CONSTRAIN

CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

# Knowledge Gains: Summary and Implication Report 4:

## CONSTRAIN journal publications & their relevance to IPCC AR6

February 2021


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

# Contents

## Context

CONSTRAIN research contributes to the scientific evidence base for improving understanding of many aspects of the climate system, including concepts such as radiative forcing, climate feedbacks and carbon budgets.

International scientific assessments, including the upcoming Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), are a key target for CONSTRAIN. This Knowledge Gain: Summary and Implication Report (KGSIR) sets out how CONSTRAIN's publications to date can support the community-wide assessment of the latest climate science represented by AR6.

As of 31 January 2021, CONSTRAIN had produced 64 journal publications, with 4 further papers accepted. Here, we summarise each publication, organising them by the most relevant AR6 Working Group I (WGI - The Physical Science Basis) chapter.

We also highlight papers relevant to Working Group III (WGIII - Mitigation of Climate Change).

Many of our publications contribute to a range of topics, cutting across both Working Groups and several chapters, so are cross-referenced and tagged with key words reflecting the focus of CONSTRAIN's research.

An update of this document, describing CONSTRAIN's full contribution to AR6, will be made available once the Working Group reports are published.

| AR6 WG and chapter | Title | CONSTRAIN focus |
|---|---|---|
| WGI Chapter 4 | Future global climate: scenario-based projections and near-term information | Characterisation of uncertainties in near-term projections over the next 20-50 years; internal variability |
| WGI Chapter 5 | Global carbon and other biogeochemical cycles and feedbacks | Latest insights on forcing, variability and feedbacks; carbon budget estimates; model evaluation; emergent constraints |
| WGI Chapter 6 | Short-lived climate forcers | Constraints on aerosol effective radiative forcing (ERF) |
| WGI Chapter 7 | The Earth's energy budget, climate feedbacks, and climate sensitivity | Equilibrium climate sensitivity; time varying feedbacks; clouds; sea surface temperatures (SST); metrics |
| WGI Chapter 8 | Water cycle changes | Energy budget analysis of regional precipitation changes; circulation, processes and phenomena |
| WGI Chapter 9 | Ocean, cryosphere, and sea level change | Evolution of the ocean heat content; ocean circulation |
| WGI Chapter 10 | Linking global to regional climate change | Regional uncertainty in temperature projections from climate emulators; regional-scale observations and phenomena |
| WGIII Chapter 2 | Emissions trends and drivers | Past and present emissions trends and sinks, including estimates of uncertainty |
| WGIII Chapter 3 | Mitigation pathways compatible with long-term goals | Paris Agreement and higher warming levels, including peaking, rates of change, sources and sinks, and cumulative emissions; uncertainty of climate response |
| WGIII Chapter 4 | Mitigation and development pathways in the near- to mid-term | Modelling of mitigation pathways in relation to mid-century strategies |
| WGIII Chapter 14 | International cooperation | Implementing mitigation pathways; international climate policy |
| **Key words:** near-term projections; internal variability; carbon budgets; climate forcers; climate feedbacks; model evaluation; aerosol forcing; climate sensitivity; SST patterns; metrics; clouds; regional observations and phenomena; regional precipitation; ocean circulation and heat content; mitigation pathways; climate policy; sources and sinks; Paris Agreement | | |

## Implications

The first phase of CONSTRAIN has aimed to deliver a timely characterisation of physical science uncertainty and how it affects projections and committed levels of warming to IPCC AR6.

The 60-plus journal publications summarised in this document serve to highlight not just the volume of CONSTRAIN's research, but also its breadth and depth.

In many cases, these publications represent progress made in the scientific understanding of fundamental concepts in climate research since publication of the IPCC's Fifth Assessment Report in 2013, including but not limited to radiative forcing, climate projections, climate sensitivity and the Earth's energy budget.

Through providing this information to AR6, CONSTRAIN also aims to support the development of robust, evidence-based climate policy and increase understanding of the latest climate science amongst a range of audiences.

This project-wide effort is also helping refine knowledge gaps and the subsequent research which will be undertaken to address them during Phase 2 of the project, which ultimately focuses on delivering constrained surface temperature projections for the 2023 UNFCCC Global Stocktake.

An update of this document, describing CONSTRAIN's full and final contribution to AR6, will be made available once the IPCC AR6 Working Group reports are published.

# Summary of knowledge gains

**For each publication, all CONSTRAIN authors are listed, with lead authors in bold.**

## WGI Chapter 4: Future global climate: scenario-based projections and near-term information

### Key knowledge gains:

- Strong mitigation choices can slow down the rate of warming in the near-term (McKenna et al. 2021), whilst a strong green COVID-19 economic recovery could keep Paris Agreement goals in sight (Forster et al. 2020a).
- The high warming rates seen in some of the latest (CMIP6) models are unlikely, but cannot be ruled out entirely, emphasising the need for rapid and deep emissions cuts (Forster et al. 2020b).
- Using historical observations can significantly reduce uncertainty in estimates of human-induced warming (Tokarska et al. 2020a; Ribes et al. 2021).

### Stringent mitigation substantially reduces risk of unprecedented near-term warming rates (McKenna et al. 2021)

**Christine M. McKenna**, Amanda C. Maycock, Piers Forster, Christopher J. Smith, Katarzyna B. Tokarska

Nature Climate Change 11, 126–131 https://doi.org/10.1038/s41558-020-00957-9

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 4**: Mitigation and development pathways in the near- to mid-term*

*#near-term projections #internal variability #mitigation pathways #Paris Agreement*

Strong greenhouse gas mitigation will have clear benefits in the second half of this century, limiting peak warming and stabilising the climate, but the near-term benefits have been less clear because human-induced temperature trends can be masked by internal variability in the climate system. McKenna et al. show that strong emissions cuts in line with the Paris Agreement 1.5°C ambition reduce the risk of unprecedented warming rates in the next 20 years from 54% to 4% (a factor of 13) compared to fossil-fuelled future, even when internal variability is taken into account. This means that strong mitigation can bring near- as well as longer-term benefits, slowing down the rate of warming and providing a greater chance to adapt to and avoid the worst impacts.

### Current and future global climate impacts resulting from COVID-19 (Forster et al. 2020a)

**Piers Forster**, Robin Lamboll, Joeri Rogelj, Deborah Rosen, Carl-Friedrich Schleussner, Christopher J. Smith

Nature Climate Change 10, 913–919 https://doi.org/10.1038/s41558-020-0883-0

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 4:** Mitigation and development pathways in the near- to mid-term*

*#near-term projections #mitigation pathways #Paris Agreement #climate policy*

The COVID-19 pandemic led to a sudden reduction in both greenhouse gas emissions and air pollutants. Forster et al. use national mobility data to estimate global emission reductions from February to June 2020, finding that global NOx emissions had declined by as much as 30% by April 2020. This led to a short-term cooling in early 2020 but was offset by a ~20% reduction in global SO2 emissions, weakening the aerosol cooling effect and causing short-term warming. Overall, they estimate that the direct effect of the pandemic on climate will be negligible (a cooling of 0.01°C by 2030 compared to following current national policies). In contrast, a strong green recovery could avoid 0.3°C of future warming by 2050, keeping the Paris Agreement Long Term Temperature Goal in sight.

### Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research (Lamboll et al. 2020)

**Robin Lamboll**, Joeri Rogelj

Geoscientific Model Development 13, 5259–5275 https://doi.org/10.5194/gmd-13-5259-2020

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers; **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 4:** Mitigation and development pathways in the near- to mid-term*

*#near-term projections #climate forcers #mitigation pathways*

Integrated assessment models (IAMs) project future anthropogenic emissions. These can be used as input for climate models, but the full list of emissions is long and most IAMs do not model all of them. Lamboll et al. have developed Silicone, an open-source Python package, to infill anthropogenic emissions of unmodelled species based on other reported emissions projections. For example, Silicone can infer N2O emissions in one scenario based on its CO2 emissions, plus the relationship between the two species in other scenarios. Silicone can therefore broaden the range of IAMs available for exploring future climate projections. There are a variety of infilling options, suitable in different cases, with examples provided.

## Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6 (Tebaldi et al. accepted)

Reto Knutti, Olivier Boucher, Roland Séférian

Earth System Dynamics Discussions. https://doi.org/10.5194/esd-2020-68

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#model evaluation #internal variability #mitigation pathways*

Tebaldi et al. present a broad overview of CMIP6 ScenarioMIP outcomes from a multi-model ensemble according to the new SSP-based scenarios. Average temperature and precipitation projections under a wide range of forcings are documented as global averages and geographic patterns, and are found to span a wider range than the CMIP5 projections. This due to both the wider range of radiative forcing that the new scenarios cover and higher climate sensitivities in some of the new models compared to their CMIP5 predecessors. Times of crossing various warming levels are also computed, with all scenarios reaching 1.5°C of warming in the second half of the current decade. 2°C of warming is reached as early as the late 2030s under SSP5-8.5, but as late as the late 2050s under SSP1-2.6.

## Incremental improvements of 2030 targets insufficient to achieve the Paris Agreement goals (Geiges et al. 2020)

Alexander Nauels, Carl-Friedrich Schleussner

Earth System Dynamics 11, 697–708 https://doi.org/10.5194/esd-11-697-2020

*Also relevant to **WGI Chapter 10**: Linking global to regional climate change; **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 4:** Mitigation and development pathways in the near- to mid-term*

*#mitigation pathways #climate policy #Paris Agreement*

Geiges et al. assess different scenarios for updated Nationally Determined Contributions (NDCs), finding that incremental improvements, even if global, do not align with the Paris Agreement 1.5°C ambition. Instead, a transformational increase in 2030 ambition is required to achieve the Paris goals and avoid the worst impacts of climate change. They provide estimates for global mean temperature increase by 2100 for different incremental NDC update scenarios and illustrate climate impacts under those scenarios for extreme temperature, long-term sea-level rise and economic damages for the most vulnerable countries. They also project a reduction in the gross domestic product (GDP) of tropical countries of around 60% compared to a no-climate-change scenario, and long-term sea-level rise of close to 2m in 2300. About half of these impacts can be avoided by limiting warming to 1.5°C or below.

## Latest climate models confirm need for urgent mitigation (Forster et al. 2020b)

Piers Forster, Amanda C. Maycock, Christine McKenna, Christopher J. Smith

Nature Climate Change 10, 7–10 https://doi.org/10.1038/s41558-019-0660-0

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity; and **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#mitigation pathways #climate sensitivity*

Many of the most recent (CMIP6) climate models show greater future warming than their predecessors, as well as higher equilibrium climate sensitivities (ECS) than the previous model generation (CMIP5). Forster et al. argue that the CMIP6 models showing the highest warming are unlikely to be representative of the real world, and that CMIP6 projections of global surface temperature should not be relied on alone for policy decisions. The new results nonetheless still have scientific value and strengthen the case for urgent mitigation: comparing the model results with other lines of evidence suggests that their warming rates may be high, but at the same time they cannot be ruled out entirely, emphasising the need for rapid and deep emissions cuts.

## Making climate projections conditional on historical observations (Ribes et al. 2021)

Aurélien Ribes

Science Advances 7, 4, eabc0671 https://doi.org/10.1126/sciadv.abc0671

*Also relevant to **WGI Chapter 7:** The Earth's energy budget, climate feedbacks, and climate sensitivity; and **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#near-term projections #climate sensitivity #mitigation pathways*

Ribes et al. use the latest climate models, improved observations and a new statistical method to narrow estimates of past and future human-induced warming, warming to date, warming rate, the response to a range of future emissions scenarios, and climate sensitivity. The results suggest that historical observations can be used to significantly reduce uncertainty in human-induced warming, typically by a factor of 3 in the past and near-term (by 2040), and by a factor of 2 in the long-term (late 21st century). In addition, narrowing the range of climate sensitivity means that the lower end of previous estimates of 21st century warming can now be excluded. This has implications for climate impacts and the need for urgent mitigation.

## Past warming trend constrains future warming in CMIP6 models (Tokarska et al. 2020a)

**Katarzyna B. Tokarska**, Christopher J. Smith, Reto Knutti

Science Advances 6, 12, eaaz9549 https://doi.org/10.1126/sciadv.aaz9549

*Also relevant to **WGI Chapter 5**: Global carbon and other biogeochemical cycles and feedbacks;*

***WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity; and **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#near-term projections #emergent constraints #climate sensitivity #mitigation pathways*

Several CMIP6 models project stronger warming than seen in past assessments. Tokarska et al. show that the models' future warming projections correspond to how they recreate recent warming. This allows the future warming projections to be constrained, based on how consistent they are with the observations. Using the constrained CMIP6 models, the midpoint of warming projections is 16% lower by 2050 in high emissions scenarios, and 14% lower by 2050 in ambitious mitigation scenarios, compared to the full CMIP6 range. The constrained CMIP6 projections are also consistent with CMIP5 models, and the results also show that most CMIP6 models with high climate sensitivity overestimate recent warming trends.

## For other papers relevant to future global climate, scenario-based projections and near-term information see also:

**WGI Chapter 5: Global carbon and other biogeochemical cycles and feedbacks**

- The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions (Jones et al. 2019) https://doi.org/10.5194/gmd-12-4375-2019

  *#carbon budgets #model evaluation #mitigation pathways*

- Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2 (MacDougall et al. 2020) https://doi.org/10.5194/bg-17-2987-2020

  *#carbon budgets #model evaluation #mitigation pathways #climate feedbacks #climate forcers #ocean circulation and heat content*

**WGI Chapter 6: Short-lived climate forcers**

- Climate impacts of COVID-19 induced emission changes (Gettleman et al. 2020) https://doi.org/10.1029/2020GL091805

  *#climate forcers #aerosol forcing*

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- How large does a large ensemble need to be? (Milinski et al. 2020) https://doi.org/10.5194/esd-11-885-2020

  *#climate forcers #model evaluation #internal variability*

## WGI Chapter 5: Global carbon and other biogeochemical cycles and feedbacks

### Key knowledge gains:

- Remaining carbon budget estimates have been calculated, but caution is still needed in interpreting results, particularly as the size of the budget decreases. There is however a better understanding of the assumptions and uncertainties involved. The latest estimates of the remaining carbon budget suggest that while it is small and rapidly decreasing, the Paris Agreement goals remain within reach. (e.g. Tokarska et al. 2021, Tokarska et al. 2020b, Matthews et al. 2020).
- Paris Agreement-compatible emissions pathways often assume a temperature overshoot, after which the global mean temperature response is reversible, but the carbon cycle response is dependent on the CO2 emission pathway. This may have implications for environmental changes other than global mean temperature rise (Tokarska et al. 2019b).
- The Zero Emissions Commitment (ZEC) - the change in global mean temperature expected once net CO2 emissions cease, is meanwhile likely to be close to zero on multi-decadal timescales (MacDougall et al. 2020).
- Model evaluation and improvements have been applied to individual models (e.g. Séférian et al. 2019), as well as modelled quantities such as compatible fossil fuel emissions pathways (Liddicoat et al. 2020), sea-air CO2 fluxes (Gehlen et al. 2020) and carbon-climate feedbacks (Arora et al. 2020).

### Global Carbon Budget 2020 (Friedlingstein et al. 2020)

Piers Forster, Thomas Gasser, Roland Séférian

Earth System Science Data 12, 4, 3269–3340 https://doi.org/10.5194/essd-12-3269-2020

*Also relevant to **WGIII Chapter 2**: Emissions trends and drivers*

*#carbon budgets #internal variability #sources and sinks*

The Global Carbon Budget 2020 describes the data sets and methodology used to quantify CO2 emissions and their redistribution among the atmosphere, land and ocean, along with their uncertainties. Components include fossil and land-use change CO2 emissions, atmospheric CO2 concentration and its growth rate, and the ocean and terrestrial CO2 sinks. Preliminary data for 2020, accounting for COVID-19-induced changes in emissions, suggests a decrease in fossil CO2 emissions relative to 2019 of about 7 %. The carbon budget imbalance - the difference between the estimated total emissions and the estimated changes in the atmosphere, ocean, and terrestrial biosphere - is a measure of imperfect data and understanding, although there is a near balance between estimated sources and sinks over the last decade.

## An integrated approach to quantifying uncertainties in the remaining carbon budget (Tokarska et al. 2021)

**Katarzyna B. Tokarska**, Joeri Rogelj, Christopher J. Smith, Piers Forster, Reto Knutti

Communications Earth & Environment 2, 7 https://doi.org/10.1038/s43247-020-00064-9

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#carbon budgets #mitigation pathways*

The remaining carbon budget quantifies the limit on future CO2 emissions to keep global warming below a certain level. Carbon budgets are however subject to uncertainties, as well as to non-CO2 climate influences. Tokarska et al. use observations to estimate the Transient Climate Response to Cumulative CO2 Emissions (TCRE) and integrate geophysical and socioeconomic uncertainties into the remaining carbon budget. This leads to an estimated TCRE of 0.44 °C per 1000 GtCO2 emitted and, including geophysical uncertainties, a remaining carbon budget for staying within 1.5°C of 440 GtCO2 from 2020 onwards. Additional socioeconomic uncertainties and decisions regarding future non-CO2 emissions can further reduce or increase the 1.5 °C remaining carbon budget by ±170 GtCO2.

## Uncertainty in carbon budget estimates due to internal climate variability (Tokarska et al. 2020b)

**Katarzyna B Tokarska**, Joeri Rogelj, Carl-Friedrich Schleussner, Roland Séférian, Reto Knutti

Environmental Research Letters 15, 10, 104064 https://doi.org/10.1088/1748-9326/abaf1b

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#carbon budgets #model evaluation #internal variability*

Tokarska et al. quantify the impact of internal variability on remaining carbon budgets, as well as on the ratio of CO2-induced warming to cumulative emissions or Transient Climate Response to Emissions (TCRE), in individual models, using two different approaches. The results show that internal variability contributes approximately ±0.09 °C to the overall uncertainty in human-induced warming to-date. Using TCRE to calculate the remaining carbon budget leads to a spread in Paris-compatible remaining carbon budgets as large as ±50 PgC, whilst differences in TCRE due to internal variability in individual models can be as large as ±0.1 °C/1000 PgC. Using climate models to calculate the remaining carbon budget leads to a spread of between ±30 and ±40PgC. These results highlight the need for caution when interpreting small remaining carbon budgets.

## Opportunities and challenges in using remaining carbon budgets to guide climate policy (Matthews et al. 2020)

Katarzyna B. Tokarska, Joeri Rogelj, Piers Forster, Reto Knutti, Roland Séférian

Nature Geoscience 13, 769–779 https://doi.org/10.1038/s41561-020-00663-3

*Also relevant to: **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 14**: International cooperation*

*#carbon budgets #mitigation pathways #Paris Agreement #climate policy*

Estimates of remaining carbon budgets vary and the inherent uncertainties, which can be scientific or socio-economic, have policy implications. Different methodological choices and assumptions can also underlie carbon budget calculations. Matthews et al. provide recommendations on how to calculate remaining carbon budgets in a transparent way and discuss the implications for international and national climate policies. The latest estimates of the remaining carbon budget suggest that while it is small and rapidly decreasing, the Paris Agreement goals remain within reach.

## Recommended temperature metrics for carbon budget estimates, model evaluation and climate policy (Tokarska et al. 2019a)

**Katarzyna B. Tokarska**, Carl-Friedrich Schleussner, Joeri Rogelj

Nature Geoscience 12, 964–971 https://doi.org/10.1038/s41561-019-0493-5

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity; and **WGIII Chapter 14:** International cooperation*

*#carbon budgets #model evaluation #metrics #Paris Agreement #climate policy*

Some recent estimates of Paris Agreement-compatible remaining carbon budgets are larger than previously thought. Tokarska et al. explain the reasons behind these increases and discuss how the choice of temperature metric, and the reference period, influence the remaining carbon budget. Tokarska et al. argue that the choice of the temperature metric should depend on the context, and when discussing the Paris Agreement, a temperature metric consistent with the science that underlies the Agreement should be used. Transparency and understanding of the implications of such choices for climate policy are crucial.

## Estimating and tracking the remaining carbon budget for stringent climate targets (Rogelj et al. 2019a)

**Joeri Rogelj**, Piers Forster, Christopher J. Smith, Roland Séférian

Nature 571, 335–342 https://doi.org/10.1038/s41586-019-1368-z

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 14:** International cooperation*

*#carbon budgets #mitigation pathways #climate feedbacks #Paris Agreement #climate policy*

Global warming is roughly proportional to the total amount of carbon dioxide released into the atmosphere, making it possible to estimate the remaining carbon budget, or the total amount of anthropogenic carbon dioxide that can still be emitted into the atmosphere, which still allows us to hold global average temperature increase within the Paris Agreement limits of 1.5 or 2°C. However, the wide range of estimates for the remaining carbon budget reduces its effectiveness. Rogelj et al. present a framework that allows estimates of the remaining carbon budget to be tracked and improved as the science advances, helping to reconcile differences between current estimates, and reduce uncertainty in future estimates.

## Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot (Tokarska et al. 2019b)

**Katarzyna B. Tokarska**, Joeri Rogelj

Earth's Future 7, 121283-1295 https://doi.org/10.1029/2019EF001312

*Also relevant to **WGI Chapter 9**: Ocean, cryosphere, and sea level change; and **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#carbon budgets #mitigation pathways #ocean circulation and heat content #Paris Agreement*

Emissions pathways consistent with meeting the Paris Agreement often assume a temperature overshoot, in which a given temperature is first exceeded and later returned to, assuming large-scale carbon dioxide removal from the atmosphere. After an overshoot, the global mean temperature response is reversible, but the carbon cycle response is dependent on the CO2 emission pathway, and the magnitude of the overshoot: after an overshoot, more carbon is stored in the ocean and less on land. As a result, carbon budgets do not differ much among overshoot and non-overshoot scenarios, but higher levels of overshoot may have implications for limiting environmental changes other than global mean temperature rise.

## The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions (Jones et al. 2019)

Joeri Rogelj, Katarzyna B. Tokarska, Roland Séférian

Geoscientific Model Development 12, 4375–4385 https://doi.org/10.5194/gmd-12-4375-2019

*Also relevant to **WGI Chapter 4**: Future global climate; and **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#carbon budgets #model evaluation #mitigation pathways*

The Zero Emissions Commitment (ZEC) - the amount of future warming that can be expected once CO2 emissions cease - is important for estimating the remaining carbon budget. IPCC SR1.5 assumed that the ZEC is close to zero, but previous research has shown significant uncertainty in the ZEC. Quantitative information on ZEC is a key gap in our knowledge, yet it is crucial for verifying whether carbon budgets need to be adjusted to account for any unrealised temperature change resulting from past CO2 emissions. The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) aims to quantify the amount of temperature change occurring after CO2 emissions cease, and investigate the geophysical drivers behind the climate response.

## Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2 (MacDougall et al. 2020)

Joeri Rogelj, Martine Michou, Roland Séférian

Biogeosciences 17, 2987–3016 https://doi.org/10.5194/bg-17-2987-2020

*Also relevant to **WGI Chapter 4**: Future global climate; **WGI Chapter 9**: Ocean, cryosphere, and sea level change; and **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#carbon budgets #model evaluation #mitigation pathways #climate feedbacks #climate forcers #ocean circulation and heat content*

The Zero Emissions Commitment (ZEC) is the change in global mean temperature expected once net CO2 emissions cease, and is critical for calculating the remaining carbon budget. The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) was established to gain a better understanding of the ZEC, with 18 Earth system models participating. All models conducted an experiment where atmospheric CO2 concentration increases exponentially until 1000 PgC has been emitted, before emissions are set to zero. 50 years after emissions cease, the model experiments show a ZEC of −0.36 to 0.29°C (median −0.05°C), although they also show a wide variety of behaviours after emissions cease, with some continuing to warm and others cooling substantially. Overall, the most likely value of ZEC on multi-decadal timescales is close to zero.

## Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth system processes in present-day and future climate (Séférian et al. 2019)

**Roland Séférian**, Pierre Nabat, Martine Michou, Jessica Vial, Aurélien Ribes, Romain Roehrig

Journal of Advances in Modeling Earth Systems 11, 12, 4182-4227
https://doi.org/10.1029/2019MS001791

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#sources and sinks #model evaluation #climate feedbacks #climate forcers*

CNRM-ESM2-1 is the second-generation Earth system (ES) model developed by CNRM-CERFACS for CMIP6. CNRM-ESM2-1 introduces more complexity compared to its predecessor by adding interactive components such as carbon cycle, aerosols, and atmospheric chemistry. The two models display comparable performance at replicating modern observations although the mean climate of CNRM-ESM2-1 is slightly warmer due to land cover-aerosol interactions leading to a smaller aerosol burden, and a different surface radiative budget and climate. There are greater differences when it comes to the model response to external forcing and future climate projections, with future warming up to 10% lower in CNRM-ESM2-1. The representation of land vegetation and the CO2-water-stomatal feedback explains about 60% of this difference, with the rest driven by other feedbacks.

## Compatible fossil fuel $CO_2$ emissions in the CMIP6 Earth system models' historical and Shared Socioeconomic Pathway experiments of the 21st century (Liddicoat et al. 2020)

Roland Séférian

Journal of Climate 1-72 Early Online Release https://doi.org/10.1175/JCLI-D-19-0991.1

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals*

*#climate feedbacks #model evaluation #emissions pathways*

Liddicoat et al. present the ocean and land carbon cycle responses of nine Earth system models (ESMs) participating in CMIP6. The models' ocean carbon cycle responses are in close agreement, but there is considerable spread in their land carbon cycle responses. $CO_2$ emissions from fossil fuel burning and industry are also calculated from historical and Shared Socioeconomic Pathways (SSP). The mean fossil fuel emissions match the historical record well, and the models' fossil fuel emission rates are consistent with those from Integrated Assessment Models (IAMs). The ESMs require fossil fuel emissions to reduce to zero and subsequently become negative in SSP1-1.9, SSP1-2.6, SSP4-3.4 and SSP5-3.4.

## Quantification of chaotic intrinsic variability of sea-air $CO_2$ fluxes at interannual timescales (Gehlen et al. 2020)

Roland Séférian

Geophysical Research Letters 47, 22, e2020GL088304 https://doi.org/10.1029/2020GL088304

*#sources and sinks*

Sea-air $CO_2$ fluxes vary both regionally and from year to year. This is largely due to changes in large-scale atmospheric patterns, but ocean internal dynamics could also contribute. This study quantifies these two sources of variability and their role in fluctuations of sea-air $CO_2$ fluxes over large oceanic regions. It shows that Chaotic intrinsic variability (CIV), which emerges spontaneously in the ocean, is a significant contributor to variability on interannual to decadal timescales and can drive random fluctuations of sea-air $CO_2$ fluxes on interannual timescales. These fluctuations are substantial over areas of high kinetic energy, accounting for over 76% of the total interannual variance of sea-air $CO_2$ fluxes in some places.

## Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models (Arora et al. 2020)

Olivier Boucher, Roland Séférian

Biogeosciences 17, 4173–4222 https://doi.org/10.5194/bg-17-4173-2020

*#climate feedbacks #model evaluation*

Land and ocean have taken up about half of anthropogenic carbon emissions since the preindustrial period. Comparing different Earth system models with the carbon cycle allows us to assess how carbon uptake by land and ocean differs among the models, providing an estimate of the uncertainty in our understanding of how land and ocean respond to increasing atmospheric $CO_2$. This paper summarises results from CMIP5 and CMIP6, using a scenario in which CO2 increases at a rate of 1 % yr−1 from its preindustrial value. The carbon–concentration and carbon–climate feedback parameters provide a measure of the response of ocean and land carbon pools to changing atmospheric CO2 concentration and the resulting change in global climate respectively. The strength of both feedbacks is an order of magnitude more over land than over ocean. The results from the 11 CMIP6 models analysed do not differ significantly from CMIP5.

## For other papers relevant to global carbon and other biogeochemical cycles and feedbacks see also:

**WGI Chapter 4: Future global climate: scenario-based projections and near-term information**

- Past warming trend constrains future warming in CMIP6 models (Tokarska et al. 2020a) https://doi.org/10.1126/sciadv.aaz9549

  *#near-term projections #emergent constraints #climate sensitivity*

**WGI Chapter 6: Short-lived climate forcers**

- Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models (Thornhill et al. 2021a) https://doi.org/10.5194/acp-21-1105-2021

  *#climate forcers #aerosol forcing #climate feedbacks #climate sensitivity*

- Efficacy of climate forcings in PDRMIP models (Richardson et al. 2019) https://doi.org/10.1029/2019JD030581

  *#climate forcers #model evaluation #climate sensitivity #aerosol forcing*

## WGI Chapter 6: Short-lived climate forcers

### Key knowledge gains:

- Falling aerosol emissions due to COVID-19-related drops in activity led to a slight warming in spring 2020. Aerosols made a larger contribution to COVID-19-related changes in radiative forcing and temperature than changes in ozone, CO2 and contrails (Gettleman et al. 2020).
- Improvements have been made to anthropogenic aerosol representation, forcing and feedbacks in climate models (Thornhill et al. 2021a, Cherian and Quaas 2020, Watson-Parris et al. 2020), including a narrowing of the range of aerosol forcing compared to CMIP5 (Smith et al. 2020a), although there is still a spread across models (Richardson et al. 2019).
- Using new satellite retrievals of aerosol number, size, and shape show that the negative radiative forcing due to aerosol-cloud interactions is more than a factor of 2 stronger than AR5's estimate (Hasekamp et al. 2019), whilst volcanic aerosol forcing may have been overestimated previously (Marshall et al. 2020).

### Climate impacts of COVID-19 induced emission changes (Gettleman et al. 2020)

Robin Lamboll, Piers Forster

Geophysical Research Letters e2020GL091805 https://doi.org/10.1029/2020GL091805

*Also relevant to **WG1 Chapter 4**: Future global climate*

*#climate forcers #aerosol forcing*

Gettleman et al. use two Earth system models (ESMs) to simulate the impact of COVID-19-related falls in activity on emissions. Reductions in emissions of aerosols and their precursors, chiefly black carbon (BC) and sulfate (SO4), led to reductions in anthropogenic aerosol cooling through aerosol-cloud interactions, creating a small net warming effect in spring 2020. The peak impact of these aerosol changes on global surface temperature is very small (+0.03K). However, the aerosol changes are the largest contribution to radiative forcing and temperature changes as a result of COVID-19 affected emissions, larger than ozone, CO2 and contrail effects.

### Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models (Thornhill et al. 2021a)

Martine Michou, Pierre Nabat, Roland Séférian

Atmospheric Chemistry and Physics 21, 1105–1126 https://doi.org/10.5194/acp-21-1105-2021

*Also relevant to **WGI Chapter 5**: Global carbon and other biogeochemical cycles and feedbacks; and **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#climate forcers #aerosol forcing #climate feedbacks #climate sensitivity*

Thornhill et al. address multiple pathways for aerosol and chemical feedbacks in CMIP6 models focusing on changes in natural emissions (dust, sea salt, dimethyl sulfide, biogenic volatile organic compounds (BVOCs) and lightning) and reaction rates for methane and ozone chemistry. The feedback terms are given by multiplying the sensitivity of a pathway to climate change by the radiative effect of the change. They find that the overall climate feedback through chemistry and aerosols is negative in CMIP6 models due to increased negative aerosol forcing as the climate warms, principally due to increased emissions of sea salt and BVOCs. Increased chemical loss of ozone and methane also contributes to a negative feedback.

### Efficacy of climate forcings in PDRMIP models (Richardson et al. 2019)

Piers Forster, Christopher J. Smith, Amanda C. Maycock, Timothy Andrews, Olivier Boucher, Gunnar Myhre, Bjørn Samset

JGR Atmospheres, 124, 23, 12824-12844 https://doi.org/10.1029/2019JD030581

*Also relevant to **WGI Chapter 5**: Global carbon and other biogeochemical cycles and feedbacks; and **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#climate forcers #model evaluation #climate sensitivity #aerosol forcing*

Differences in how climate forcers are represented in climate models, in terms of how effective they are at increasing surface temperature, may affect estimates of climate sensitivity, so quantifying the efficacy of different climate forcers, such as methane, sulfate and black carbon, is important. This study presents a multi-model analysis of different forcers using the Precipitation Driver and Response Model Intercomparison Project (PDRMIP). Instantaneous radiative forcing differs considerably across forcing agents and models. Effective radiative forcing (ERF) is a better predictor of global mean temperature change, but there is still notable spread across the models.

### Trends in AOD, clouds, and cloud radiative effects in satellite data and CMIP5 and CMIP6 model simulations over aerosol source regions (Cherian and Quaas 2020)

Johannes Quaas

Geophysical Research Letters 47, 9, e2020GL087132 https://doi.org/10.1029/2020GL087132

*See also **WG1 Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#aerosol forcing #clouds*

Significant geographic trends in anthropogenic aerosol emissions identified since 2001 (when detailed satellite observations became available) include strong falls over Europe and North America, a rise and then fall over China, and a strong rise over India. Regional trends in aerosol optical depth (AOD) and cloud radiative effects in both CMIP5 and CMIP6 are broadly consistent with the satellite observations in most parts of Europe, North America and India, with those from CMIP6 models being better than CMIP5 over western North America (increasing) and eastern China (decreasing), pointing to improvements over CMIP5.

### Constraining uncertainty in aerosol direct forcing (Watson-Parris et al. 2020)

Christopher J. Smith

Geophysical Research Letters 47, 9, e2020GL087141 https://doi.org/10.1029/2020GL087141

*#aerosol forcing*

The strength of aerosol forcing is a major uncertainty in establishing total present-day anthropogenic forcing. Much of this is due to uncertainty in how much of the aerosol in the present-day atmosphere is anthropogenic, due to a lack of historical observations. Using observations of aerosol optical depth, Watson-Parris et al. present a robust relationship between total present-day aerosol optical depth and the anthropogenic contribution, provide a reduced likely range of the anthropogenic component, and further show that this allows the uncertainty in the cooling effect of aerosols to be reduced.

### Analysis of polarimetric satellite measurements suggests stronger cooling due to aerosol-cloud interactions (Hasekamp et al. 2019)

Johannes Quaas

Nature Communications 10, 5405 https://doi.org/10.1038/s41467-019-13372-2

*Also relevant to **WGI Chapter 8**: Water cycle changes*

*#aerosol forcing #clouds*

Anthropogenic aerosol emissions increase the amount of cloud condensation nuclei and consequently cloud droplet concentration and cloud albedo. The negative radiative forcing due to aerosol cloud interactions (RFaci) is one of the most uncertain radiative forcing terms in IPCC AR5. Hasekamp et al. show that previous observation-based studies underestimate aerosol-cloud interactions because they used measurements of aerosol optical properties that are not directly related to cloud formation and are hampered by uncertainties in the measurements. They overcome this by using new polarimetric satellite retrievals of aerosol number, size, and shape. The resulting RFaci estimate is −1.14 $Wm^{-2}$, more than a factor of 2 stronger than AR5's estimate.

### Large variations in volcanic aerosol forcing efficiency due to eruption source parameters and rapid adjustments (Marshall et al. 2020)

Christopher J. Smith, Piers Forster, Timothy Andrews

Geophysical Research Letters 47, 19, e2020GL090241 https://doi.org/10.1029/2020GL090241

*#aerosol forcing #clouds*

The relationship between volcanic stratospheric aerosol optical depth (SAOD) and volcanic radiative forcing is key for quantifying volcanic climate impacts. IPCC AR5 used a scaling factor between SAOD and volcanic forcing based on climate model simulations of the 1991 Mt. Pinatubo eruption, which may not be appropriate for all eruptions. Using aerosol-chemistry-climate simulations of eruptions with different sulfur dioxide emissions, latitudes, emission altitudes, and seasons, Marshall et al. find that the volcanic SAOD-radiative forcing relationship varies widely depending on time since an eruption, eruption latitude and season, as these affect aerosol dispersion and incoming solar radiation. Our revised SAOD-radiative forcing relationships suggest that volcanic forcing has been previously overestimated, and that the eruptions reduce the cooling effect of clouds.

### Historical total ozone radiative forcing derived from CMIP6 simulations (Skeie et al. 2020)

Gunnar Myhre, Martine Michou, Bjørn H. Samset

npj Climate and Atmospheric Science 3, 32 https://doi.org/10.1038/s41612-020-00131-0

*#climate forcers*

Radiative forcing (RF) time series for total ozone from 1850 up to the present day are calculated based on historical simulations from 10 CMIP6 models. The ozone RF in 2010 relative to 1850 is 0.35 W m−2, based on models with both tropospheric and stratospheric chemistry. Excluding one model with a negative present-day total ozone RF gives a value of 0.39 W m−2. The remaining models have RF close to or stronger than that in IPCC AR5, most likely due to the new precursor emissions used in CMIP6.

### Present-day and historical aerosol and ozone characteristics in CNRM CMIP6 simulations (Michou et al. 2019)

**Martine Michou**, Pierre Nabat, Marc Mallet, Romain Roehrig, Roland Séférian

Journal of Advances in Modelling Earth Systems 12, 1, e2019MS001816
https://doi.org/10.1029/2019MS001816

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#climate forcers #aerosol forcing #clouds #model evaluation*

Characteristics and radiative forcing of aerosol and ozone are analysed for two configurations of the CNRM and Cerfacs climate model over the historical period (1850–2014), using several CMIP6 simulations. Present-day anthropogenic aerosol ERF, aerosol-radiation ERF, and aerosol cloud ERF are fully within CMIP5 estimates and, respectively, -1.10, -0.36, and -0.81 Wm-2 for CNRM-CM6-1 and -0.21, -0.61, and -0.74 Wm-2 for CNRM-ESM2-1. Differences between the two models are mainly due to the interactivity of the aerosol scheme. Present-day stratospheric ozone ERF (-0.04Wm-2) agrees with that of CMIP6.

### Effective radiative forcing from emissions of reactive gases and aerosols – a multi-model comparison (Thornhill et al. 2021b)

Piers Forster, Martine Michou, Gunnar Myhre, Pierre Nabat, Christopher J. Smith

Atmospheric Chemistry and Physics 21, 853–874 https://doi.org/10.5194/acp-21-853-2021

*#aerosol forcing #climate forcers #model evaluation*

This paper quantifies the pre-industrial (1850) to present-day (2014) effective radiative forcing (ERF) of anthropogenic emissions of NOX, volatile organic compounds (VOCs; including CO), SO2, NH3, black carbon, organic carbon, and concentrations of methane, N2O and ozone-depleting halocarbons, using CMIP6 models. Changes in the concentrations and emissions of these species can lead to changes in species that affect the Earth's radiation budget such as ozone, stratospheric water vapour, secondary aerosols, and methane. Thornhill et al. break down the ERFs from each emitted species into the contributions from the composition changes. Differences in ERFs calculated for the different models reflect differences in the complexity of their aerosols and chemistry, especially in the case of methane.

## For other papers relevant to short-lived climate forcers see also:

**WGI Chapter 4: Future global climate: scenario-based projections and near-term information**

- Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research (Lamboll et al. 2020) https://doi.org/10.5194/gmd-13-5259-2020

  *#climate forcers #mitigation pathways*

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- On the climate sensitivity and historical warming evolution in recent coupled model ensembles (Flynn and Mauritsen 2020) https://doi.org/10.5194/acp-20-7829-2020

  *#climate sensitivity #climate feedbacks #clouds #aerosol forcing*

- Energy budget constraints on historical radiative forcing (Andrews and Forster 2020) https://doi.org/10.1038/s41558-020-0696-1

  *#climate forcers #climate feedbacks #climate sensitivity #aerosol forcing*

- Emergent constraints on Earth's transient and equilibrium response to doubled CO2 from post-1970s global warming (Jiménez-de-la-Cuesta & Mauritsen 2019) https://doi.org/10.1038/s41561-019-0463-y

  *#climate sensitivity #SST patterns #aerosol forcing*

- The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018 (Lee et al. 2021) https://doi.org/10.1016/j.atmosenv.2020.117834

  *#climate forcers #clouds #metrics*

- Effective radiative forcing and adjustments in CMIP6 models (Smith et al. 2020a) https://doi.org/10.5194/acp-20-9591-2020

  *#aerosol forcing #climate forcers #clouds*

- On the structure of instantaneous radiative forcing kernels for greenhouse gases (Maycock et al. 2020) https://doi.org/10.1175/JAS-D-19-0267.1

  *#climate forcers #climate feedbacks*

**WGI Chapter 10: Linking global to regional climate change**

- The effect of anthropogenic aerosols on the Aleutian Low (Dow et al. 2021) https://doi.org/10.1175/JCLI-D-20-0423.1

*#regional observations and phenomena #aerosol forcing #ocean circulation and heat content*

- The Southern Hemisphere midlatitude circulation response to rapid adjustments and sea surface temperature driven feedbacks (Wood et al. 2020)

  *#regional observations and phenomena #climate feedbacks #clmate forcers*

## WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity

### Key knowledge gains:

- The likely range of Equilibrium Climate Sensitivity (ECS) is 2.3–4.5K. ECS lower than 2K is difficult to reconcile with the evidence, whilst values greater than 4.5K are relatively unlikely, but cannot be entirely ruled out (Sherwood et al. 2020). Emergent constraints also suggest a 95% probability of ECS being below 5K (Renoult et al. 2020). Temporal variability in surface temperatures (Annan et al. 2020) and post-1970 aerosol observations (Jiménez-de-la-Cuesta and Mauritsen 2019) may also provide useful constraints on ECS.
- High estimates of ECS in CMIP6 models compared to CMIP5 are likely due to changes in mixed-phase cloud processes and Antarctic sea ice representation (Flynn and Mauritsen 2020).
- Estimates of aerosol effective radiative forcing (ERF) have been narrowed in CMIP6 compared to CMIP5 (Smith et al. 2020a), whilst historical ERF has also been constrained to a range representing an almost 40% reduction compared to that of IPCC AR5, suggesting that ERF may be too small in up to one-third of CMIP5 climate models (Andrews and Forster 2020).
- There is broad consistency between observed and modelled (CMIP5 and CMIP6) Sea Surface Temperature (SST patterns) in most ocean regions when internal variability is accounted for (Olonscheck et al. 2020). Internal variability may however be too small to significantly affect estimates of climate sensitivity (Lewis and Mauritsen 2021).
- Caution is needed when applying new concepts and metrics, such as GWP*, to existing policy contexts, including the Paris Agreement, as this can lead to inconsistencies in interpretation. GWP* should also only be used at the global level (Schleussner et al. 2019; Rogelj et al. 2019b).

### An assessment of Earth's climate sensitivity using multiple lines of evidence (Sherwood et al. 2020)

Piers Forster, Timothy Andrews, Reto Knutti, Thorsten Mauritsen, Maria Rugenstein, Katarzyna B. Tokarska

Reviews of Geophysics 58, 4, e2019RG000678 https://doi.org/10.1029/2019RG000678

*#climate sensitivity #climate feedbacks*

Sherwood et al. assess the evidence on Equilibrium Climate Sensitivity (ECS) including feedback processes, and the palaeo- and historical climate records. ECS lower than 2K is difficult to reconcile with the evidence, whilst the Last Glacial Maximum provides strong evidence against values greater than 4.5K. Other lines of evidence also show that this is relatively unlikely but cannot be entirely ruled out. The likely ECS range is 2.3–4.5K, lifting the lower end of the range compared to past assessments. As such it now appears extremely unlikely that ECS could be low enough to avoid warming above 2°C under a high-emission future scenario.

## A Bayesian framework for emergent constraints: case studies of climate sensitivity with PMIP (Renoult et al. 2020)

Thorsten Mauritsen

Climate of the Past 16, 1715–1735 https://doi.org/10.5194/cp-16-1715-2020

*#climate sensitivity*

Renoult et al. introduce a Bayesian framework for using models and observations together to constrain future climate change, obtaining Equilibrium Climate Sensitivity (ECS) values of 2.7K and 2.3K using two different model and dataset ensembles to study two different time periods (Last Glacial Maximum and mid-Pliocene Warm Period). They also combine the two periods to constrain ECS further to 2.5K. This also leads to 95% probability of climate sensitivity mostly below 5K. Although some fundamental challenges remain, this paper provides progress towards the potential use of emergent constraints in future estimates of climate sensitivity.

## On the climate sensitivity and historical warming evolution in recent coupled model ensembles (Flynn and Mauritsen 2020)

Thorsten Mauritsen

Atmospheric Chemistry and Physics 20, 7829–7842 https://doi.org/10.5194/acp-20-7829-2020

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#climate sensitivity #climate feedbacks #clouds #aerosol forcing*

The Earth's equilibrium climate sensitivity (ECS) to a doubling of atmospheric CO2, along with the transient climate response (TCR) and greenhouse gas emissions pathways, determines the amount of future warming. CMIP5 models estimate that ECS lies between 2.0 and 4.7K, whereas the CMIP6 spread is 1.8–5.5K, with 5 out of 25 models exceeding 5K. Flynn and Mauritsen compare the CMIP5 and CMIP6 models and find the difference to be the result of shortwave radiation feedbacks, particularly over the Southern Ocean, driving the shift towards larger ECS values in many of the CMIP6 models. These results suggest that changes in mixed-phase cloud processes and Antarctic sea ice representation are the likely causes of the larger ECS values. In addition, the CMIP6 models exhibit less historical warming than expected, despite an increase in TCR, likely the result of some CMIP6 models applying too strong aerosol cooling.

## What could we learn about climate sensitivity from variability in the surface temperature record? (Annan et al. 2020)

Thorsten Mauritsen, Bjorn Stevens

Earth System Dynamics 11, 709–719 https://doi.org/10.5194/esd-11-709-2020

*#climate sensitivity #internal variability*

Many previous studies have used observations to constrain equilibrium climate sensitivity, but it has also been argued that temporal variability in surface air temperatures could be used. Annan et al. examine what can be learnt about climate sensitivity from surface air temperature records, from 1880 to the present. They find that the constraint provided by variability is skewed and is stronger for low sensitivity and weaker for higher values, and variability can only provide a tight constraint when sensitivity is very low. The results suggest that variability is a potentially useful tool in helping to constrain equilibrium climate sensitivity, but caution is needed in interpreting precise results.

## Emergent constraints on Earth's transient and equilibrium response to doubled CO2 from post-1970s global warming (Jiménez-de-la-Cuesta and Mauritsen 2019)

Thorsten Mauritsen

Nature Geoscience 12, 902–905 https://doi.org/10.1038/s41561-019-0463-y

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#climate sensitivity #SST patterns #aerosol forcing*

Future global warming is determined by both greenhouse gas emission pathways and Earth's transient and equilibrium climate response to a doubling of atmospheric CO2. Observations suggest that the transient response is around 1.3K and the equilibrium response 1.5–2.0K, which is at the lower end of climate model estimates. The main uncertainties are poorly known aerosol-induced cooling since industrialisation, and temporary cooling from evolving sea surface temperature patterns. Jiménez-de-la-Cuesta and Mauritsen examine post-1970s warming, taking advantage of more consistent aerosol cooling during this period, to establish a relationship between the transient response and post-1970s warming in CMIP5 models. This constrains the transient response to 1.67K and provides a best estimate of climate sensitivity of 2.83K, depending on the pattern effects in the models. If the real world's surface temperature pattern effects are substantially stronger, then equilibrium sensitivity may be higher.

## Understanding the extreme spread in climate sensitivity within the Radiative-Convective Equilibrium Model Intercomparison Project (Becker and Wing 2020)

Tobias Becker

Journal of Advances in Modeling Earth Systems 12, 10, e2020MS002165 https://doi.org/10.1029/2020MS002165

*Also relevant to **WGI Chapter 10**: Linking global to regional climate change*

*#climate sensitivity #climate feedbacks #clouds #model evaluation #regional observations and phenomena*

Climate feedback parameters range widely across the Radiative-Convective Equilibrium Model Intercomparison Project (RCEMIP), from −6 to 3 W $m^{-2}$ $K^{-1}$. More than 70–80% of the spread can be explained by cloud processes, for example low climate sensitivities are associated with an increase of shallow cloud fraction and/or an increase in convective aggregation with warming. General Circulation Models (GCMs) also have a lower overall climate sensitivity than Cloud Resolving Models (CRMs) because in most GCMs convective aggregation increases with warming, whereas in CRMs, convective aggregation shows no consistent temperature trend. Overall, our results indicate that climate sensitivity might be underestimated by global climate models.

## Clouds and convective self-aggregation in a multimodel ensemble of radiative-convective equilibrium simulations (Wing et al. 2020)

Tobias Becker, Sandrine Bony, Romain Roehrig, Bjorn Stevens

Journal of Advances in Modeling Earth Systems 12, 9, e2020MS002138
https://doi.org/10.1029/2020MS002138

*Also relevant to **WGI Chapter 10**: Linking global to regional climate change*

*#clouds #climate sensitivity #climate feedbacks #model evaluation*

The Radiative-Convective Equilibrium Model Intercomparison Project (RCEMIP) is an intercomparison of multiple types of numerical models configured in radiative-convective equilibrium (RCE). RCE represents an ideal version of the tropical atmosphere that has long been used to study basic questions in climate science. Wing et al. use RCE to investigate the role of clouds and convective activity in cloud feedbacks, climate sensitivity, convective aggregation, and equilibrium climate. Whilst there are large differences in how the models simulate temperature, humidity, and cloudiness, in most models, the amount of high clouds decreases as the climate warms. Nearly all models show a tendency for clouds to cluster together, leading to a drier atmosphere with fewer clouds. However, there is no conclusive result for how cloud clustering changes as the climate warms.

## Tuning the MPI-ESM1.2 Global Climate Model to improve the match with instrumental record warming by lowering its climate sensitivity (Mauritsen and Roeckner 2020)

Thorsten Mauritsen

Journal of Advances in Modeling Earth Systems 12, 5, e2019MS002037
https://doi.org/10.1029/2019MS002037

*#climate sensitivity #climate feedbacks #model evaluation #clouds*

Mauritsen and Roeckner systematically tune the sensitivity of the MPI-ESM1.2 climate model atmospheric component (ECHAM6.3) to improve its match to historical observations. This was done by targeting an Equilibrium Climate Sensitivity (ECS) of about 3K, slightly lower than in the previous model generation, which warmed more than observed. The tuned model exhibits excellent fidelity with observed warming over the past century. In comparison, an alternative approach with high climate sensitivity compensated by strong aerosol cooling produces results colder than observations in the second half of the century. In the process, several controls on cloud feedback, some of which confirm recently proposed hypotheses, were also identified.

## Energy budget constraints on historical radiative forcing (Andrews and Forster 2020)

Timothy Andrews, Piers Forster

Nature Climate Change 10, 313–316 https://doi.org/10.1038/s41558-020-0696-1

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#climate forcers #climate feedbacks #climate sensitivity #aerosol forcing*

Understanding radiative forcing is fundamental for understanding past and future climate change, but there is still significant uncertainty in both quantifying radiative forcing and representing it in models.

Andrews and Forster use measurements of global mean surface temperature change and Earth's total heat uptake alongside estimates of the Earth's radiative response to constrain historical (1861–1880 to near-present) effective radiative forcing (ERF) to 2.3 W m−2. The range (5-95% confidence) represents an almost 40% reduction compared to that of IPCC AR5, and suggests that ERF may be too small in up to one third of CMIP5 climate models.

## Effective radiative forcing and adjustments in CMIP6 models (Smith et al. 2020a)

**Christopher J. Smith**, Gunnar Myhre, Olivier Boucher, Jean-Louis Dufresne, Pierre Nabat, Martine Michou, Timothy Andrews, Piers Forster

Atmospheric Chemistry and Physics 20, 9591–9618 https://doi.org/10.5194/acp-20-9591-2020

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#aerosol forcing #climate forcers #clouds #model evaluation*

Effective radiative forcing (ERF) is a key metric for evaluating human and natural influence on the climate. Smith et al. evaluate ERF in 17 CMIP6 models that have contributed to the Radiative Forcing Model Intercomparison Project (RFMIP). Present-day (2014) global-mean anthropogenic forcing relative to pre-industrial (1850) levels is 2.00 W m−2, comprised of 1.81 W m−2 from CO2, 1.08 W m−2 from other well-mixed greenhouse gases, −1.01 W m−2 from aerosols and −0.09 W m−2 from land use change. Uncertainties are typically within 0.1 W m−2. The remaining 0.21 W m−2 is likely to be from ozone. The spread of aerosol forcing ranges from −0.63 to −1.37 W m−2, a less negative and narrower range than from 10 CMIP5 models. The spread in 4×CO2 forcing has also narrowed in CMIP6 compared to 13 CMIP5 models.

## New generation of climate models track recent unprecedented changes in Earth's radiation budget observed by CERES (Loeb et al. 2020)

Timothy Andrews, Piers Forster

Geophysical Research Letters 47, 5, e2019GL086705 https://doi.org/10.1029/2019GL086705

*#clouds #SST patterns*

Loeb et al. use observations from the Clouds and the Earth's Radiant Energy System (CERES) to evaluate how seven state-of-the-art climate models represent changes in the Earth's radiation budget during and following the so-called global warming "hiatus" of the early 21st century. The models were provided with observations of sea-surface temperature (SST) and sea-ice boundary conditions as well as natural and anthropogenic forcings. There is remarkable agreement between observed and simulated differences in reflected solar and emitted thermal infrared radiation between the post-hiatus and hiatus periods. Furthermore, a model's ability to correctly relate Earth's radiation budget and surface temperature is found to depend upon how well it represents reflected solar radiation changes in regions dominated by low clouds, particularly those over the eastern Pacific Ocean.

### The effect of rapid adjustments to halocarbons and N2O on radiative forcing (Hodnebrog et al. 2020)

Gunnar Myhre, Timothy Andrews, Bjørn Samset, Christopher J. Smith

Climate and Atmospheric Science 3, 43 https://doi.org/10.1038/s41612-020-00150-x

*Also relevant to **WGI Chapter 8**: Water cycle changes*

*#climate forcers #clouds*

Rapid adjustments occur after an external driver (e.g. CO2) is introduced to the climate system, and involve changes in e.g. atmospheric temperature, water vapour and clouds, independent of sea surface temperature changes. Knowledge of such adjustments is needed to estimate effective radiative forcing (ERF), a useful indicator of surface temperature change, and to understand global precipitation changes. Yet, rapid adjustments have not been analysed in any detail for certain compounds, including halocarbons and N2O. Hodnebrog et al. show that rapid adjustments due to CFC-11, CFC-12 and N2O are substantial, but that the resulting flux changes approximately cancel out. The CFCs also lead to a larger increase in precipitation compared to other well-mixed greenhouse gases, largely due to cloud adjustments.

### Broad consistency between observed and simulated trends in sea surface temperature patterns (Olonscheck et al. 2020)

**Dirk Olonscheck**, Maria Rugenstein, Jochem Marotzke

Geophysical Research Letters 47, 10, e2019GL086773 https://doi.org/10.1029/2019GL086773

*Also relevant to **WGI Chapter 9**: Ocean, cryosphere and sea level change*

*#SST patterns #internal variability*

Climate model simulations agree well with the observations of global mean sea surface temperature, but their ability to realistically represent changes in the patterns of sea surface temperatures (SST) has been questioned. Using an unprecedented number of simulations from different models, including those contributing to CMIP5 and CMIP6, Olonscheck et al. show that observed and simulated trends in SST patterns are globally consistent in most ocean regions when accounting for internal variability. For each model, a few individual simulations recreate the observed patterns, and in some regions, the observed changes may be an extreme realisation of the Earth's possible behavior.  Alternatively, the models may be systematically biased but large internal variability leads to some good matches with the observations.

### Negligible unforced historical pattern effect on climate feedback strength found in HadISST-Based AMIP simulations (Lewis and Mauritsen 2021)

Thorsten Mauritsen

Journal of Climate 34, 1, 39–55 https://doi.org/10.1175/JCLI-D-19-0941.1

*#climate feedbacks #climate sensitivity #climate forcers #SST patterns*

Natural variability in sea surface temperature (SST) patterns over the historical period have been thought to lead to low estimates of climate sensitivity based on instrumental records. This pattern effect (the effect of evolving surface temperature patterns on climate feedback strength) has been found in simulations using GCMs driven by the SST from the AMIPII dataset and sea ice changes. Lewis and Mauritsen show that whether natural variability in the historical pattern effect is found depends on the underlying SST dataset used. If it is as small over the historical record as the findings suggest, the SST patterns are unlikely to significantly bias climate sensitivity estimates based on long-term instrumental observations.

### The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018 (Lee et al. 2021)

Piers Forster

Atmospheric Environment 244, 117834 https://doi.org/10.1016/j.atmosenv.2020.117834

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#climate forcers #clouds #metrics*

The growth in aviation since 1960, and especially from 2013–2018, has led to an increase in climate impacts, with CO2 emissions increasing by a factor of 6.8 to 1034 Tg CO2 yr−1.  Lee et al. present a new approach for evaluating the climate impacts of aviation, in terms of both radiative forcing (RF) and effective radiative forcing (ERF) and provide these values for 2000–2018. Contrail cirrus (contrails plus the cirrus cloudiness they lead to) produce the largest warming, followed by CO2 and NOx, whereas the formation and emission of sulfate aerosols leads to cooling. For 2018, the net aviation ERF is +100.9 milliwatts m−2 with major contributions from contrail cirrus, CO2, and NOx.  More than half of the aviation net ERF was due to non-CO2 emissions.  Based on global warming potentials (GWP*), total aviation emissions are currently warming the climate at approximately three times the rate of aviation CO2 emissions alone.

## Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement (Schleussner et al. 2019)

**Carl-Friedrich Schleussner**, Alexander Nauels, Joeri Rogelj

Environmental Research Letters 14, 12, 124055 https://doi.org/10.1088/1748-9326/ab56e7

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 14**: International cooperation*

*#climate forcers #metrics #Paris Agreement #climate policy #mitigation pathways*

Addressing non-CO2 greenhouse gas (GHG) emissions is integral to both climate change mitigation and climate policy. Comparing emissions of short- and long-lived GHGs needs to account for differences in their effects on climate, and their persistence. Different metrics give different estimates, and so GHG emissions reduction targets need to take account of these metrics. Schleussner et al. present the impact that a recently proposed GHG metric (GWP*) would have on the Paris Agreement.  They show that interpreting the Paris Agreement goals using a metric like GWP* can lead to inconsistencies, potentially even undermining the agreement, and that great care is needed when applying new concepts to existing climate policy.

## Unintentional unfairness when applying new greenhouse gas emissions metrics at country level (Rogelj et al. 2019b)

**Joeri Rogelj**, Carl-Friedrich Schleussner

Environmental Research Letters 14, 11, 114039 https://doi.org/10.1088/1748-9326/ab4928

*Also relevant to **WGIII Chapter 3**: Mitigation pathways compatible with long-term goals; and **WGIII Chapter 14**: International cooperation*

*#metrics #climate forcers #Paris Agreement #mitigation pathways #climate policy*

The Paris Agreement sets out that rapid reductions in GHG emissions are needed to keep global warming to safe levels. A new approach, known as GWP* has been suggested as a way of comparing long- and short-lived GHGs. However, comparisons of non-CO2 GHGs using GWP* metrics depend on past emissions, raising questions of equity and fairness when applied below global levels. GWP* would put most developing countries at a disadvantage, and national emission estimates that use GWP* are very sensitive to arbitrary choices. GHG metrics like GWP* should therefore only be used at the global level, and a common, transparent and equitable accounting metric is vital for the Paris Agreement's effectiveness and integrity.

### The HadGEM3-GA7.1 radiative kernel: the importance of a well-resolved stratosphere (Smith et al. 2020b)

Christopher J. Smith

Earth System Science Data 12, 2157–2168 https://doi.org/10.5194/essd-12-2157-2020

*#climate forcers #model evaluation*

Smith et al. present top-of-atmosphere and surface radiative kernels based on the atmospheric component (GA7.1) of the UK Met Office HadGEM3 general circulation model. They show that the use of radiative kernels for forcing adjustments in idealised CO2 perturbation experiments is greatest where there is sufficiently high resolution in the stratosphere in both the climate model and the radiative kernel. This is because stratospheric cooling to a CO2 perturbation continues to increase with height, and low-resolution kernels or climate model output are unable to fully resolve the full stratospheric temperature adjustment. The standard atmospheric model data available in CMIP6 represents a substantial advantage over CMIP5.

### How large does a large ensemble need to be? (Milinski et al. 2020)

Dirk Olonscheck

Earth System Dynamics 11, 885–901 https://doi.org/10.5194/esd-11-885-2020

*Also relevant to **WGI Chapter 4**: Future global climate*

*#climate forcers #model evaluation #internal variability*

Large model ensembles with 30 to 100 members are commonly used to quantify the forced response and internal variability in various components of the climate system. Ensemble size is relevant for designing or choosing a large ensemble, as well as for designing targeted sensitivity experiments, but there is no consensus on the ideal or even sufficient size for a large ensemble. Milinski et al. introduce an objective method to estimate the required ensemble size and demonstrate its use for global mean near-surface air temperature, local temperature and precipitation, and variability in the El Niño–Southern Oscillation (ENSO) region and central United States for the Max Planck Institute Grand Ensemble (MPI-GE). They show that more ensemble members are needed to quantify variability than forced response, with the largest ensemble sizes needed to detect changes in internal variability. The required ensemble size also depends on the quantity being studied and the error acceptable to the user.

### Presentation and evaluation of the IPSL-CM6A-LR climate model (Boucher et al. 2020)

**Olivier Boucher**, Rémy Bonnet, Sandrine Bony, Jean-Louis Dufresne, Jessica Vial

Journal of Advances in Modelling Earth Systems 12, 7, e2019MS002010
https://doi.org/10.1029/2019MS002010

*#internal variability #climate forcers #climate sensitivity #climate feedbacks #model evaluation*

This study presents the global climate model IPSL-CM6A-LR, developed at IPSL to study natural climate variability and climate response to natural and anthropogenic forcings as part of CMIP6. The model's climatology, particularly in terms of radiation, temperature, precipitation, and wind, is strongly improved compared to previous versions, although several biases common to many models persist. The equilibrium climate sensitivity and transient climate response have both increased from the previous version used in CMIP5.

### On the structure of instantaneous radiative forcing kernels for greenhouse gases (Maycock et al. 2020)

**Amanda C. Maycock**, Christopher J. Smith

Journal of the Atmospheric Sciences Early Online Release https://doi.org/10.1175/JAS-D-19-0267.1

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers*

*#climate forcers #climate feedbacks*

The SOCRATES offline radiative transfer code is used to investigate the magnitude and structure of the instantaneous radiative forcing kernels (IRFKs) for five major greenhouse gases (GHGs, CO2, CH4, N2O, CFC-11, and O3). All gases produce IRFKs that peak in the tropical upper troposphere, but the variation in current background concentration of gases substantially affects the size of the IRFK. For example, when the background concentration of CO2 is reduced from parts per million to parts per trillion, the peak of the IRFK increases by a factor of 642. The altitude of the IRFK maximum also differs, with most gases peaking near 150-200 hPa. Overall, the use of IRFKs to estimate IRF is accurate for small perturbations but becomes inaccurate for larger changes in concentration (e.g. a doubling).

### Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al. accepted)

Olivier Boucher, Jim Haywood, Pierre Nabat, Roland Séférian

Atmospheric Chemistry and Physics Discussions https://doi.org/10.5194/acp-2020-732

*#climate forcers*

Solar geoengineering has received increased attention in recent years as a potential temporary solution to offset global warming. One method of approximating global-scale solar geoengineering in climate models is via solar reduction experiments. Two generations of models in the Geoengineering Model Intercomparison Project (GeoMIP) have simulated offsetting a quadrupling of CO2 concentration with solar reduction, an experiment designed to elicit large responses in the models. Kravitz et al. show that energetics, temperature, and hydrological cycle changes in this experiment are statistically indistinguishable between the two ensembles and the only major differences involve highly parameterized and uncertain processes. They conclude that the model response to global solar dimming remains robust.

### For other papers relevant to the Earth’s energy budget, climate feedbacks, and climate sensitivity see also:

**WGI Chapter 4: Future global climate: scenario-based projections and near-term information**

- Latest climate models confirm need for urgent mitigation (Forster et al. 2020b) https://doi.org/10.1038/s41558-019-0660-0

  *#near-term projections #climate sensitivity #mitigation pathways*

- Making climate projections conditional on historical observations (Ribes et al. 2021) https://doi.org/10.1126/sciadv.abc0671

  *#near-term projections #climate sensitivity #mitigation pathways*

- Past warming trend constrains future warming in CMIP6 models (Tokarska et al. 2020a) https://doi.org/10.1126/sciadv.aaz9549

  *#near-term projections #emergent constraints #climate sensitivity*

**WG1 Chapter 5: Global carbon and other biogeochemical cycles and feedbacks**

- Recommended temperature metrics for carbon budget estimates, model evaluation and climate policy (Tokarska et al. 2019a) https://doi.org/10.1038/s41561-019-0493-5

  *#carbon budgets #model evaluation #metrics #Paris Agreement #climate policy*

- Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth system processes in present-day and future climate (Séférian et al. 2019) https://doi.org/10.1029/2019MS001791

  *#sources and sinks #model evaluation #climate feedbacks #climate forcers*

**WGI Chapter 6: Short-lived climate forcers**

- Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models (Thornhill et al. 2021a) https://doi.org/10.5194/acp-21-1105-2021

  *#climate forcers #aerosol forcing #climate feedbacks #climate sensitivity*

- Efficacy of climate forcings in PDRMIP models (Richardson et al. 2019) https://doi.org/10.1029/2019JD030581

  *#climate forcers #model evaluation #climate sensitivity #aerosol forcing*

- Trends in AOD, clouds, and cloud radiative effects in satellite data and CMIP5 and CMIP6 model simulations over aerosol source regions (Cherian and Quaas 2020) https://doi.org/10.1029/2020GL087132

  *#aerosol forcing #clouds*

- Present-day and historical aerosol and ozone characteristics in CNRM CMIP6 simulations (Michou et al. 2019) https://doi.org/10.1029/2019MS001816

  *#climate forcers #aerosol forcing #clouds #model evaluation*

**WGI Chapter 9: Ocean, cryosphere, and sea level change**

- Multiple drivers of the North Atlantic warming hole (Keil et al. 2020) https://doi.org/10.1038/s41558-020-0819-8

*#ocean circulation and heat content #regional observations and phenomena #clouds #climate feedbacks*

**WGI Chapter 10: Linking global to regional climate change**

- Observational evidence for a stability Iris effect in the Tropics (Saint-Lu et al. 2020) https://doi.org/10.1029/2020GL089059

  *#regional observations and phenomena #clouds #climate feedbacks*

- A sensitivity study of Arctic air-mass transformation using large eddy simulation (Dimitrelos et al. 2020) https://doi.org/10.1029/2019JD031738

  *#regional observations and phenomena #clouds*

- A new look at the daily cycle of trade wind cumuli (Vial et al. 2019) https://doi.org/10.1029/2019MS001746

  *#regional observations and phenomena #regional precipitation #clouds*

- Sugar, gravel, fish, and flowers: Dependence of mesoscale patterns of trade-wind clouds on environmental conditions (Bony et al. 2020) https://doi.org/10.1029/2019GL085988

  *#regional observations and phenomena #clouds #climate feedbacks*

- Shallow Cumulus Cloud Feedback in Large Eddy Simulations - Bridging the Gap to Storm Resolving Models (Radtke et al. in press)

  *#clouds #climate feedbacks #regional observations and phenomena*

- The Southern Hemisphere midlatitude circulation response to rapid adjustments and sea surface temperature driven feedbacks (Wood et al. 2020)

  *#regional observations and phenomena #climate feedbacks #clmate forcers*

- Decomposing the response of the stratospheric Brewer–Dobson circulation to an abrupt quadrupling in CO2 (Chrysanthou et al. 2020) https://doi.org/10.5194/wcd-1-155-2020

  *#SST patterns #climate forcers*

## WG1 Chapter 8: Water cycle changes

### Key knowledge gains:

- Precipitation from intense oceanic cyclones in the mid-latitudes increases by 7% with each K of warming, and their future precipitation change could potentially be projected using a reliable global precipitation observation network (Kodama et al. 2019).
- Although some aspects of tropical precipitation representation have improved in CMIP6 models, alternative approaches could better inform how tropical precipitation might change with anthropogenic warming (Fiedler et al. 2020).

### A new perspective for future precipitation change from intense extratropical cyclones (Kodama et al. 2019)

Bjorn Stevens, Thorsten Mauritsen

Geophysical Research Letters 46, 21, 12435-12444 https://doi.org/10.1029/2019GL084001

*Also relevant to **WGI Chapter 10**: Linking global to regional climate change*

*#regional observations and phenomena #regional precipitation*

Extratropical cyclones are major contributors to precipitation in the midlatitudes. They include intense oceanic cyclones that pose a natural hazard, making reliable projections of future change with global warming of great interest. Kodama et al. analyze the first ever global climate simulations of these oceanic extratropical cyclones, and find that their structure, frequency, and precipitation compare well with satellite observations. Simulated precipitation from intense oceanic cyclones increases at a rate of 7% per K of warming. In addition, the rate of precipitation change is closely related to the current precipitation contrast between the northern and southern hemispheres, suggesting that future precipitation change associated with intense oceanic cyclones could be projected using a reliable global precipitation observation network.

### Simulated tropical precipitation assessed across three major phases of the Coupled Model Intercomparison Project (CMIP) (Fiedler et al. 2020)

Tobias Becker, Maria Rugenstein, Bjorn Stevens

Monthly Weather Review 148, 9, 3653–3680 https://doi.org/10.1175/MWR-D-19-0404.1

*Also relevant to **WGI Chapter 10**: Linking global to regional climate change*

*# regional observations and phenomena #regional precipitation #model evaluation*

Tropical precipitation is evaluated across models from CMIPs 3,5 and 6. There are some improvements in tropical precipitation in the CMIP6 models, but no general improvement on different temporal and spatial scales, whilst tropical precipitation occurs still too frequently. There are however continuous improvements across the CMIP phases for the number of consecutive dry days, for the Madden–Julian oscillation and El Niño–Southern Oscillation, and for the trends in dry months in the twentieth century. The observed increase in extreme wet months is, however, not captured by any of the CMIP phases, and the regional biases are larger than the climate change signal one hopes to use the models to identify. Fiedler et al. suggest exploring alternative approaches such as high-resolution storm-resolving models that can better inform us about how tropical precipitation might change with anthropogenic warming.

## For other papers relevant to water cycle changes see also:

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- The effect of rapid adjustments to halocarbons and N2O on radiative forcing (Hodnebrog et al. 2020) https://doi.org/10.1038/s41612-020-00150-x

  *#climate forcers #clouds*

**WGI Chapter 10: Linking global to regional climate change**

- A new look at the daily cycle of trade wind cumuli (Vial et al. 2019) https://doi.org/10.1029/2019MS001746

  *#regional observations and phenomena #regional precipitation #clouds*

**WGI Chapter 6: Short-lived climate forcers**

- Analysis of polarimetric satellite measurements suggests stronger cooling due to aerosol-cloud interactions (Hasekamp et al. 2019) https://doi.org/10.1038/s41467-019-13372-2

  *#aerosol forcing #clouds*

## WGI Chapter 9: Ocean, cryosphere, and sea level change

### Key knowledge gains:

- Progress has been made in understanding how several phenomena will respond to temperature increase, including the North Atlantic warming hole, the evolution of which is dominated by increased ocean heat transport out of the region to higher latitudes and shortwave cloud feedbacks (Keil et al. 2020).
- Regional temperature increases could potentially lead to both increases and decreases in eddy activity (Yuval and Kaspi 2020).

### Multiple drivers of the North Atlantic warming hole (Keil et al. 2020)

Thorsten Mauritsen, Dirk Olonscheck

Nature Climate Change 10, 667–671 https://doi.org/10.1038/s41558-020-0819-8

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity; and **WGI Chapter 10**: Linking global to regional climate change*

*#ocean circulation and heat content #regional observations and phenomena #clouds #climate feedbacks*

A region in the North Atlantic Ocean has been observed to cool, a phenomenon known as the warming hole. This has been linked to a slowdown of the Atlantic meridional overturning circulation, which reduces ocean heat transport into the region. Keil et al. show that with global warming, increased ocean heat transport out of the region to higher latitudes and shortwave cloud feedback dominate how the warming hole evolves. Climate model simulations also show that accelerating heat transport to higher latitudes is attributable to anthropogenic forcing, whereas the slowdown in overturning circulation is within the bounds of natural variability. Both processes are critical to understanding the past and future evolution of the warming hole.

### Eddy activity response to global warming–like temperature changes (Yuval and Kaspi 2020)

Yohai Kaspi

Journal of Climate 33, 4, 1381–1404 https://doi.org/10.1175/JCLI-D-19-0190.1

*Also relevant to **WGI Chapter 10**: Linking global to regional climate change*

*#ocean circulation and heat content #regional observations and phenomena*

Global warming projections show anomalous temperature increases both at surface level in the Arctic and in the upper troposphere at lower latitudes. Yuval and Kaspi find that these temperature increases could potentially lead to both increases and decreases in eddy activity. Using state-of-the art models, they find that the changes to eddy energy are dominated by the lower-latitude upper-troposphere warming, whereas eddy heat flux changes are dominated by the Arctic amplification.

## Projected land ice contributions to 21st century sea level rise (Edwards et al. in press)

Christine M. McKenna, Christopher J. Smith

Paper in press with Nature and under embargo at the time of publication of this document.

## For other papers relevant to ocean, cryosphere and sea level change see also:

**WGI Chapter 5: Global carbon and other biogeochemical cycles and feedbacks**

- Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot (Tokarska et al. 2019b)

  *#carbon budgets #mitigation pathways #ocean circulation and heat content #Paris Agreement*

- Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2 (MacDougall et al. 2020) https://doi.org/10.5194/bg-17-2987-2020

  *#carbon budgets #model evaluation #mitigation pathways #climate feedbacks #climate forcers #ocean circulation and heat content*

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- Broad consistency between observed and simulated trends in sea surface temperature patterns (Olonscheck et al. 2020) https://doi.org/10.1029/2019GL086773

  *#SST patterns #internal variability*

**WGI Chapter 10: Linking global and regional climate change**

- The effect of anthropogenic aerosols on the Aleutian Low (Dow et al. 2021) https://doi.org/10.1175/JCLI-D-20-0423.1

  *#regional observations and phenomena #aerosol forcing #ocean circulation and heat content*

## WGI Chapter 10: Linking global to regional climate change

### Key knowledge gains:

- New understanding has been gained in several areas of cloud behaviour and effects, including anvil clouds in the tropics (Saint-Lu et al. 2020), Arctic clouds and their warming effect on sea ice (Dimitrelos et al. 2020), shallow cumulus cloud formation in the trades (Vial et al. 2019, Radtke et al. in press), and the various patterns and amounts of trade-wind clouds (Bony et al. 2020).
- Further knowledge has been gained on the poleward shift of the Southern Hemisphere jet stream (Wood et al. 2021), the influence of anthropogenic aerosols on the Pacific decadal oscillation (PDO) and Aleutian low (Dow et al. 2021), southern hemisphere circulation (Wood et al. 2020), the Brewer-Dobson circulation (Chrysanthou et al. 2020), and the equatorial Pacific sea surface temperature gradient (Watanabe et al. 2021).
- As well as increasing understanding of regional phenomena, these developments have implications for climate feedbacks, climate sensitivity, patterns of circulation, and the climate response to warming.

### Observational evidence for a stability Iris effect in the Tropics (Saint-Lu et al. 2020)

Sandrine Bony, Jean-Louis Dufresne

Geophysical Research Letters 47, 14, e2020GL089059 https://doi.org/10.1029/2020GL089059

*Also relevant to **WGI Chapter 7**: Earth's energy budget, climate feedbacks, and climate sensitivity*

*#regional observations and phenomena #clouds #climate feedbacks*

Anvil clouds cover extensive areas of the tropics, and their response to global warming can affect cloud feedbacks and climate sensitivity. A growing number of models and theories suggest that when the tropical atmosphere warms, anvil clouds rise and their coverage decreases, but observations are limited. Saint-Lu et al. use measurements from the spaceborne CALIPSO lidar to analyze the behavior of anvil clouds, finding strong evidence for anvil rise and coverage decrease in response to tropical warming, associated with an increase in static stability and a reduction in clear sky radiatively-driven mass convergence at the anvil height. This is consistent with the stability Iris mechanism suggested by theory and modelling studies.

### A sensitivity study of Arctic air-mass transformation using large eddy simulation (Dimitrelos et al. 2020)

Rodrigo Caballero

JGR Atmospheres 125, e2019JD031738 https://doi.org/10.1029/2019JD031738

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#regional observations and phenomena #clouds*

Arctic air mass transformation is linked to the evolution of low-level mixed-phase clouds. Knowing the sensitivity of these clouds to different parameters and physical processes helps to predict the cloud lifetime and radiative properties, and thus the warming effect on the sea ice surface. Dimitrelos et al. examine the lifecycle of these clouds during winter when there is advection of moist and warm air over sea ice. The results show that radiative cooling at the surface gives rise to fog, which subsequently rises and transforms into a mixed-phase cloud. The cloud persists for about 5 days and increases the surface temperature by on average 17 °C. With increased ice crystal concentrations, the surface temperature is on average 6 °C cooler. Increasing the number of cloud condensation nuclei (ice crystals) therefore leads to a form of the cloud that only weakly warms the surface.

## A new look at the daily cycle of trade wind cumuli (Vial et al. 2019)

**Jessica Vial**, Sandrine Bony, Bjorn Stevens

Journal of Advances in Modeling Earth Systems 11, 10, 3148-3166
https://doi.org/10.1029/2019MS001746

*Also relevant to **WGI Chapter 7:** The Earth's energy budget, climate feedbacks, and climate sensitivity; and **WGI Chapter 8**: Water cycle changes*

*#regional observations and phenomena #regional precipitation #clouds*

Vial et al. describe the daily cycle of oceanic shallow cumulus clouds during winter in the North Atlantic Trades. Models and observations clearly show pronounced daily variations in cloudiness, both near cloud base and below the trade inversion. The daily cycle reflects the evolution of two cloud populations: (i) nonprecipitating small cumuli with weak vertical extent, which grow during the day to a maximum around sunset, and (ii) deeper precipitating clouds with a stratiform cloud layer below the trade inversion, which grow during the night to a maximum just before sunrise. They find that cloudiness near cloud base, thought to be key a determinant of the Earth's climate response to warming, can vary strongly on these timescales. This daily cycle could be used to test how models represent the physical processes controlling cloudiness near cloud base.

## Shallow cumulus cloud feedback in large eddy simulations - bridging the gap to storm resolving models (Radtke et al. in press)

Thorsten Mauritsen

Atmospheric Chemistry and Physics Discussions https://doi.org/10.5194/acp-2020-1160 (preprint)

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#clouds #climate feedbacks #regional observations and phenomena*

The response of shallow trade cumulus clouds to global warming is a leading source of uncertainty in interpreting the Earth's climate and making climate projections. Radtke et al. use field observations to simulate shallow trade wind cumulus clouds using a climate model in a control and a 4K warmed climate. The overall vertical structure of the cloud layer is surprisingly robust across the model simulations. In the warmer climate, cloud cover reduces, constituting a positive shortwave cloud feedback. Cloud thickening, resulting from more water vapor in a warmer climate, acts as a compensating feedback. The feedbacks however depend on the model resolution dependence, and overall suggest that storm resolving models may exaggerate the trade wind cumulus cloud feedback.

## Sugar, gravel, fish, and flowers: Dependence of mesoscale patterns of trade-wind clouds on environmental conditions (Bony et al. 2020)

Sandrine Bony, Jessica Vial, Bjorn Stevens

Geophysical Research Letters 47, 10, e2019GL085988 https://doi.org/10.1029/2019GL085988

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#regional observations and phenomena #clouds #climate feedbacks*

Satellite images show that trade-wind clouds in the tropics exhibit a diverse range of patterns. Over the tropical western Atlantic, these patterns are referred to as flowers, fish, gravel, and sugar. Bony et al. show that these four patterns can be identified via satellite measurements. On daily and year-to-year timescales, near-surface wind speed and the stability of the lower atmosphere determine the occurrence of the different patterns. Each pattern is also associated with a different cloud amount, impacting the radiative cooling of the Earth differently. The results suggest global warming might affect the frequency of different cloud patterns, which might in turn affect the Earth's radiative response to warming in a way that has not been previously considered.

## Role of sea surface temperature patterns for the Southern Hemisphere jet stream response to CO2 forcing (Wood et al. 2021)

Christine M McKenna, Amanda C Maycock

Environmental Research Letters 16, 014020 https://doi.org/10.1088/1748-9326/abce27

*#regional observations and phenomena #SST patterns*

The Southern Hemisphere eddy-driven jet stream has been shown to move poleward in climate models in response to greenhouse gas forcing, but the magnitude of this shift is uncertain. CMIP6 models simulate a smaller shift of the jet than CMIP5 in response to an abrupt quadrupling in $CO_2$, despite their larger global average surface warming. Most of the long-term jet shift occurs in the first decade, when the difference between CMIP5 and CMIP6 models emerges. Wood et al. suggest the smaller poleward jet shift in CMIP6 is related to the weaker increase in the southerly sea surface temperature (SST) gradient across the southern extratropics, and that SST patterns are an important source of uncertainty for the shift of midlatitude circulation in response to $CO_2$ forcing.

## The effect of anthropogenic aerosols on the Aleutian Low (Dow et al. 2021)

Amanda C. Maycock, Christopher J. Smith

Journal of Climate 34, 5, 1725–1741 https://doi.org/10.1175/JCLI-D-20-0423.1

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers; and **WGI Chapter 9**: Ocean, cryosphere, and sea level change*

*#aerosol forcing #regional observations and phenomena #ocean circulation and heat content*

Past studies have suggested that regional trends in anthropogenic aerosols can influence the Pacific decadal oscillation (PDO) through modifying the Aleutian low. This study analyses changes to the

Aleutian low in climate models forced with global and regional black carbon (BC) and sulfate aerosol. The results show the Aleutian low weakened by a tenfold global increase in BC. This is linked to heating from BC absorption over India and East Asia, whilst sources of BC outside of East Asia enhance the weakening of the Aleutian low. The responses of the Aleutian low to global and regional increases in sulfate aerosols over Asia are not consistent across the climate models, and are not strong, differing from previous studies which suggest the increase in sulfate aerosols over Asia during the early twenty-first century weakened the Aleutian low and affected the PDO.

## The Southern Hemisphere midlatitude circulation response to rapid adjustments and sea surface temperature driven feedbacks (Wood et al. 2020)

Amanda C. Maycock, Piers Forster, Timothy Andrews, Olivier Boucher, Gunnar Myhre, Bjørn Samset

Journal of Climate 33, 22, 9673 -9690 https://doi.org/10.1175/JCLI-D-19-1015.1

*Also relevant to **WGI Chapter 6**: Short-lived climate forcers and **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#regional observations and phenomena #climate feedbacks #clmate forcers*

Rapid adjustments can affect the midlatitude circulation and contribute to long-term circulation responses in climate simulations. This study examines rapid adjustments in the Southern Hemisphere (SH) circulation using nine models from the Precipitation Driver and Response Model Intercomparison Project (PDRMIP) for a doubling of carbon dioxide; a tripling of methane, a fivefold increase in sulfate aerosol, a tenfold increase in black carbon aerosol, and a 2% increase in solar constant. In coupled ocean experiments, the SH eddy-driven jet shifts poleward and strengthens with global warming, with the strongest response found in austral summer, but results vary for the different forcings, demonstrating the need to understand rapid adjustments in the region as well as the effect of changing sea surface temperatures (SSTs).

## Decomposing the response of the stratospheric Brewer–Dobson circulation to an abrupt quadrupling in CO2 (Chrysanthou et al. 2020)

Amanda C. Maycock

Weather and Climate Dynamics 1, 155–174 https://doi.org/10.5194/wcd-1-155-2020

*Also relevant to **WGI Chapter 7**: The Earth's energy budget, climate feedbacks, and climate sensitivity*

*#SST patterns #climate forcers*

Chrysanthou et al. use the UK Met Office HadGEM3-A model to break down the long-term (101–150 year) response of the Brewer–Dobson circulation (BDC) to an abrupt quadrupling in CO2 into (1) a rapid atmospheric adjustment, (2) a contribution from the global-average sea surface temperature (SST) change (+3.4K), and (3) an SST pattern effect. The results confirm the most important factor for the acceleration of the BDC in the lower stratosphere under increased CO2 is global SST changes. They also quantify for the first time that the rapid adjustment to CO2 is of similar importance to SSTs for the increased BDC in the upper stratosphere. This demonstrates a potential for a fast and slow timescale of the response of the BDC to greenhouse gas forcing, with the relative prominence of those timescales being height dependent.

## Enhanced warming constrained by past trends in equatorial Pacific sea surface temperature gradient (Watanabe et al. 2021)

Thorsten Mauritsen

Nature Climate Change 11, 33–37 https://doi.org/10.1038/s41558-020-00933-3

*#regional observations and phenomena #natural variability #SST patterns*

The equatorial Pacific zonal sea surface temperature (SST) gradient, known to be a pacemaker of global warming, has strengthened since the mid-twentieth century. However, most CMIP5 models suggest a weakening of the gradient from the past to the future. Watanabe et al. show that the intensifying SST gradient from 1951–2010 could be due to internal climate variability. Models that simulate historical strengthening of the SST gradient commonly exhibit reversed future trends. Using these models as a constraint, the rate of global-mean temperature rise is amplified by 9–30%, with higher values occurring in low-emission scenarios, because internal variability has a greater impact when the externally forced response is smaller.

## For other papers relevant to linking global and regional climate change see also:

**WGI Chapter 4: Future global climate: scenario-based projections and near-term information**

- Incremental improvements of 2030 targets insufficient to achieve the Paris Agreement goals (Geiges et al. 2020) https://doi.org/10.5194/esd-11-697-2020

  *#mitigation pathways #climate policy #Paris Agreement*

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- Understanding the extreme spread in climate sensitivity within the Radiative-Convective Equilibrium Model Intercomparison Project (Becker and Wing 2020) https://doi.org/10.1029/2020MS002165

  *#climate sensitivity #climate feedbacks #clouds #model evaluation #regional observations and phenomena*

- Clouds and convective self-aggregation in a multimodel ensemble of radiative-convective equilibrium simulations (Wing et al. 2020) https://doi.org/10.1029/2020MS002138

  *#clouds #climate sensitivity #climate feedbacks #model evaluation*

**WGI Chapter 9: Ocean, cryosphere, and sea level change**

- Multiple drivers of the North Atlantic warming hole (Keil et al. 2020) https://doi.org/10.1038/s41558-020-0819-8

  *#ocean circulation and heat content #regional observations and phenomena #clouds #climate feedbacks*

- Eddy activity response to global warming–like temperature changes (Yuval and Kaspi 2020) https://doi.org/10.1175/JCLI-D-19-0190.1

*#ocean circulation and heat content #regional observations and phenomena*

**WGI Chapter 8: Water cycle changes**

- A new perspective for future precipitation change from intense extratropical cyclones (Kodama et al. 2019) https://doi.org/10.1029/2019GL084001

  *#regional observations and phenomena #regional precipitation*

- Simulated Tropical Precipitation Assessed across Three Major Phases of the Coupled Model Intercomparison Project (CMIP) (Fiedler et al. 2020) https://doi.org/10.1175/MWR-D-19-0404.1

  *# regional observations and phenomena #regional precipitation*

# CONSTRAIN & AR6 Working Group III: Mitigation of climate change

Although CONSTRAIN's main focus is a contribution to the physical science basis assessed by AR6 Working Group I (WGI), many of its publications are also highly relevant to Working Group III (WGIII), particularly in terms of mitigation pathways and international climate policy.

Key papers described above are listed again here under the relevant WGIII chapter.

## WGIII Chapter 2: Emissions trends and drivers

**WG1 Chapter 5: Global carbon and other biogeochemical cycles and feedbacks**

- Global Carbon Budget 2020 (Friedlingstein et al. 2020) https://doi.org/10.5194/essd-12-3269-2020

  *#carbon budgets #internal variability #sources and sinks*

## WGIII Chapter 3: Mitigation pathways compatible with long-term goals

**WG1 Chapter 4: Future global climate: scenario-based projections and near-term information**

- Stringent mitigation substantially reduces risk of unprecedented near-term warming rates (McKenna et al. 2021) https://doi.org/10.1038/s41558-020-00957-9

  *#near-term projections #internal variability #mitigation pathways #Paris Agreement*

- Current and future global climate impacts resulting from COVID-19 (Forster et al. 2020a) https://doi.org/10.1038/s41558-020-0883-0

  *#near-term projections #mitigation pathways #Paris Agreement #NDCs #climate policy*

- Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research (Lamboll et al. 2020) https://doi.org/10.5194/gmd-13-5259-2020

  *#near-term projections #climate forcers #mitigation pathways*

- Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6 (Tebaldi et al. accepted) https://doi.org/10.5194/esd-2020-68

  *#model evaluation #internal variability #mitigation pathways*

- Incremental improvements of 2030 targets insufficient to achieve the Paris Agreement goals (Geiges et al. 2020) https://doi.org/10.5194/esd-11-697-2020

  *#mitigation pathways #climate policy #Paris Agreement*

- Latest climate models confirm need for urgent mitigation (Forster et al. 2020b) https://doi.org/10.1038/s41558-019-0660-0

*#near-term projections #climate sensitivity #mitigation pathways*

- Making climate projections conditional on historical observations (Ribes et al. 2021) https://doi.org/10.1126/sciadv.abc0671

  *#near-term projections #climate sensitivity #mitigation pathways*

- Past warming trend constrains future warming in CMIP6 models (Tokarska et al. 2020a) https://doi.org/10.1126/sciadv.aaz9549

  *#near-term projections #emergent constraints #climate sensitivity #mitigation pathways*

**WG1 Chapter 5: Global carbon and other biogeochemical cycles and feedbacks**

- An integrated approach to quantifying uncertainties in the remaining carbon budget (Tokarska et al. 2021) https://doi.org/10.1038/s43247-020-00064-9

  *#carbon budgets #mitigation pathways*

- Uncertainty in carbon budget estimates due to internal climate variability (Tokarska et al. 2020b) https://doi.org/10.1088/1748-9326/abaf1b

  *#carbon budgets #model evaluation #internal variability*

- Opportunities and challenges in using remaining carbon budgets to guide climate policy (Matthews et al. 2020) https://doi.org/10.1038/s41561-020-00663-3

  *#carbon budgets #mitigation pathways #Paris Agreement #climate policy*

- Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot (Tokarska et al. 2019b)

  *#carbon budgets #mitigation pathways #ocean circulation and heat content #Paris Agreement*

- Estimating and tracking the remaining carbon budget for stringent climate targets (Rogelj et al. 2019a) https://doi.org/10.1038/s41586-019-1368-z

  *#carbon budgets #mitigation pathways #climate feedbacks #Paris Agreement #climate policy*

- The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions (Jones et al. 2019) https://doi.org/10.5194/gmd-12-4375-2019

  *#carbon budgets #model evaluation #mitigation pathways*

- Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2 (MacDougall et al. 2020) https://doi.org/10.5194/bg-17-2987-2020

  *#carbon budgets #model evaluation #mitigation pathways #climate feedbacks #climate forcers #ocean circulation and heat content*

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement (Schleussner et al. 2019) https://doi.org/10.1088/1748-9326/ab56e7

*#climate forcers #metrics #Paris Agreement #climate policy #mitigation pathways*

- Unintentional unfairness when applying new greenhouse gas emissions metrics at country level (Rogelj et al. 2019b) https://doi.org/10.1088/1748-9326/ab4928

  *#metrics #climate forcers #Paris Agreement #mitigation pathways #climate policy*

- Compatible Fossil Fuel CO2 emissions in the CMIP6 Earth System Models' Historical and Shared Socioeconomic Pathway experiments of the 21st Century (Liddicoat et al. 2020) https://doi.org/10.1175/JCLI-D-19-0991.1

  *#climate feedbacks #model evaluation #emissions pathways*

## WGIII Chapter 4: Mitigation & development pathways in the near- to mid-term

**WG1 Chapter 4: Future global climate: scenario-based projections and near-term information**

- Stringent mitigation substantially reduces risk of unprecedented near-term warming rates (McKenna et al. 2021) https://doi.org/10.1038/s41558-020-00957-9

  *#near-term projections #internal variability #mitigation pathways #Paris Agreement*

- Current and future global climate impacts resulting from COVID-19 (Forster et al. 2020a) https://doi.org/10.1038/s41558-020-0883-0

  *#near-term projections #mitigation pathways #Paris Agreement #NDCs #climate policy*

- Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research (Lamboll et al. 2020) https://doi.org/10.5194/gmd-13-5259-2020

  *#near-term projections #climate forcers #mitigation pathways*

- Incremental improvements of 2030 targets insufficient to achieve the Paris Agreement goals (Geiges et al. 2020) https://doi.org/10.5194/esd-11-697-2020

  *#mitigation pathways #climate policy #Paris Agreement*

## WGIII Chapter 14: International cooperation

**WGI Chapter 5: Global carbon and other biogeochemical cycles and feedbacks**

- Opportunities and challenges in using remaining carbon budgets to guide climate policy (Matthews et al. 2020) https://doi.org/10.1038/s41561-020-00663-3

  *#carbon budgets #mitigation pathways #Paris Agreement #climate policy*

- Recommended temperature metrics for carbon budget estimates, model evaluation and climate policy (Tokarska et al. 2019a) https://doi.org/10.1038/s41561-019-0493-5

*#carbon budgets #model evaluation #metrics #Paris Agreement #climate policy*

- Estimating and tracking the remaining carbon budget for stringent climate targets (Rogelj et al. 2019a) https://doi.org/10.1038/s41586-019-1368-z

  *#carbon budgets #mitigation pathways #climate feedbacks #Paris Agreement #climate policy*

**WGI Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity**

- Inconsistencies when applying novel metrics for emissions accounting to the Paris agreement (Schleussner et al. 2019) https://doi.org/10.1088/1748-9326/ab56e7

  *#climate forcers #metrics #Paris Agreement #climate policy #mitigation pathways*

- Unintentional unfairness when applying new greenhouse gas emissions metrics at country level (Rogelj et al. 2019b) https://doi.org/10.1088/1748-9326/ab4928

  *#metrics #climate forcers #Paris Agreement #mitigation pathways #climate policy*

## 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.

An update of this document detailing CONSTRAIN's full contribution to AR6 will be published once the Working Group reports are available.

## 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

Rosen, D.Z. and Clarke, J. (2021) CONSTRAIN journal publications and their relevance to IPCC AR6. Knowledge Gains: Summary and Implication Report 4. The CONSTRAIN Project doi:10.5281/zenodo.4535676

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

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