Apportionment of the present-day forcing by methane using UKESM1: The role of chemistry-aerosol-cloud interactions

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The pre-industrial (PI; Year 1850) to present-day (PD; Year 2014) increase in methane concentration leads to a global mean effective radiative forcing (ERF) of 0.97 ± 0.04 W m⁻² in the UK’s Earth System Model, UKESM1. In comparison with the multi-model estimate of 0.75 ± 0.10 W m⁻² from the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP), UKESM1 has the highest methane ERF and lies outside the 1-sigma range. This is, in part, due to UKESM1 including interactive chemistry and positive indirect effects, such as methane-driven changes in tropospheric ozone. However, UKESM1 is the only model within AerChemMIP whose contribution to the methane ERF from tropospheric adjustments is positive – this is largely driven by the strong positive cloud adjustment in UKESM1, in contrast to other models. In this work, we apportion the total methane ERF between direct and indirect effects (including adjustments) and provide a process-based understanding of what is driving the positive cloud adjustment in UKESM1.

Using additional UKESM1 paired simulations, we apportion the total methane ERF between its direct methane contribution and indirect contributions from ozone, water vapour, and aerosols. This approach offers the advantage that linearity is not assumed and it distinguishes between cloud effects that are dynamically-driven via changes in temperature and those that are aerosol-mediated. By analysing the chemistry-aerosol budgets and the cloud responses, we find that the PI to PD increase in methane leads to an indirect positive aerosol ERF of up to 0.3 ± 0.06 W m⁻², with a near-zero contribution from the instantaneous radiative forcing from aerosol-radiation interactions. Methane-driven changes in oxidants alter the relative contributions of the different sulphur dioxide oxidation pathways, causing a change in new particle formation rates and a shift in the aerosol size distribution towards fewer but larger particles. There is a resulting decrease in cloud droplet number concentration, an increase in cloud droplet effective radius, and a decrease in liquid water path in marine stratocumulus regions from aerosol-cloud interactions (mainly through the cloud lifetime effect). There is a subsequent change in the cloud radiative effect, with the positive change in the shortwave dominating over the negative change in the longwave. However, when aerosol-cloud interactions are disabled, the change in the cloud radiative effect is negative and is dominated by the reduction of cirrus clouds in the tropics, thus making UKESM1 more consistent with the other AerChemMIP models.
These results can explain some of the diversity in multi-model estimates of methane forcing and highlight the importance of chemistry-aerosol-cloud interactions when quantifying climate forcing by reactive greenhouse gases.