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**CONSTRAIN Workshop on rapid adjustments**
Leipzig University, 28 – 30 November 2022

Group photo, 29 November 2022

**Workshop report**
28-30 November, 2022. Leipzig, Germany

The CONSTRAIN Work package A "Effective radiative forcing and rapid adjustments" contributes to the overall project objective of delivering a better understanding and quantification of the drivers of climate change, in energetic terms. As the title of the work package indicates, rapid adjustments are a key element of this objective.

Rapid adjustments are processes that occur in immediate response to a perturbation by a driver and the instantaneous radiative forcing (IRF) and themselves impact the top- of-energy radiation budget of the planet.

A number of questions with regard to the rapid adjustments required discussion towards conclusions and recommendations:

1. What exactly is meant and how should we define adjustments?
2. What makes adjustments particularly relevant?
3. How can we learn about the processes, quantify them from reference data and constrain them in Earth system models?

The workshop addressed all these questions through contributed presentations and discussion sessions. It was held in hybrid form to encourage participation from a wide group, including COSTRAIN researchers and invited external participants.

One of the starting points of the discussion was the revision or refinement of the definition of adjustments in the recent Intergovernmental Panel on Climate Change, Working group I, 6th Assessment report (Forster et al., 2021). The IPCC AR6 Report defined adjustments to be independent of time scales (rendering the "rapid" obsolete), but as a state after an instantaneous radiative forcing (IRF) is introduced but at which the surface temperatures remain unchanged ($\Delta T s(x,y) = 0$). This is consistent with the initial ideas by Gregory et al. (2004) that, however, considered only the global mean. Subsequently, it was the IPCC AR5 (Boucher et al., 2013) that introduced the concept of rapid adjustments, later explained in more detail by Sherwood et al. (2015). The fixed-surface-temperature definition is problematic in that it differs from the common approach to investigate adjustments using climate models that fixes just sea surface temperatures and sea-ice, but lets the land surface temperatures evolve (Forster et al., 2016). A continuation of this discussion identified that the term “rapid adjustment” may be misleading in case time scales are considered irrelevant. If it is about constant temperatures, instead, one could specify “isothermal” or “fixed-surface-temperature” adjustments. More generally, one could speak simply of “adjustments” or specify “radiative adjustments”.

In the discussion, however, it became clear quickly that it seemed more interesting to go beyond pure definition discussions that were perceived as rather technical. Specific definitions rather could follow after identifying specific scientific hyoptheses.

There were, in particular, three aspects that were highlighted as important for the discussion:

Mechanisms of adjustments
Impacts beyond relevance for the global-mean top-of-atmosphere energy budget
Possibilities to observe mechanisms rather than rely entirely on model results

In terms of mechanisms, seven different aspects were discussed and highlighted.

1. *Thermodynamic adjustments* describe the fact that vertical profiles, within the atmosphere, of radiation flux divergence lead to vertically-different temperature anomalies that may be accompanied by corresponding moisture anomalies and, via anomalies in relative humidity, imply changes in cloudiness. It is important to note that perturbations to greenhouse gases mainly act in the terrestrial spectrum, which has distinct differences from agents such as black carbon that lead to absorption in the solar spectrum. An interesting hybrid is methane, for which the solar absorption is a particular uncertainty especially with regard to the adjustments. This includes the effect in the stratosphere.
2. *Adjustments to land surfaces* are very relevant as if the land-surface temperature responds quickly to radiative perturbations, less than a month. Additionally, it remains important to understand the adjustments in response to land-use changes, including the subsequent change in evaportranspiration and dust emissions, as only the albedo change is considered as part of the IRF.
3. *Physiological adjustments* are relevant in response to $CO_2$ changes and subsequent changes in plant stomatal aperture leading to changes in evaportranspiration. While this effect is usually considered in Earth system models that also treat dynamical vegetation, longer-term adjustments such asup to biota shifts may occur, and these may play out at time scales of up to decades.
4. *Microphysical changes* are relevant in response to aerosols acting as cloud condensation nuclei or ice nucleating particles. Only the initial perturbation if cloud particle concentrations (droplets or ice crystals) is considered for the IRF, all subsequent changes in particular to cloud horizontal and vertical extent are the result of adjustments. Alterations of precipitation formation mechanisms or turbulent mixing in response to cloud particle number perturbations are the specific reasons for adjustments of cloud horizontal and vertical extent. In case of aerosol perturbations, these microphysical adjustments are considered particularly relevant but uncertain.
5. *Chemical adjustments* are relevant for greenhouse gases that undergo chemical transformations in the atmosphere, such as the conversion from methane to stratospheric water vapour when reacting with stratospheric ozone.
6. *Dynamical adjustments* that may follow e.g. thermodynamical adjustments, as these may induce anomalous circulations at various scales. When allowing for land surface warming, this anomalous circulation is global in nature with an anomalous land-sea breeze. The anomalous circulations influence cloud adjustments in the tropics (e.g. Hadley/Walker circulations) and extratropics (e.g. jet streams).
7. *Paleo-climate changes, ice sheets* – radiative drivers of the global climate system to several of the orbital cycles are by definition adjustments, since zero global-mean IRF is involved, and yet the difference in meridional absorbed solar radiation induces large shifts in climate. It is thus interesting to at least allude tounderstand theseis phenomenanon when considering adjustments.

In terms of implications beyond the global radiation budget, adjustments play a large role. IRF by definition only affects the top-of-atmosphere radiation budget, but several adjustment mechanisms also affect (as detailed above) clouds and circulation. Even more important perhaps is the impact on the hydrological cycle that follows from the coupling between the energy and water cycles. Other relevant impacts are on temperature patterns, on boundary- layer height and stability and with this, boundary-layer wind.

The third topic discussed was how to observe adjustments. A broad discussion of this was on the microphysical adjustments to aerosols, where satellite observations may be used if sampled in opportunistic experiments (Christensen et al., 2022) or evaluated in a statistical way. A clear example is the observation of stratospheric cooling in response to greenhouse gases. Also other adjustment mechanisms may be observable e.g. after large volcanic eruptions or in the wake of large fires, although so far this is not well studied. Time series e.g. of the top-of-atmosphere radiation budget (e.g. by CERES satellite data) may allow for process understanding of adjustment processes. In combination of models and data, emergent constraints are conceivable for some adjustment mechanisms. An example could be, if feasible, the observation of changes in absorption optical depth and its impact on precipitation. It is to be noted that the processes in general are to be seen as partial derivatives, i.e. are state-dependent.

On the basis of this very productive workshop, the participants decided to elaborate on these conclusions, questions, and recommendations in a peer-reviewed publication.

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**Appendix 1**

**Participants list**

| # | Name | First name | Affiliation |
|---|---|---|---|
| In person | | | |
| 1 | Block | Karoline | U Leipzig |
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| 22 | Mülmenstädt | Johannes | PNNL Richland |
| 23 | O’Connor | Fiona | UK Met Office Exeter |
| 24 | Pincus | Robert | Lamont Doherty |
| 25 | Smith | Chris | U Leeds / IIASA Laxenburg |
| 26 | Takemura | Toshi | U Kyushu |

## Appendix 2

**Programme**

**Monday 28 November 2022**
14.00 h Welcome, logistics (Piers, Gunnar, Johannes)

***Topic 1. Definition of effective forcing, land temperatures, time scales***
14.30 h Camilla Stjern: “Timescales of climate responses to carbon dioxide and aerosols”
14.50 h Piers Forster: “Rapid adjustment or climate feedback, what was done in AR6”
15.10 h Chris Smith: “Methane shortwave absorption mutes the warming and wetting from its longwave effects”
15.30 h Discussions
16.00 h Coffee

16.30 h Tim Andrews: “ERF in a GCM with fixed land temperatures”
16.50 h Johannes Mülmenstädt: “Twilight zone between adjustments and feedbacks”
17.10 h Discussions
17.30 h End day 1
20.00 h Dinner, Moritzbastei (moritzbastei.de)

**Tuesday 29 November 2022**
***Topic 2. Rapid adjustment processes in high resolution models compared to GCMs***
9.00 h Oivind Hodneborg: “Aerosol-radiation interactions on global to local scales”
9.20 h Fabian Senf: “On mechanisms that drive regional cloud cover reduction due to absorbing aerosol effects over land”
9.40 h Guy Dagan: “Sub-tropical aerosols enhance tropical cloudiness – a remote aerosol- cloud lifetime effect in CRM simulations”
10.00 h Discussions
10.30 h Coffee

***Topic 3. General understanding and observations of rapid adjustments***
11.00 h Bjorn Samset: “Aerosol absorption has an underappreciated role in historical precipitation change - and may cause havoc for near-term CMIP6 projections”
11.20 h Amanda Maycock: “Rapid adjustments in large-scale circulation” (online)
11.40 h Keith Shine: “SW greenhouse gas forcing and understanding differing TOA and tropopause perspectives”
12.00 h Velle Toll: “Anthropogenic aerosol hot spots for constraining ACI”
12.30 h Lunch

13.30 h Ed Gryspeerdt: “Cloud temporal development, adjustments and feedbacks”
13.50 h Hailing Jia: “Observed decadal trends: Implications for aerosol-cloud interactions”
14.10 h Fiona O’Connor: “The strong positive cloud adjustment in the CH4 ERF from UKESM1”
14.30h Discussions
14.50 h Coffee and Discussions
15.20 h Johannes Mülmenstädt: “Negative LWP–Nd correlations but, paradoxically, negative LWP adjustment in GCMs”
15.40 h Paulo Ceppi: “Cloud adjustments to diverse forcing agents”
16.00 h Casey Wall: “Assessing ERFaci over the Global Ocean”
16.20 h Ryan Kramer: “The Role of IRF vs Rapid Adjustments in ERF Spread”
16.40 h Discussions
18.00 h End day 2
20.00 h Dinner, Zchacha (facebook.com/Zchaca.Restaurant/)

**Wednesday 30 November 2022**
***Topic 4. Conclusions***
9.00 h Conclusions about constraints for rapid adjustments
10.30 h Coffee
11.00 h Recommendations on definitions and constraints
12.30 h End of meeting