Effective radiative forcing in the aerosol-climate model CAM5.3-MARC-ARG

Benjamin S. Grandey1, Daniel Rothenberg2, Alexander Avramov3, Qinjian Jin2, Hsiang-He Lee1, Chien Wang2,1

1Center for Environmental Sensing and Modeling, Singapore-MIT Alliance for Research and Technology, Singapore

2Center for Global Change Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

3Department of Environmental Sciences, Emory University, Atlanta, Georgia, USA

*Correspondence to*: Benjamin S. Grandey (benjamin@smart.mit.edu)

**Abstract.** TODO

# 1 Introduction

TODO

# 2 Method

## 2.1 Modal aerosol modules (MAM3 and MAM7)

The Community Earth System Model version 1.2.2 (CESM 1.2.2) contains the Community Atmosphere Model version 5.3 (CAM5.3). Within CAM5.3, the default aerosol model is a modal aerosol module with three log-normal modes (MAM3) (Liu et al., 2012). Optionally, a more detailed model aerosol module with seven log-normal modes (MAM7) (Liu et al., 2012) can be used instead of MAM3. The seven modes included in MAM7 are Aitken, accumulation, primary carbon, fine soil dust, fine sea salt, coarse soil dust, and course sea salt. Within each of these modes, MAM7 simulates the mass mixing ratios of internally-mixed sulphate, ammonium, primary organic carbon, secondary organic carbon, black carbon, soil dust, and sea salt (Liu et al., 2012). In MAM3, three simplifications are made: first, the primary carbon mode is merged into the accumulation mode; second, the fine soil dust and fine sea salt modes are also merged into the accumulation mode; third, the coarse soil dust and course sea salt modes are merged with each other; and fourth, ammonium is implicitly included via sulphate and is no longer explicitly simulated. As a result, MAM3 simulates just three modes: Aitken, accumulation, and coarse. This reduces the computational expense. More recently, a version containing four modes (MAM4) (Liu et al., 2016), has also been coupled to CAM5.3, but we do not consider MAM4 in this study.

The MAM aerosols interact with radiation, allowing aerosol direct and semi-direct effects to be represented. The aerosols can act as cloud condensation nuclei via the ARG activation scheme (Abdul-Razzak and Ghan, 2000) and can also act as ice nuclei. Via such activation, the aerosols are coupled to the stratiform cloud microphysics (Gettelman et al., 2010; Morrison and Gettelman, 2008), allowing aerosol indirect effects on stratiform clouds to be represented. These indirect effects dominate the effective radiative forcing due to aerosols in CAM version 5.1 (Ghan et al., 2012). In comparison to many other global climate models, this effective radiative forcing due to aerosols in CAM5.1 is relatively strong (Shindell et al., 2013).

## 2.2 The two-Moment, Multi-Modal, Mixing-state-resolving Aerosol model for Research of Climate (MARC)

The two-Moment, Multi-Modal, Mixing-state-resolving Aerosol model for Research of Climate (MARC), which is based on the aerosol scheme by Wilson et al. (Wilson et al., 2001), simulates the evolution of mixtures of aerosol species. Previous versions of MARC have used both in cloud-resolving model simulations (Ekman et al., 2004, 2006, 2007; Engström et al., 2008; Wang, 2005a, 2005b) and in global climate model simulations (Ekman et al., 2012; Kim et al., 2008, 2014).

As documented by Rothenberg et al. (Rothenberg et al., 2017), MARC has been coupled to the Community Atmosphere Model version 5.3 (CAM5.3) within the Community Earth System Model version 1.2.2 (CESM 1.2.2). In this configuration, MARC replaces the MAM3 aerosol model.

MARC tracks the number concentrations and mass concentrations of different lognormal modes. The externally-mixed modes include three pure sulphate modes (nucleation, Aitken, and accumulation), pure organic carbon (OC), and pure black carbon (BC). The internally-mixed modes include mixed organic carbon plus sulphate (MOS) and mixed black carbon plus sulphate (MBS). In MOS, it is assumed that the organic carbon and sulphate are mixed homogeneously within each particle. In MBS, it is assumed that each particle contains a black carbon core surrounded by a sulphate shell. Mineral dust and sea-salt are represented using sectional single-moment schemes, each with four size bins. Rothenberg et al. (Rothenberg et al., 2017) contains further details.

In addition to interacting with radiation, the aerosols interact with the stratiform cloud microphysics scheme using standard stratiform cloud microphysics scheme, as would be the case with the standard MAM3 configuration of CAM5.3. Various aerosol activation schemes can be used with MARC (Rothenberg et al., 2017), including versions of a recently-developed polynomial chaos expansion scheme (Rothenberg and Wang, 2016, 2017). The choice of activation scheme can substantially influence the effective radiative forcing (Rothenberg et al., 2017). In order facilitate comparison between the MAM3 and MARC aerosol models, we have chosen to keep the activation scheme constant in this study – hence, as is the case for the MAM3 and MAM7 simulations, the ARG activation scheme (Abdul-Razzak and Ghan, 2000) is also used for the MARC simulations. We refer to this configuration as “CAM5.3-MARC-ARG”.

## 2.3 Computational performance

In order to assess the computational performance of MARC, in comparison to MAM3 and MAM7, six timing simulations have been performed. The configuration of these simulations is described in the caption of Table 1.

Before looking at the results, it is worth noting that the default radiation diagnostics differ between MARC and MAM3/MAM7. As highlighted by Ghan (Ghan, 2013), in order to calculate the direct radiative effect of aerosols, a second radiation call is required in order to diagnose “clean-sky” fluxes – in this diagnostic clean-sky radiation call, interactions between aerosols and radiation are switched off. In MARC, these clean-sky fluxes are diagnosed by default. However, in MAM3/MAM7, these clean-sky fluxes are not diagnosed by default, although simulations can be configured to include the necessary diagnostics. The inclusion of the clean-sky diagnostics increases computational expense. Hence, in order to facilitate a fair comparison between MARC and MAM3/MAM7, we have performed two simulations for each aerosol model: one with clean-sky diagnostics switched on, and one with clean-sky diagnostics switched off.

The results from the timing simulations are shown in Table 1. When clean-sky diagnostics are switched off, as would ordinarily be the case for long climate-scale simulations, MARC leads to only a 6% increase in computational cost compared to a standard configuration with MAM3. MAM7 is considerably more expensive. When clean-sky diagnostics are switched on, as is the case for the comparison simulations described below, the computational cost of MARC is very similar to that of MAM3.

## 2.4 Comparison simulations

In order compare results from MARC, MAM3, and MAM7, five simulations are performed:

1. “MAM3\_2000”, which uses MAM3 with year-2000 aerosol (and aerosol precursor) emissions;
2. “MAM7\_2000”, which uses MAM7 with year-2000 aerosol emissions;
3. “MARC\_2000”, which uses MARC with year-2000 aerosol emissions;
4. “MAM3\_1850”, which uses MAM3 with year-1850 aerosol emissions;
5. “MARC\_1850”, which uses MARC with year-1850 aerosol emissions.

The three simulations using year-2000 emissions facilitate comparison of aerosol fields and cloud fields. The two simulations using year-1850 emissions further facilitate analysis of the radiative effects produced by MAM3 and MARC.

The emissions follow the default MAM3/MAM7 emissions files, described in the Supplement of Liu et al. (Liu et al., 2012) and based on (Lamarque et al., 2010). 2.5% of the sulphur dioxide is emitted as sulphate. For the MAM3/MAM7 simulations, the aerosol emissions from some sources follow a vertical profile (Liu et al., 2012). For the MARC simulations, sulphur emissions follow the same vertical profile; but all OC, BC and volatile organic compounds are emitted at the surface. Mineral dust and sea-salt emissions are not prescribed, being calculated “online”.

CESM 1.2.2, with CAM5.3, is used. Greenhouse gas concentrations and sea-surface temperatures (SSTs) are prescribed using year-2000 climatological values, based on the “F\_2000\_CAM5” component set. The CAM5.3 atmosphere is run at a horizontal resolution of 1.9°×2.5° with 30 levels in the vertical. Clean-sky radiation diagnostics are included, facilitating diagnosis of the direct radiative effect. The Cloud Feedback Model Intercomparison Project (CFMIP) Observational Simulator Package (COSP) (Bodas-Salcedo et al., 2011) is switched on, although the COSP diagnostics are not analysed in this manuscript. Each simulation is run for 32 years, and the first one year and eleven months are excluded as spin-up – hence, an alaysis period of 30 years is available, with each analysis year starting in December.

## 2.5 Diagnosis of radiative effects

Pairs of prescribed-SST simulations, with differing aerosol emissions, facilitate diagnosis of aerosol effective radiative forcing via the “radiative flux perturbation” approach (Haywood et al., 2009). When clean-sky radiation diagnostics are available, the effective radiative forcing can be decomposed into contributions from different radiative effects (Ghan, 2013). Note: throughout this paper, we use the term “radiative forcing” only when referring to effective radiative forcing, defined as the radiative flux perturbation between a simulation using year-1850 emissions and a simulation using year-2000 emissions; we use the term “radiative effect” more generally.

The shortwave (SW) effective radiative forcing (*ERFSW*) can be decomposed as follows:

(1)

where ∆refers to the difference between the year-2000 and year-1850 simulations, *DRESW* is the direct radiative effect, *CRESW* is the clean-sky SW cloud radiative effect, and *SRESW* is the surface albedo radiative effect. These components are defined as follows:

(2)

(3)

(4)

(5)

where *F* is the net SW flux at top-of-atmosphere (TOA), *Fclean* is the clean-sky net SW flux at TOA, and *Fclean,clear* is the clean-sky clear-sky Snet W flux at TOA. It is worth noting that *Fclean,clear* is also sensitive to near-infrared absorption by water vapour – hence, *SRESW*, the so-called “surface albedo” radiative effect, can also be impacted by changes in water vapour.

The longwave (LW) effective radiative forcing (*ERFLW*) is calculated as follows:

(6)

where *L* is the net LW flux at TOA, *Lclear* is the clear-sky LW flux at TOA, and *CRELW* is the LW cloud radiative effect.

The net effective radiative forcing (*ERFSW+LW*) is simply

. (7)

All of the quantities mentioned Eqns. 1-7 are calculated at TOA. The analysis below will also consider absorption by aerosols in the atmosphere (*AAASW*), as follows:

(8)

where is the net SW flux at the Earth’s surface, and is the clean-sky net SW flux at the Earth’s surface.

# 3 Results

TODO

## 3.1 Aerosol column loading

TODO

## 3.2 Direct radiative effect

TODO

## 3.3 Cloud radiative effect

TODO

## 3.4 Surface albedo radiative effect

TODO

## 3.5 Net effective radiative forcing

TODO

# 4 Conclusions

TODO

# Code and data availability

The MARC source code is available at <https://github.mit.edu/marc/marc_cesm/>. For this study, MARC commit “ff48dbe” has been used. Model namelist files, configuration scripts, and analysis code are available at <https://github.com/grandey/p17c-marc-comparison/> (doi:TODO). The model output data analysed in this paper are available at TODO (doi:TODO).

# Author contributions

TO-DO.

# Acknowledgements

This research is supported by the National Research Foundation of Singapore under its Campus for Research Excellence and Technological Enterprise programme. The Center for Environmental Sensing and Modeling is an interdisciplinary research group of the Singapore-MIT Alliance for Research and Technology. This research is also supported by the U.S. National Science Foundation (AGS-1339264) and the U.S. Department of Energy, Office of Science (DE-FG02-94ER61937). We would like to acknowledge high-performance computing support from Cheyenne (doi:10.5065/D6RX99HX) provided by NCAR’s Computational and Information Systems Laboratory, sponsored by the National Science Foundation. Thanks are due to Zheng Lu and Xiaohong Liu for advice about model configuration, especially MAM7.

# References

Abdul-Razzak, H. and Ghan, S. J.: A parameterization of aerosol activation: 2. Multiple aerosol types, J. Geophys. Res., 105(D5), 6837–6844, doi:10.1029/1999JD901161, 2000.

Bodas-Salcedo, A., Webb, M. J., Bony, S., Chepfer, H., Dufresne, J.-L., Klein, S. A., Zhang, Y., Marchand, R., Haynes, J. M., Pincus, R. and John, V. O.: COSP: Satellite simulation software for model assessment, Bull. Am. Meteorol. Soc., 92(8), 1023–1043, doi:10.1175/2011BAMS2856.1, 2011.

CESM Software Engineering Group: CESM User’s Guide (CESM1.2 Release Series User’s Guide), [online] Available from: http://www.cesm.ucar.edu/models/cesm1.2/cesm/doc/usersguide/ug.pdf [accessed 2017-10-31], 2015.

Ekman, A. M. L., Wang, C., Wilson, J. and Ström, J.: Explicit simulations of aerosol physics in a cloud-resolving model: a sensitivity study based on an observed convective cloud, Atmos. Chem. Phys., 4(3), 773–791, doi:10.5194/acp-4-773-2004, 2004.

Ekman, A. M. L., Wang, C., Ström, J. and Krejci, R.: Explicit Simulation of Aerosol Physics in a Cloud-Resolving Model: Aerosol Transport and Processing in the Free Troposphere, J. Atmos. Sci., 63(2), 682–696, doi:10.1175/JAS3645.1, 2006.

Ekman, A. M. L., Engström, A. and Wang, C.: The effect of aerosol composition and concentration on the development and anvil properties of a continental deep convective cloud, Q. J. R. Meteorol. Soc., 133(October), 937–948, doi:10.1002/qj.108, 2007.

Ekman, A. M. L., Hermann, M., Groß, P., Heintzenberg, J., Kim, D. and Wang, C.: Sub-micrometer aerosol particles in the upper troposphere/lowermost stratosphere as measured by CARIBIC and modeled using the MIT-CAM3 global climate model, J. Geophys. Res. Atmos., 117(D11), n/a-n/a, doi:10.1029/2011JD016777, 2012.

Engström, A., Ekman, A. M. L., Krejci, R., Ström, J., de Reus, M. and Wang, C.: Observational and modelling evidence of tropical deep convective clouds as a source of mid-tropospheric accumulation mode aerosols, Geophys. Res. Lett., 35(23), L23813, doi:10.1029/2008GL035817, 2008.

Gettelman, A., Liu, X., Ghan, S. J., Morrison, H., Park, S., Conley, A. J., Klein, S. A., Boyle, J., Mitchell, D. L. and Li, J.-L. F.: Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the Community Atmosphere Model, J. Geophys. Res., 115(D18), D18216, doi:10.1029/2009JD013797, 2010.

Ghan, S. J.: Technical Note: Estimating aerosol effects on cloud radiative forcing, Atmos. Chem. Phys., 13(19), 9971–9974, doi:10.5194/acp-13-9971-2013, 2013.

Ghan, S. J., Liu, X., Easter, R. C., Zaveri, R., Rasch, P. J., Yoon, J.-H. and Eaton, B.: Toward a Minimal Representation of Aerosols in Climate Models: Comparative Decomposition of Aerosol Direct, Semidirect, and Indirect Radiative Forcing, J. Clim., 25(19), 6461–6476, doi:10.1175/JCLI-D-11-00650.1, 2012.

Haywood, J., Donner, L., Jones, A. and Golaz, J.-C.: Global Indirect Radiative Forcing Caused by Aerosols: IPCC (2007) and Beyond, in Clouds in the Perturbed Climate System: Their Relationship to Energy Balance, Atmospheric Dynamics, and Precipitation, edited by J. Heintzenberg and R. Charlson, MIT Press., 2009.

Kim, D., Wang, C., Ekman, A. M. L., Barth, M. C. and Rasch, P. J.: Distribution and direct radiative forcing of carbonaceous and sulfate aerosols in an interactive size-resolving aerosol–climate model, J. Geophys. Res., 113(D16), D16309, doi:10.1029/2007JD009756, 2008.

Kim, D., Wang, C., Ekman, A. M. L., Barth, M. C. and Lee, D.-I.: The responses of cloudiness to the direct radiative effect of sulfate and carbonaceous aerosols, J. Geophys. Res. Atmos., 119(3), 1172–1185, doi:10.1002/2013JD020529, 2014.

Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K. and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10(15), 7017–7039, doi:10.5194/acp-10-7017-2010, 2010.

Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., Lamarque, J.-F., Gettelman, A., Morrison, H., Vitt, F., Conley, A., Park, S., Neale, R., Hannay, C., Ekman, A. M. L., Hess, P., Mahowald, N., Collins, W., Iacono, M. J., Bretherton, C. S., Flanner, M. G. and Mitchell, D.: Toward a minimal representation of aerosols in climate models: description and evaluation in the Community Atmosphere Model CAM5, Geosci. Model Dev., 5(3), 709–739, doi:10.5194/gmd-5-709-2012, 2012.

Liu, X., Ma, P.-L., Wang, H., Tilmes, S., Singh, B., Easter, R. C., Ghan, S. J. and Rasch, P. J.: Description and evaluation of a new four-mode version of the Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model, Geosci. Model Dev., 9(2), 505–522, doi:10.5194/gmd-9-505-2016, 2016.

Morrison, H. and Gettelman, A.: A New Two-Moment Bulk Stratiform Cloud Microphysics Scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and Numerical Tests, J. Clim., 21(15), 3642–3659, doi:10.1175/2008JCLI2105.1, 2008.

Rothenberg, D. and Wang, C.: Metamodeling of Droplet Activation for Global Climate Models, J. Atmos. Sci., 73(3), 1255–1272, doi:10.1175/JAS-D-15-0223.1, 2016.

Rothenberg, D. and Wang, C.: An aerosol activation metamodel of v1.2.0 of the pyrcel cloud parcel model: development and offline assessment for use in an aerosol–climate model, Geosci. Model Dev., 10(4), 1817–1833, doi:10.5194/gmd-10-1817-2017, 2017.

Rothenberg, D., Avramov, A. and Wang, C.: On the representation of aerosol activation and its influence on model-derived estimates of the aerosol indirect effect, Atmos. Chem. Phys. Discuss., (August), 1–35, doi:10.5194/acp-2017-680, 2017.

Shindell, D. T., Lamarque, J.-F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W. J., Conley, a. J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J.-H. and Lo, F.: Radiative forcing in the ACCMIP historical and future climate simulations, Atmos. Chem. Phys., 13(6), 2939–2974, doi:10.5194/acp-13-2939-2013, 2013.

Wang, C.: A modeling study of the response of tropical deep convection to the increase of cloud condensation nuclei concentration: 1. Dynamics and microphysics, J. Geophys. Res., 110(D21), D21211, doi:10.1029/2004JD005720, 2005a.

Wang, C.: A modeling study of the response of tropical deep convection to the increase of cloud condensation nuclei concentration: 2. Radiation and tropospheric chemistry, J. Geophys. Res., 110(D22), D22204, doi:10.1029/2005JD005829, 2005b.

Wilson, J., Cuvelier, C. and Raes, F.: A modeling study of global mixed aerosol fields, J. Geophys. Res. Atmos., 106(D24), 34081–34108, doi:10.1029/2000JD000198, 2001.

# Tables

Table 1: Results from six timing simulations. Each of these simulations consists of “20-day model runs with restarts and history turned off” (CESM Software Engineering Group, 2015), repeated five times in order to assess variability. The repetition of each simulation allows standard errors to be calculated via calculation of corrected sample standard deviation. For consistency, all runs have been submitted on the same day. For each run, 720 processors, spread across 20 nodes on Cheyenne (doi:10.5065/D6RX99HX), have been used. As with the year-2000 comparison simulations (Section 2.4), a model resolution of 1.9° × 2.5° is used, SSTs and greenhouse gas concentrations are prescribed using year-2000 climatological values, and aerosol and aerosol precursor emissions follow year-2000 emissions. In contrast to the comparison simulations, COSP has not been used in these timing simulations. The simulation costs shown represent the total cost of all model components, including components (such as the land scheme) that do not directly interact with the aerosol model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Aerosol model | Clean-sky radiation diagnostics | Notes | CESM simulation cost  **±** standard error, (processor hours / model year) | Relative simulation cost (% above MAM3 with clean-sky diagnostics switched OFF) |
| MAM3 | OFF | Standard CAM5.3 | 325.5±0.8 | 0.0% |
| MAM7 | OFF | Standard CAM5.3 + MAM7 | 435.6±1.5 | 33.8% |
| MARC | OFF | Clean-sky diagnostics switched off via modification of source code | 344.3±0.7 | 5.8% |
| MAM3 | ON | Diagnostic clean-sky radiation call specified in simulation namelist | 362.3±0.8 | 11.3% |
| MAM7 | ON | Diagnostic clean-sky radiation call specified in simulation namelist | 472.2±1.0 | 45.1% |
| MARC | ON | Standard CAM5.3-MARC-ARG | 361.1±0.7 | 10.9% |

# Figures