Lawrence Livermore National Laboratory

PCMDI
Earth System Model Evaluation Project

CMIP Forcings:
Where we've come from and where we're going

Paul J. Durack and the CMIP Climate Forcings Task Team

CMIP Coupled Model Intercomparison Project
Climate Forcings

CERES Science Team Meeting
LLNL, B170
October 2024

LLNL-PRES-869936

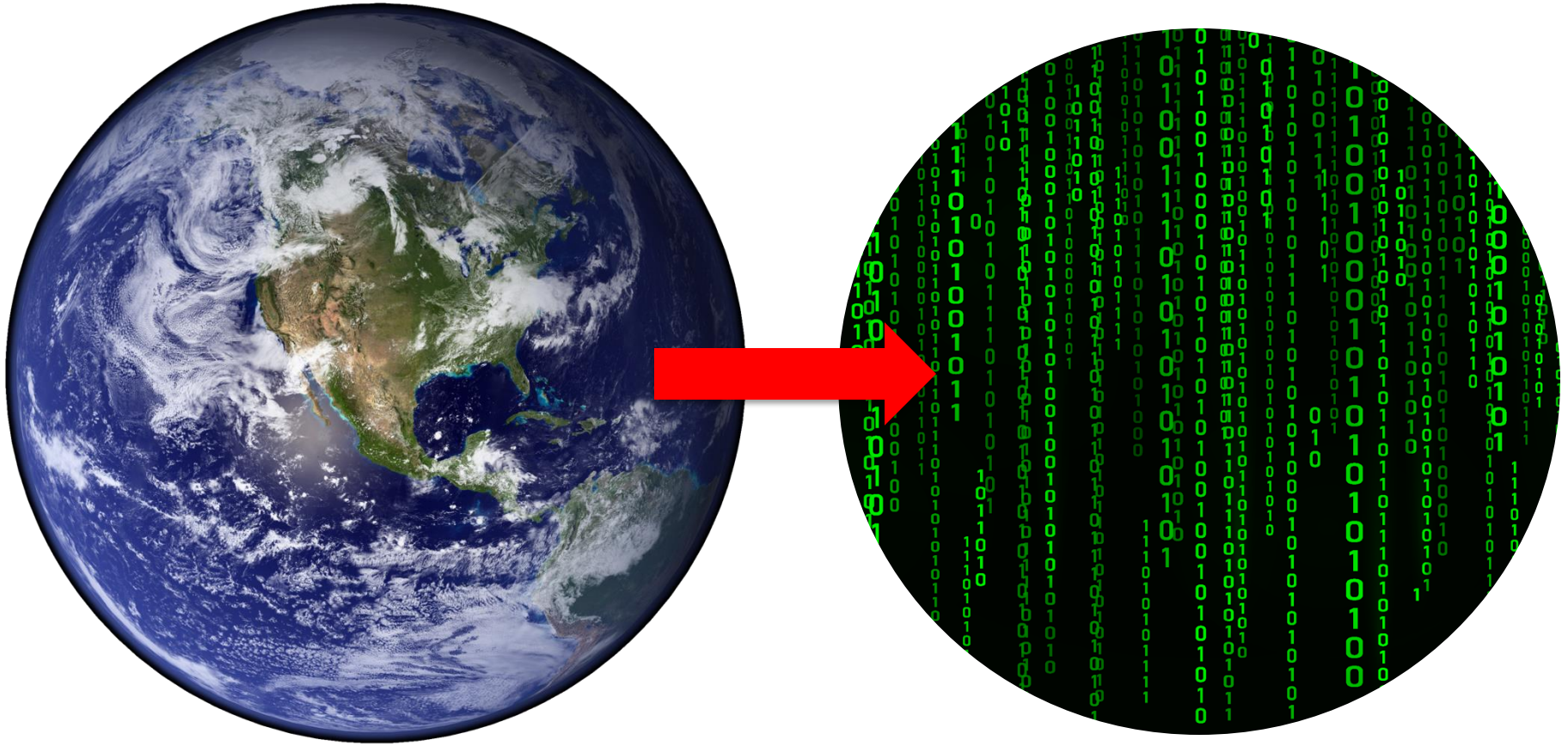
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Talk overview

- Climate model - 101 refresher
- Climate Model Intercomparison Projects (MIPs)
- MIPs and climate model evolution
- Climate forcing in MIPs
- CMIP6 – current and learnings
- CMIP7 – planning the next phase
- CMIP future

Climate model evolution

What is a climate model?



Climate model evolution

How do they work?

NOAA

Climate model evolution

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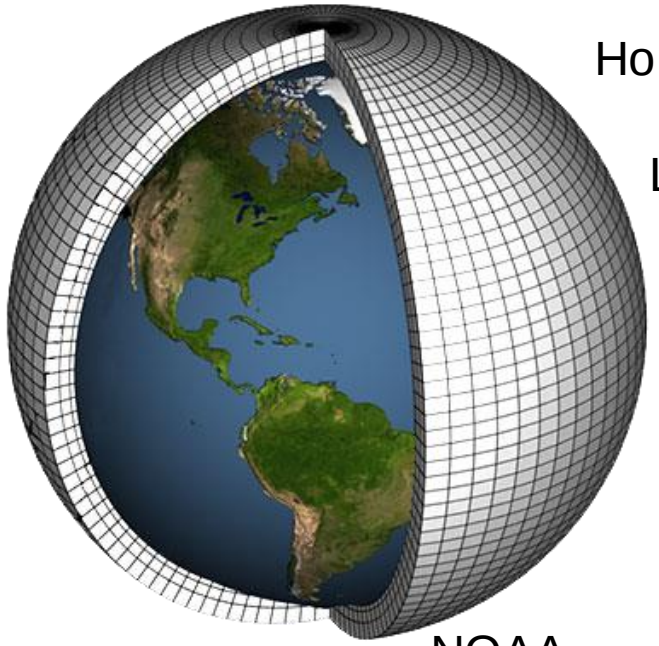

Horizontal Grid
Latitude
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NOAA

Climate model evolution

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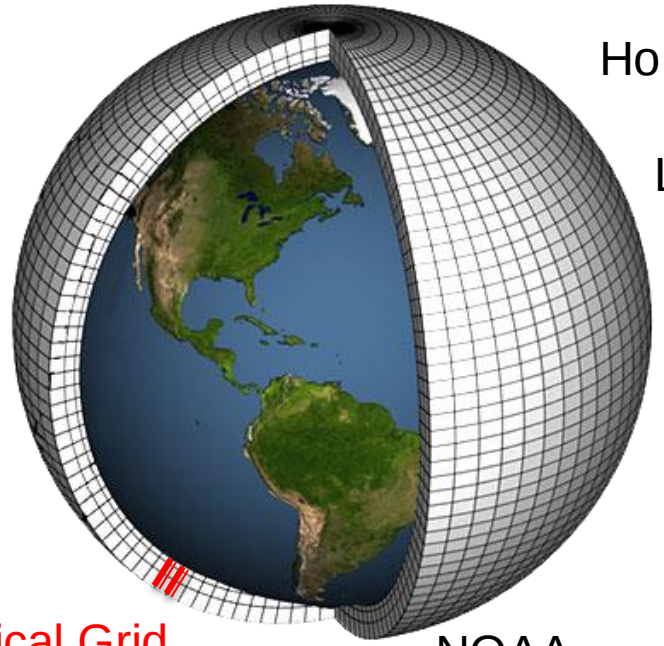

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Latitude
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Vertical Grid
Height, Pressure or depth

NOAA

Climate model evolution

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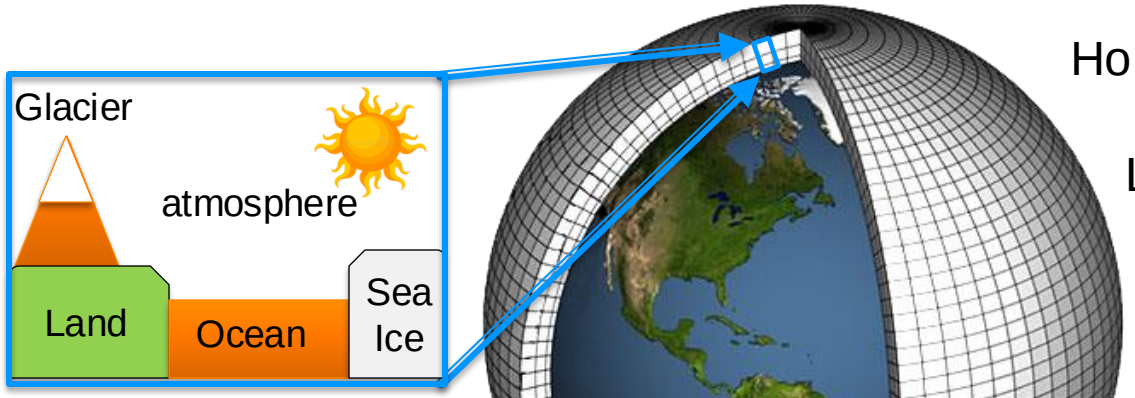

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NOAA

Climate model evolution

How do they work?

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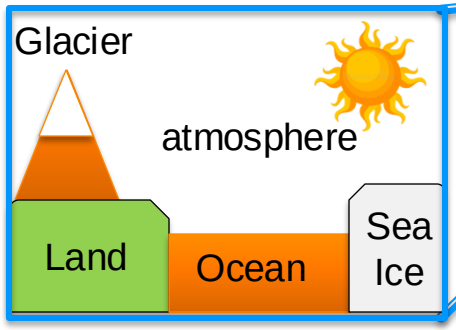

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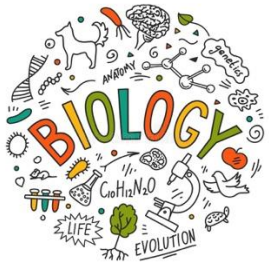

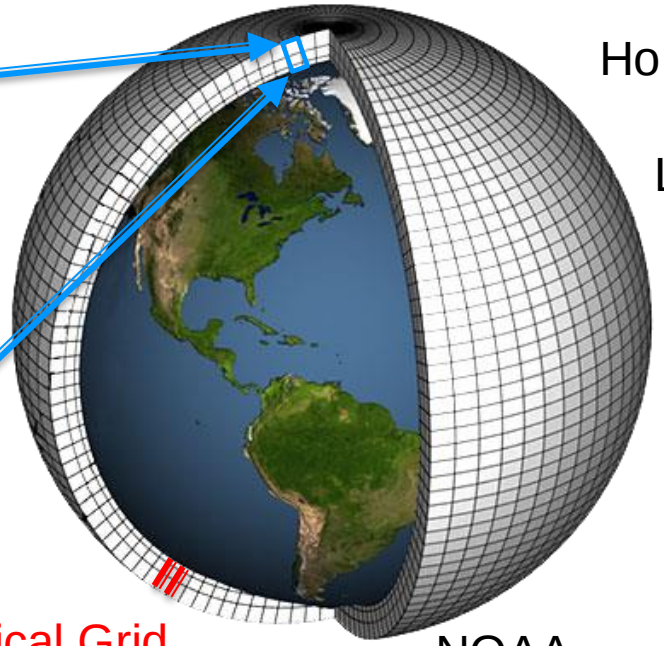

Horizontal Grid
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Climate model evolution

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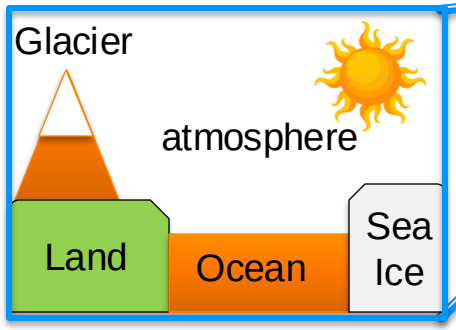

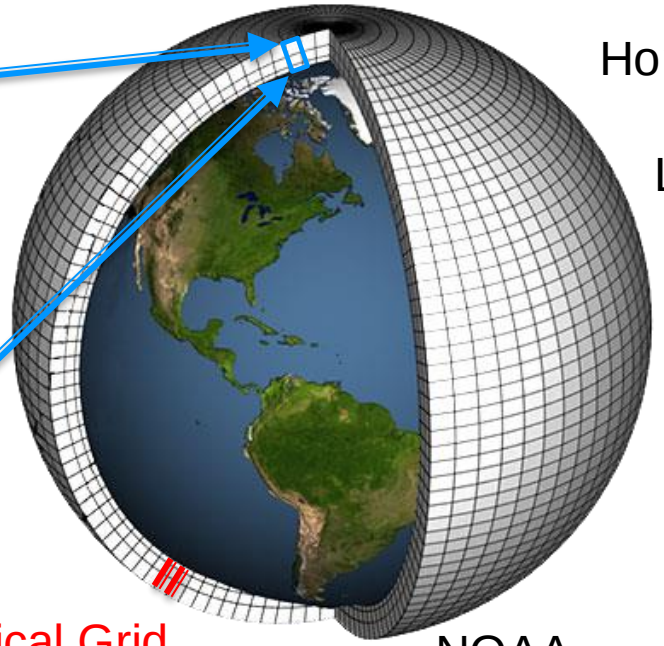

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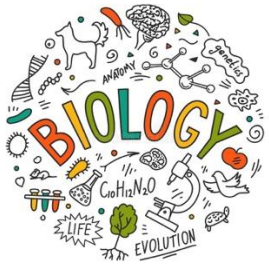
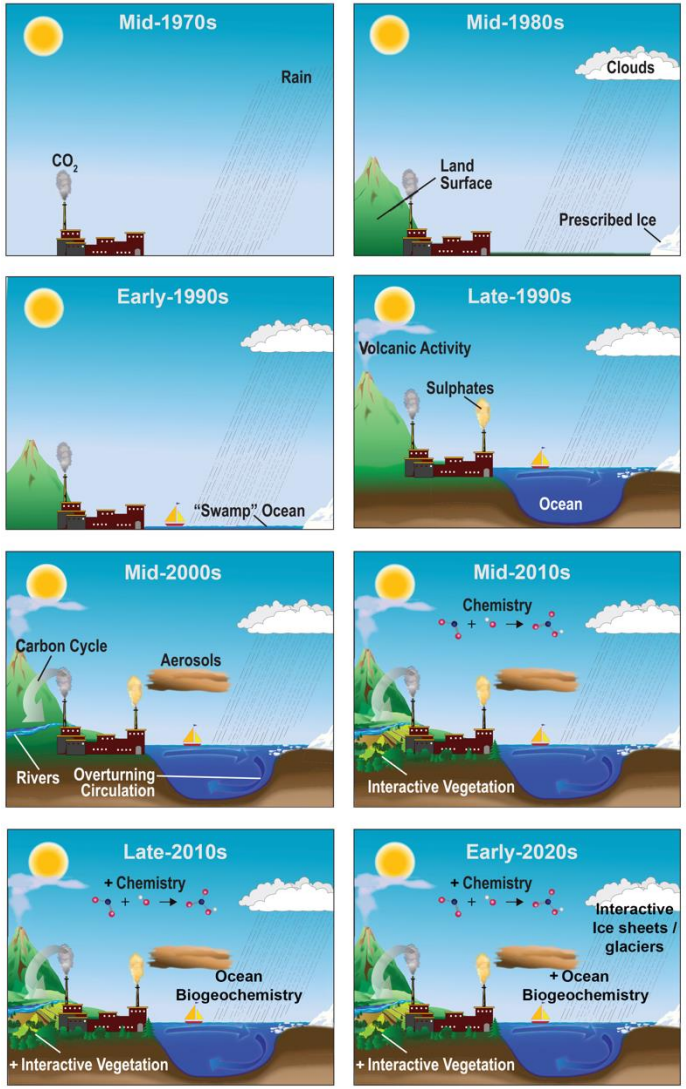


Each process is distilled into code

Vertical Grid
Height, Pressure or depth

NOAA

Climate model evolution



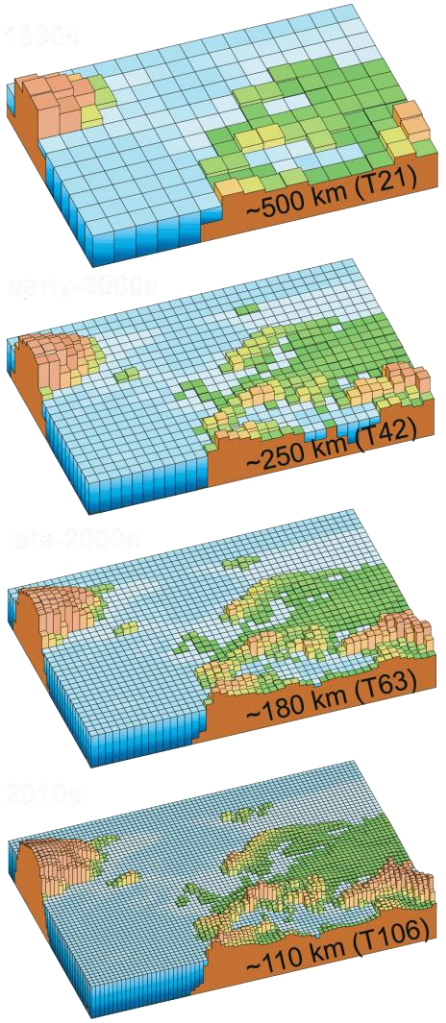
How have models improved?

- 1970s - Atmosphere-only (AGCM)
- 1990s - **+** ocean and ice (OAGCM)
- 2000s - **+** interactive land surface, dynamic oceans
- 2010s - **+** carbon cycle, atmospheric chemistry, vegetation
- **Today - + chemistry, biological complexity Earth System Models (ESM)**

Climate model evolution

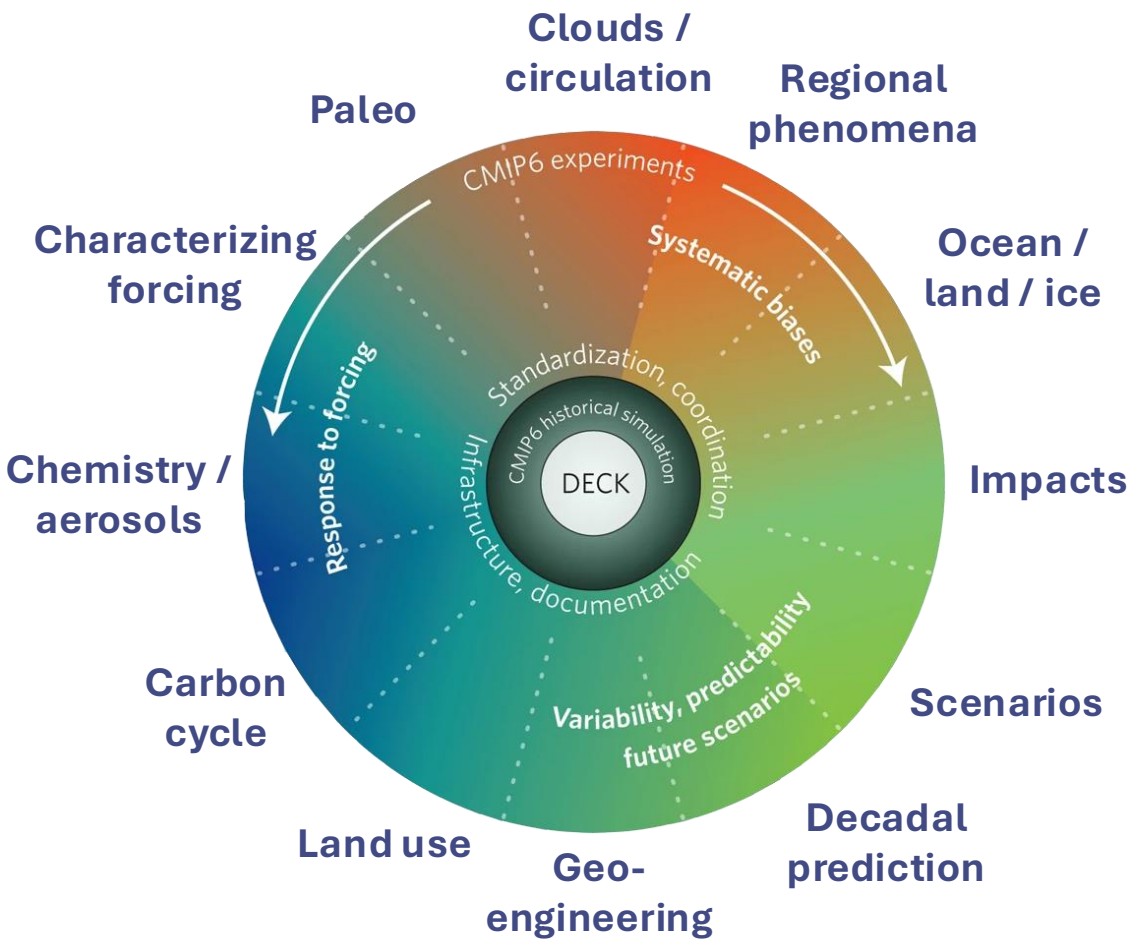
How have models improved?

- As models became more complete Earth simulators, also increasing resolution
- 1990s – USA CONUS ~50 grid cells
- Early 2000s – USA CONUS ~200 grid cells
- Late 2000s – USA CONUS ~400 grid cells
- 2010s – USA CONUS ~1000 grid cells
- **Today – USA CONUS ~100000 grid cells**



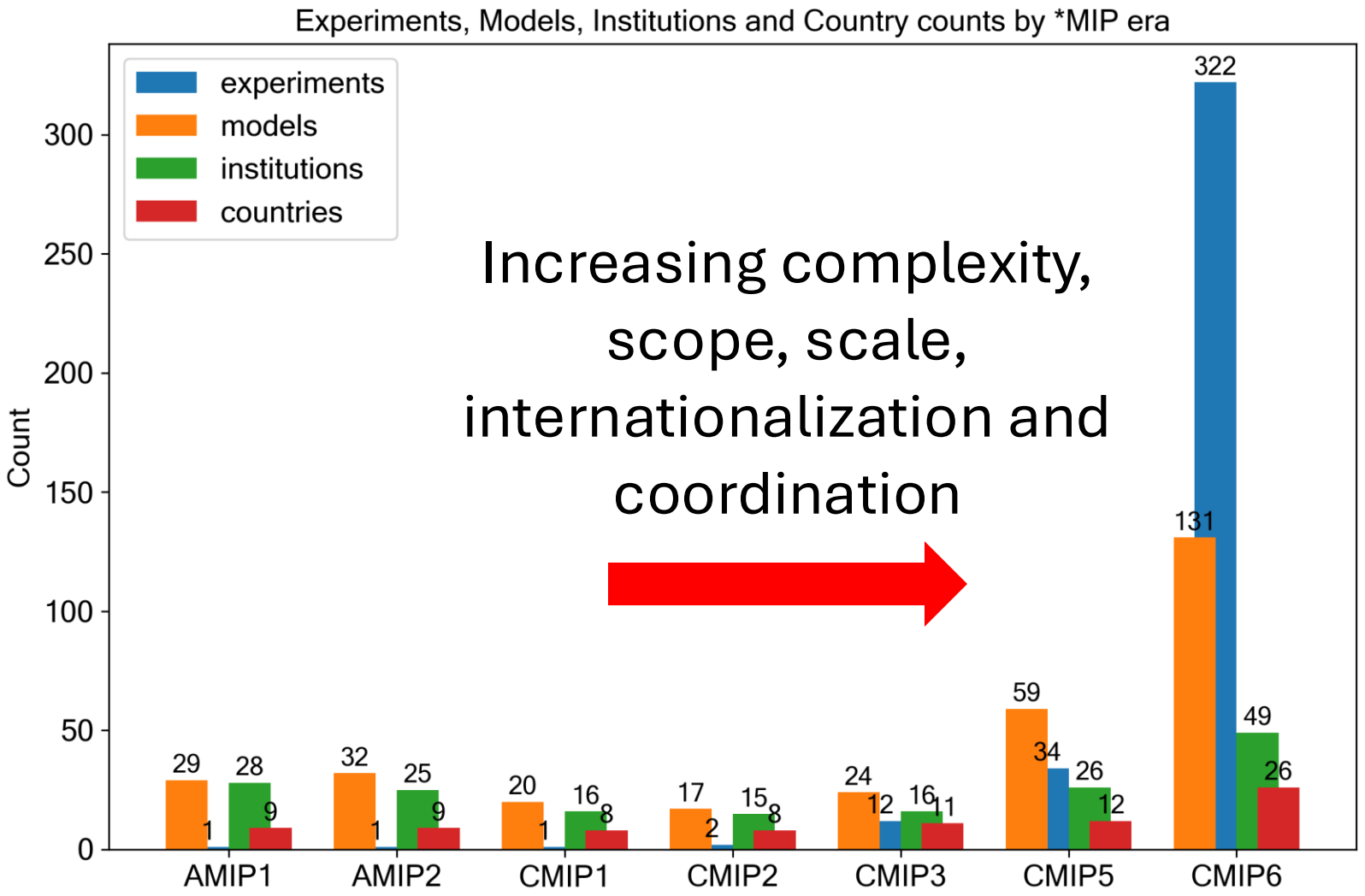
Model Intercomparison Projects (MIPs)

- Coupled Model Intercomparison Project (CMIP)
- CMIP6 latest phase, 2013-present
  - Started with AMIP (atmosphere-only), 1990
  - Coupled atmosphere and ocean (CMIP), 1995
- Targeted model experimentation, standardized protocols
  - Experimental (simulation length, model components)
  - Forcing (idealized or historical-proxy forcings)
  - Data quantities, identities and formats
- Over decades, MIPs nurtured nascent climate research community into coordinated and calibrated research enterprise
- National and international climate assessments depend on international MIPs



CMIP6 latest phase

Decadal evolution of MIP community



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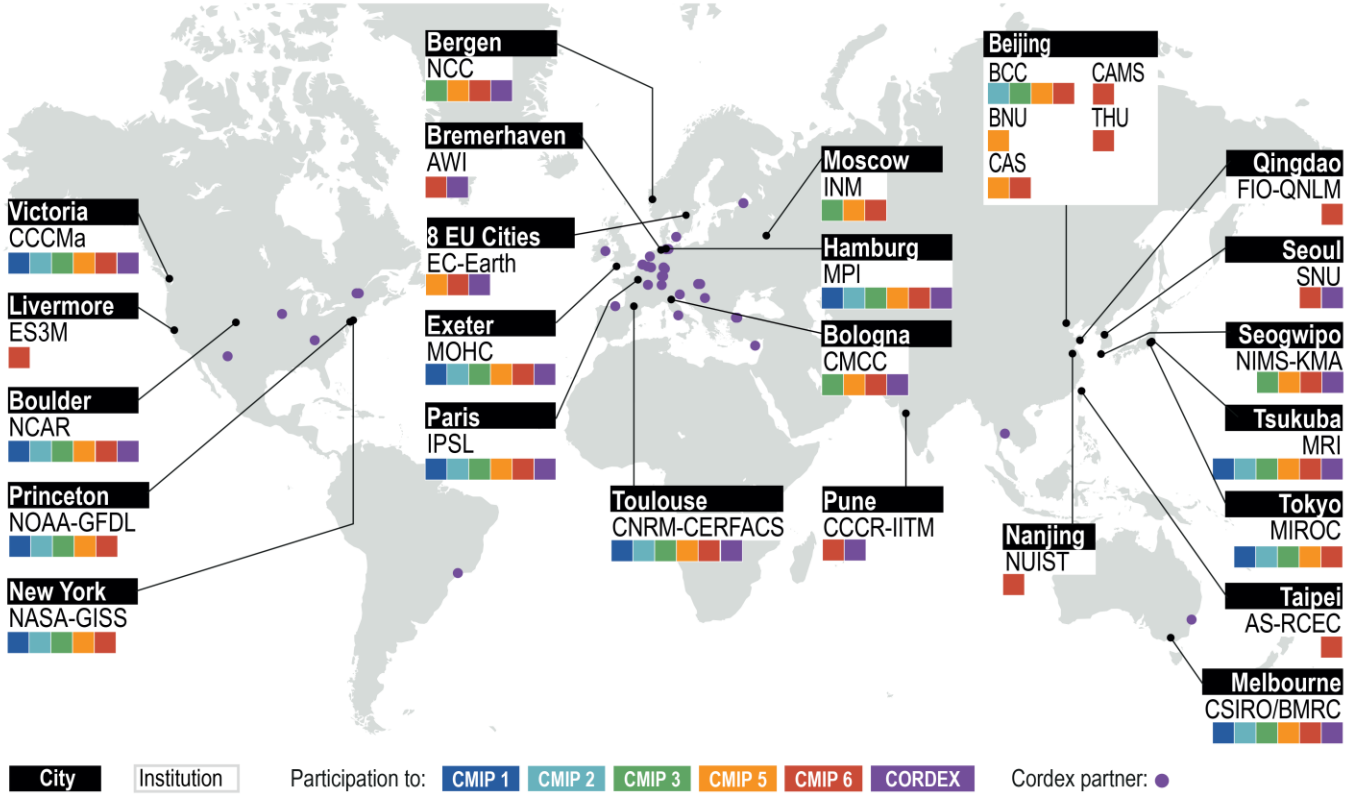
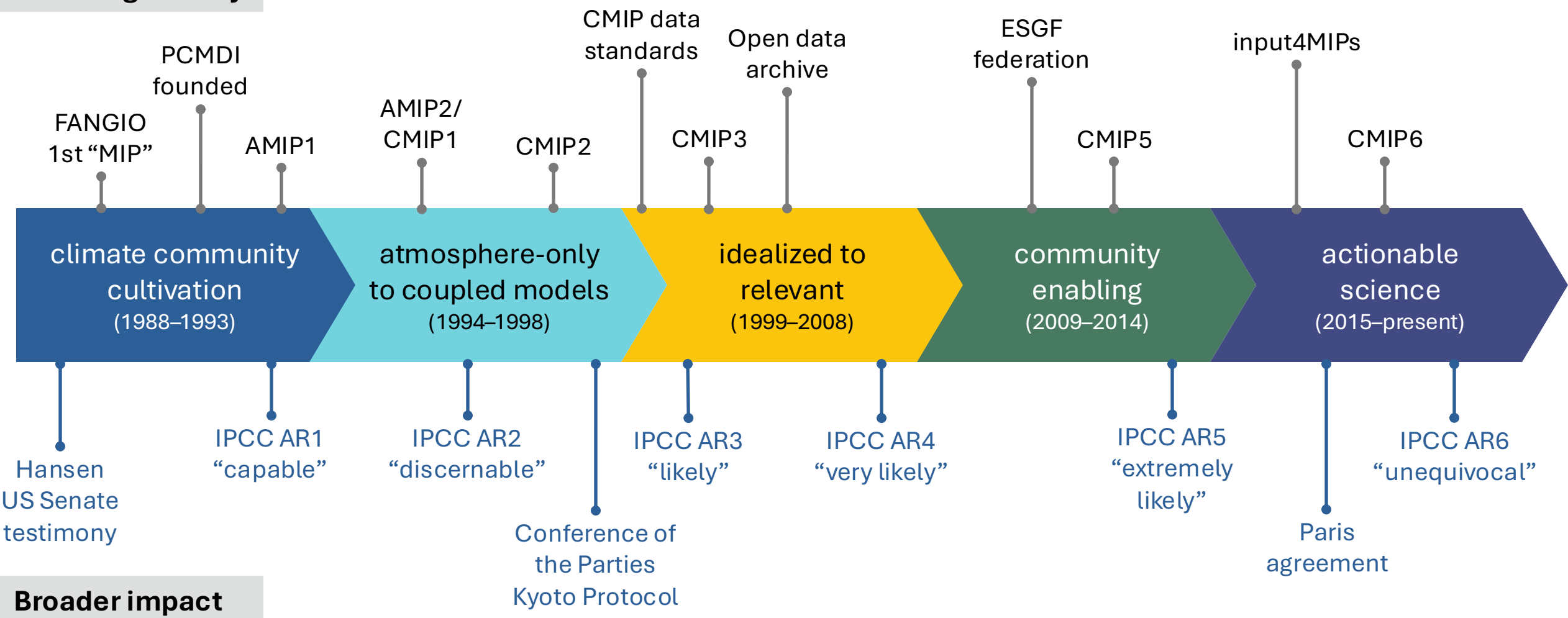
Internationalization of MIPs



MIP science - broad and growing impact

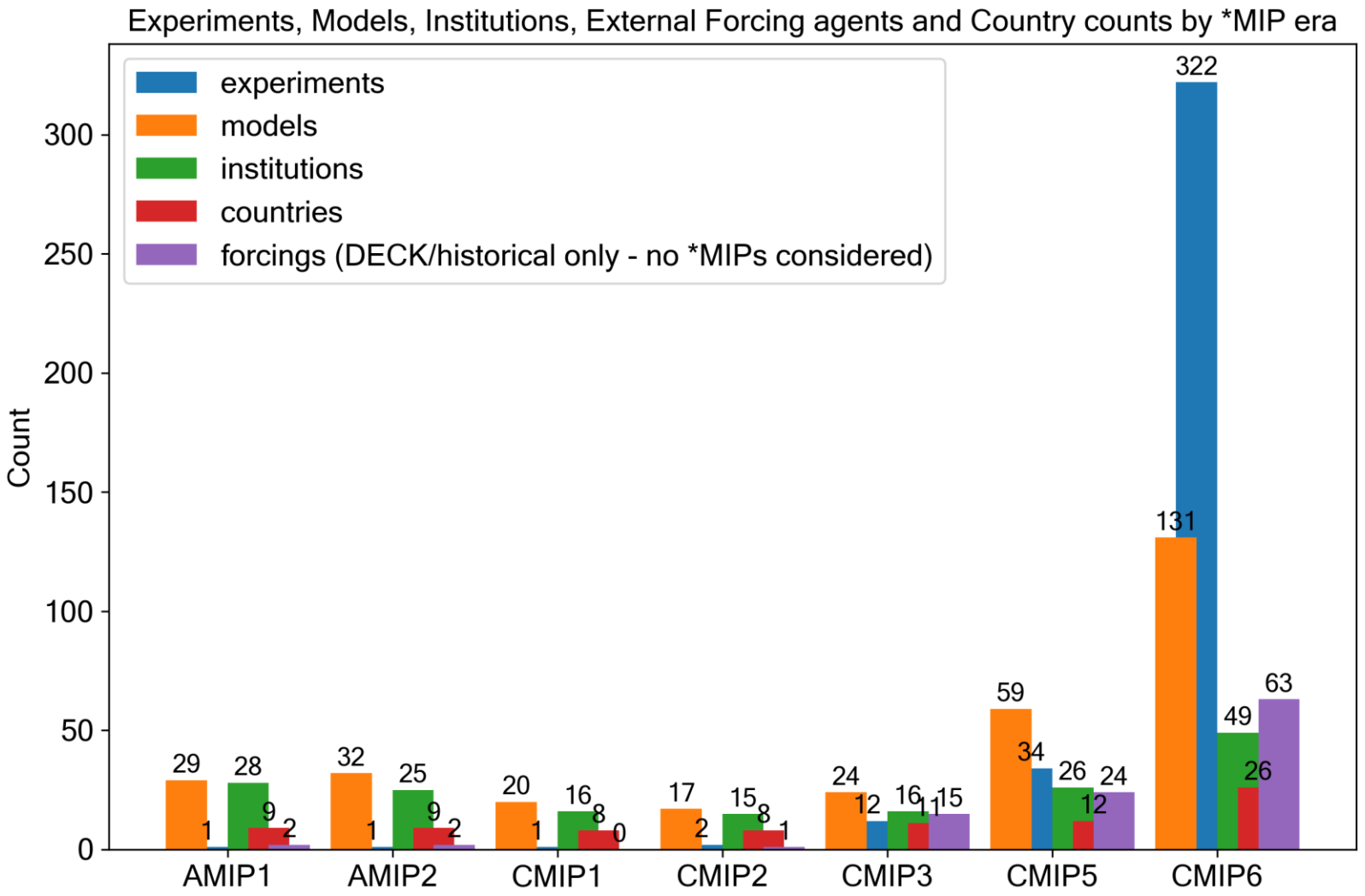
Modeling activity



Broader impact

Timeline not to scale

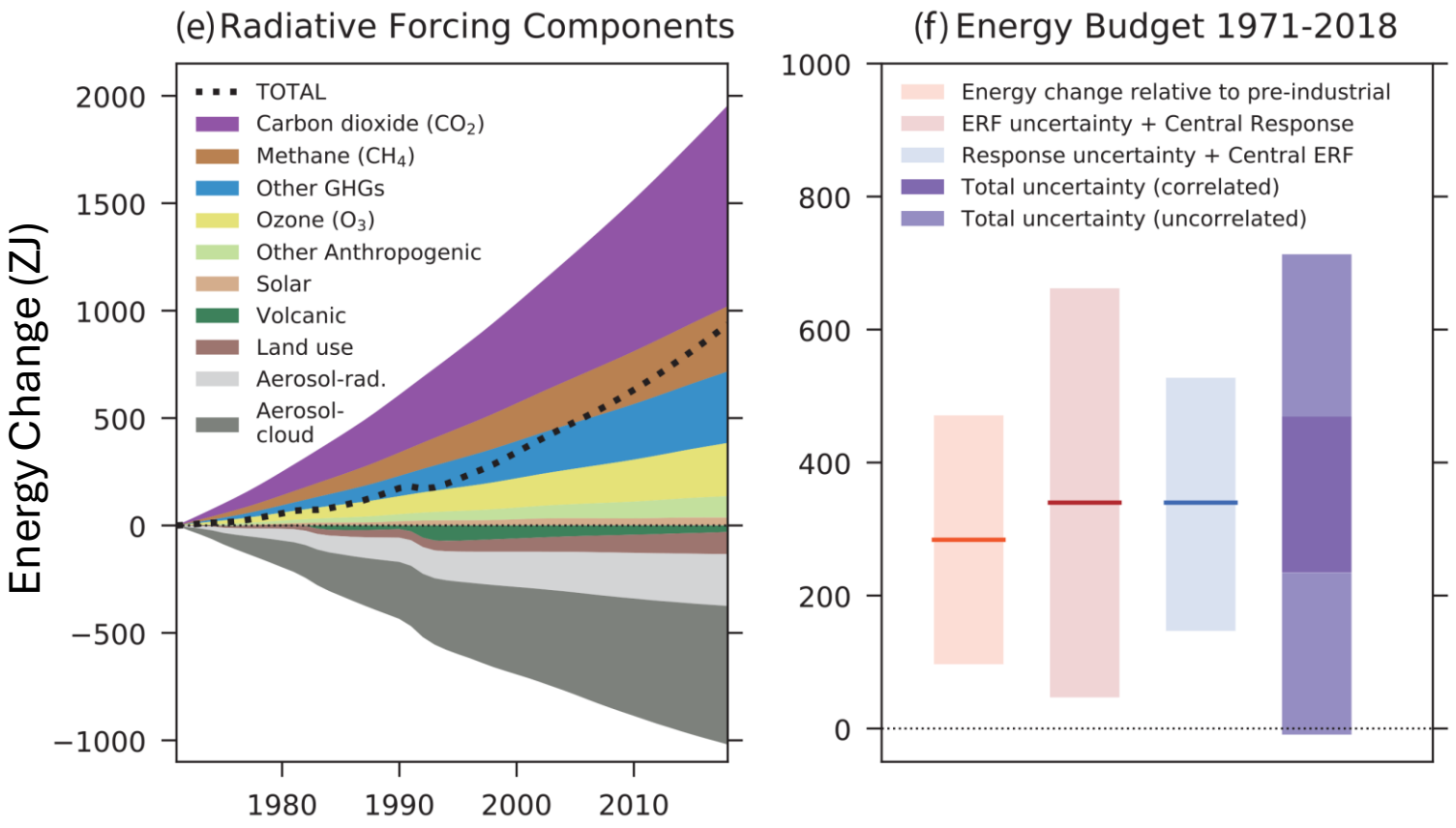
How about climate forcing?



Climate forcing through MIP phases

Forcing/MIP era	AMIP1[a]	AMIP2[b]	CMIP1[c]	CMIP2[d]	CMIP3[e] 20c3m	CMIP5[f] historical	CMIP6[g] historical	~CMIP7[h] historical
SST & sea ice (amip exp.)	1979-1988	1979-1996	-	-	1979-2002	1979-2008	1979-2014	1979-2022
Greenhouse gases	CO_2 345 ppm (fixed)	CO_2 348 ppm, CH_4 1650 ppbv, N_2O 306 ppbv (fixed)	fixed	fixed and 1% idealized	Y, ~5 species	Y, ~9 species	Y, 46 species	Y, 46 species
Ozone	-	climatology	-	fixed	Y, $^1/_2$ groups	Y	Y	Y
Sulphate aerosols (in/direct)	-	climatology	-	-	Y, $^1/_2$ groups	Y, $^2/_5$ groups	Y	Y
Black/organic carbon	-	-	-	-	Y, $^1/_2$ groups	Y, $^4/_5$ groups	Y	Y
Land use change	-	(active)	-	-	Y, $^1/_3$ groups	Y, $^3/_4$ groups	4 states	1 state
Solar irradiance	1365 Wm^{-2} (fixed)	1365 Wm^{-2} (fixed)	fixed	fixed	Y, $^1/_2$ groups	Y, $^9/_{10}$ groups	Y	Y
Volcanic aerosols	-	-	-	-	Y, $^1/_2$ groups	3 variants, $^9/_{10}$ groups	Y	Y
Nitrogen deposition	-	-	-	-	-	-	4 species	4 species
Total varying forcings	2	2	0	1 (idealized)	~15	~24	~63	~63+
Data delivery	ftp	ftp	ftp	ftp	~	~	input4MIPs	input4MIPs

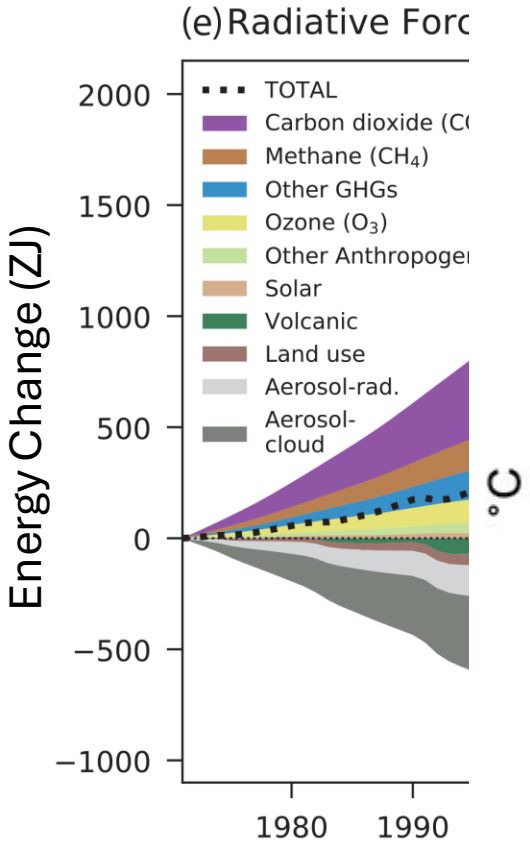
Why care about time-varying forcing?



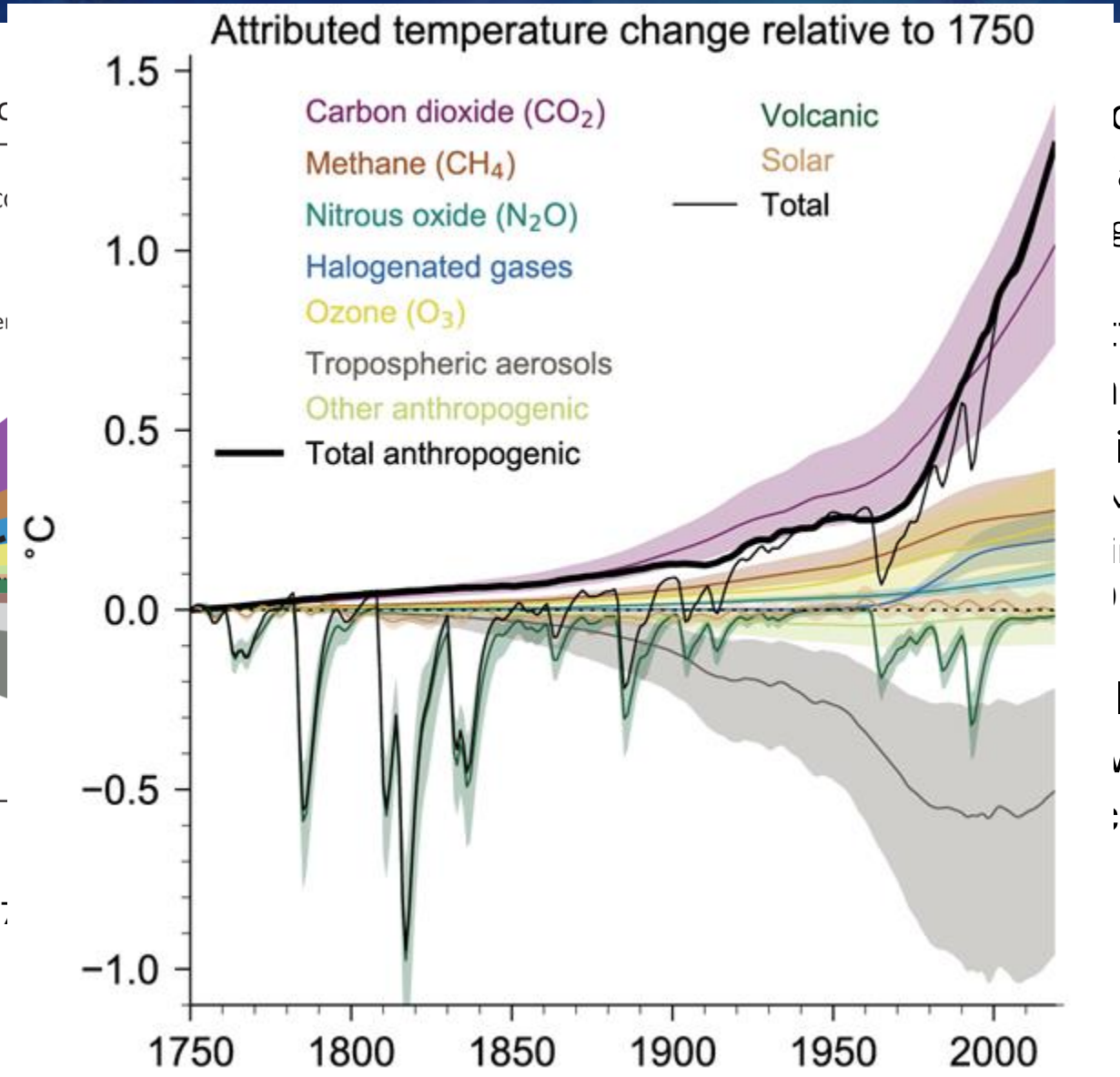
Forster *et al.*, 2021, IPCC Ch7 Box7.2 Fig 1, 10.1017/9781009157896.009

- Forcings drive climate change and variability
  - E.g. Maher *et al.*, 2015 and many others
- Getting forcing (and model responses!) right underpins climate change attribution and future projection utility
  - CMIP6 included "hot models" with higher climate sensitivity that Sherwood *et al.*, 2020/ IPCC AR6 assessed range
  - IPCC AR6 developed "contrained projections" models weighted by observed agreement
- CMIP projection user community growing markedly – being used for decision-making

Why care about time-varying forcing?



Forster *et al.*, 2021, IPCC Ch7



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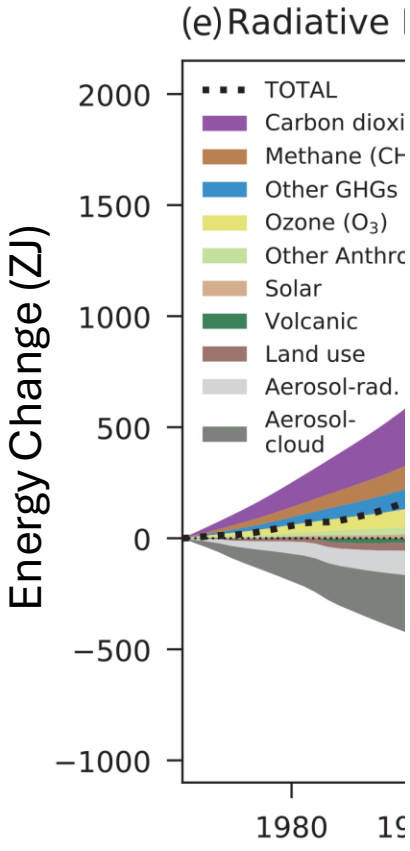
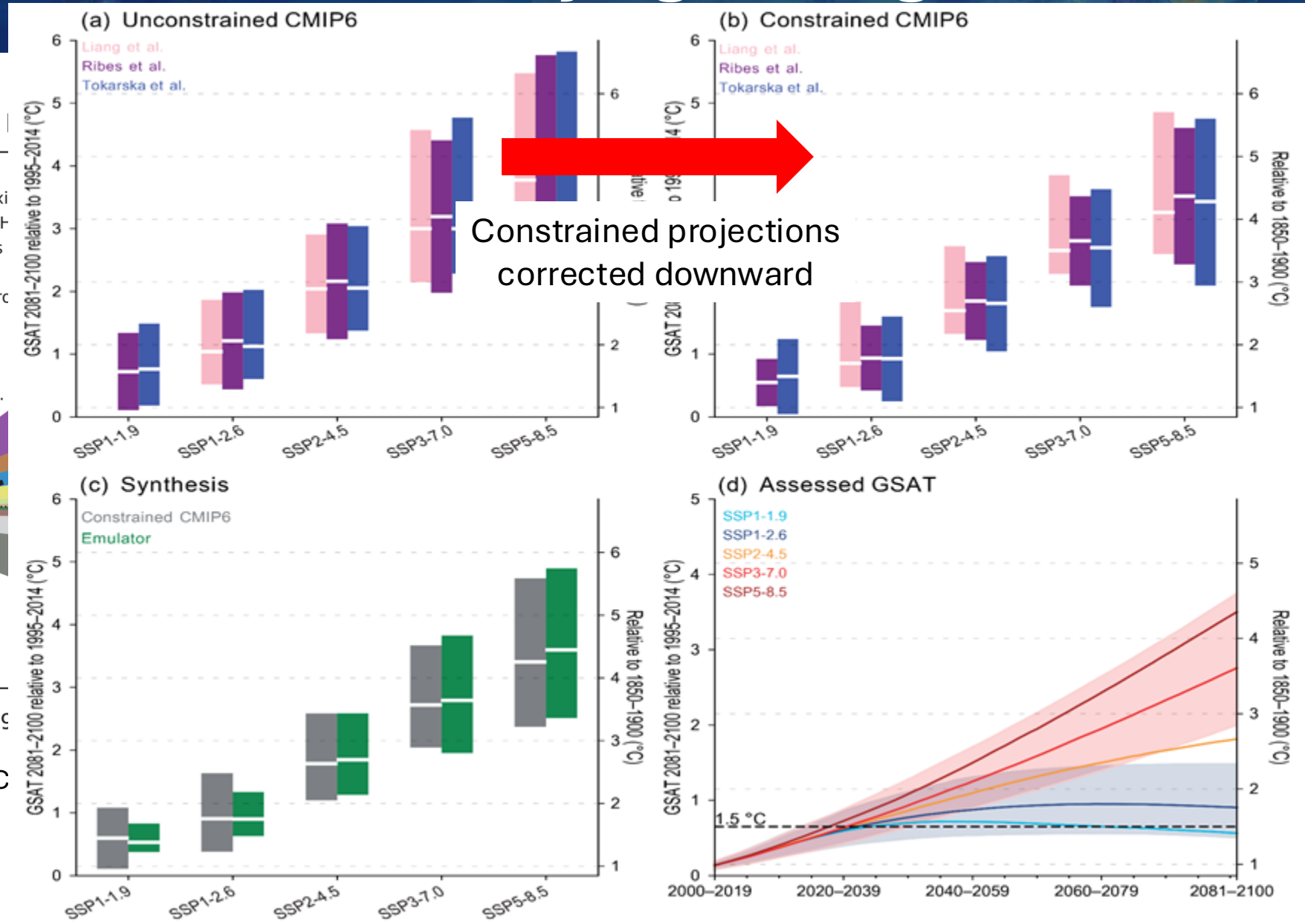


Forster *et al.*, 2021, IPCC



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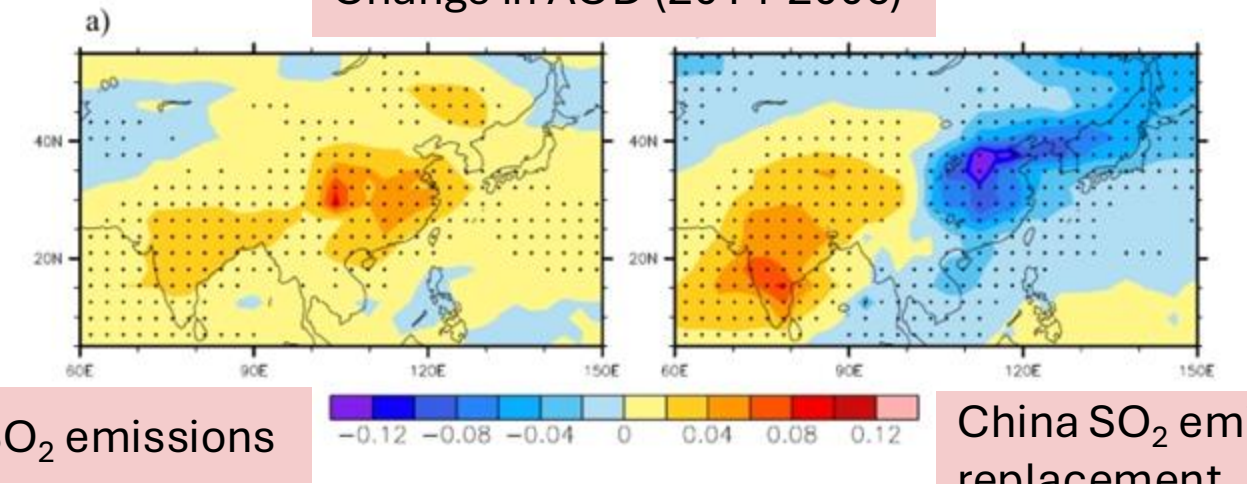
Forcing impact on climate

- Past CMIP analyses highlight simulated climate discrepancies due to forcing
  - CMIP3, models that **excluded volcanic/stratospheric aerosol optical depth (SAOD) forcing** had ocean heat content (OHC) warming trends 2-4x higher than observations (Domingues et al., 2008, NAT)
  - CMIP5, **SAOD forcing corrections** brought early 21st century OHC warming rates down in line with observations (Durack et al., 2018, Oceanog.); Model simulations without effects of moderate modern volcanoes (after 2000) overestimate observed tropospheric warming since 1998 (Santer et al., 2014, NATGeo; Schmidt et al., 2014, NATGeo)
  - CMIP6, models failed to capture observed dipole pattern of AOD trends over Asia during 2006-2014 due to the **underestimate of SO2 emissions decline in China** (Wang et al., 2021, NPJ; see also Paulot et al., 2018, ACP, Quaas et al., 2022, ACP)

Change in AOD (2014-2006)



CMIP6 SO_2 emissions

China SO_2 emissions PKU inventory replacement

Wang *et al.*, 2021, NPJ, 10.1038/s41612-020-00159-2

CMIP6 Forcing collection

Table 1. Forcing Data Sets (Version 6.2.11) Generated for Use in the CMIP6 DECK, Historical, and Satellite MIP Experiments

CMIP6 DECK and Historical Simulations

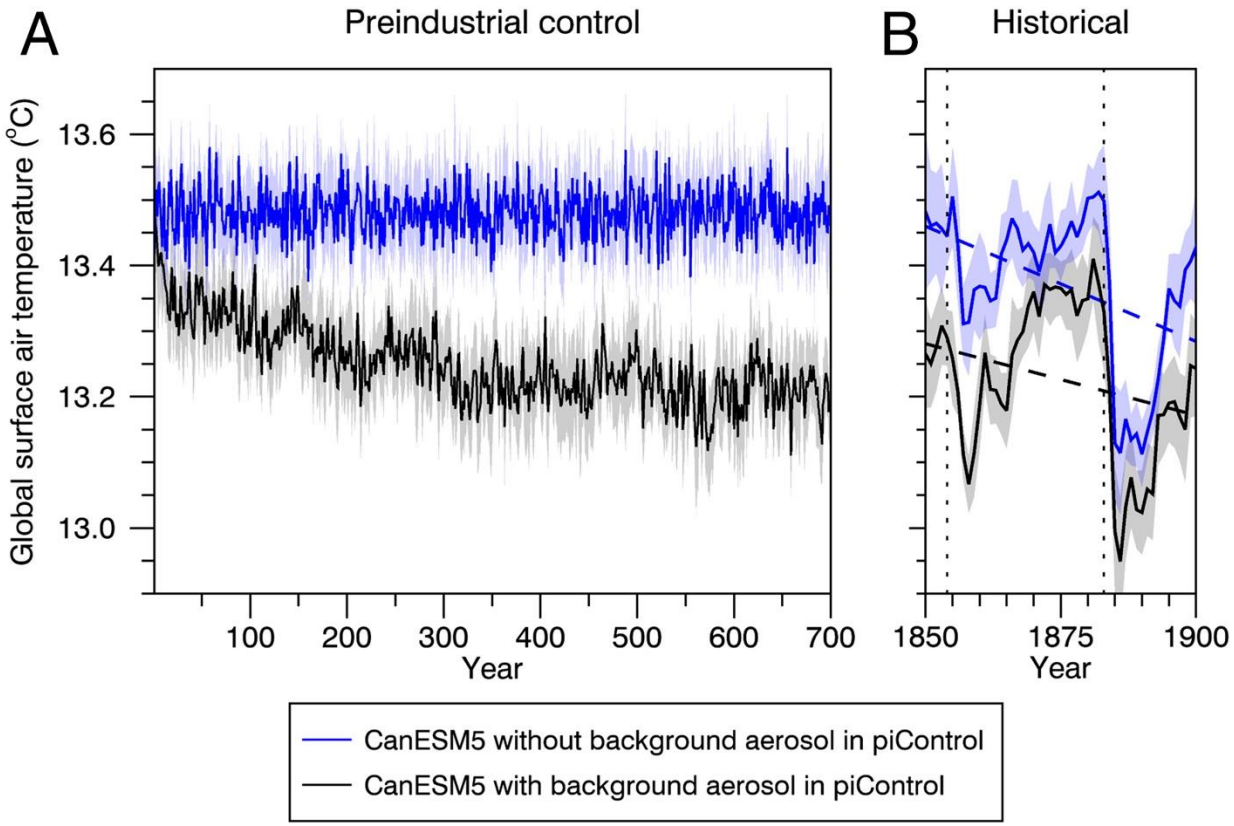
Data Set	Temporal Range	Data Set Version	Documentation
Historical anthropogenic short-lived climate forcing (SLCF), carbon dioxide and methane emissions	1750–2014	2017-05-18, 2017-08-30, 2017-10-05 (aircraft sulfur dioxide)	*Hoesly et al.* [2017a, 2017b, 2017c, 2017d, 2018]
Historical biomass burning emissions	1750–2015	1.2	*van Marle et al.* [2016, 2017]
Historical land use changes	850–2015	2.1h	Land-Use Harmonization (LUH2), *Hurtt et al.* [2017]
Historical greenhouse gas historical concentrations	0–2014	1.2.0	*Meinshausen and Vogel* [2016], *Meinshausen et al.* [2017]
Historical stratospheric aerosols	1850–2014	3.0.0	*Thomason et al.* [2017]
Historical ozone	1850–2014	1.0	*Hegglin et al.* [2016a]
Historical nitrogen deposition	1850–2014	2.0	*Hegglin et al.* [2016b]
Solar forcing	1850–2299	3.2	*Matthes et al.* [2017a, 2017b]
Aerosol optical properties	1850–2100	1.0	*Stevens et al.* [2017]
Historical sea surface temperature (SST) and sea ice	1870–2017	1.1.4	*Durack and Taylor* [2018]

- Past CMIP phases uncovered forcing impacts on simulated climate across models
- Until CMIP3, forcing datasets generated ad hoc by modeling centers for their simulation needs
- In CMIP5, few forcings generated explicitly, shared across groups for coordinated experiments
- For CMIP6, coordination leapt forward through input4MIPs ESGF project collecting and collating many required forcings – one stop shop for modeling groups, facilitating use, ensuring a more homogeneous “historical” simulation archive
- Also see also Gleckler obs4MIPs talk, 1:30 pm

Durack *et al.*, 2018, EOS, 10.1029/2018EO101751

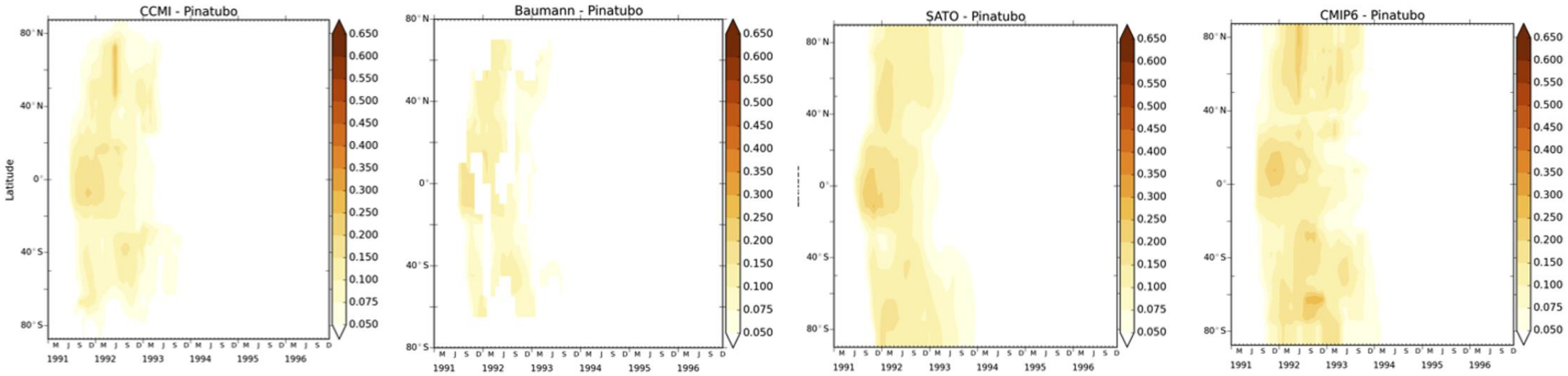
CMIP6 piControl experimental protocol

- Modeled climate is the result of
  - —Transient forcing
  - —Radiative response
  - —Modeled feedbacks
- CMIPx piControl and historical experimental design changed over time
- Address step change deficiency - piControl (fixed forcing) no volcanoes to historical (transient forcing 1850-present) beginning with very large Kie Besi (1861) and Krakatoa (1883) volcanic eruptions heavy SAOD loads
- Incorporate climatological average volcanic aerosol as piControl experimental protocol



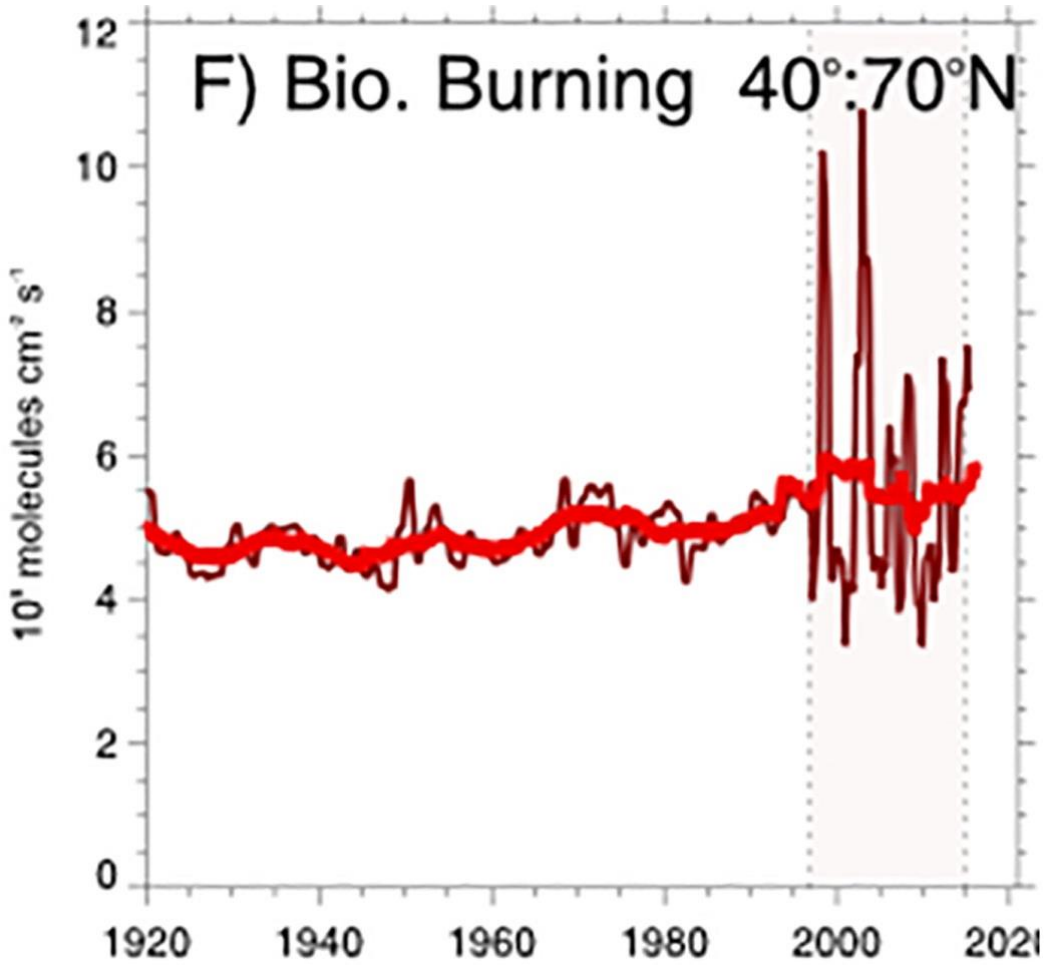
Fyfe *et al.*, 2021, PNAS, 10.1073/pnas.2016549118

Learning through CMIP6 - volcanoes



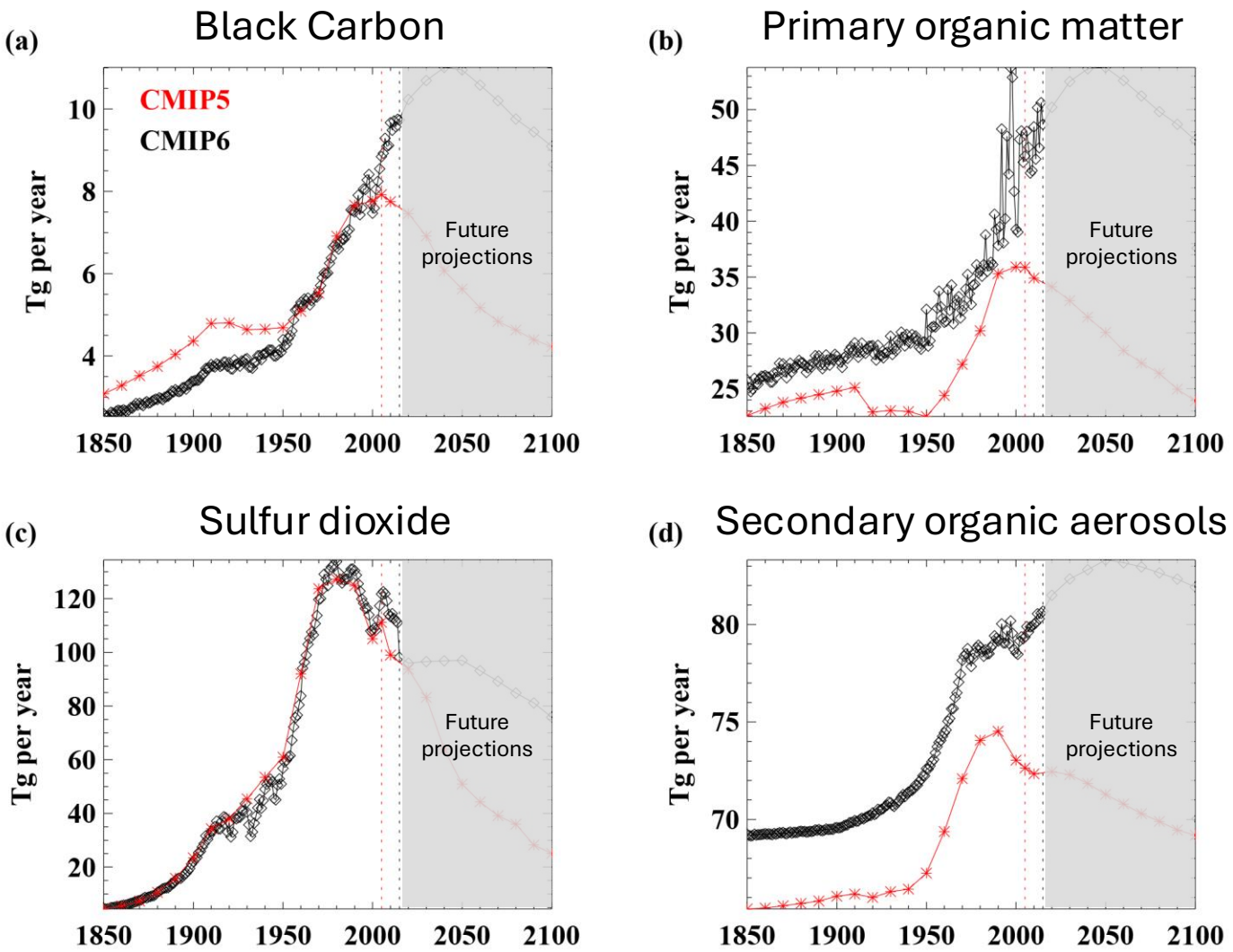
Unpublished from Myriam Khodri (IPSL) highlighting Pinatubo SAOD forcing larger in CMIP6 than previous datasets

Learning through CMIP6 – biomass burning emissions



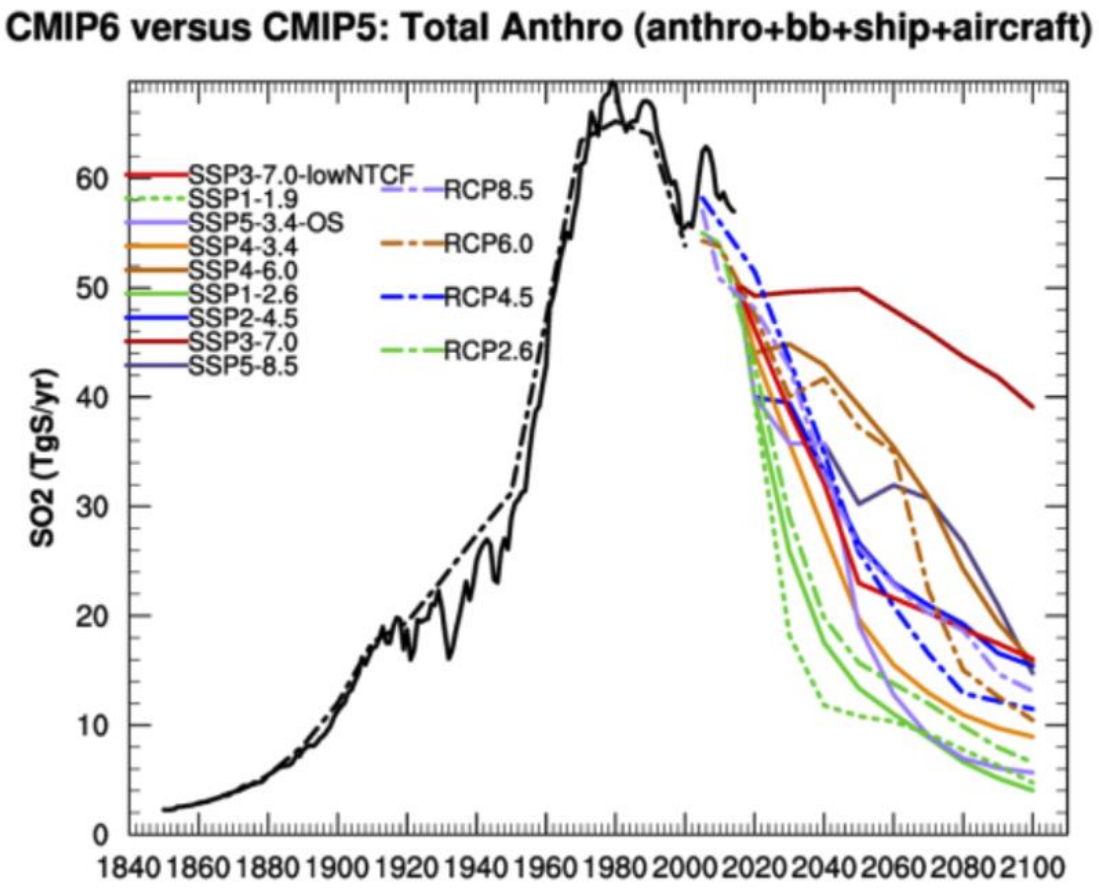
Fasullo *et al.*, 2022, GRL, 10.1029/2021GL097420

Learning through CMIP6 – anthropogenic emissions



Holland *et al.*, 2021, GMD, 10.5194/gmd-17-1585-2024

Learning through CMIP6 – anthropogenic emissions



Unpublished from Vaishali Naik (NOAA-GFDL)

CMIP7 Forcing

Forcing datasets availability

CMIP Coupled Model Intercomparison Project
Climate Forcings

The Climate Forcings TT is working to update the following CMIP DECK forcing suite:

Data set	Forcing dataset	Status	Expected ESGF publication
1	Anthropogenic short-lived climate forcer (SLCF) and CO2 emissions	In publication queue	September 2024
2	Open biomass burning emissions	Data in preparation and final metadata checks	September 2024
3	Land use	Data in preparation	September 2024
4	Greenhouse gas historical concentrations	Preliminary dataset available	v0.3.0 (0001-01 to 2022-12) available
5	Stratospheric volcanic SO2 emissions and aerosol optical properties	Preliminary dataset available	v1.1.3 available (1750-01 to 2023-12)
6	Ozone concentrations	Depends on 1, 2, 4, 5 and 8	~January 2025; 3 months after dependent datasets
7	Nitrogen deposition	Depends on 1, 2, 4, 5 and 8	~January 2025; 3 months after dependent datasets
8	Solar	Preliminary dataset available	v4.3 (1850-01 to 2023-12) available
9	AMIP sea-surface temperature and sea-ice boundary forcing	Final v1 dataset available. v2 dataset awaiting HadISST v2.4 release	v1.1.9 (1870-01 to 2022-12) available
10	Aerosol optical properties/MACv2-SP	Depends on 1, test dataset being produced in the meantime	~November 2024; Expected a month after dependent datasets

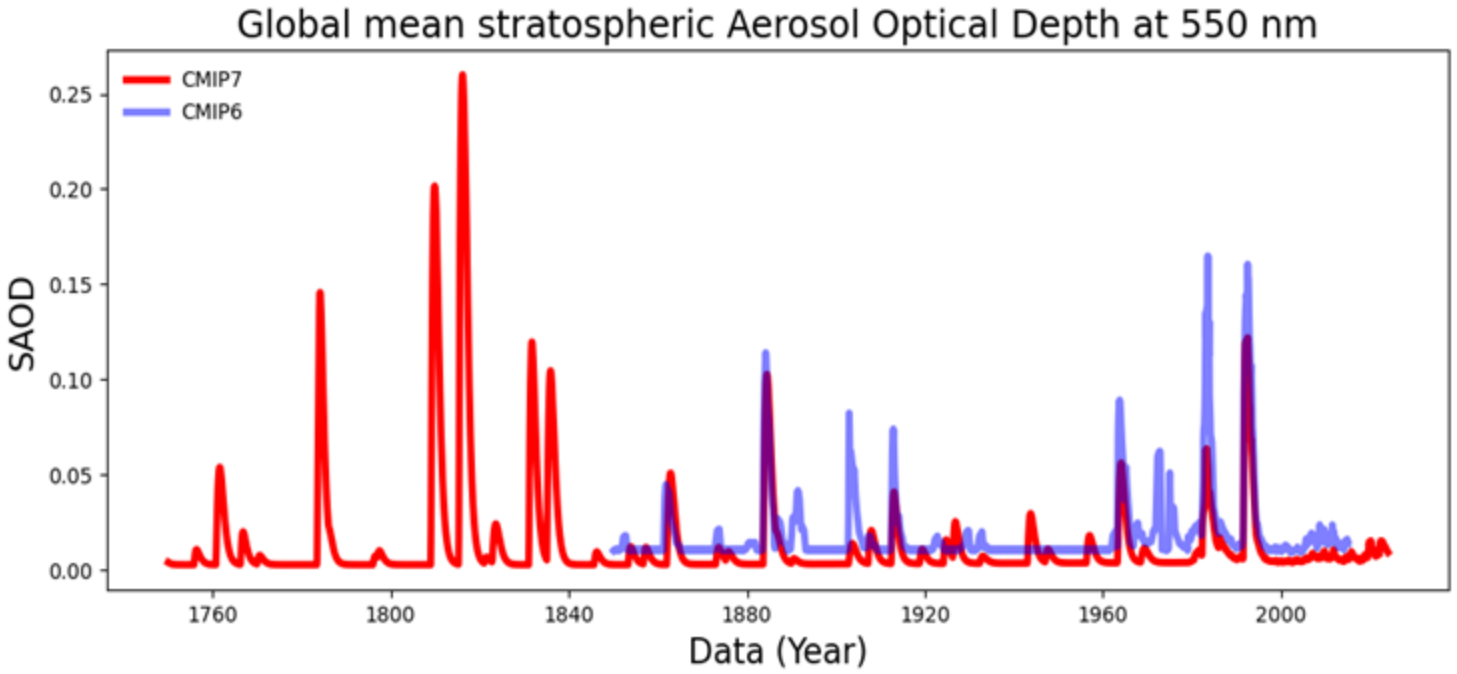
Please check the table above for the availability of datasets or on input4MIPs ESGF Project. Once datasets become available, this website will be updated with the latest information, documentation, and download links. When available, the future CMIP7 version 1 data will be identified for modelling groups to begin their CMIP7 AR7 Fast Track simulations.

- For CMIP7, further leverage CMIP coordination advantages
- Build CMIP Task Team to meet CMIP historical data needs
- Build on progress, fix CMIP6-era dataset issues
- Temporally extend dataset coverage to near real-time, ensuring no CMIP6 ~5 year gap (2014 to 2019)
- Once CMIP7 needs met, expand to tackle uncertainty
  - —Evaluate uncertainty for CMIP7-era datasets
  - —Identify largest simulation sensitivities to forcing
  - —Identify missing forcing agents (new model components?)
  - —Parallel analysis approaches
  - —Higher resolution native forcing data?
  - —Realize regular updates (~annual)

https://wcrp-cmip.org/cmip7-task-teams/forcings

CMIP7+ forcing improvement: new volcanic

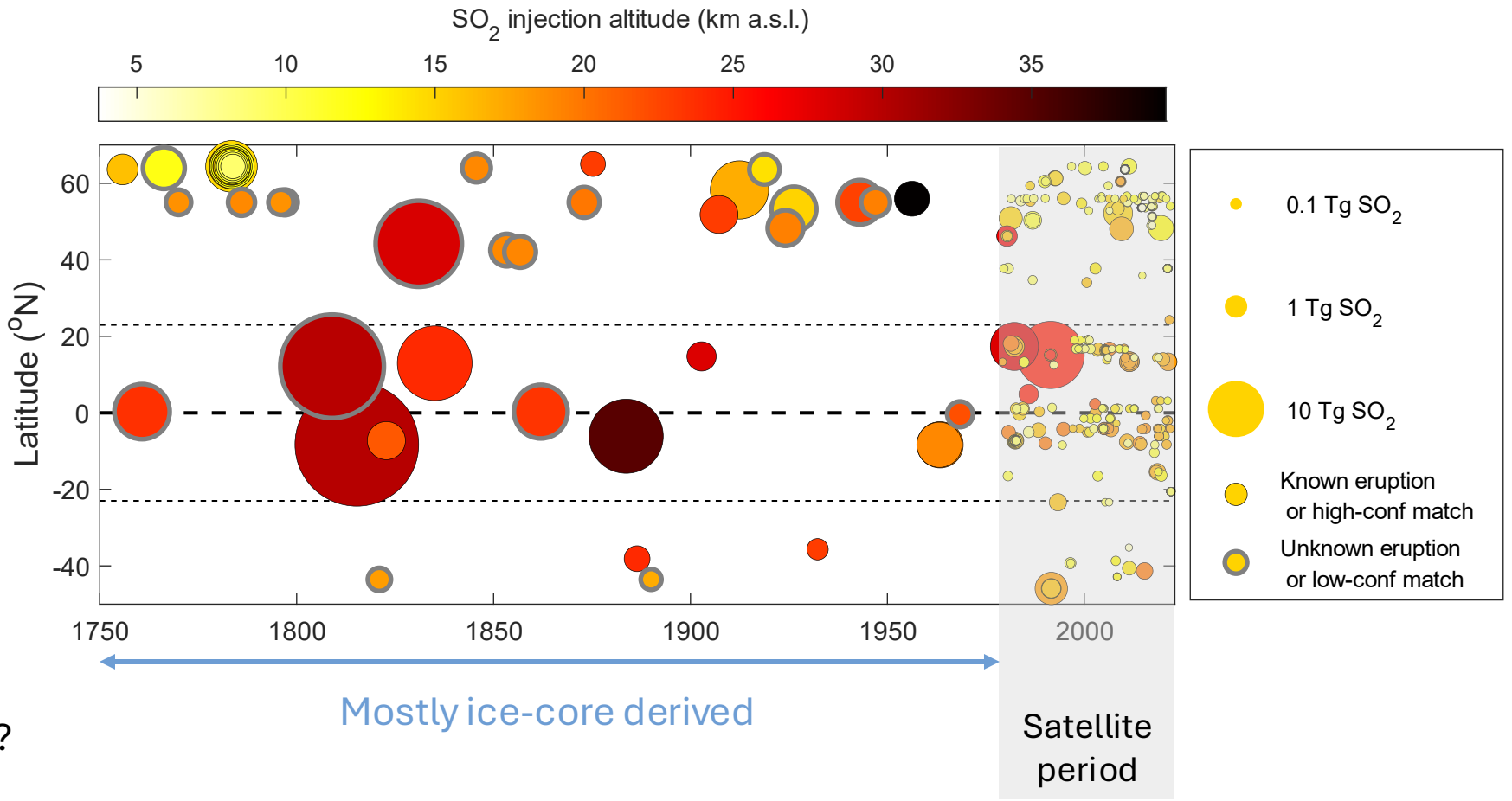
- CMIP7 volcanic dataset v0
  - 1850-2015 global mean SAOD larger in CMIP6 vs CMIP7
  - Higher CMIP6 peak SAOD for key eruptions (Krakatoa 1883, Santa Maria 1902, Agung 1963)
  - Numerous differences on timing/presence of eruptions likely to impact climate variability (e.g. 1920s, 1940s – significant CMIP7 forcing missing in CMIP6
  - Spatiotemporal changes, far less uniform across latitude/hemisphere in CMIP7 contrasted to CMIP6



Aubry *et al.*, in prep

CMIP7+ forcing improvement target: volcanic

- CMIP7 volcanic dataset v0
  - Small magnitude eruptions (<<10 Tg SO_2) missing pre-satellite
  - Current generation SAOD inventories omit ~1 Tg SO_2 yr^{-1} – equivalent of 7x Pinatubo 1991-like eruptions missing per century = 15 Tg SO_2 ~0.3degC global cooling
  - Provide uncertainty quantification
  - Add pyroCb emissions?
  - Volcanic emissions beyond sulfur?



Aubry *et al.*, in prep

CMIP7+ forcing improvement target: SSTs and sea ice

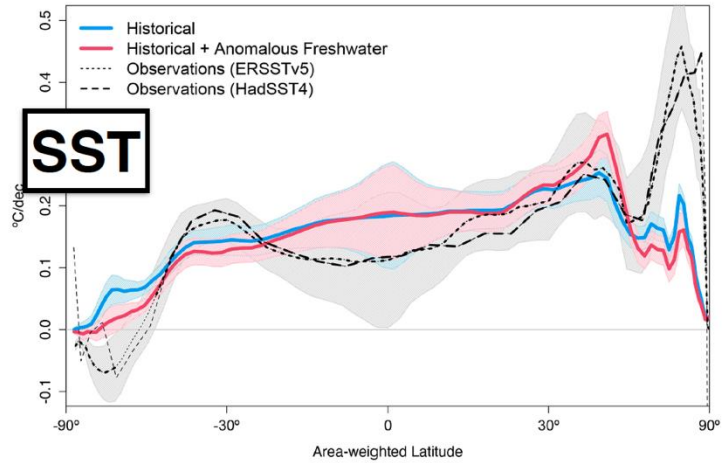
See Zelinka talk
11 am

Identify missing forcings

Goddard Institute for Space Studies

SST and Sea Ice Trend Differences 1990-2019

Significant impact in SH SST

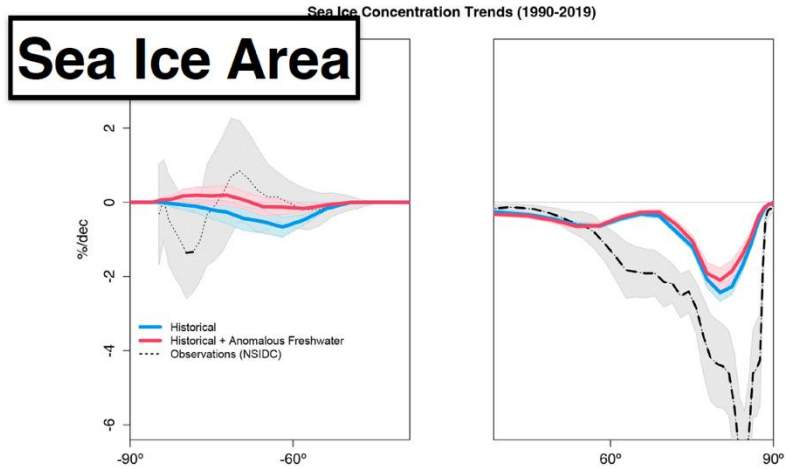


Historical control

w/anomalous FW

Anomalous freshwater forcing – Antarctica, Greenland, glaciers; Schmidt *et al.*, in prep

Large enough to flip sign of ensemble Antarctic sea ice trend



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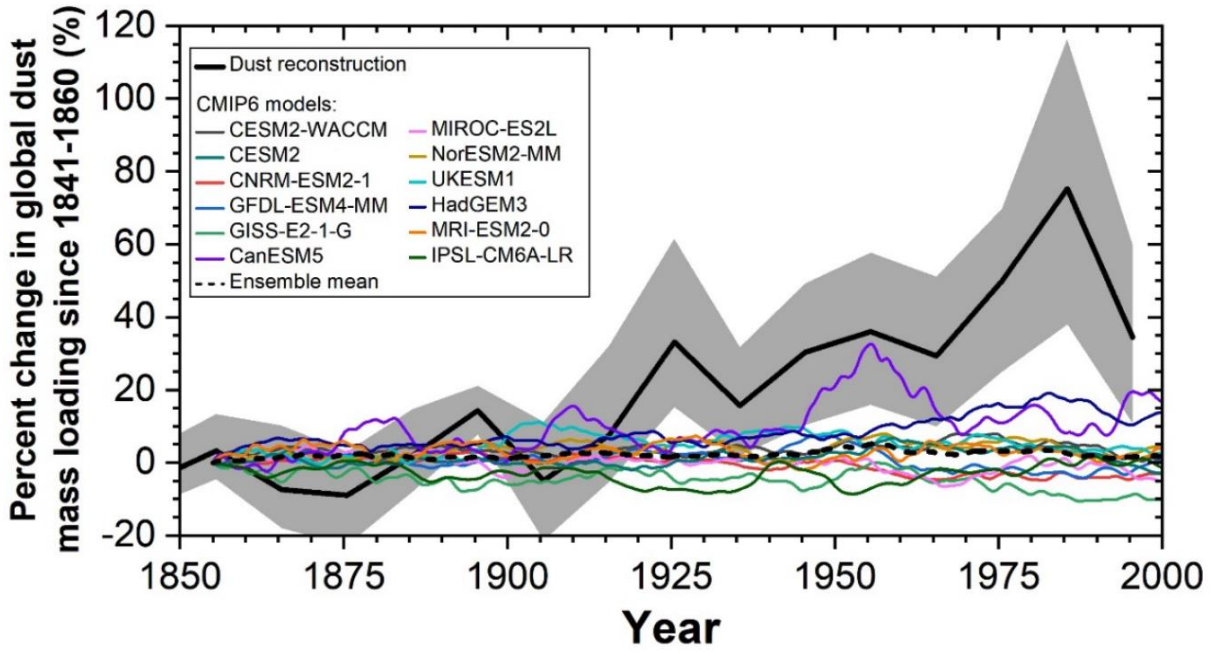
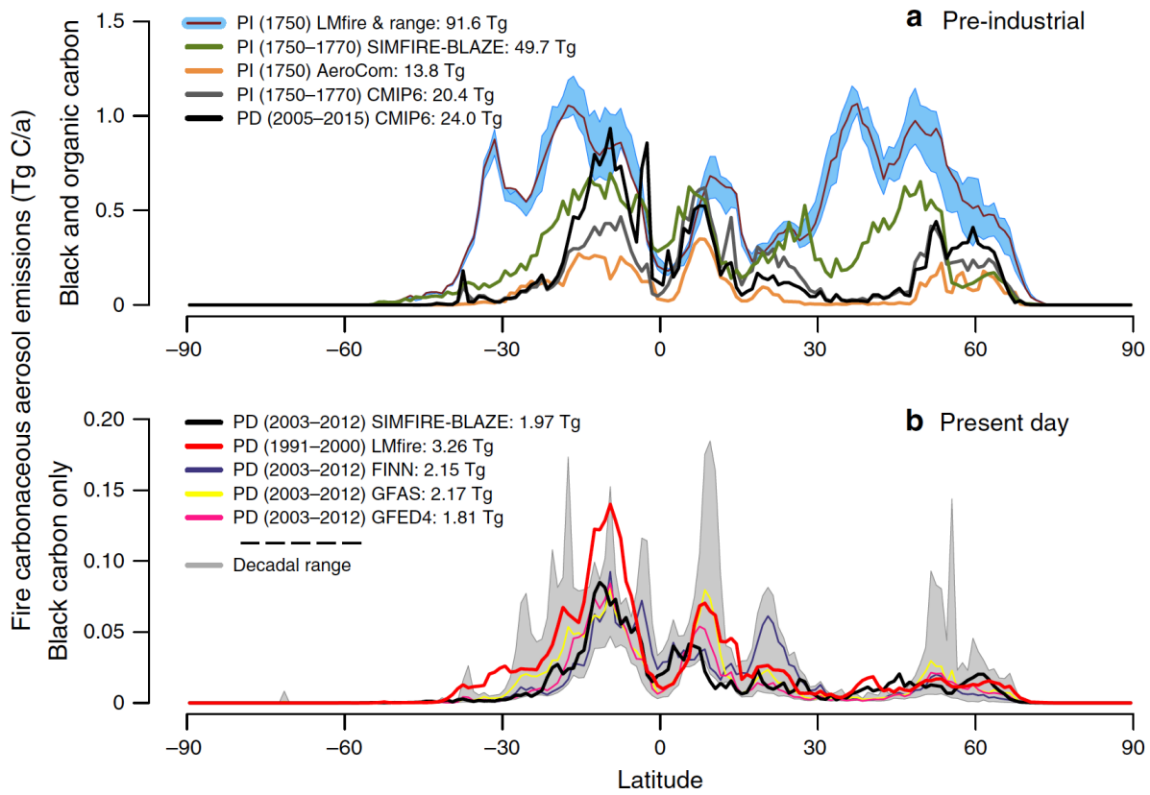
Identify missing/unrepresented forcings



Aeolian dust; Kok *et al.*, 2023, NATEarthEnv, 10.1038/s43017-022-00379-5

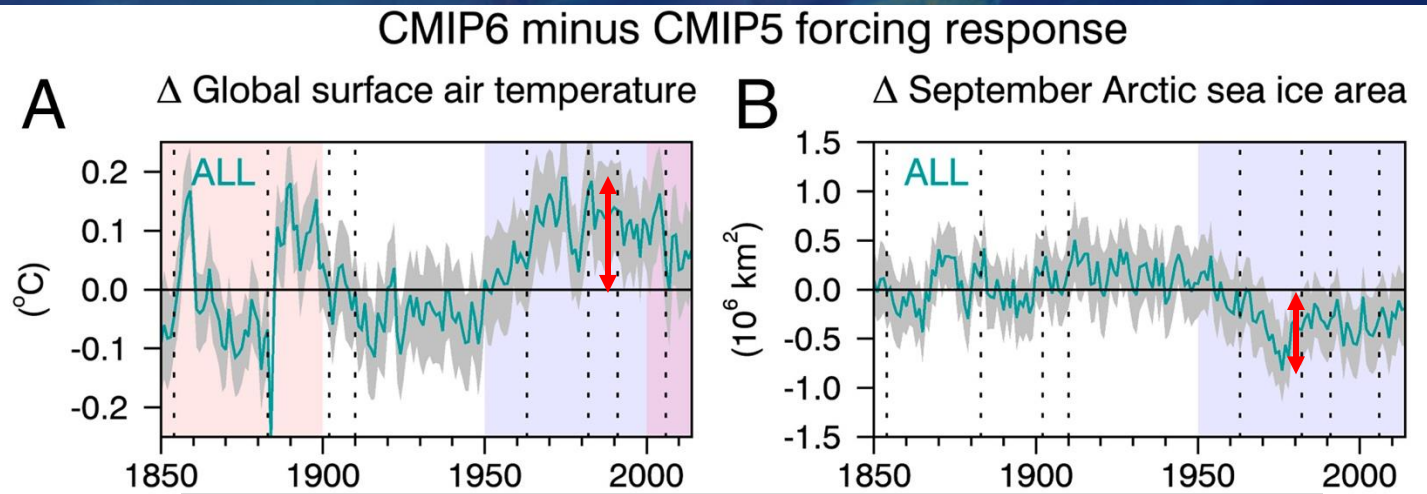


Pre-industrial fire carbon emissions;
Hamilton *et al.*, 2018, NATComms, 10.1038/s41467-018-05592-9

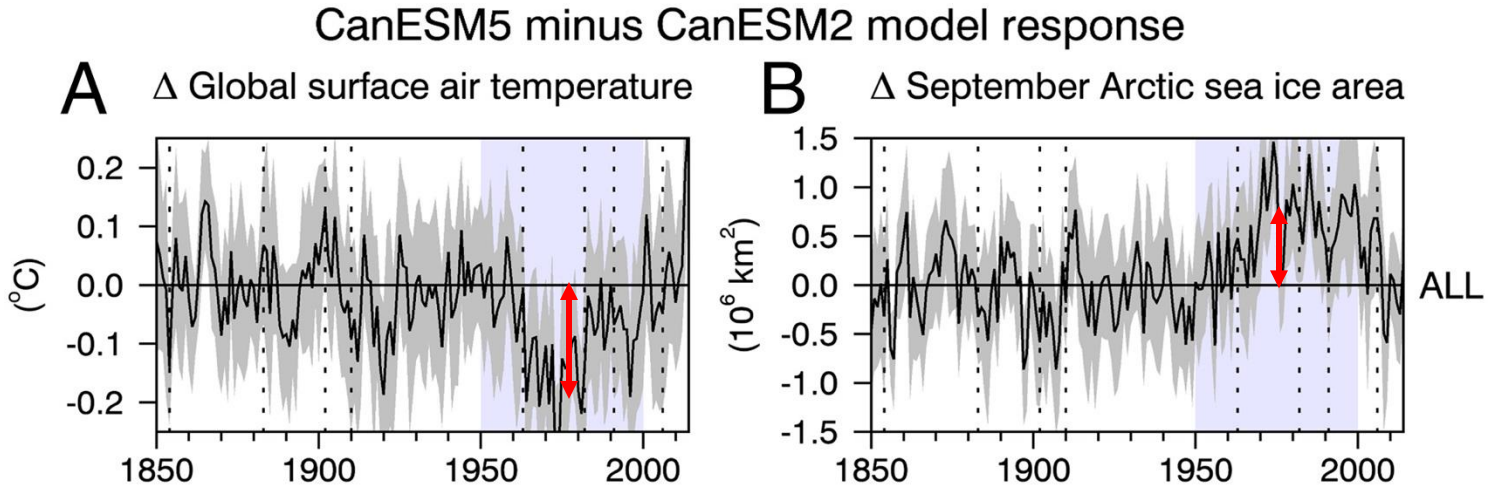
Model and forcing sensitivity – CanESM5/CanESM2

- During AR6/CMIP6 CCCma ran ESM variants with large ensembles
- CMIP6 era CanESM5
  - —CMIP6 forcings 50 members
  - —CMIP5 forcings 10 members
- CMIP5 era CanESM2
  - —CMIP5 forcings 5 members
- "..results provide evidence that global change uncertainty arising between different forcing estimates can be as large as uncertainty arising from different model versions.."

Fyfe *et al.*, 2021, PNAS, 10.1073/pnas.2016549118



↑ CMIP6 vs CMIP5 forcing difference – same model ↑



↑ CanESM5 vs CanESM2 model difference – same CMIP5 forcing ↑

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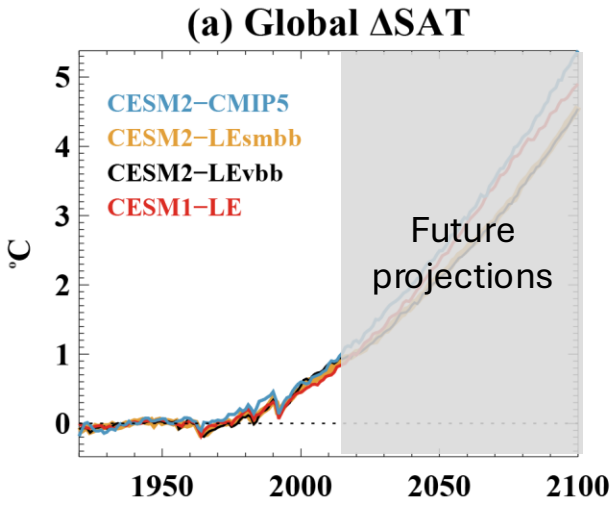
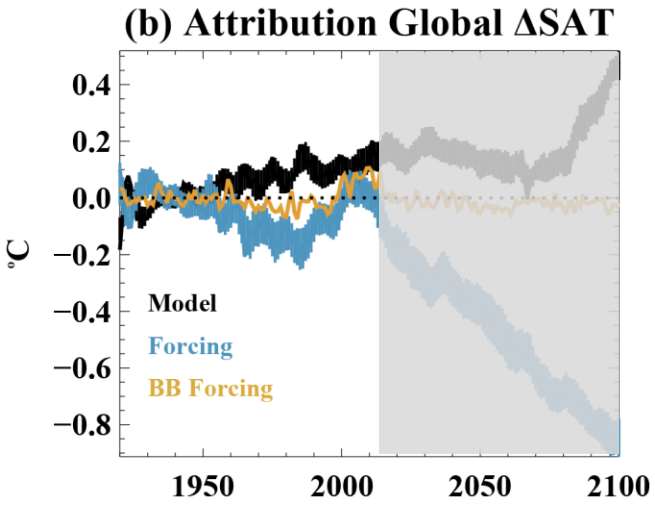
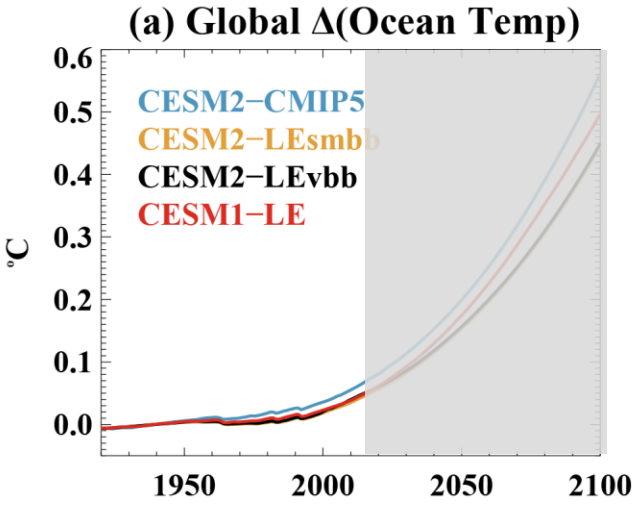
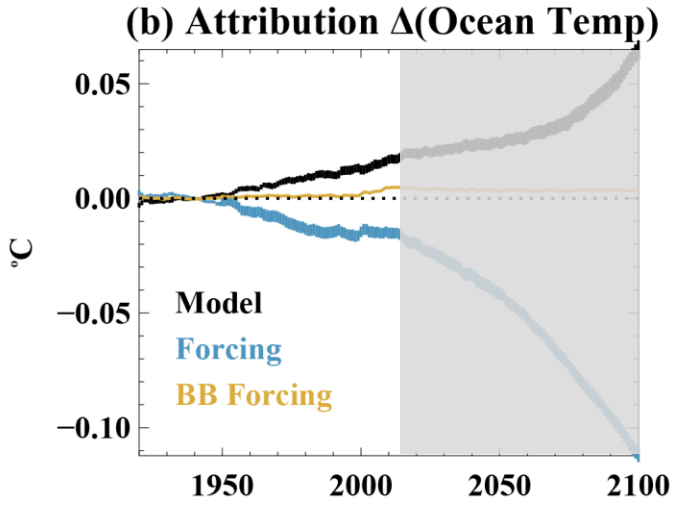
Model and forcing sensitivity – CESM2/CESM1









- NCAR ran CESMx large ensemble variants
- CMIP6 era CESM2-LE
  - —CMIP6 forcings 50 members (CESM2-LEvbb)
  - —CMIP5 forcings 10 members (CESM2-CMIP5)
- CMIP5 era CESM1-LE
  - —CMIP5 forcings 15 members
- "..For global mean, CMIP6 forcing drives reduced ocean heat uptake, and global surface air temperature change relative to the CMIP5 forcing. Model structural changes between CESM2 and CESM1 counteract this, driving larger global average warming in CESM2.."

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Holland *et al.*, 2021, GMD, 10.5194/gmd-17-1585-2024

Planning beyond CMIP7

- Recognition continued forcing datasets updating and delivery requires rethink
- Many research and operational programs have a need for up-to-date forcings to enable latest model development and simulations
- Ascertain how best to optimize research dependent forcing development with ”operational” delivery
- Bring forcing dataset providers, modeling groups and funding agencies together to determine future opportunities
- 28th October 2024, Reading UK

https://wcrp-cmip.org/event/forcings-workshop/

CMIP Coupled Model Intercomparison Project | WCRP

About CMIP | CMIP7 | CMIP Data | News and Events | Resources

/ Events

« All Events

Workshop: Pathway to regular and sustained delivery of climate forcing datasets

28 October @ 13:00 - 31 October @ 13:00 GMT

CMIP Coupled Model Intercomparison Project | ECMWF | esa

Links & Downloads

Workshop registration form →

CMIP Climate Forcings Task Team →

Detailed programme and logistics (as of 13 Sept) →

Context

In discussions around a potential sustained mode or “operational” CMIP activity, provision of climate forcing datasets has been identified as high priority for moving to a regular delivery mode to meet user needs and sustained by appropriate funding, resources and infrastructure. Indeed, one of the CMIP Climate Forcing Task Team core goals is to “Work with teams to identify, develop, document and deliver an updated and expanded forcing collection to near real time”. There is strong agreement around this ambition; however, the reality of implementation is complex and the funding landscape remains fragmented. In addition, we recognize that the very development of climate forcing datasets has a foot in basic research developing the knowledge of historical evolution of forcing agents, and quantifying their uncertainties, which has to occur in parallel to their “operational” use – both need to be sustained and augmented if the ambition is to be realized.

This four day workshop will be an opportunity to review the current provision model, discuss the key challenges, hear from users and potential users of the data, co-create a range of practical implementation options, develop the vision and generate concrete actions towards regular and sustained climate forcings dataset delivery. The outcomes of the workshop will feed into the CMIP sustained mode scoping study being led by Helene Hewitt (CMIP Panel Co-chair) and Greg Flato (WGCM Co-chair).

Registration

Deadline for registrations: Monday 30th September 2024

Summary

- Progress in understanding and attributing observed climate changes possible through MIP activities extending across 5 decades
- International coordination, standardized experimentation and multi-model approaches key
- Ongoing progress will be made through
  - —Better coordinating, understanding and using existing forcing data
  - —Quantifying known uncertainties second step
  - —Understanding how forcings are implemented across model configurations, and their differences
  - —Ascertain funding sources and approaches to realizing “operational” forcing provision

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