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The important and varying role of rapid adjustments on the top of atmosphere energy budget

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The effective radiative forcing (ERF) metric is recommended for use in RFMIP (the Radiative Forcing Model Intercomparison Project), which is a contributing component to CMIP6. ERF is the difference in top-of-atmosphere (TOA) net radiation flux in atmosphere-only climate model integrations (one with a perturbed forcing, one with climatological forcing) with climatological sea-surface temperatures and sea ice applied in both runs to exclude ocean feedbacks. ERF is the sum of the direct radiative effects of the forcing agent (the instantaneous radiative forcing; IRF) plus any atmospheric adjustment to the forcing that changes the TOA energy budget (the rapid adjustment). For some forcing agents, ERF is substantially different to IRF, resulting from significant rapid adjustments. Interestingly, the rapid adjustment differs in sign, strength and mechanism for diverse forcing species.

In this multi-model study the rapid adjustments to five forcing agents (CO_2, CH_4, solar irradiance, black carbon, and sulfate aerosol) are analysed across ten participating models of the Precipitation Driver and Response Intercomparison Project (PDRMIP). Radiative kernels are used to isolate rapid adjustments from changes in clouds, specific humidity, stratospheric temperature, tropospheric temperature, surface temperature, and surface albedo. We show that different rapid adjustment processes are dominant for different forcing agents. It is well-known for example that stratospheric cooling for CO_2 forcing induces a positive rapid adjustment. This stratospheric temperature change was the only adjustment process considered in the "traditional" definition of radiative forcing (RF). By coincidence, the tropospheric and surface adjustments sum to (but are not necessarily individually) about zero for CO_2 forcing, which is why ERF and RF were seen to be similar when these metrics were compared in the IPCC Fifth Assessment Report. However, the tropospheric rapid adjustments dominate over the stratospheric temperature adjustment for black carbon forcing, and unlike for CO_2 forcing, the sum of adjustments is negative overall. Tropospheric plus surface adjustments do not sum to zero for solar or sulfate forcing either, meaning that the traditional RF is not an appropriate metric in the general case.

While the rapid adjustments due to non-cloud processes tend to be consistent in magnitude and sign across models, the rapid adjustments due to clouds are highly model dependent, particularly for sulfate forcing. This is due in part to the inclusion or omission and varying strengths of the cloud albedo effect and cloud lifetime effect between models. We use other approaches alongside the kernel method (partial radiative perturbations and a cloud kernel based on the ISCCP simulator) to obtain different measures for obtaining the cloud adjustment for the sulfate forcing experiment. In some cases we are able to isolate the cloud albedo effect from the cloud lifetime effect. Interestingly, we find a large diversity in the strength of the cloud albedo effect in models where this can be evaluated, which directly affects the magnitude of ERF.