Improving aerosol processes and radiative forcing in preparation for UKESM1

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UKESM1 is developed on top of the coupled physical model, HadGEM3-GC3 (hereafter GC3). GC3 consists of the Unified Model (UM) atmosphere, JULES land surface scheme, NEMO ocean model and the CICE sea ice model. The UM atmosphere in GC3 is Global Atmosphere version 7 (GA7). Inclusion in GA7 of both a new cloud microphysics parameterization and the new GLOMAP aerosol scheme led to a concern the model might exhibit a strong negative historical aerosol radiative forcing (*i.e. a strong aerosol-induced cooling due to increasing anthropogenic emission of aerosol and aerosol precursors over the past ~150 years*) with potentially detrimental impacts on the overall historical simulation of both GC3 and UKESM1.

A protocol was therefore developed to assess the Effective Radiative Forcing (ERF) of the main climate forcing agents over the historical period (~1850 to 2000), namely; well mixed greenhouse gases (GHGs), aerosols and aerosol precursors, tropospheric ozone and land use change. This protocol follows that of the CMIP6 RFMIP project (Andrews 2014, Pincus et al. 2016). The aim was to assess the change in the mean top-of-atmosphere (TOA) ERF between average pre-industrial (~1850 in our experiments) and present-day (~2000) conditions. In particular to assess the aerosol ERF, with a requirement that the **total** (all forcing agents) historical ERF be positive. Initial tests revealed an aerosol ERF of -2.2 Wm^{-2}, significantly stronger than the -1.4 Wm^{-2} simulated by HadGEM2-A (Andrews 2014) and also outside the IPCC AR5 5-95% range of -1.9 to -0.1 Wm^{-2}. As a result of the large (negative) aerosol ERF, the total ERF diagnosed over the historical period was approximately 0 Wm^{-2}. Figure 1 shows the total (left) and clear-sky (right) net aerosol ERF in GA7 for 20-year simulations centred on year 2000 minus simulations centred on 1850. The largest aerosol ERF is seen over, and downstream of, the main Northern Hemisphere pollutant regions (East Asia, North-East USA and Europe). The difference between the total and clear sky ERF indicates the bulk of the negative ERF arises through aerosol-cloud forcing.
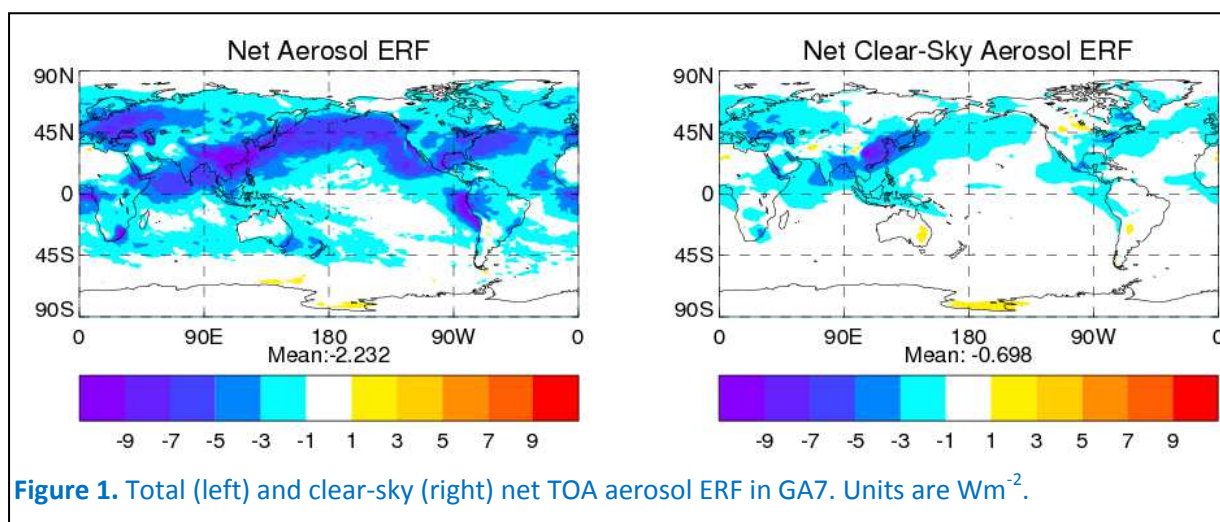

Figure 1. Total (left) and clear-sky (right) net TOA aerosol ERF in GA7. Units are Wm^{-2}.

We therefore investigated aspects of GA7 that could be causing this strong aerosol forcing and, where possible, introduced new processes and/or improved existing process descriptions to address these. The goal of this effort was to develop an atmosphere model configuration solidly based on GA7.0 that:

1. Had a less negative aerosol ERF and thereby a total historical ERF of >+ 0.5 Wm^{-2}
2. Had a pre-industrial top-of-atmosphere radiative balance of 0.0 ± 0.5 Wm^{-2}.
3. Did not degrade the many performance improvements delivered by GA7.0.

In September 2016 a GA7.1 configuration was defined, comprised of GA7 plus a suite of parameterization improvements and new process descriptions not originally in GA7, that resulted in a reduction in the aerosol ERF from -2.2 Wm^{-2} to -1.4 Wm^{-2} (with an implied total ERF for 2000 – 1850 of ~+0.8 Wm^{-2}) and a pre-industrial TOA radiation balance of -0.04 Wm^{-2}. The 3 primary developments leading to the aerosol ERF reduction were;

1. A new parameterization representing the observed sensitivity of cloud droplet size distributions to the pollutant (aerosol) content of the atmosphere, referred to as the cloud droplet spectral dispersion effect (Rotstayn and Liu 2009).

2. An improved treatment of the refractive index for black carbon aerosol absorption, following Bond *et al*. (2013), combined with more detailed look-up tables for aerosol optical properties enabling more accurate spectral resolution of aerosol solar absorption.

3. Guided by observations in McCoy *et al*. (2015), inclusion of an oceanic source of marine organic particles through augmentation of the parameterized marine emission of oceanic dimethyl sulphide (DMS) and subsequent treatment of this increased aerosol in the GLOMAP scheme.

In addition to these 3 developments, a number of more minor improvements were also made to; (i) the aerosol activation scheme in GLOMAP, (ii) the scheme for generating liquid water in mixed phase clouds and (iii) the representation of shallow convective cloud fraction. Importantly, all of these developments were either improvements to existing parameterizations or new processes that increase the realism of GA7.1 and thereby GC3.1. Figure 2 shows the resulting aerosol ERF simulated by GA7.1, with significant reduction in regions of maximum ERF in figure 1. The majority of the aerosol ERF decrease occurs through a reduction in aerosol-cloud forcing.
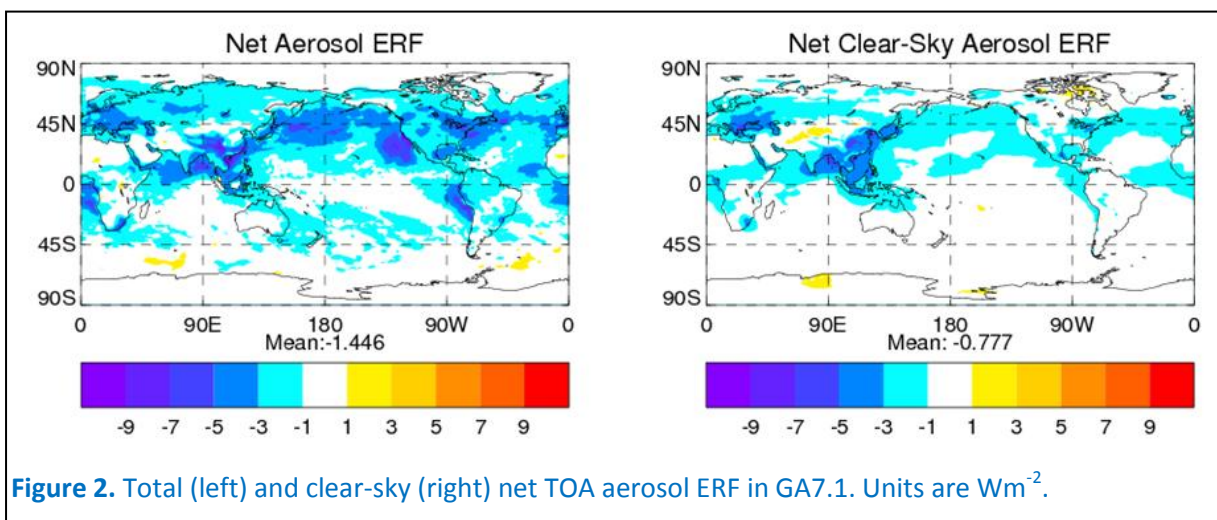

Figure 2. Total (left) and clear-sky (right) net TOA aerosol ERF in GA7.1. Units are Wm^{-2}.

GA7.1 is now the atmospheric component of HadGEM3-GC3.1 which forms the physical coupled model core of UKESM1.

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