PI to PD anthropogenic forcings in UKESM1, including attribution of the methane forcing

Fiona M. O’Connor, Ben Johnson, Jane Mulcahy, Luke Abraham, Mohit Dalvi, Gerd Folberth, Paul Griffiths, Catherine Hardacre, James Keeble, Olaf Morgenstern, Sungbo Shim, João Teixeira, Steven Turnock, Jonny Williams, Guang Zeng

Atmospheric Science Conference, Birmingham, July 2019
Outline of Presentation

❖ Brief overview of UKESM1
❖ Define ERF & outline AerChemMIP/RFMIP
❖ Pre-Industrial to Present-Day ERFs
❖ Focus on : ① Aerosol forcing
             ② Apportionment of CH₄ forcing
❖ Conclusions
Overview of UKESM1

UKESM1 – United Kingdom’s Earth System Model

- HadGEM3-GC3.1 is the core physical model with N96 resolution (~140km) and 1° NEMO Ocean
- Terrestrial carbon and nitrogen cycles, with dynamic vegetation and land-use change
- UKCA Tropospheric-Stratospheric chemistry, coupled to two-moment aerosol scheme, GLOMAP-mode, with sulphate, black carbon, organic carbon, and sea salt
- Mass-based 6-bin dust scheme
- Ocean biogeochemistry MEDUSA

Sellar et al., Under review, JAMES
Effective Radiative Forcing

\[ ERF = IRF + \sum_{i} A_i \]
UKESM1’s Contribution to RFMIP and AerChemMIP

• Aiming to do all AerChemMIP experiments except piClim-NH3 (No ammonium nitrate scheme)

• Aiming to do Tier 1 RFMIP experiments

• Collaboration between:

  Met Office Hadley Centre (MOHC)

  National Centre for Atmospheric Science (NCAS)

  Korean Meteorological Agency (KMA)

  National Institute for Water and Atmosphere Research, NZ (NIWA)
Pre-industrial to Present-Day ERFs

IPCC AR5 (Myhre et al., 2013):

- Aerosols
- Greenhouse gases
- Total anthropogenic

<table>
<thead>
<tr>
<th>Forcing Type</th>
<th>ERF</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG</td>
<td>+2.89</td>
</tr>
<tr>
<td>Aerosol</td>
<td>-1.13</td>
</tr>
<tr>
<td>Trop. O3 precursors</td>
<td>+0.15</td>
</tr>
<tr>
<td>LU</td>
<td>-0.22</td>
</tr>
<tr>
<td>Total Anthro</td>
<td>+1.63*</td>
</tr>
</tbody>
</table>

Diagnosed from the difference in net TOA from paired UKESM1 experiments following AerChemMIP & RFMIP protocols

*Needs to be re-run with corrected LU
Global Distribution of Forcings

GHGs

ERF (Wm$^{-2}$): 2.89 ± 0.04

Aerosol

ERF (Wm$^{-2}$): -1.13 ± 0.04

Total Anthropogenic

ERF (Wm$^{-2}$): 1.63 ± 0.03

Trop. O3 precursors

Land use

Negative forcing from O3 and/or aerosols LU and Aer stronger outweighs positive than GHG forcing

GHG forcing
Breakdown of Aerosol ERF (1)

<table>
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<th>Forcing Type</th>
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<tr>
<td>Aerosol</td>
<td>-1.13</td>
</tr>
<tr>
<td>BC</td>
<td>+0.34</td>
</tr>
<tr>
<td>OC</td>
<td>-0.27</td>
</tr>
<tr>
<td>Anthropogenic SO2</td>
<td>-1.45</td>
</tr>
<tr>
<td>SUM: SO2+BC+OC</td>
<td>-1.38</td>
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- Sulphate ACI is the strongest negative contribution to aerosol forcing
- BC absorption almost offsets scattering by SU and OC
- The ACI therefore dominates the negative aerosol forcing, with the SU being the main part of that
- Forcings don’t add up quite linearly so that the “all” aerosol forcing is 0.25 Wm⁻² less negative than the sum of individual aerosol forcings
Breakdown of Aerosol ERF (2)

<table>
<thead>
<tr>
<th>Forcing Type</th>
<th>ERF</th>
</tr>
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<tbody>
<tr>
<td>Aerosol</td>
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<tr>
<td>SUM: SO2+BC+OC</td>
<td>-1.38</td>
</tr>
<tr>
<td>Anthropogenic SO2 (H2SO4 bugfix)</td>
<td>-1.33</td>
</tr>
</tbody>
</table>

- Sulphate ACI is the strongest negative contribution to aerosol forcing
- BC absorption almost offsets scattering by SU and OC
- The ACI therefore dominates the negative aerosol forcing, with the SU being the main part of that.
- Forcings don’t add up quite linearly so that the “all” aerosol forcing is 0.25 Wm\(^{-2}\) less negative than the sum of individual aerosol forcings → This may potentially be affected by H2SO4 bug which reduces SO2 ERF by ~0.12Wm\(^{-2}\)
Breakdown of Methane ERF (1)

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>NET</th>
<th>LW&lt;sub&gt;CS&lt;/sub&gt;</th>
<th>SW&lt;sub&gt;CS&lt;/sub&gt;</th>
<th>LW&lt;sub&gt;CRE&lt;/sub&gt;</th>
<th>SW&lt;sub&gt;CRE&lt;/sub&gt;</th>
<th>NET&lt;sub&gt;CS&lt;/sub&gt;</th>
<th>NET&lt;sub&gt;CRE&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔCH₄</td>
<td>+0.93 ±0.04</td>
<td>+0.72 ±0.02</td>
<td>+0.14 ±0.02</td>
<td>-0.39 ±0.02</td>
<td>+0.46 ±0.03</td>
<td>+0.86 ±0.03</td>
<td>+0.07 ±0.03</td>
</tr>
</tbody>
</table>

a) PI q / g kg<sup>-1</sup>  
b) PI O<sub>3</sub> / ppmv  
c) PI AOD  
d) Δq / %  
e) ΔO<sub>3</sub> / %  
f) 10x ΔAOD

- ERF is dominated by LW CS forcing, with the CRE in the SW and LW offsetting each other
- PI-to-PD CH₄ perturbation → Changes in stratospheric q, O<sub>3</sub>, and aerosol
Breakdown of Methane ERF (2)

<table>
<thead>
<tr>
<th>Agent</th>
<th>ERF1</th>
<th>ERF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CH(_4)</td>
<td>+0.93 ± 0.04</td>
<td>+0.95 ± 0.06</td>
</tr>
<tr>
<td>ACI</td>
<td>+0.20 ± 0.06</td>
<td>+0.16 ± 0.03</td>
</tr>
<tr>
<td>ARI</td>
<td>-0.07 ± 0.06</td>
<td>0.0 ± 0.03</td>
</tr>
<tr>
<td>O(_3)</td>
<td>+0.21 ± 0.05</td>
<td>+0.20 ± 0.03*</td>
</tr>
<tr>
<td>Strat. q</td>
<td>0.0 ± 0.06</td>
<td>0.0 ± 0.03*</td>
</tr>
<tr>
<td>CH(_4) only</td>
<td>+0.59 ± 0.03</td>
<td>+0.59 ± 0.03</td>
</tr>
</tbody>
</table>

(ERF1) Additional pairs to attribute total ERF to individual forcing agents by elimination

(ERF2) Additional pairs to calculate forcing for each agent/interaction individually

- Additional paired experiments to apportion the total methane ERF to different forcers
- Forcings appear to add linearly
- Methane *alone* accounts for more than 60% of the total methane ERF
- Earth System interactions, including chemistry-aerosol coupling, increase the PI-to-PD CH\(_4\) ERF by more than 50%

Now look at ① methane-only forcing

② Aerosol forcing, *solely* driven by methane

* Simulations still running!
Using a simplified expression for CH₄ RF (Etminan et al., 2016) gives: +0.56±0.07 Wm⁻²

BUT with only a small contribution in the SW (i.e. 0.03 Wm⁻² or 6 %)
Methane-only forcing (2)

Use RFMIP PI Baseline Test Case to investigate CS forcing in HadGEM2 and UKESM1:

PI CASE – run stand-alone SOCRATES with HadGEM2 and UKESM1 spectral files
PI CASE with PD CH4 – run stand-alone SOCRATES with HadGEM2 and UKESM1 spectral files

Each Test Case has 100 profiles – when averaged, give approximate annual-mean global-mean IRF

- Small positive forcing in the CS SW: Consistent with ERF experiments and line-by-line calculations (Etminan et al. 2016)
- HadGEM2 CS SW forcing should be zero! CS SW forcing was actually due to dust response!

Thanks to J. Manners and O. Jamil for RFMIP stand-alone set up
Methane-only forcing (3)

Use RFMIP PI Baseline Test Case to investigate differences in CS forcing between HadGEM2 and UKESM1:

Test Cases:
1. **PI baseline** – run stand-alone SOCRATES with HadGEM2 and UKESM1 spectral files
2. **PI baseline with PD CH4** – run stand-alone SOCRATES with HadGEM2 and UKESM1 spectral files

Each Test Case has 100 profiles – when averaged, give approximate annual-mean global-mean IRF

- Spectral change in the LW explain differences in HadGEM2 and UKESM1 CS LW forcing (Walters et al., 2019)

Thanks to J. Manners and O. Jamil for RFMIP stand-alone set up
Aerosol forcing attributable to methane (1)

\[ \Delta \text{Total: -0.2\%} \]

- 14.4\% (87\%)
- 1.6\%
- OH

\[ \Delta \text{Total: -0.6\%} \]

(41\%)
- 14.4\%
- OH (g)
- \( \text{H}_2\text{SO}_4 \)

(49\%)
+ 12.3\%
- \( \text{H}_2\text{O}_2 \) (aq)

+ 0.2\%
(10\%)
- O3 (aq)

Condensation across soluble modes of aerosol size distribution

DMS \rightarrow SO2

\( \text{NO}_3 \)
+ 9.3\%
(13\%)

Ems \rightarrow Dep

SO2 \rightarrow OH (+12.3\%)

\[ -14.4\% \]

\[ +12.3\% \]

\[ +0.2\% \]

SO2+OH

SO2+H2O2

SO2+O3
Aerosol forcing attributable to methane (2)

Methane perturbation:
- Increase in cloud effective radius
- Clouds become less reflective
- Consistent with positive aerosol forcing
Conclusions

• Net anthropogenic forcing is negative over NH continents (LU & aerosols)

• O3/Aerosol forcing outweighs positive LLGHG forcing over SH high latitudes

• Aerosol forcing dominated by ACI & mainly driven by SO2

• Methodology for apportioning total forcing to different agents (e.g. methane)

• Methane perturbation → Changes in SO2 oxidation pathways → Reduction in CCN and CDNC → Increase in cloud effective radius → Positive aerosol forcing

• Earth-system interactions, including chemistry-aerosol interactions, are important for quantifying climate forcing
Extra Slides
Offline SOCRATES runs (3)

Use RFMIP (Pincus et al., 2016) Test Cases to investigate differences in forcing between HadGEM2 and UKESM1:

Test Cases: 1. PI baseline – run stand-alone SOCRATES with GA7/UKESM1 and HadGEM2 spectral files
   2. PI baseline with PD CH4 – run stand-alone SOCRATES with GA7/UKESM1 and HadGEM2 spectral files

Each Test Case has 100 profiles – when averaged, give approximate annual-mean global-mean instantaneous radiative fluxes

From these calculations, the clear-sky HadGEM2 forcing should be larger than GA7 by 0.14 Wm⁻²

But the reported HG2 CS SW forcing of -0.13 Wm⁻² cancels it out!

What is the cause of that anomalous HadGEM2 forcing?
HadGEM2: one ensemble member

Lack of constraint over land leads to a highly variable dust response and a negative SW forcing!

Forcing *not* attributable to methane

No dust response evident in UKESM1 experiments

<table>
<thead>
<tr>
<th></th>
<th>LW_{CS}</th>
<th>SW_{CS}</th>
<th>LW_{CRE}</th>
<th>SW_{CRE}</th>
<th>NET_{CS}</th>
<th>NET_{CRE}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ens 1</td>
<td>+0.72</td>
<td>-0.04</td>
<td>-0.21</td>
<td>+0.10</td>
<td>+0.68</td>
<td>-0.10</td>
</tr>
<tr>
<td>Ens 2</td>
<td>+0.67</td>
<td>-0.07</td>
<td>-0.28</td>
<td>+0.14</td>
<td>+0.59</td>
<td>-0.14</td>
</tr>
<tr>
<td>Ens 3</td>
<td>+0.83</td>
<td>-0.28</td>
<td>-0.20</td>
<td>+0.12</td>
<td>+0.55</td>
<td>-0.07</td>
</tr>
<tr>
<td>Mean</td>
<td>+0.74</td>
<td>-0.13</td>
<td>-0.23</td>
<td>+0.12</td>
<td>+0.61</td>
<td>-0.11</td>
</tr>
</tbody>
</table>
SO$_2$ oxidation

OH

H$_2$O$_2$

O$_3$

a) Control: SO$_2$ + OH oxidation rate ($10^7$ mol S/s)

b) Experiment: SO$_2$ + OH oxidation rate ($10^7$ mol S/s)

c) (Exp-Ctl) diff. in SO$_2$ + OH oxidation rate ($10^7$ mol S/s)

a) Control: SO$_2$ + H$_2$O$_2$ oxidation rate ($10^7$ mol S/s)

b) Experiment: SO$_2$ + H$_2$O$_2$ oxidation rate ($10^7$ mol S/s)

c) (Exp-Ctl) diff. in SO$_2$ + H$_2$O$_2$ oxidation rate ($10^7$ mol S/s)

a) Control: SO$_2$ + O$_3$ oxidation rate ($10^4$ mol S/s)

b) Experiment: SO$_2$ + O$_3$ oxidation rate ($10^4$ mol S/s)

c) (Exp-Ctl) diff. in SO$_2$ + O$_3$ oxidation rate ($10^4$ mol S/s)
**HC ERF**

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</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>-0.33</td>
<td>+0.40</td>
<td>-0.50</td>
<td>+0.21</td>
<td>-0.44</td>
<td>-0.10</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

**SW**

Clear-sky SW ERF (W/m²)

**LW**

Clear-sky LW ERF (W/m²)
Stratospheric Chemistry Performance

Comparison of 20-year modelled climatology vs NIWA-BS TCO v3.4

- Model underestimates O3 by up to 60 DU in Nov/Dec over Antarctica
- Good agreement with S. Pole record in October
- In Nov/Dec, the model only tracks the deepest O3 holes & does not reproduce the observed variability
- Model produces too large negative trends during spring and summer at high latitudes in both hemispheres

Sellar et al., Under review, JAMES
HC ERF – Another cause of negative forcing? Aerosol forcing through ARI?

Can use double call diagnostics to separate ARI from ACI
HC ERF – Another cause of negative forcing?
Aerosol forcing through ACI?