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CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

KNOWLEDGE GAINS: SUMMARY AND IMPLICATION REPORT 2

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STATE-OF-THE-ART UNDERSTANDING OF RAPID ADJUSTMENTS

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KEY MESSAGES

- This KGSIR summarises recent advances in understanding rapid adjustments to perturbations of anthropogenic forcing agents, and their implications for climate research.
- The dominant rapid adjustments for historical changes in greenhouse gases are stratospheric (positive perturbation to Earth energy budget) and tropospheric (negative) temperature adjustments, with further contributions from water vapour and clouds (both positive).
- The rapid adjustments for aerosols are dominated by cloud adjustments, especially the response of cloud fraction (strongly negative) and cloud liquid water path (positive).
- Knowledge gains were due to dedicated multi-model intercomparison projects (PDRMIP, RFMIP) and improved satellite data analysis in combination with modelling.
- Next steps within CONSTRAIN are to improve the process-level understanding and quantify the temporal evolution of rapid adjustments.

CONTEXT

The Intergovernmental Panel on Climate Change (IPCC), in its 5th Assessment Report (AR5; Boucher et al., 2013; Myhre et al., 2013), introduced the concept of effective radiative forcings (ERF; Myhre and Quaas, 2020). ERF is composed of the instantaneous radiative forcing (net radiation flux change at the top of atmosphere introduced by a forcing agent with everything else kept fixed) and rapid adjustments (RA; net radiation flux change at the top of the atmosphere due to processes in response to the forcing agent that act at time scales shorter than the ocean surface warming, i.e. at constant sea surface temperatures).

Some of these rapid changes are related to feedback processes that act in response to changes in (global-mean) surface temperature – e.g. the changes in tropospheric temperature, water vapour, or surface albedo: these feedback processes also act at fast time scales in response to land surface warming; this rapid contribution is considered here as rapid adjustment. Note that this definition is under scientific debate. Others, especially the adjustments to aerosol-cloud interactions, are only acting at the short time scales considered in RA, not at the much longer feedback time scales.

Since AR5, much effort has been invested in better understanding and quantifying RA processes, and we now know that there are multiple RA mechanisms in response to the introduction of forcing agents that impact the Earth's radiation budget (Fig. 1). We also know that clouds make a key contribution, in particular with regard to aerosol-cloud interactions (also shown in Fig. 1). This KGSIR summarises recent advances in understanding these rapid adjustments, and their implications for climate research.

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RAPID ADJUSTMENTS TO GREENHOUSE GASES

Knowledge gains on rapid adjustments to CO_2 are primarily from newly available multi-climate model ensembles, particularly the Precipitation Driver and Response Model Intercomparison Project (PDRMIP, Myhre et al., 2017) and the Radiative Forcing Model Intercomparison Project (RFMIP, Pincus et al., 2016) as part of the 6th Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016).

The most recent analysis, with significant contributions from the CONSTRAIN project, is by Smith et al. (2020) and the results in terms of RA are reported in Fig. 2. To do so, the contributions of individual mechanisms to the overall RA are isolated using the radiative kernel technique (Soden et al., 2008) which computes the perturbation of the top-of-atmosphere radiation budget for a unit perturbation of an atmospheric or surface state variable.

Altogether, RA contribute about 40% to the total anthropogenic ERF. For well-mixed greenhouse gases (WMGHG), this is about 30%. For CO_2, the total RA equals approximately the net effect from the adjustment of stratospheric temperatures (a positive change in the Earth energy budget). The net effect of tropospheric adjustments for CO_2 is small: water vapour increase and reduction in (mid-level) cloudiness as positive adjustments are offset by additional Planck cooling from rapid land surface temperature increases (Smith et al., 2020).

These results generally apply to all well-mixed greenhouse gases taken together (Smith et al., 2020; Fig. 2). However, isolating N_2O, ozone and CFCs changes the picture slightly: for N_2O and CFCs, the stratospheric temperature adjustment is small, whilst other processes are as discussed for CO_2, so that the net RA is much less positive than in the case of CO_2. For ozone, the tropospheric temperature adjustment is as strong as the stratospheric adjustment, and of opposite sign. Its overall positive RA is dominated by the positive contributions of the other adjustment processes, mainly due to water vapour.

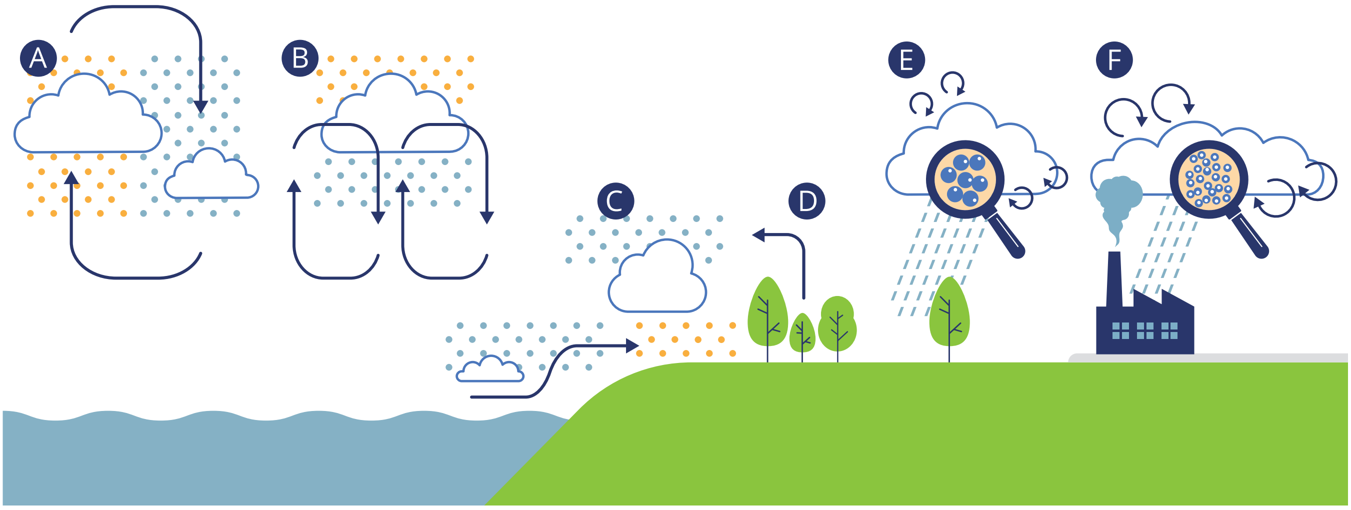

FIGURE 1: *Rapid adjustment processes. Perturbations of the atmospheric composition can cause (A) horizontal and (B) vertical gradients in radiative heating (dotted orange) or cooling (dotted blue) that drive circulations – in the case of vertical heating differences this is partly in response to changes in atmospheric stability and convection – and thus changes in cloud patterns and subsequently radiation budget changes/flux divergence of the atmosphere (orange/blue). Similarly, land and ocean surfaces may respond to the changes in atmospheric composition on different time scales, implying heating gradients and circulation changes (C). Changes in direct vs. diffuse solar radiation, and in CO_2 concentrations, induce changes in plant growth and water use efficiency, with impacts on water vapour fluxes and cloudiness (D). Aerosol particles cause specific cloud modifications (unpolluted, E, vs. polluted cloud, F): the droplet numbers are enhanced at larger aerosol concentrations, with adjustments due to slowdown of precipitation formation rates and enhancement of entrainment-mixing. This is currently believed to enhance cloud horizontal extent and reduce cloud vertical extent (see text for more details). Adapted from Sherwood et al. (2015) and CONSTRAIN (2019).*

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RAPID ADJUSTMENTS TO AEROSOLS

The state of the art knowledge on rapid adjustment to aerosol-radiation interactions is unchanged since the start of the CONSTRAIN project in July 2019: modelling evidence suggests that various processes, including clouds, water vapour, and temperature profiles contribute to the net negative RA that is a small fraction for the scattering aerosol, but offsets about half of the forcing for absorbing aerosol (Stjern et al., 2017; Smith et al., 2018; Bellouin et al., 2020).

In terms of aerosol-cloud interactions, the dominant RA is changes in cloudiness. Two bulk quantities can be distinguished (Fig. 1): cloud horizontal extent (cloud fraction) and cloud liquid water path (LWP).

The state of the art knowledge for cloud fraction is unchanged: statistical analysis of satellite data suggests an increase in cloud fraction in response to anthropogenic increases in droplet concentrations (Gryspeerdt et al., 2016; Bellouin et al., 2020), implying almost a doubling of the radiative forcing due to aerosol-cloud interactions (RFaci).

For LWP, there is now evidence that the net effect is a small decrease, offsetting about a quarter of the RFaci (Gryspeerdt et al., 2019; Toll et al., 2019). In the RFMIP GCMs, the overall RA to aerosol-cloud interactions contributes about 20% to the total ERF (Fig. 2).

RAPID ADJUSTMENTS TO LAND USE

No major advances have been made regarding understanding RA for land use and land cover changes. The multi-model ensemble suggests an RA that to a substantial degree (75%) offsets the small negative forcing (Fig. 2; Smith et al., 2020). However, due to the smallness of the effect, this number is very uncertain.

IMPLICATIONS

Knowledge gain on rapid adjustments is essential to better quantifying the effective radiative forcing of climate change. RA, especially from CO_2 and aerosols, are now known to constitute a substantial fraction of the overall response of radiation-relevant state variables to perturbations of the atmospheric composition.

Thanks to their short time scales, RA are relatively easy to constrain using observations and process-scale modelling – this is reflected in the improved quantification of RA described here, which in turn leads to improved knowledge on the overall response of the climate system to anthropogenic perturbations in terms of both aerosol-cloud interactions and greenhouse gases:

AEROSOL-CLOUD INTERACTIONS

RA to aerosol-cloud interactions, as represented in large-scale atmospheric models, are not sufficiently well parameterised to yield reliable quantification. Progress thus comes from analysis of observations – in particular, satellite observations – in combination with improved theoretical understanding and modelling.

The revised quantification of the RA of cloud water path response is now increasingly robustly constrained as a small offset of the negative forcing (positive contribution). More work on the RA of cloud horizontal extent is needed; current state of the art points to a strong amplification of the IRF due to aerosol-cloud interactions. A stronger negative aerosol ERF implies larger near-future warming relative to today as the aerosol concentration decreases in air quality improvement efforts.

GREENHOUSE GASES

Current quantification of tropospheric RA to greenhouse gases point to a small net effect. This implies that the ERF is approximately the same as the stratosphere-adjusted radiative forcing of previous assessments of the greenhouse gas forcings.

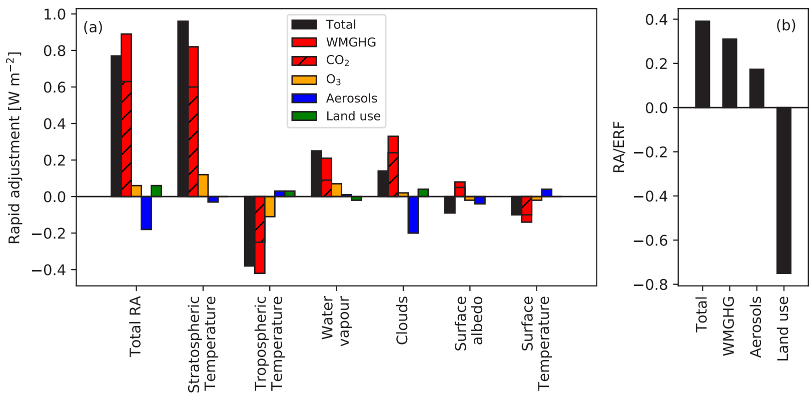

FIGURE 2: *Rapid adjustments (a) diagnosed from the RFMIP/CMIP5 multi-model ensemble by Smith et al. (2020). The total RA (black) is split into its components using the radiative kernel technique. (b) Ratio of total rapid adjustment to ERF for selected forcing agents.*

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ABOUT THIS KNOWLEDGE GAINS: SUMMARY AND IMPLICATION REPORT

CONSTRAIN’s Knowledge Gains: Summary and Implication Reports outline CONSTRAIN’s contributions to the peer reviewed literature (knowledge gains), and summarise the implications for both the scientific community and broader society. This report and other CONSTRAIN publications are available at http://constrain-eu.org.

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ABOUT CONSTRAIN

The 2015 Paris Agreement sets out a global action plan to avoid dangerous climate change by limiting global warming to well below 2°C, whilst pursuing efforts to limit warming to 1.5°C. However, predicting how the climate will change over the next 20-50 years, as well as defining the emissions pathways that will set and keep the world on track, requires a better understanding of how several human and natural factors will affect the climate in coming decades. These include how atmospheric aerosols affect the Earth’s radiation budget, and the roles of clouds and oceans in driving climate change.

The EU-funded CONSTRAIN project, a consortium of 14 European partners, is developing a better understanding of these variables, feeding them into climate models to reduce uncertainties, and creating improved climate projections for the next 20-50 years on regional as well as global scales.

In doing so, CONSTRAIN will take full advantage of existing knowledge from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) as well as other Horizon 2020 and European Research Council projects.

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