# Supplemental Material for

# Effective Radiative forcing from emissions of reactive gases and aerosols – a multimodel comparison

**The table of models used in the paper with information on resolution and aerosol and chemistry modules.**

Table S 1 Table of model properties, aerosol schemes, and chemistry (SU = sulphate; OA = organic aerosol; BC = black carbon; DU = dust; SS = sea salt; NO3 =nitrate)

| Earth System Model (component models) | Resolution | Description of aerosol module | References |
|---|---|---|---|
| IPSL-CM6A-LR (LMDz, INCA) | 1.25°(lat) x 2.5°(lon) 79 vertical levels LMDzORINCA Two | LMDzORINCA<br>Two-moment (mass and number) aerosol scheme with 5 lognormal modes.<br>Aerosols were pre-calculated from an atmosphere-only configuration and then prescribed as monthly climatologies<br>O3 is prescribed from the CMIP6 official dataset.<br>Components included: SU, BC, OA, SS, DU, NO3 | (Balkanski et al. 2010)<br>(Hauglustaine et al. 2014) |

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| UKESM11<br><br>(HadGEM3,<br><br>UKCA, JULES) | 1.25°(lat) x<br><br>1.88°(lon)<br><br>85 vertical<br><br>levels | UKCA contains the GLOMAP-mode aerosol microphysics scheme<br><br>Two-moment (mass and number) aerosol scheme with 5 lognormal modes (nucleation soluble, Aitken soluble, Aitken insoluble, accumulation soluble, coarse soluble)<br><br>Components included: SU, BC, OA, SS, DU*<br><br>*Dust component tracked independently in six size bins<br><br>UKCA contains a stratosphere-troposphere chemistry scheme, consisting of 84 tracers, 81 species, 199 bimolecular reactions, 25 uni- or termolecular reactions, 5 heterogeneous, 3 aqueous phase reactions, and 59 photolytic reactions. Secondary aerosol formation of sulphate and secondary organic aerosol is determined by the interactive oxidants. | (Sellar et al.)<br><br>(Williams et al. 2018)<br><br>(Walters et al. 2019)<br><br>(Kuhlbrodt et al. 2018)<br><br>GLOMAP-mode by (Mann et al. 2010)<br><br>(Mulcahy et al. 2018)<br><br>Mulcahy et al. (2019) submitted<br><br>Chemistry by<br><br>(Morgenstern et al. 2009)<br><br>(O'Connor et al. 2014)<br><br>Archibald et al. (2019) |

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|---|---|---|---|
| CNRM-ESM2-1<br>(ARPEGEClimatv6.3,<br>ISBA-CTRIP,<br>TACTIC,<br>REPROBUS,<br>PISCES) | 1.4°(lat) x<br>1.4°(lon)<br>91 vertical<br>levels | Aerosols: TACTIC_v2 tropospheric aerosol bin scheme. 12 bins in total for SU, BC, OA, SS, DU, with 3 bins for SS, and 3 bins for DD.<br>REPROBUS_v2 stratospheric chemistry scheme with 63 variables, 44 transported by the model large-scale transport scheme, and 168 chemical reactions, among which 39 photolysis and 9 heterogeneous reactions | (Michou et al. 2015; Roland Séférian et al. 2016)<br>(R. Séférian et al.) 2019<br>Michou et al 2019<br>Model description<br>website:<br>http://www.umrcnrm.<br>fr/cmip6/spip.ph<br>p?article10 |
| NorESM2<br>CAM6-Nor, CLM5) | 1.9°(lat) x<br>2.5°(lon)<br>32 vertical<br>levels | OsloAero6<br>Production-tagged aerosol module with background lognormal modes (Aitken, accumulation, coarse). Process tracers can alter the shape and composition of the initially lognormal background modes to generate mixtures.<br>Components included: SU, BC, OA, SS, DU | (Kirkevåg et al. 2018) |

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|---|---|---|---|
| MRI | MRI-AGCM3.5: TL159; 320 x 160 lon/lat,<br>MASINGAR mk-2r4c: TL95; 192 x 96 lon/lat,<br>MRI-CCM2.1: T42; 128 x 64 lon/lat, with 80 vertical levels | MASINGAR mk-2r4c is an aerosol model that is a component of MRI-ESM2.0. MASINGAR mk-2r4c treats atmospheric aerosol physical and chemical processes (e.g., emission, transport, diffusion, chemical reactions, and dry and wet depositions). The size distributions of sea salt and mineral dust are divided into 10 discrete bins and those of other aerosols are represented by lognormal size distributions.<br>Components included: SU, BC, OA, SS, DU | (Yukimoto et al. 2019)<br>(Adachi et al. 2013) |
| MIROC6 | 1.4$^{o}$ (lat) x 1.4$^{o}$ (lon) | Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS) predicts mass mixing ratios of the main tropospheric aerosols, includes gas phase chemistry<br>Components included: SU, BC, OA, SS, DU | Takemura (2018, http://www.cger.nies.go.jp/publications/report/i138/i138.pdf |

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|---|---|---|---|
| BCC-ESM1<br>(BCC-AGCM3-Chem,<br>BCC-AVIM2,<br>MOM4-L40,<br>SIS) | 2.8125º (lat) x 2.8125º (lon)<br>26 vertical levels with top level at 2.914 hPa | The model prognoses mass distribution of five aerosol types including sulfate, dust, black carbon, organic carbon, and sea salt based on their emissions (and precursor emissions), chemical production for sulfate and secondary organics, dry and wet (rainout and washout) deposition, transport by advection, and dry and wet convection.<br><br>Components included: SU, BC, OA, SS, DU<br>Effects of aerosols on radiation, cloud, and precipitation are treated. | (Wu et al. 2019a) |
| GFDL | (C96 96x96 cells)<br>33 vertical levels | The model prognoses mass distribution of five aerosol types including sulfate, dust, black carbon, organic carbon, and sea salt based on their emissions (and precursor emissions), chemical production for sulfate and secondary organics, dry and wet (rainout and washout) deposition, transport by advection, and dry and wet convection.<br><br>Components included: SU, BC, OA, SS, DU | Horowitz et al in prep 2019, Dunne et al in prep 2019 |

(Table for European models updated from:
Crescendo Report Horizon 2020
H2020-SC5-2014 Advanced Earth-system models
(Grant Agreement 641816)

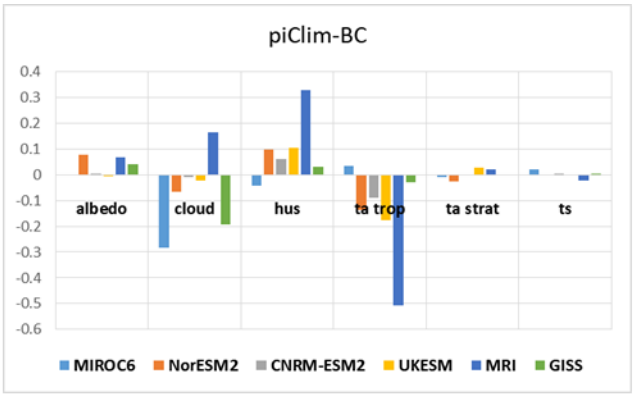
**Table of the 1850-2014 ERFs calculated from the TOA flux differences for each model for each experiment.**

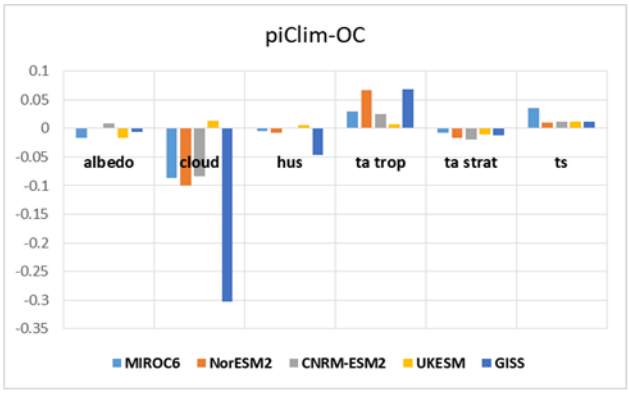
Table S 2 ERFs calculated for all models and experiments with available diagnostics

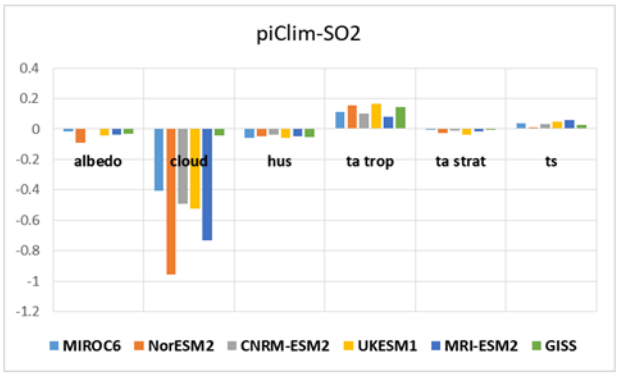
| ERF $Wm^{-2}$ | CNRM-ESM2 | UKESM | IPSL | MRI-ESM2 | BCC-ESM1 | MIROC6 | NorESM2 | GFDL-ESM4 | GISS-E2-1 |
|---|---|---|---|---|---|---|---|---|---|
| **aer** | -0.74 | -1.13 | -0.63 | -1.21 | | -1.01 | -1.21 | -0.70 | -0.90 |
| **BC** | 0.11 | 0.32 | | 0.25 | | -0.21 | 0.30 | | 0.06 |
| **CH4** | 0.44 | 0.93 | | 0.70 | 1.01 | | 0.37 | 0.68 | 0.78 |
| **HC** | -0.10 | -0.33 | | 0.31 | | | | 0.06 | 0.28 |
| **N2O** | 0.32 | | | 0.188 | | | 0.23 | | 0.20 |
| **NTCF** | -0.74 | -1.12 | | -1.08 | 0.14 | -0.89 | | -0.51 | -0.92 |
| **OC** | -0.17 | -0.27 | | -0.32 | | -0.23 | -0.22 | | -0.44 |
| **SO2** | -0.75 | -1.45 | | -1.37 | | -0.64 | -1.28 | | -0.62 |
| **O3** | | 0.14 | | 0.06 | | | | 0.27 | 0.23 |
| **NOx** | | -0.085 | | -0.02 | | | | 0.14 | 0.16 |
| **NH3** | | | | | | | | | -0.08 |
| **VOC** | | 0.2099 | | -0.03 | | | | -0.15 | 0.22 |
| **NTCF - aer** | 0.00 | 0.01 | | 0.13 | | 0.12 | | 0.19 | -0.02 |

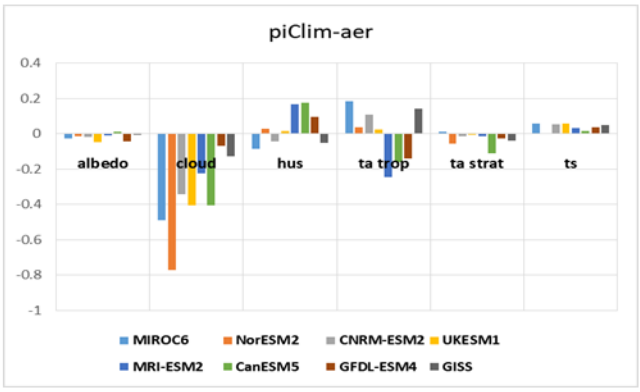
**Kernel Breakdown of rapid adjsutments for each experiment**

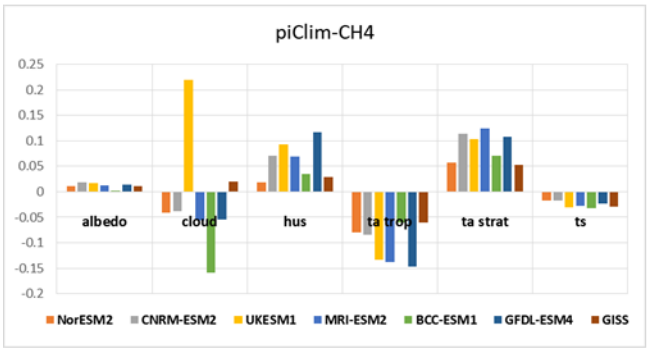
The full breakdowns of the rapid adjustments as calculated from the kernels is shown for each of the models and experiments where the relevant data was available, and shows the differences in models for how the rapid adjustments from different processes contributed to the overall rapid adjustment.

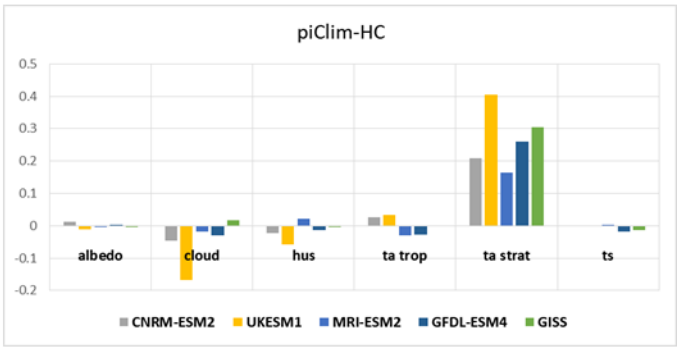


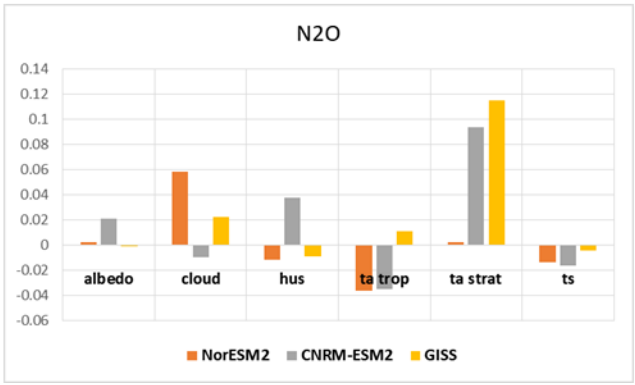




**Figure S 1 Breakdown of rapid adjustments for all models with available diagnostics**

**AOD scaling**

In Fig (S2) we compare the ERF originally calculated from the radiative fluxes for the (piClim-xx –piClim-control) experiments – referred to as Calc ERF to the ERF contributions obtained from using the AOD scaling, e.g. the BC OD in the piClim-BC experiment. In general, the change in the single species is responsible for most of the change in the ERF in these experiments, however in the MIROC6 piClim-OC experiment there is a significant contribution from the organic carbon, indicating this is not as clean a method for obtaining the scaling in this case as for the other models and experiments. In the case of NorESM2 for the SO2 experiment we


**Figure S 2 Comparison of the ERF calculated from radiative fluxes with that from the ERF from AOD-scaled values.**

also have some contribution from the OA, which may be attributable to the way the nucleation scheme works in NorESM2. Their nucleation scheme looks at the combination of H2SO4 and low-volatile organic vapours (precursors of SOA), so changing the SO2 emissions might therefore indirectly change the pathway for the SOA precursors, leading to a shift in how much nucleates and how much condensates. This might lead to a difference in lifetime of SOA (which is part of OM), leading to differences in the OM burden or AOD. (Dirk Olive, pers. Communication).

The rapid adjustments for the CH4 experiment are broken down to show the model differences and the contributions of the individual rapid adjustments to the overall rapid adjustment contribution to the ERF.

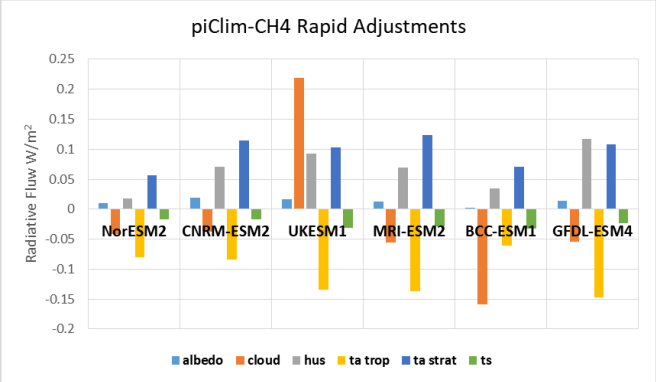



**Figure S 3 Rapid adjustments for each model for the piClim-CH4 experiments**

## Plots of the Ghan Calculations for the Chemically reactive species

We also plotted the breakdown of the ERF into the ERFari, ERFcloud and the ERFcs,af (clear sky, no aerosol) for the chemically reactive species, shown in Fig. S4 below.


**Figure S 4 Breakdown of the ERF for chemically reactive species into ERFari, ERFaci and ERFcs,af**

Table S 3 Column ozone, and ozone changes resulting from changes concentrations (CH4, N2O, HC) or emissions (NOX, VOC, O3, NTCF) of reactive gases. The multi model mean does not include the results for CNRM-ESM2 for tropospheric ozone.

| Experiment | UKESM1 | | CNRM-ESM2 | | GFDL-ESM4 | | CESM2-WACCM | | GISS-E2 | | MRI-ESM2 | | Multi-model | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | trop | strat | trop | strat | trop | strat | trop | strat | trop | strat | trop | strat | trop | strat |
| Control DU | 25.65 ±0.05 | 313.3 ±0.3. | | 273.3 ±0.2 | 20.15 ±0.19 | 267.0 ±0.2 | 19.88 ±0.02 | 252.8 ±0.1 | 26.44 ±0.03 | 258.5 ±0.4 | 20.45 ±0.04 | 294.8 ±0.1 | 22.5 ±2.9 | 282 ±23 |
| CH4 DU | +3.03 ±0.08 | +1.8 ±0.6 | | +4.0 ±0.3 | +2.50 ±0.04 | +2.1 ±0.3 | +2.70 ±0.03 | 3.7 ±0.2 | +2.17 ±0.05 | +5.3 ±0.2 | +2.45 ±0.04 | +2.9 ±0.5 | +2.6 ±0.3 | +3.3 ±1.2 |
| NOx DU | +5.10 ±0.08 | | | | +6.62 ±0.03 | +1.1 ±0.2 | +6.2 ±0.04 | +0.8 ±0.3 | +9.19 ±0.05 | +1.0 ±0.2 | +4.09 ±0.05 | +10.5 ±0.5 | +6.2 ±1.7 | +3.4 ±4.1 |
| VOC DU | +1.6 | | | | +1.94 ±0.03 | +2.5 ±0.2 | | | +1.90 ±0.05 | -1.9 ±0.3 | +1.99 ±0.05 | +2.0 ±0.5 | +1.9 ±0.2 | +0.9 ±1.9 |
| O3 DU | +7.0 | | | | +9.46 ±0.03 | +2.8 ±0.2 | | | +11.38 ±0.05 | -0.5 ±0.3 | +7.51 ±0.04 | +7.2 ±0.5 | +8.8 ±1.7 | +3.1 ±3.2 |
| NTCF DU | +6.33 ±0.08 | +5.5 ±0.6 | | | +9.06 ±0.03 | +3.3 ±0.2 | | | +9.92 ±0.05 | +0.2 ±0.2 | +7.19 ±0.04 | +7.2 ±0.5 | +8.1 ±1.4 | +3.2 ±2.9 |
| HC DU | -2.15 ±0.07 | -38.7 ±0.6 | | -19.1 ±0.8 | -1.51 ±0.03 | -23.2 ±0.2 | | -10.6 ±0.8 | -2.54 ±0.05 | -24.2 ±0.2 | -0.41 ±0.05 | -13.4 ±0.5 | -1.4±0.9 | -21.5 ±9.1 |
| N2O DU | | | | -5.6 ±0.3 | | | 0.09 ±0.05 | -3.6 ±0.3 | +0.22 ±0.04 | -7.6 ±0.2 | -0.05 ±0.04 | -4.7 ±0.5 | +0.1 ±0.1 | -5.3 ±1.5 |

Table S 4 Methane lifetime (years), and change due to each experiment (%). Multi-model mean and standard deviation. Lifetimes assume a soil loss of 120 years. Stratospheric loss is included in the model calculations.

| Experiment | UKESM1 | CESM2-WACCM | GFDL-ESM4 | BCC | GISS-E2 | MRI-ESM2 | Multi-model |
|---|---|---|---|---|---|---|---|
| Control years | 8.0 | 8.7 | 9.6 | 6.3 | 13.4 | 10.1 | 10.0 ±1.9 |
| CH4 % | +22 | +22 | +21 | +26 | +18 | +22 | 22±3 |
| NOx % | -25 | -35 | -33 | | -46 | -26 | -33±8 |
| VOC % | +11 | | +15 | | +27 | +21 | +19±6 |
| O3 % | -19 | | -24 | | -40 | -20 | -16±9 |
| HC % | -4.9 | | -7.5 | | -0.6 | -2.4 | -3.7 ±2.4 |
| N2O | -1.2 | -2.8 | | | -3.9 | -1.3 | -2.0 ±1.1 |