MACC Work Package G-AER 3
Monitoring of aerosol direct and indirect forcing

Deliverable D_G-AER_3.2

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The main interactions between natural and anthropogenic aerosols and the climate system are through scattering and absorption of radiation (direct effect), and modification of the microphysical properties of clouds, impacting the cloud albedo (first indirect effect) and the cloud efficiency to precipitate (second indirect effect). Anthropogenic aerosols, emitted into the atmosphere by human activities, are considered external to the climate system, and their direct and indirect effects are termed forcing.

In this work package, the ECMWF Integrated Forecast System (IFS) aerosol re-analysis and forecast products are used to obtain estimates of the direct and first indirect forcings. Estimates are provided for the shortwave spectrum, at the top of atmosphere and surface.

In a previous deliverable, published in November 2010, we described the algorithm used to quantify the anthropogenic aerosol optical depth (AOD) and the corresponding direct and first indirect forcings. The algorithm was then applied to the GEMS re-analysis, produced in the previous European project GEMS, the precursor to MACC. Since then, the same algorithm has been applied to the more recent MACC re-analysis and results are presented in this deliverable. Thanks to the structure of the MACC project, any improvements in re-analysed aerosols benefit aerosol radiative forcing estimates. In addition, the product resulting from the sum of the direct and first indirect estimates and representing the total aerosol radiative forcing is described.

1. Improvements in the estimation of the anthropogenic aerosol optical depth

Evaluation of the GEMS re-analysis revealed a tendency to overestimate total AODs compared to ground-based measurements. This has been tracked down to a global positive bias in aerosol retrievals by the MODIS instruments, which are assimilated into the IFS as part of the aerosol forecast and re-analysis. The bias is now corrected in the MACC re-analysis. Other changes between the two re-analyses include improvements to the modelling of mineral dust and organic matter aerosols, and a change in the emission dataset used for biomass-burning aerosols [Engelen *et al.* 2011]. Overall, these changes lead to smaller total AODs in the MACC re-analysis. Figure 1 shows distributions of total AOD at 0.55 μm in the GEMS and MACC re-analyses and their difference, for the period 2003–2005 which is the longest publicly-available overlap between the two datasets. On a global average, the total AOD decreases from 0.192 in GEMS to 0.173 in MACC. Decreases happen over the middle and high latitudes of the North Hemisphere, especially in the industrial regions of Eastern United States, Eastern Europe, and China. In Africa, Saharan aerosols, expected to be mineral dust, and aerosols over the Congo basin, expected to be biomass-burning, have decreased as well. The only significant increases in total AOD happen over the Arabian Peninsula and Iran.

The aerosol identification algorithm developed by this work package partitions the total AODs into mineral dust, sea-salt, fine-mode natural, and anthropogenic AODs. The anthropogenic AOD is then supplied to the algorithms estimating the aerosol radiative forcing. Figure 2 shows distributions of anthropogenic AOD at 0.55 μm in the GEMS and MACC re-analyses and their difference, again for the period 2003–2005. On a global average, the anthropogenic AOD decreases by 25%, from 0.062 in GEMS to 0.047 in MACC. This large decrease is a consequence of the decrease in total AOD over North Hemisphere continents and biomass-burning regions, where anthropogenic aerosols are predominantly located. The new global estimate is closer to previous satellite-based estimate of the anthropogenic aerosol optical depth: Bellouin *et al.* (2008) have an anthropogenic optical depth of 0.043 when using MODIS retrievals directly.

Using the MACC instead of GEMS re-analysis also impacts the AODs of the other aerosol types. Mineral dust AOD increases from 0.033 in GEMS to 0.039 in MACC, with large decreases in the Saharan plume and increases over India and China. Sea-salt AOD decreases from 0.085 in GEMS to 0.077 in MACC, with the largest decreases being in the North Atlantic. The fine-mode natural AOD decreases from 0.012 in GEMS to 0.009 in MACC, with decreases collocated with those shown for the anthropogenic AOD.

2. Improvements in the estimation of aerosol direct radiative forcing

Using the MACC re-analysis for the period 2003–2005, the shortwave direct radiative forcing (DRF) with respect to natural aerosols is –1.57 Wm^{-2} in clear-sky and at the top of the atmosphere, down from –1.93 Wm^{-2} in GEMS. Smaller anthropogenic AODs exert a weaker DRF so the decrease is expected. When scaled to all-sky conditions by assuming a DRF of zero in cloudy-sky, aerosol DRF is –0.53 Wm^{-2} (Figure 3). The corresponding satellite-based estimate is –0.65 Wm^{-2} [Bellouin *et al.* 2008]. The difference between the two estimates is due to the positive DRFs obtained over the Sahara desert. Aerosol retrievals over bright deserts are difficult and Bellouin *et al.* (2008) do not give DRF estimates over the Sahara. In contrast, the ECMWF IFS does not suffer from such limitations and positive forcings over the Sahara increase the global average. Estimates from numerical models constrained by satellite observations yield –0.4 ± 0.2 Wm^{-2} [Quaas *et al.* 2009]. This value is consistent with the MACC estimate.

At the surface, the MACC estimate of DRF is –3.57 Wm^{-2} in clear-sky conditions. The atmospheric absorption of shortwave radiation by present-day anthropogenic aerosols is therefore 2 Wm^{-2} in clear-sky conditions.

The aerosol direct radiative effect (DRE) is exerted by both natural and anthropogenic aerosols and is computed with respect to an atmosphere with no aerosols. The MACC estimate of the shortwave DRE in clear-sky conditions at the top of the atmosphere is

–7.3 Wm^{-2} for the period 2003–2005. The GEMS estimate was –7.9 Wm^{-2} but was derived from overestimated optical depths. Sea-salt is the main contributor to the clear-sky DRE estimated in MACC, with –3.9 Wm^{-2} (53 %). It is followed by anthropogenic aerosols (–1.8 Wm^{-2}, 25 %), mineral dust (–1.3 Wm^{-2}, 18 %), and fine-mode natural aerosols (–0.3 Wm^{-2}, 4 %).

3. Improvements in the estimation of aerosol indirect radiative forcing

The statistical algorithm used to estimate the aerosol indirect radiative forcing (IRF) due to the first indirect effect has remained unchanged. In addition, estimates given in the previous deliverable already used cloud products from the MACC re-analysis. These products are dedicated diagnostics produced from short forecasts initialised from the MACC re-analysis. The first available time step, 1 hour after initialisation, is used. The only change in this deliverable is therefore the use of the MACC-derived anthropogenic AOD, as described in section 1.

Figure 4 shows distributions of sensitivity of cloud droplet number concentration to anthropogenic changes in total AOD, for the anthropogenic AOD derived from GEMS and MACC re-analyses for the year 2003. Distributions are similar for both re-analyses, with smaller values being obtained from MACC as anthropogenic AODs are smaller.

Figure 5 shows a comparison of the IRF due to the first aerosol indirect effect derived from GEMS and MACC anthropogenic AODs for the year 2003. The patterns broadly agree, with smaller forcings now estimated. Globally-averaged annual IRF are –0.44 Wm^{-2} in GEMS and –0.31 Wm^{-2} in MACC. This new estimate is closer to the –0.20 ± 0.1 Wm^{-2} derived from a statistical analysis of satellite data [Quaas *et al.* 2008]. Stronger IRF values are found over the stratocumulus cloud decks downwind of the subtropical continents. These regions are associated with low clouds which are sensitive to changes in aerosol optical depth, large amounts of solar radiation from being in the Tropics, and large anthropogenic AODs from nearby biomass-burning sources. Over Europe, the forcing is comparable to the global-mean value.

4. Merged product of total aerosol forcing

Direct and indirect effects are different processes so are estimated by two dedicated processing chains. However, it is interesting to merge the estimated DRF and first IRF into a single product of the total aerosol radiative forcing in all-sky at the top of the atmosphere. The merged product is computed as

$$RF = (1 - CC)\, DRF_{clear} + CC\, (DRF_{cloud} + IRF_{cloud})$$

where RF is the total aerosol radiative forcing and CC is the fractional cloud cover provided by the re-analysis. Subscripts *clear* and *cloud* indicate clear-sky and cloudy-sky conditions, respectively. For the moment, DRF_{cloud} is assumed to be zero so equation above simplifies to

$$RF = (1 - CC)\, DRF_{clear} + CC\, IRF_{cloud}$$

This calculation is done on daily distributions. The IRF product, which is published at a higher resolution than the DRF product, is gridded onto the DRF product grid.

Figure 6 shows the annual distribution of RF for the year 2003. The global, annual average is –0.82 Wm^{-2}. Stronger RF values are located over North Hemisphere continents, the Gulf of Guinea, and the equatorial Pacific. This RF estimate is weaker than the estimate obtained by numerical models which have –1.5 ± 0.5 Wm^{-2}, or –1.2 ± 0.4 Wm^{-2} when constrained by satellite observations [Quaas *et al.* 2009].

Discrepancies between observation-based (here, MACC-based) and modelled estimates have been attributed to various factors. For the DRF, the use of present-day natural aerosols to represent pre-industrial aerosols may cause an overestimation of the observation-based estimate [Bellouin *et al.* 2008]. Changes in aerosol absorbing properties between pre-industrial and present-day conditions can also contribute to an overestimation [Myhre 2009]. For the IRF, numerical estimates include large contributions from the second indirect effects, which are not included in observation-based estimates and may be overestimated by models [Quaas *et al.* 2009].

5. Next phase

During the remainder of the MACC project, the aerosol forcing algorithm will be improved to account for the aerosol vertical profile and provide a first estimate of the DRF exerted by aerosols overlying clouds. The different sections of the processing chain will also be put together in preparation for the production stage and the dissemination of forcing products.

References

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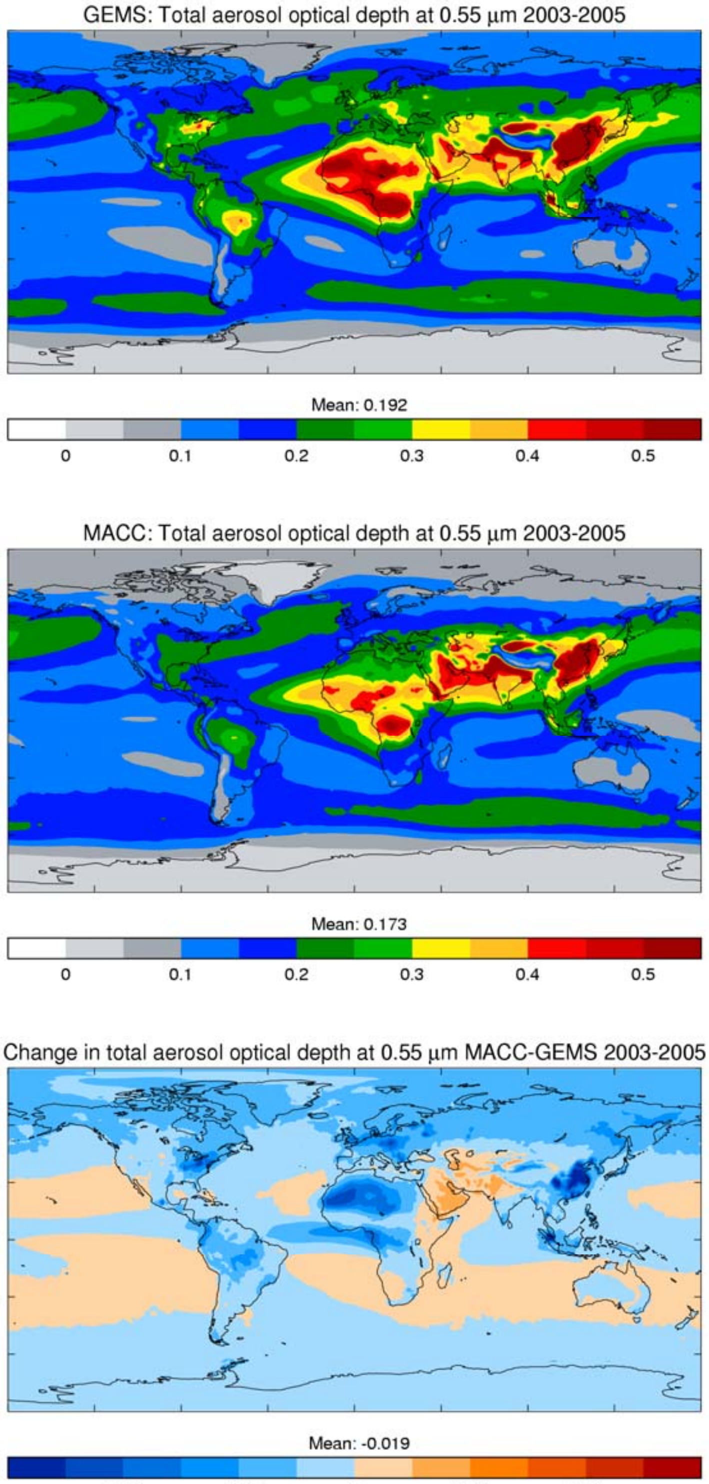

Figure 1. Total aerosol optical depth at 0.55 µm for the period 2003–2005 in the GEMS re-analysis (top panel), MACC re-analysis (middle panel) and their difference (bottom panel).

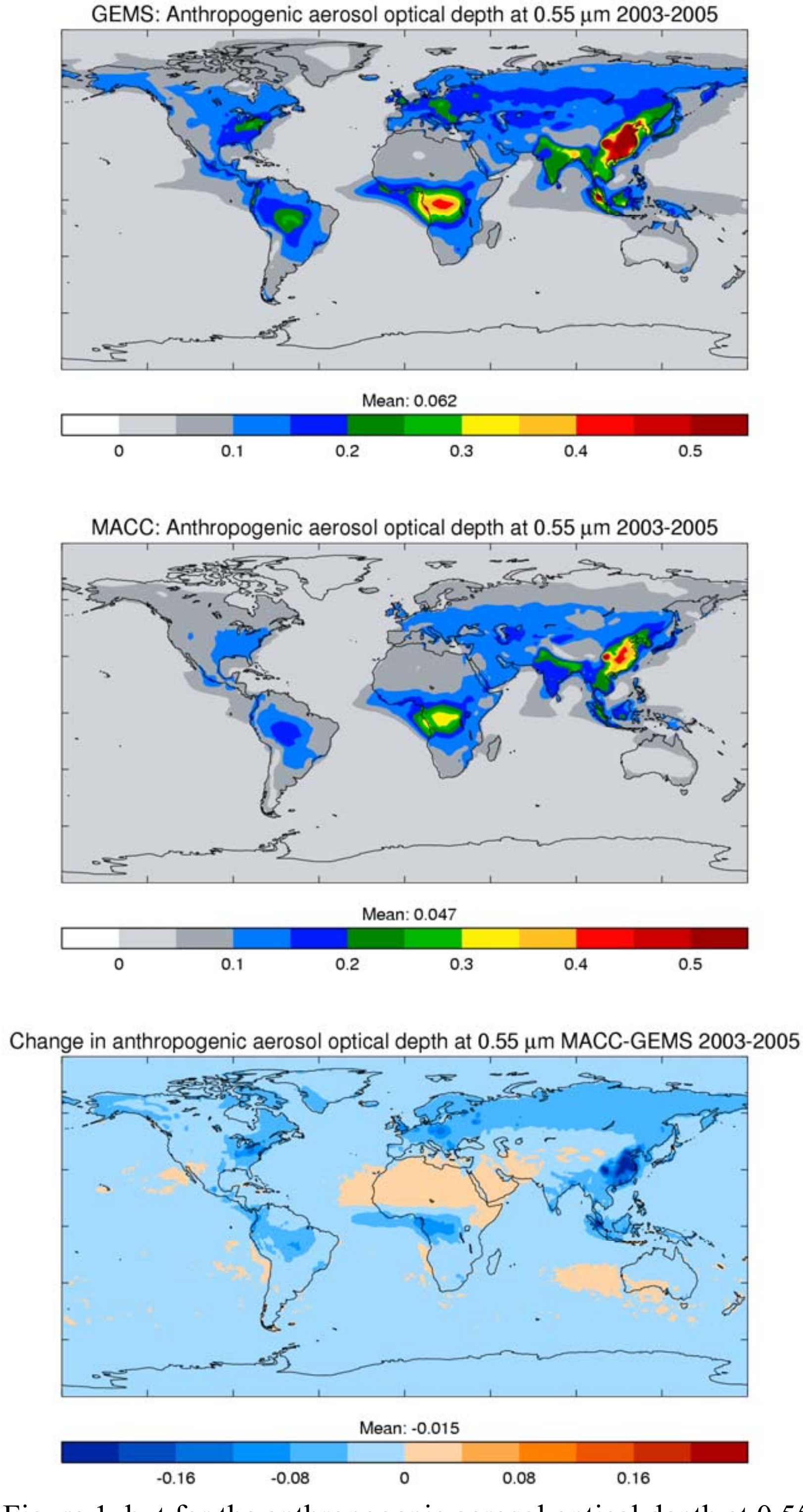

Figure 2. As Figure 1, but for the anthropogenic aerosol optical depth at 0.55 μm.

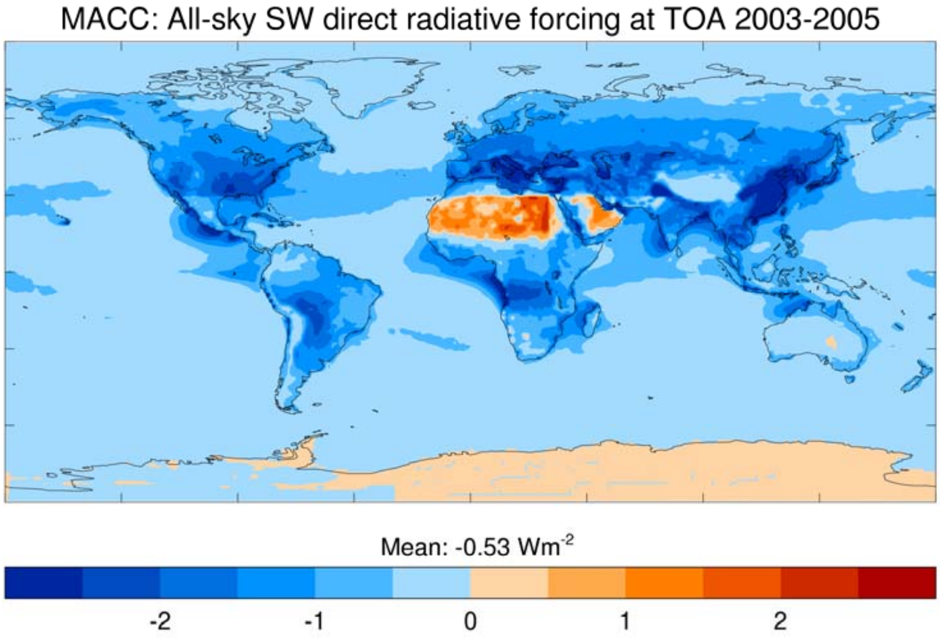

Figure 3. Shortwave direct radiative forcing (Wm^{-2}) at the top of the atmosphere and in all-sky conditions as derived from the MACC re-analysis for the period 2003–2005.

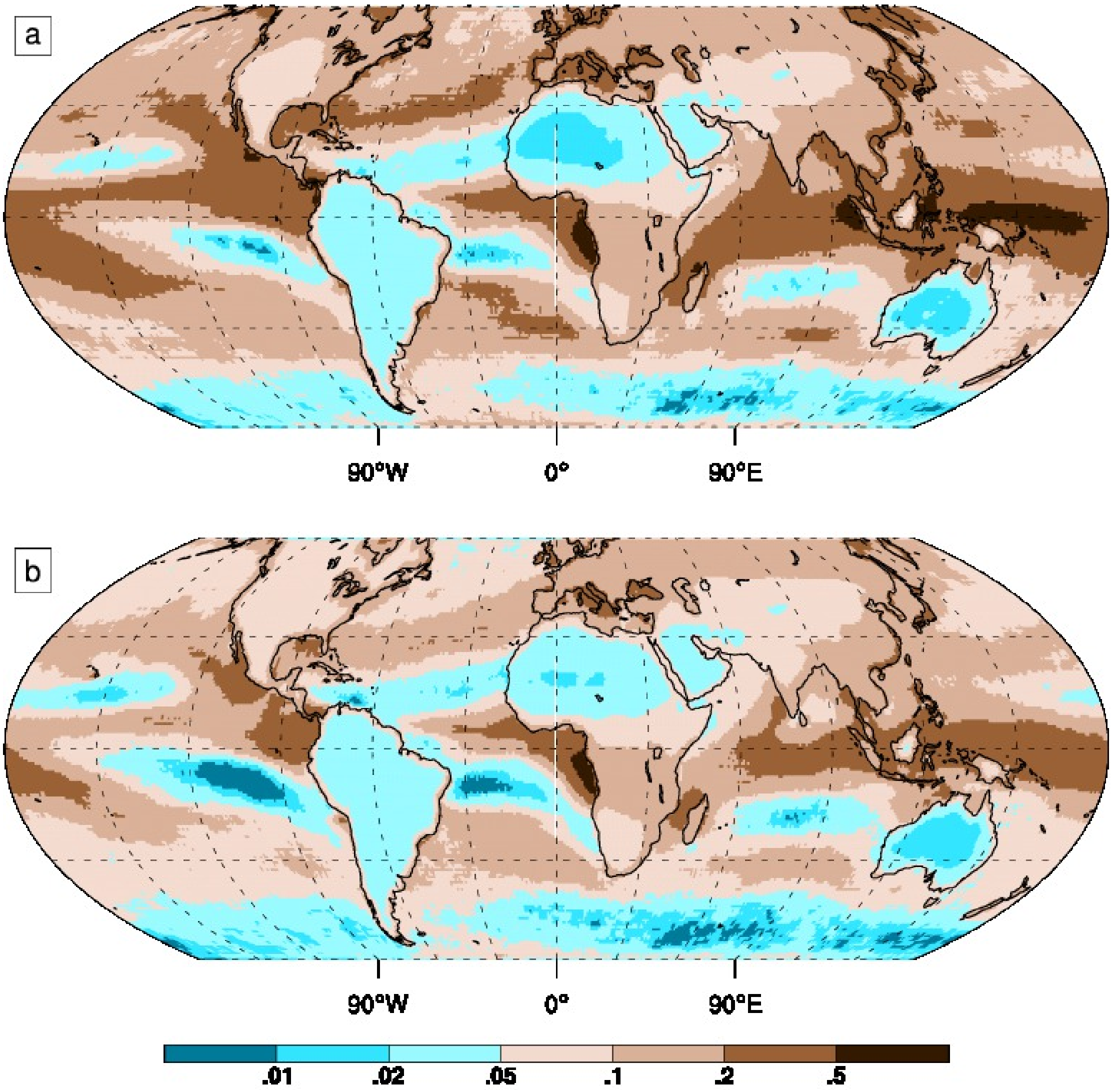

Figure 4. Sensitivity of cloud droplet number concentration to the perturbation in aerosol optical depth by anthropogenic emissions, where the anthropogenic aerosol optical depth is derived from (a) the GEMS re-analysis or (b) the MACC re-analysis for the year 2003.

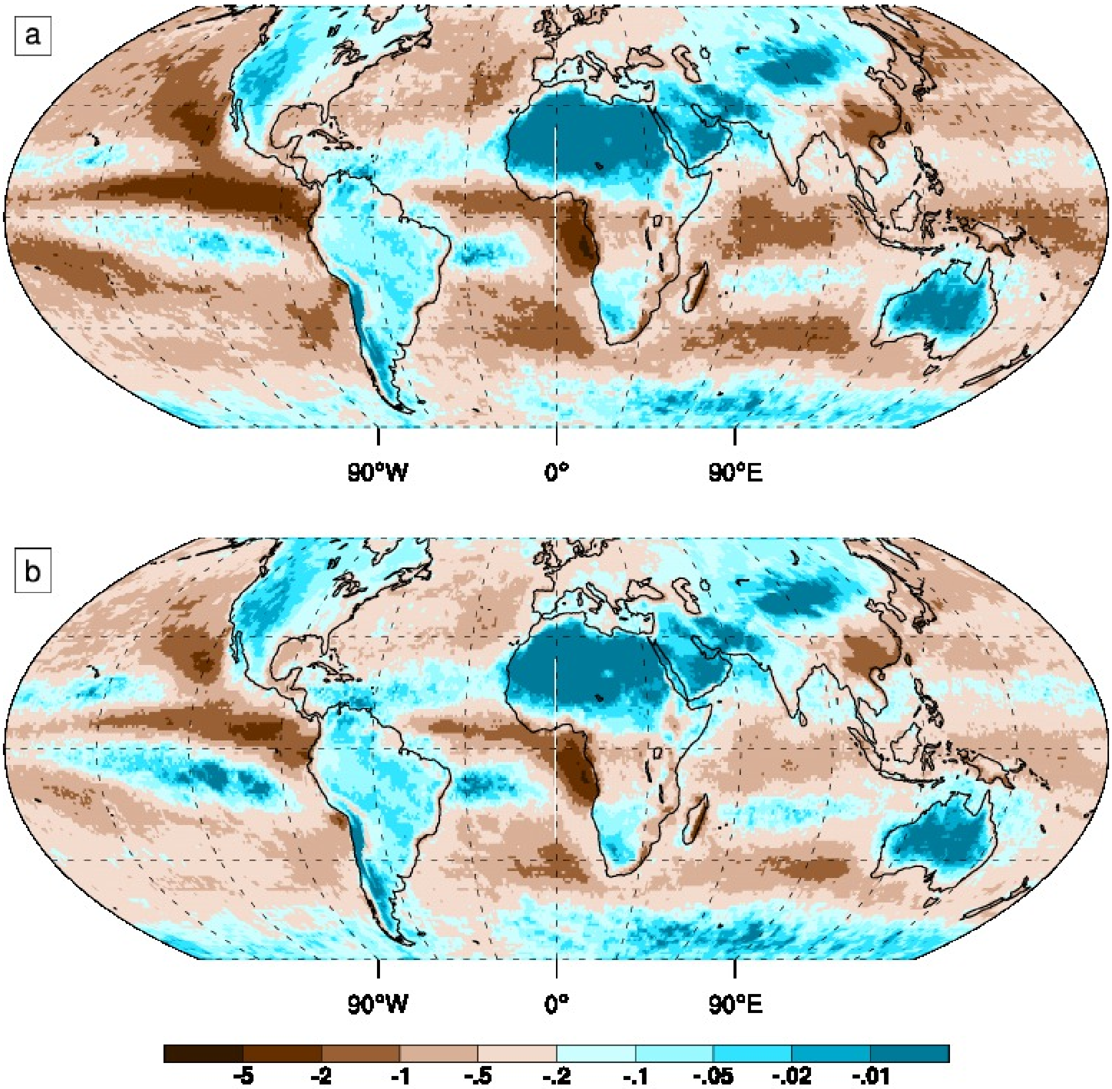

Figure 5. Radiative forcing, in Wm^{-2}, due to the first aerosol indirect effect for the year 2003, evaluated from (a) the GEMS re-analysis aerosol products and MACC re-analysis cloud products, and (b) the MACC re-analysis aerosol and cloud products. Global annual mean values are –0.44 Wm^{-2} and –0.31 Wm^{-2}, respectively.

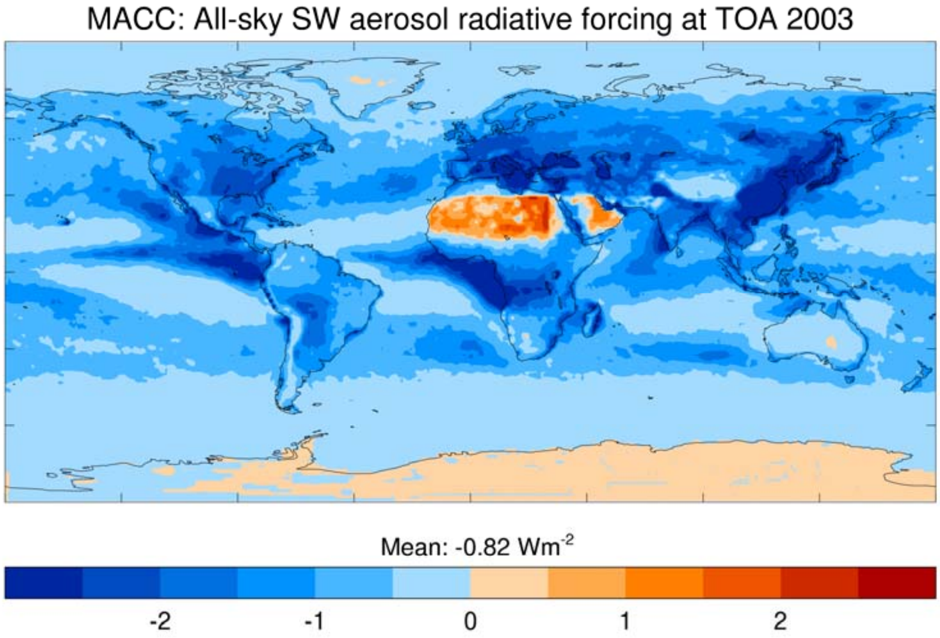

Figure 6. Total aerosol radiative forcing in all-sky conditions at the top of the atmosphere for the year 2003. This is the sum of direct and first indirect forcings estimated from the MACC re-analysis.