Horizon 2020 Societal challenge 5:
Climate action, environment,
resource efficiency and raw materials

CONSTRAIN

Constraining uncertainty of multi-decadal climate projections
GA number 820829
H2020-LC-CLA-2018-2

Deliverable number (relative in WP)	**D1.6**
Deliverable name:	End-of-project KGSIR on relative role of rapid adjustment processes and their timescales and constraint of ERF from spatiotemporal patterns (Tasks 1.2.1, 1.2.2 and 1.2.3).
WP number:	WP1
Delivery due date:	30/06/23
Actual date of submission:	30/10/23
Dissemination level:	Public
Lead beneficiary:	ULEI, UNIVLEEDS, CICERO
Responsible scientist / administrator:	Johannes Quaas
Contributor(s):	Johannes Quaas Gunnar Myhre
Internal reviewer:	Charlotte Elliott-Harvey

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

1. Changes with respect to the DoA

Change of date since the original submission (from 30/06/20232 to 31/10/2023).

2. Dissemination and uptake

This is a public deliverable and is available on the CONSTRAIN project website.

3. Short Summary of results (< 250 words)

Key messages:

- This KGSIR summarises recent advances in understanding rapid adjustments to perturbations of anthropogenic forcing agents, and their implications for climate research.
- Six different mechanisms of rapid adjustments are identified and described – thermodynamical, dynamical, microphysical, chemical, land surface and vegetation adjustments.
- Time scales of most adjustments are days to weeks, some act on scales of decades to centuries.
- Constraints from spatiotemporal patterns are obtained especially for microphysical adjustments to aerosol, but also for stratospheric temperature adjustments. Further improvements are possible.

4. Evidence of accomplishment

See attached document.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

Knowledge Gains: Summary and Implication Report

October 2023

Relative role of rapid adjustment processes and their timescales and constraint of ERF from spatiotemporal patterns

Johannes Quaas[1] and Gunnar Myhre[2]
[1]Leipzig University, Germany; [2]CICERO Oslo, Norway

Key messages

- This KGSIR summarises recent advances in understanding rapid adjustments to perturbations of anthropogenic forcing agents, and their implications for climate research.
- Six different mechanisms of rapid adjustments are identified and described – thermodynamical, dynamical, microphysical, chemical, land surface and vegetation adjustments.
- Time scales of most adjustments are days to weeks, some act on scales of decades to centuries.
- Constraints from spatiotemporal patterns are obtained especially for microphysical adjustments to aerosol, but also for stratospheric temperature adjustments. Further improvements are possible.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

Context

The Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5; Boucher et al., 2013; Myhre et al., 2013), introduced the concept of effective radiative forcings (ERF). 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).

The present KGSIR builds on the KGSIR on rapid adjustments in 2020 (Quaas and Myhre, 2020). It harvests on achievements by the CONSTRAIN project and beyond. These were discussed and analysed in depth in a CONSTRAIN workshop, 28 – 29 November 2022 in Leipzig. On the basis of this workshop and continued discussions and development, a review publication is close to submission (Quaas et al., 2024).

Main developments since the KGSIR 1 (Quaas and Myhre, 2020) are that the IPCC 6th Assessment Report (AR6; Forster et al., 2021) clearly defined the distinction between radiative forcing, rapid adjustments and feedbacks by unchanged global-mean surface temperature, rather than by time scales. As such, the community now increasingly turns to the term “radiative adjustments” rather than “rapid adjustments”.

Summary of Knowledge Gains

Rapid adjustment processes

Following the discussions within CONSTRAIN, six different mechanisms of rapid adjustments may be distinguished (Figure 1).

Thermodynamical adjustments refer to changes in temperature, humidity, and cloud patterns in response to the absorption of radiation by climate drivers. CO_2, for example, causes immediate radiative cooling in the stratosphere and weaker radiative heating in the troposphere. CO_2-induced temperature adjustments in the troposphere affect atmospheric stability, humidity, and trigger cloud changes. Additionally, changes in cloud-top radiative cooling result from altered greenhouse gas concentrations, affecting cloud lifetime. Larger cloud changes occur on longer timescales as surface temperature-driven feedbacks intensify over time. In contrast, BC primarily interacts with solar radiation, leading to rapid atmospheric warming, the extent of which depends on the BC vertical distribution. Significant cloud reductions in most of the troposphere and cloud increases near the surface occur within days to weeks. Initially, sulfate aerosols have a minor impact on radiation absorption within the atmosphere, resulting in weak adjustments. Thus, changes in atmospheric temperature and clouds are predominantly influenced by longer-term feedbacks from surface temperature changes.

Land surface temperature adjustments occur due to the spatial heterogeneity of ERF and its consequences even at global-mean constant temperatures. Land temperatures respond rapidly,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

with changes detectable within days of perturbations. The resulting temperature change pattern, ΔT_L, primarily leads to radiative adjustments by directly modifying longwave emissions, known as the Planck effect. This effect can be substantial, accounting for most of the rapid tropospheric temperature adjustments for CO_2, CH_4, and SO_4 perturbations. A way to isolate this type of adjustments from all others is by fixing not only sea surface temperatures, but also land surface temperatures in climate model integrations, as shown by CONSTRAIN work (Andrews et al., 2021).

Vegetation responds to climate drivers, impacting albedo, atmospheric humidity, CO_2 concentrations, and soil dust emissions. Increased atmospheric ozone concentrations can harm vegetation, reducing the vegetation climate influence. Aerosol increases enhance photosynthesis efficiency, reducing atmospheric CO_2. Another crucial adjustment arises from CO_2-induced changes in leaf stomatal conductance, reducing water transpiration and affecting latent and sensible heat fluxes, boundary layer conditions, and cloud cover. CO_2 fertilization by plants, which increases leaf area, also alters surface albedo and can reduce dust emissions. These adjustments are a direct consequence of CO_2 increases, independent of temperature change. They affect land temperature and contribute significantly to the total ERF due to CO_2.

Microphysical adjustments occur in response to aerosol perturbations. Changes in hydrometeor size distributions, triggered by aerosol perturbations, affect cloud microphysical processes, precipitation formation, and turbulence. These adjustments influence cloud macrophysical properties like cloud fraction and water path over hours to days, with significant regional and temperature-dependent variations. These adjustments resulting from aerosol-cloud interactions are characterized by a complex interplay of processes, with uncertain magnitude and even sign variations.

Chemical adjustments are relevant as, when reactive compounds are released into the atmosphere, atmospheric chemistry affects the abundance of radiatively active trace gases like ozone (O_3). For instance, anthropogenic nitrous oxide (N_2O) emissions exert Instantaneous Radiative Forcing (IRF) through terrestrial radiation absorption, with chemical and cloud adjustments causing further radiation budget perturbations. A similar effect is seen with halocarbon emissions. Chemical adjustments also significantly modulate the ERF from anthropogenic methane (CH_4) emissions. Changes to CH_4's lifetime, tropospheric O_3, and stratospheric water vapor, driven by CH_4, contribute to its ERF. Additionally, emissions of nitrogen oxides (NOx) and other compounds like carbon monoxide (CO) and volatile organic compounds (VOCs) impact CH_4 lifetime and ERF, highlighting the complex interplay of chemical adjustments. Moreover, changes in stratospheric and tropospheric ozone resulting from chemical adjustments contribute to an ERF, with a substantial portion linked to anthropogenic CH_4, CO, VOCs, and NOx emissions. These chemical adjustments in tropospheric ozone and hydroxyl radical production also impact secondary aerosol production and size distributions, affecting aerosol-cloud interactions and potentially changing cloud adjustments.

Dynamical adjustments are relevant if non-homogeneous patters drive circulations across scales that, in turn, lead to changes in cloud patterns and thus in the Earth radiation budget. Non-uniform aerosol forcing can influence both regional and global circulation. For instance, land surface cooling caused by aerosols can lead to changes in monsoon circulation, even without affecting sea surface temperatures. Absorbing aerosols, on the other hand, induce atmospheric heating, impacting large-scale atmospheric circulation. The location of the perturbation plays a crucial role in this modulation, particularly in the tropics, where thermally-driven circulation occurs due to the absence of a significant Coriolis force.

Relative role of rapid adjustment processes

It is not easy to disentangle the six mechanisms as discussed in the previous section across forcing agents. For this reason, this task hasn’t yet been performed. However, another way to distinguish rapid adjustment processes exists, by identifying changes to radiatively important state variables analogously to the feedback analysis. This considers fixed-sea surface temperature simulations and makes use of radiative kernel analysis. The distinguishable variables are temperatures of the surface, the troposphere, and the stratosphere, the surface albedo, the atmospheric humidity, and clouds. The results of such an analysis are shown in Figure 2 for a broad range of drivers of radiative forcing. Clearly, the relative role of these state variables strongly depends on the forcer. In particular black carbon (BC) produces strong adjustments. CO_2 and O_3 have particularly large positive adjustments due to stratospheric temperatures.

Time scales of rapid adjustment processes

The different times at which rapid adjustments occur were recently quantified by Stjern et al. (2023) in CONSTRAIN work. Their findings were drawn from idealized simulations conducted with six global climate models. The results reveal that changes in ocean temperatures become apparent after a few months, while rapid reductions in precipitation start immediately and stabilize within days, particularly for BC, where they constitute the dominant equilibrium response. In the cases of CO_2 and SO_4, the magnitude of the precipitation response gradually intensifies as surface warming or cooling progresses. For CO_2, the response changes from negative to positive after two years. Rapid cloud adjustments typically establish themselves within the first 24 hours, and although the magnitude of cloud feedbacks increases over time for CO_2 and SO_4, the spatial pattern of equilibrium cloud changes is already present within the first year. Despite some model variations, this study highlights the overall consistency of major time-dependent processes and responses simulated by current global models, emphasizing the robustness of key features in simulating responses to historical and future anthropogenic forcing.

Constraints from spatiotemporal patterns

Constraints on the adjustments can be derived from spatiotemporal patterns to the extent drivers change substantially. This has been the case for anthropogenic aerosols over the past decades. In Quaas et al. (2022) the linear trends over the time period 2000 to 2019 were evaluated in climate model integrations and in satellite retrievals. The results are shown in Figure 4. The conclusion is that in terms of cloud liquid water path, no consistent adjustment signal is found. This confirms earlier results about a small adjustment in this quantity. However, the cloud horizontal extent (cloud fraction) shows consistently positive responses. This coincides with work within CONSTRAIN that made use of the observations after the eruption of the Holuhraun volcano on Iceland in 2014. Using machine learning to construct the counterfactual case, Chen et al. (2022) found a large, positive, adjustment of cloud fraction to aerosols.

References

Andrews, T., C. J. Smith, G. Myhre, P. M. Forster, R. Chadwick, and D. Ackerley, Effective radiative forcing in a GCM with fixed surface temperatures. Journal of Geophysical Research: Atmospheres, 126, e2020JD033880, doi:10.1029/2020JD033880, 2021.

Chen, Y., Haywood, J., Wang, Y. et al. Machine learning reveals climate forcing from aerosols is dominated by increased cloud cover. Nat. Geosci. 15, 609–614, doi:10.1038/s41561-022-00991-6, 2022.

Hodnebrog, O., G. Myhre, R. Kramer, et al., The effect of rapid adjustments to halocarbons and N2O on radiative forcing. npj Clim. Atmos. Sci., 3, 43, doi: 10.1038/s41612-020-00150-x, 2020.

Levy, R. C., et al., The collection 6 MODIS aerosol products over land and ocean. Atmos. Meas. Tech., 6, 2989-3034. doi:10.5194/amt-6-2989-2013, 2013.

Marshall, L. R., C. J. Smith, P. M. Forster, et al., Large variations in volcanic aerosol forcing efficiency due to eruption source parameters and rapid adjustments, Geophys. Res. Lett., 47, e2020GL090241. doi: 10.1029/2020GL090241, 2020.

Platnick, S., et al., The MODIS cloud optical and microphysical products: Collection 6 updates and examples from terra and aqua. IEEE Transact. Geosci. Remote Sens., 55, 502-525. doi:10.1109/TGRS.2016.2610522, 2017.

Quaas, J., and G. Myhre, State-of-the-art understanding of rapid adjustments. Knowledge Gains: Summary and Implication Report 1. The CONSTRAIN Project, doi: 10.5281/zenodo.3711986, 2020.

Quaas, J., H. Jia, C. Smith, A. Albright, W. Aas, N. Bellouin, O. Boucher, M. Doutriaux-Boucher, P. Forster, D. Grosvenor, S. Jenkins, Z. Klimont, N. Loeb, X. Ma, V. Naik, F. Paulot, P. Stier, M. Wild, G. Myhre, and M. Schulz, Robust evidence for reversal in the aerosol effective climate forcing trend, Atmos. Chem. Phys., 22, 12221-12239, doi:10.5194/acp-22-12221-2022, 2022.

Quaas, J., T. Andrews, N. Bellouin, K. Block, O. Boucher, P. Ceppi, G. Dagan, S. Doktorowski, H. M. Eichholz, P. Forster, T. Goren, E. Gryspeerdt, Ø. Hodnebrog, H. Jia, R. Kramer, C. Lange, A. Maycock, J. Mülmenstädt, G. Myhre, F. M. O'Connor, R. Pincus, B. H. Samset, F. Senf, K. Shine, C. Smith, C. W. Stjern, T. Takemura, V. Toll, and C. Wall, Adjustments to climate perturbations – mechanisms, implications, observational constraints, AGU Advances, in preparation (2024).

Skeie, R. B., G. Myhre, Ø. Hodnebrog, et al., Historical total ozone radiative forcing derived from CMIP6 simulations, npj Climate and Atmospheric Science, 3, 32, doi: 10.1038/s41612-020-00131-0, 2020.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

Smith, C. J., R. Kramer, G. Myhre, et al., Effective radiative forcing and adjustments in CMIP6 models. Atmos. Chem. Phys., 20 (16), 9591-9618. doi: 10.5194/acp-20-9591-2020, 2020.

Stjern, C. W., P. M. Forster, H. Jia, et al., The time scales of climate responses to carbon dioxide and aerosols. J. Climate, 36, 3537-3551. doi: 10.1175/JCLI-D-22-0513.1, 2023.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

About the Authors

Johannes Quaas co-leads CONSTRAIN Work Package 1 “Effective radiative forcing and rapid adjustments”. He is Professor for Theoretical Meteorology at Leipzig University. His research interest is in clouds and climate change, in particular aerosol-cloud interactions, analysis of satellite observations, and atmospheric modelling. Johannes was lead author for the IPCC 6th Assessment Report Working Group I.

Gunnar Myhre is also co-lead for CONSTRAIN Work Package 1. He is Research Director at CICERO, leads the international Precipitation and Driver Response Model Intercomparison Project (PDRMIP), and is part of the steering committee of the two CMIP6 endorsed MIPs: RFMIP and AerChemMIP. He was a Lead Author for the IPCC third and fourth assessment reports and a Coordinating Lead Author for the fifth assessment report (AR5).

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.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

How to cite

Quaas, J., and G. Myhre (2023). Relative role of rapid adjustment processes and their timescales. Knowledge Gains: Summary and Implication Report. The CONSTRAIN Project, doi: 10.5281/zenodo.3711986

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

This project has received funding from the European Union's Horizon 2020 research
and innovation programme under grant agreement No 820829.

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.

web: http://constrain-eu.org

X: @constrain-eu

For more information or to contact the authors please email constrain@leeds.ac.uk

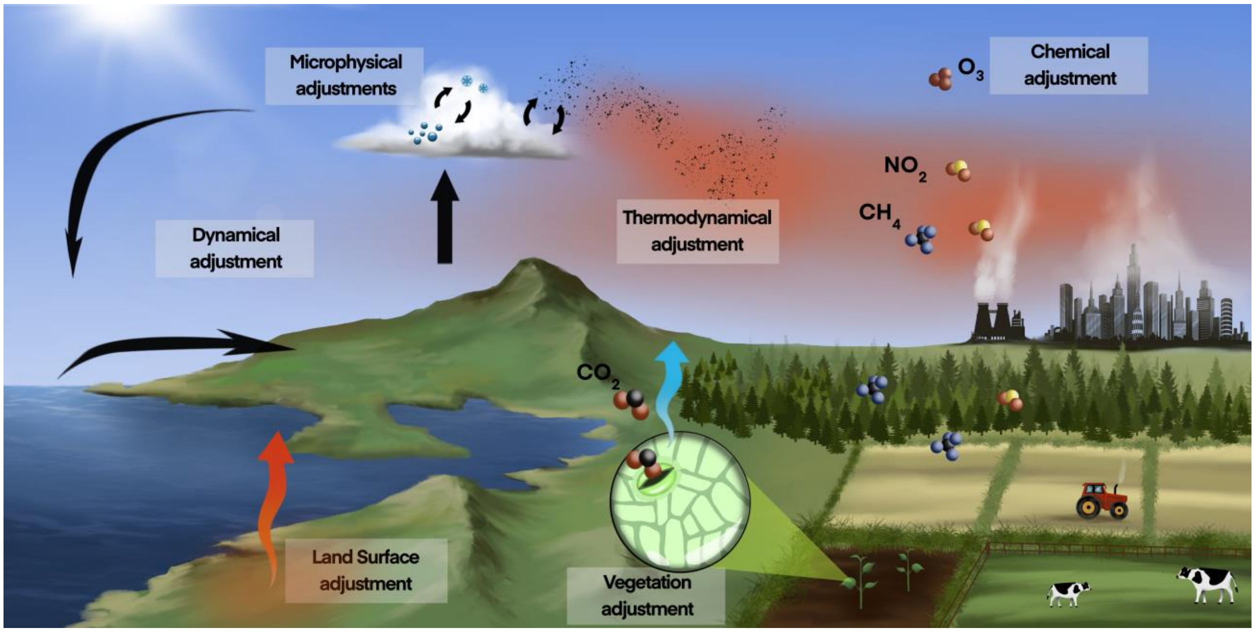

Figure 1: The six mechanisms of radiative adjustments. Figure taken from Quaas et al. (2024).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

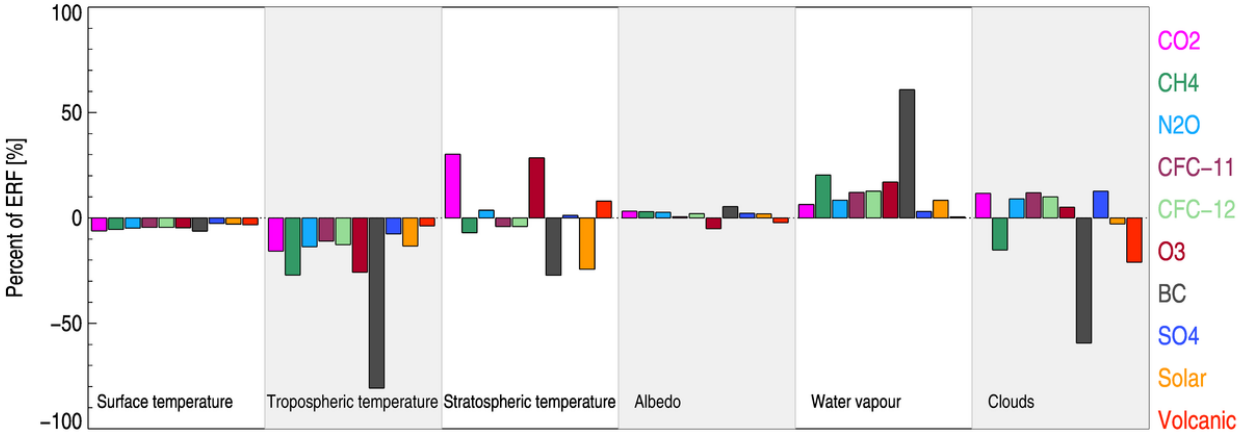

Figure 2: The percentages indicating the importance of rapid adjustment processes relative to ERF for ten different climate drivers have been derived from various sources (Hodnebrog et al., 2020; Marshall et al., 2020; Skeie et al., 2020; Smith et al., 2018). These climate drivers encompass greenhouse gases (CO2, methane/CH4, nitrous oxide/N2O, halocarbons/CFC-11 and CFC-12, and ozone/O3), as well as absorbing aerosols (BC), scattering aerosols (SO4), volcanic aerosols, and changes in incoming solar radiation. It's important to note that SO4 and volcanic aerosols contribute negatively to the ERF, signifying their cooling effect on the climate. The provided percentages represent the impact of a specific increase in each climate driver on rapid adjustment processes. Figure taken from Quaas et al. (2024).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

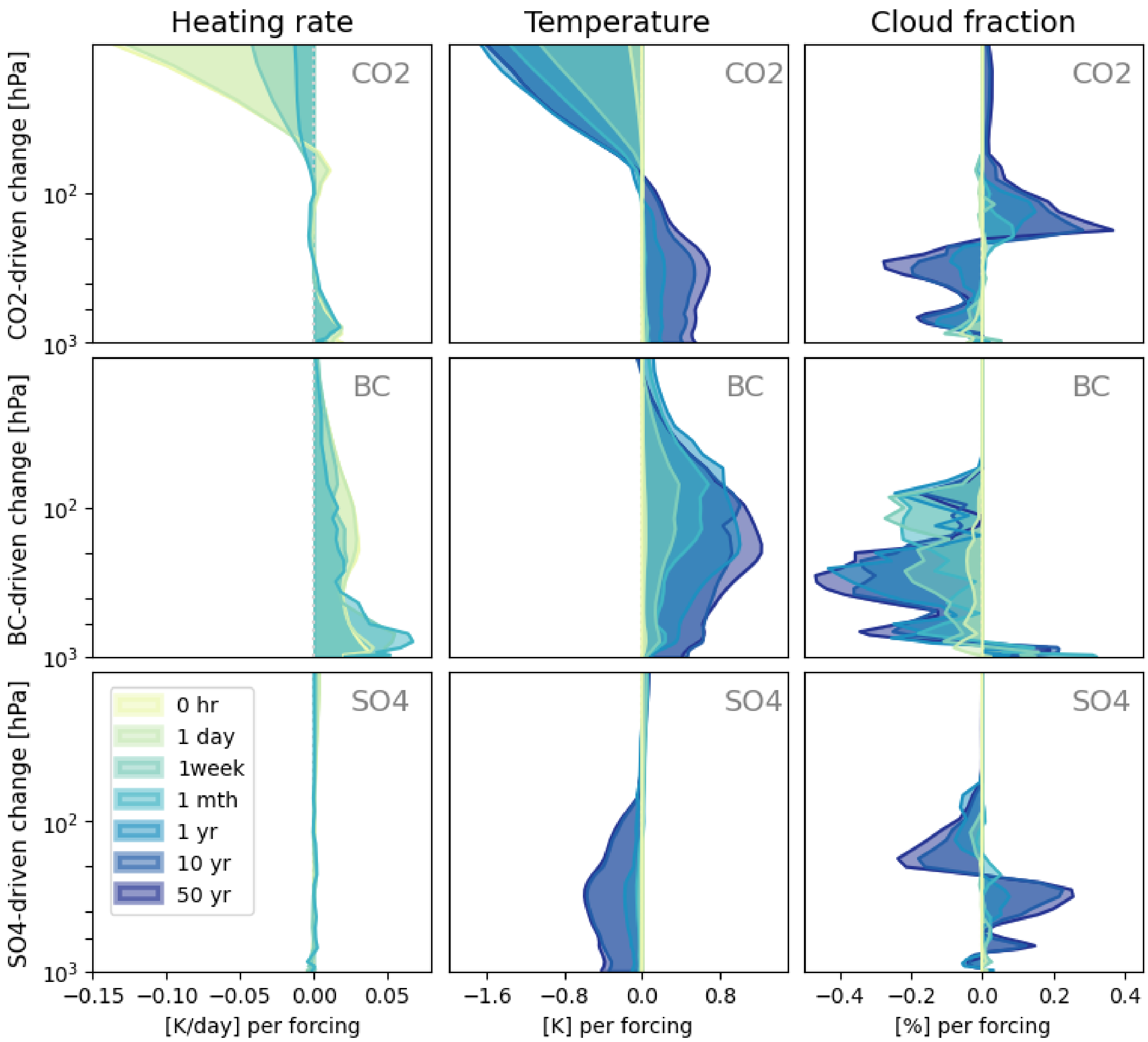

Figure 3. Vertical profiles of climate response are depicted in three sets: heating rates (in K day−1), temperature changes (K), and cloud fraction changes (%) in reaction to specified alterations in three distinct climate drivers. These drivers encompass an increase in atmospheric carbon dioxide concentrations (CO2, top row), an elevation in atmospheric black carbon concentrations (BC, middle row), and an augmentation in atmospheric sulfate concentrations (SO4, bottom row). The changes are normalized to the Instantaneous Radiative Forcing (IRF) imposed by the perturbation. The global average results, obtained by averaging the outcomes from six climate models, are presented for seven time horizons, differentiated by the color code. These findings are based on the analysis conducted by Stjern et al. (2023). Figure taken from Quaas et al. (2024).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.

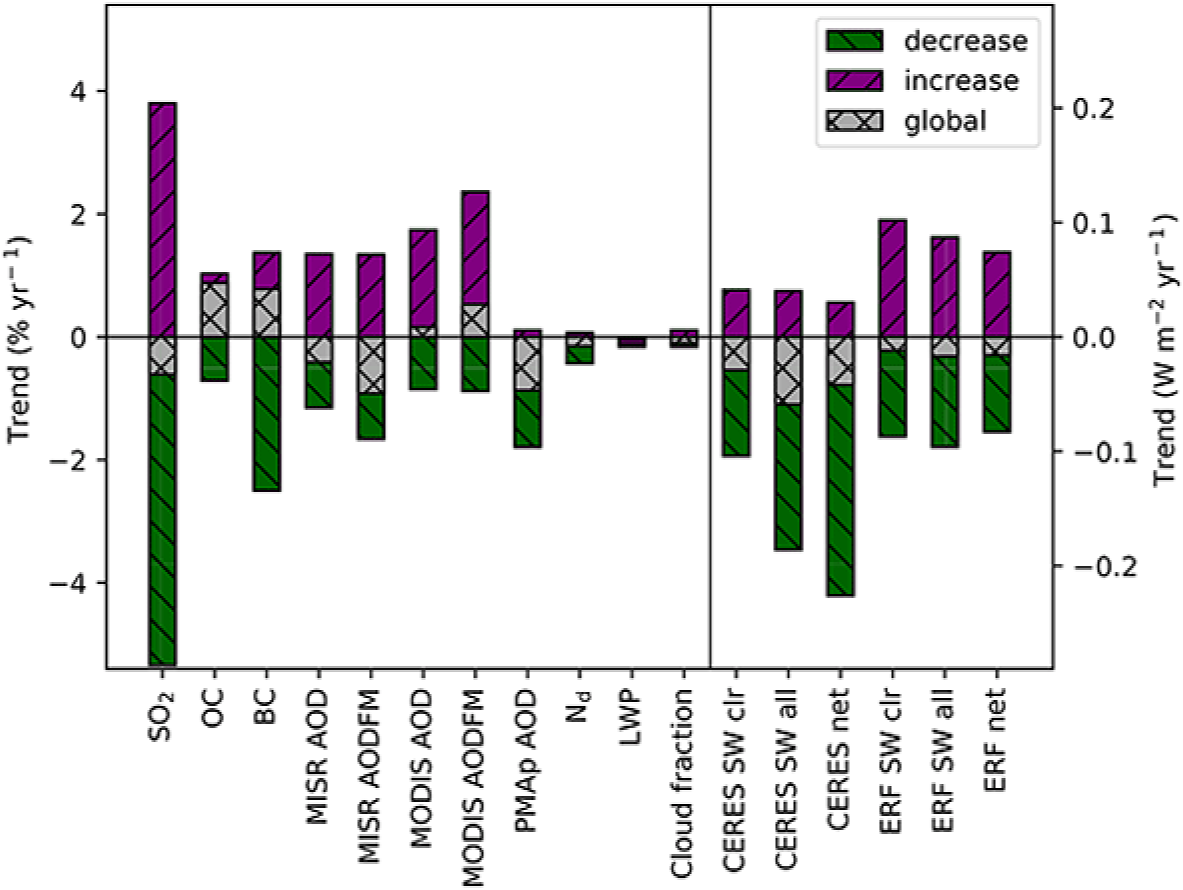

Figure 4. Constraints from spatio-temporal patterns of adjustments to aerosol perturbations. Data from satellite retrievals from the MODerate Resolution Imaging Spectroradiometer (MODIS; Levy et al., 2013; Platnick et al., 2017). Here we are particularly interested in the trends in cloud liquid water path (LWP) and in cloud fraction.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.