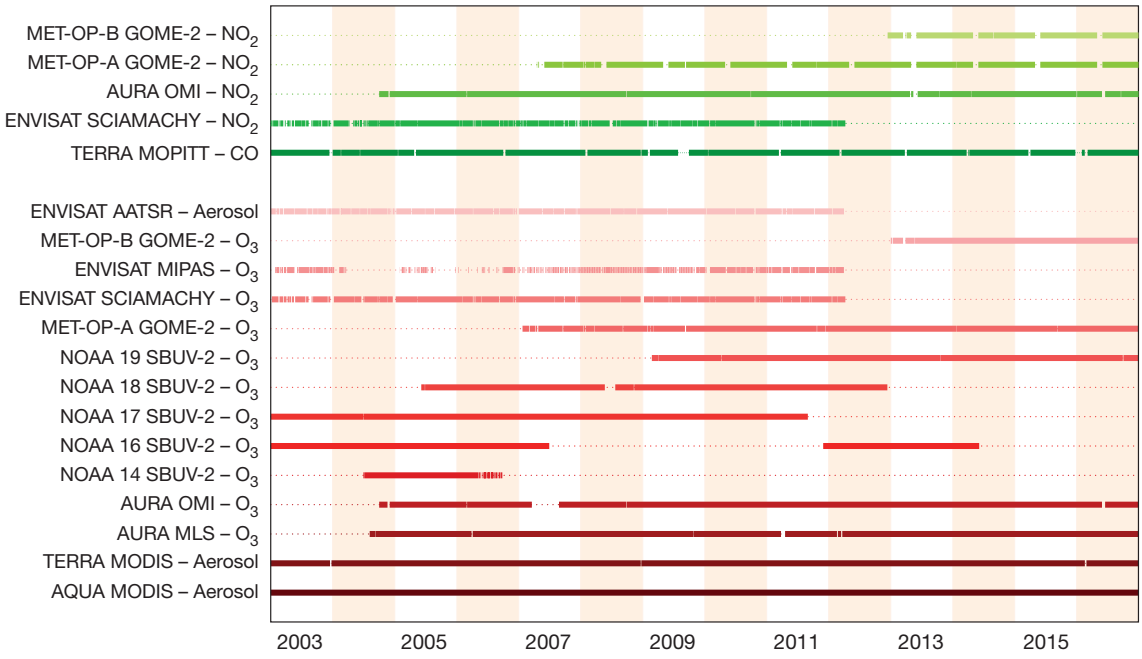

Figure 2 Atmospheric composition data assimilated in the CAMS reanalysis between 2003 and 2016.

First evaluation results

First results on the quality of CAMSRA data for O_3, CO and AOD are shown here by comparing the fields from CAMSRA with independent observations and fields from MACCRA and CIRA. The quality assessment of the reanalysis is a combined effort of ECMWF staff and a large consortium of European partner institutes contracted to validate CAMS global services. This external quality assessment makes use of Europe-wide expertise to provide an independent assessment of the data products. A comprehensive quality assessment of CAMSRA is given in a validation report available on the CAMS website (Eskes et al., 2018) and a summary is also given in Inness et al. (2018).

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The seasonal mean total column O_3 (TCO3) fields from CAMSRA and CIRA agree to within 1% when averaged over the period 2003–2016. The differences between CAMSRA and MACCRA are larger but still within 5%. All reanalyses have small positive biases with respect to independent TCO3 observations from the WOUDC ozone database, with MACCRA having the largest biases and CAMSRA the smallest (Figure 3). O_3 from CAMSRA is more consistent in time than from MACCRA. Agreement with ozonesondes is within 10% in the long-term global mean (Figure 4). The best agreement between the reanalyses and the sondes is found in the stratosphere, where the assimilated O_3 observations constrain the analyses well. Differences between the reanalyses are larger in the troposphere, where the impact of the assimilation is smaller (Inness et al., 2015) and differences in the chemistry schemes, emissions and transport become more important. CAMSRA and CIRA agree better with ozonesondes in the tropical mid- to upper troposphere than MACCRA, which shows a large underestimation here (–30%). CAMSRA agrees better with ozonesondes above 15 hPa than MACCRA, which overestimates O_3 there. This makes CAMSRA a better dataset to be used as the climatology in e.g. radiation schemes or radiance observation operators.

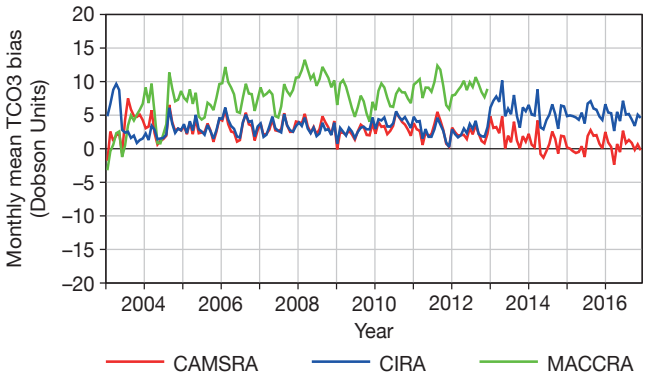

Figure 3 Time series of global monthly mean TCO3 bias for CAMSRA, CIRA and MACCRA data validated against data from the WOUDC ozone database. About 50–60 WOUDC stations were available from 2003 to 2014 and about 40 stations after 2014.

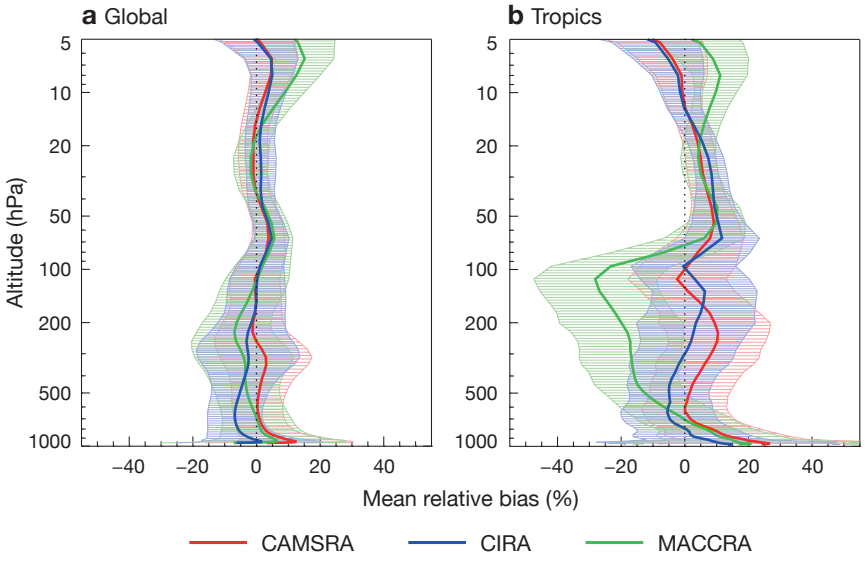

Figure 4 Mean relative O_3 bias for CAMSRA, CIRA and MACCRA data validated against ozonesonde data, averaged (a) over the globe and (b) over the tropics. The hatched areas show one respective standard deviation. For CAMSRA and CIRA, the average is calculated over the period 2003–2016, for MACCRA over the period 2003–2012.

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Differences in TCCO between CAMSRA and CIRA are smaller than 5% when averaged over the period 2003–2016. The differences between CAMSRA and MACCRA are larger, firstly because MACCRA employed a different chemistry scheme, and secondly because different fire emissions were used. Comparisons with IAGOS aircraft observations show an underestimation of CO in the free troposphere at Frankfurt Airport and South-East Asian airports for all three reanalyses, with larger underestimation in the lower troposphere (Figure 5). This underestimation is similar in CAMSRA and CIRA, while MACCRA has larger negative biases in the lower troposphere. Over Indonesia, CAMSRA and CIRA are very different from MACCRA below 700 hPa and have smaller biases. This is likely due to differences in the fire emission data used.

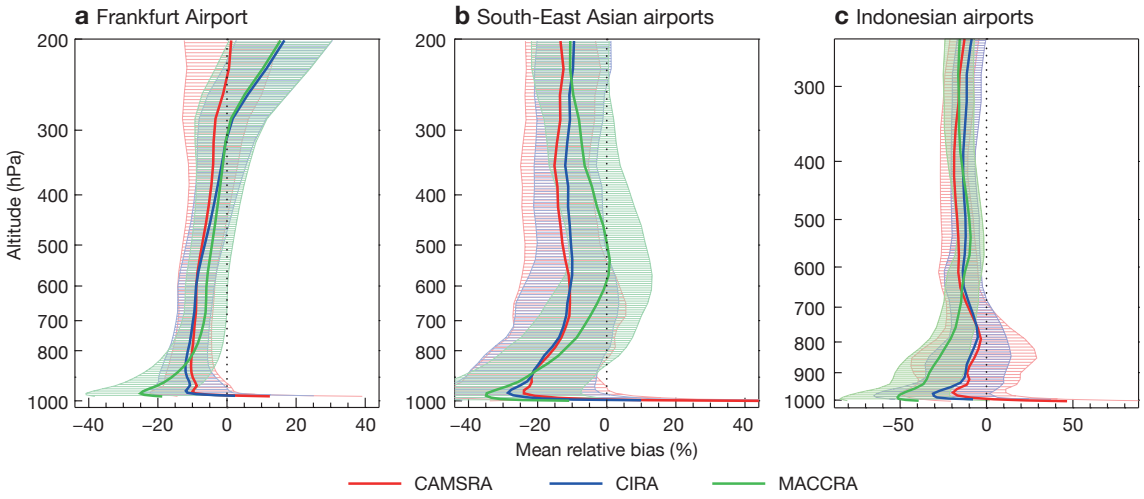

Figure 5 Mean relative CO bias for CAMSRA, CIRA and MACCRA data validated against IAGOS aircraft data at (a) Frankfurt Airport, (b) South-East Asian airports and (c) Indonesian airports (note the different x-axis scale). The hatched areas show one respective standard deviation. For CAMSRA and CIRA, the average is calculated over the period 2003–2016, for MACCRA over the period 2003–2012.

A time series of the CO bias in the lower troposphere against IAGOS data at Frankfurt Airport shows that CAMSRA is more consistent in time than MACCRA (Figure 6). In MACCRA, the assimilation of IASI TCCO satellite retrievals was included from 2008, which led to a change in the CO burden, while in CAMSRA and CIRA only TCCO data from the MOPITT satellite instrument were assimilated to achieve better temporal consistency.

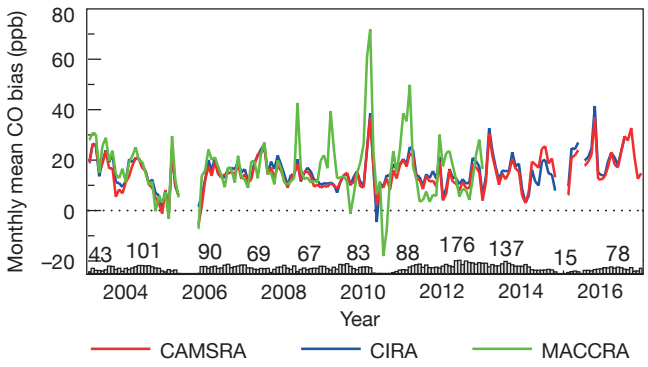

Figure 6 Time series of monthly mean CO biases for CAMSRA, CIRA and MACCRA data validated against IAGOS CO data in the lower troposphere (950–700 hPa) at Frankfurt Airport. The bar chart at the bottom shows the number of IAGOS observations used for validation.

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Total AOD values in CAMSRA are lower than in CIRA or MACCRA in many areas, but larger over India and South-East Asia, and they agree better with observations of total AOD from the AERONET database (Figure 7). The validation with AERONET data also shows some biases at measuring stations near outgassing volcanoes (in particular Mauna Loa in Hawaii and Popocatepetl near Mexico City). The very large AOD biases at those locations in CAMSRA degrade the global average bias. This is a side effect of possibly erroneous model treatment of diffuse volcanic emissions. The model-resolution orography does not resolve the height of the volcanoes. As a result, the model misrepresents the altitude of the volcanic plumes. In combination with recent enhancements to the SO_2 oxidation scheme, which improve aerosol on the global scale, this gives rise to the local biases. When calculating global mean AOD statistics, it is advisable to exclude the Mauna Loa and Mexico City stations as unrepresentative.

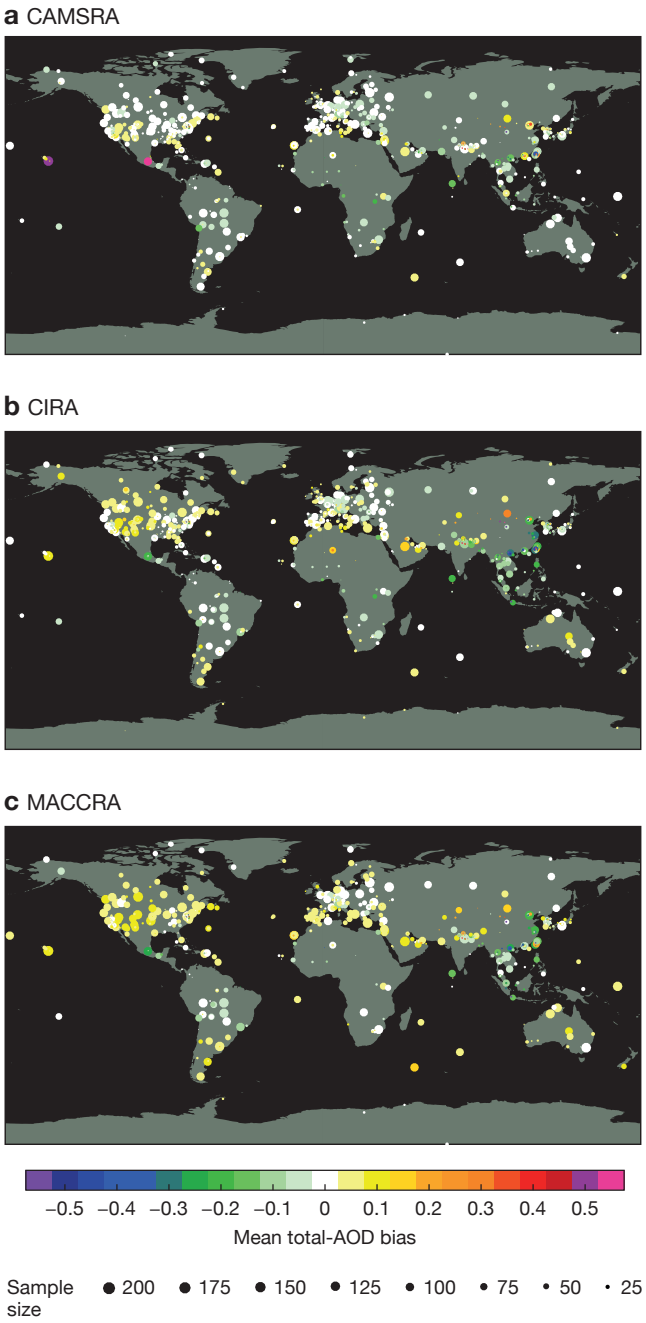

Figure 7 Mean total-AOD bias for (a) CAMSRA, (b) CIRA and (c) MACCRA data, validated against AERONET observations. For CAMSRA and CIRA, the average is calculated over the period 2003–2016, for MACCRA over the period 2003–2012.

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AOD in CAMSRA is more consistent in time than in CIRA and MACCRA, especially over Europe and North America, where CIRA and MACCRA show an increasingly positive bias with time (Figure 8).

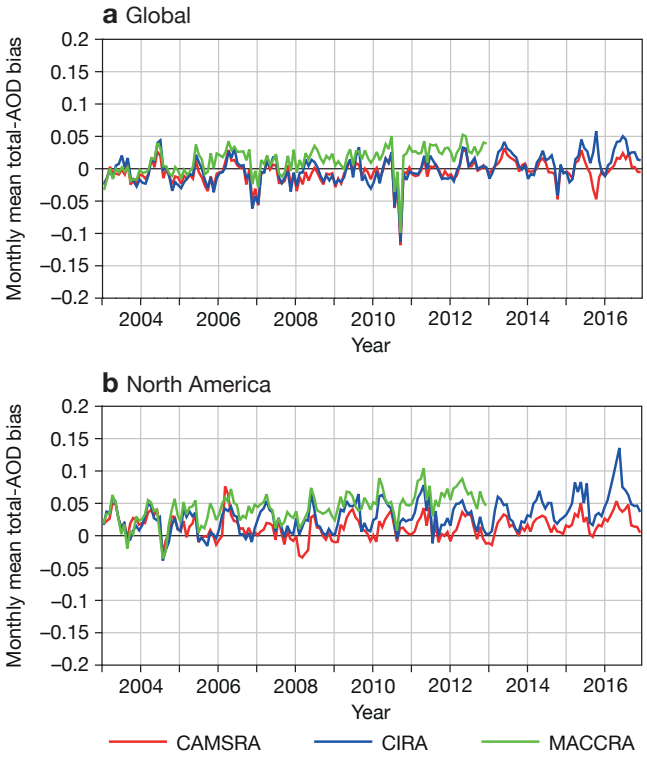

Figure 8 Time series of monthly mean total-AOD bias for CAMSRA, CIRA and MACCRA data validated against AERONET observations for (a) the globe and (b) North America. The Mauna Loa and Mexico City stations were excluded from these time series as they are unrepresentative and skew the statistics.

There are large differences in the different aerosol species between the three reanalyses (Figure 9). Part of the reason is that aerosol speciation is not well constrained by the assimilated AOD observations. Relative to the two earlier reanalyses, CAMSRA shows a reduction in desert dust, sulphates and black carbon in the southern hemisphere, compensated by an increase in organic matter and black carbon in the northern hemisphere. The reduction in sulphate globally is particularly strong relative to CIRA, where sulphate was greatly overestimated (Flemming et al., 2017b). More work is needed to validate the individual aerosol components.

Access to data and outlook

CAMSRA is of better quality and provides better temporal consistency than its predecessors. It also provides more chemical species, and data are available at a higher temporal and spatial resolution. In total, 56 tropospheric chemical species of the CB05 chemical mechanism, 12 aerosol components and many additional diagnostics, such as total columns and extinction coefficients, can be obtained from the CAMS reanalysis. The CAMS reanalysis data are freely available from *http://atmosphere.copernicus.eu* and can serve a multitude of users, ranging from small and medium-sized enterprises in the solar-energy sector to scientists and policy-makers. The data can be used to analyse the state of the atmosphere or to identify trends that have developed over the past years or decades. Furthermore, the CAMS reanalysis can be used to compute climatologies, evaluate models, benchmark other reanalyses or serve as boundary conditions for regional models for past periods.

The CAMS reanalysis is being continued, running shortly behind real time, and additional years will become available in the future, one year each year. A reanalysis for the greenhouse gases CH_4 and CO_2 is currently being produced separately.

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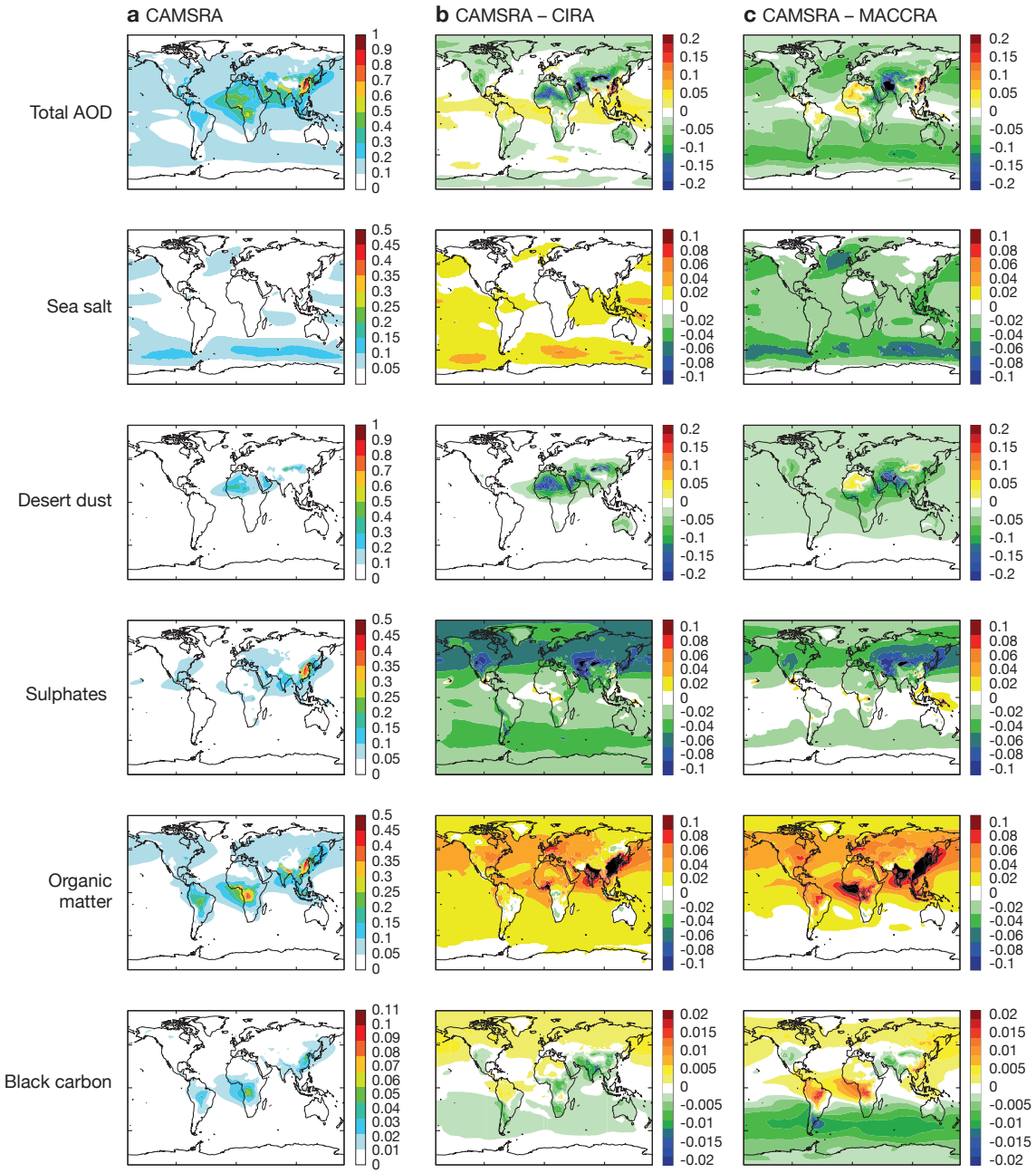

Figure 9 Annually averaged AOD species from (a) CAMSRA, (b) the difference between CAMSRA and CIRA and (c) the difference between CAMSRA and MACCRA (2003–2012 only). AOD is unitless.

The following institutes contribute to the global validation of CAMS products: Royal Netherlands Meteorological Institute (KNMI); Academy of Athens (AA); Aarhus University (AU); Aristotle University of Thessaloniki (AUTH); Institut d'Aéronomie spatiale de Belgique (BIRA-IASB); Barcelona Supercomputing Center and the State Meteorological Agency of Spain (BSC/AEMET); Laboratoire des Sciences du Climat et de l'Environnement (CEA-LSCE); Centre National de la Recherche Scientifique et Université Paul Sabatier – Laboratoire d'Aérologie (CNRS-LA); Deutscher Wetterdienst – Hohenpeissenberg Meteorological Observatory (DWD); Institute of Environmental Physics, University of Bremen (IUP-UB); Norwegian Meteorological Insitute (MET-NO); Max Planck Institute for Meteorology (MPG); Science and Technology (S&T); Uni Bremen Campus GmbH (UBC).

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Further reading

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