CMIP6 Status: highlights, lessons learned, challenges

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The World Climate Research Programme's Coupled Model Intercomparison Project

WGCM 23rd Session

9 December 2020

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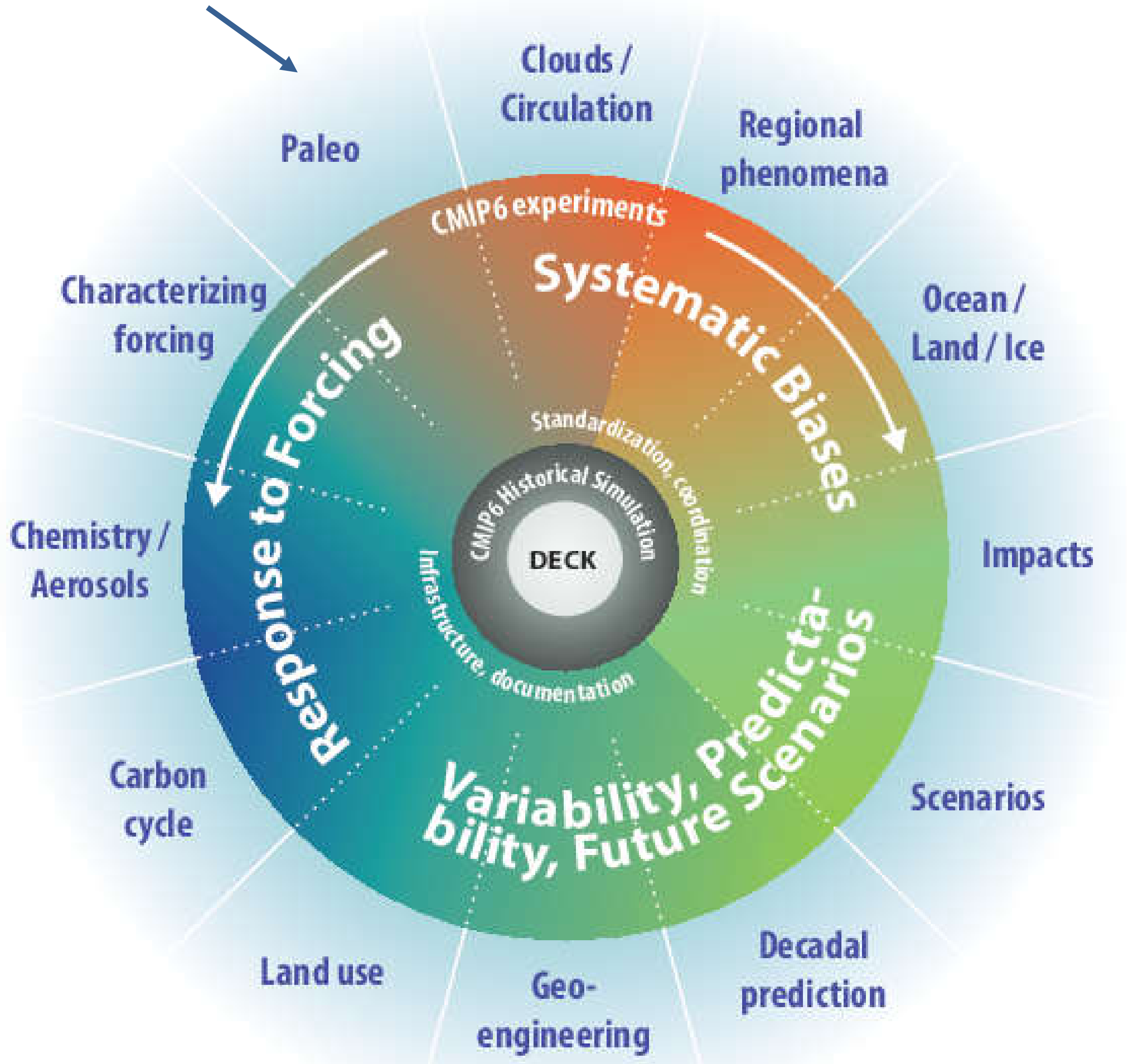
CMIP6 Design

The World Climate Research Programme's
Coupled Model Intercomparison Project

CMIP: a More Continuous and Distributed Organization

(3) CMIP-Endorsed Model Intercomparison Projects (MIPs)



Eyring et al., GMD, 2016

1) A handful of common experiments

DECK (entry card for CMIP)

i. AMIP simulation (~1979-2014)
ii. Pre-industrial control simulation
iii. 1%/yr CO_2 increase
iv. Abrupt 4xCO_2 run

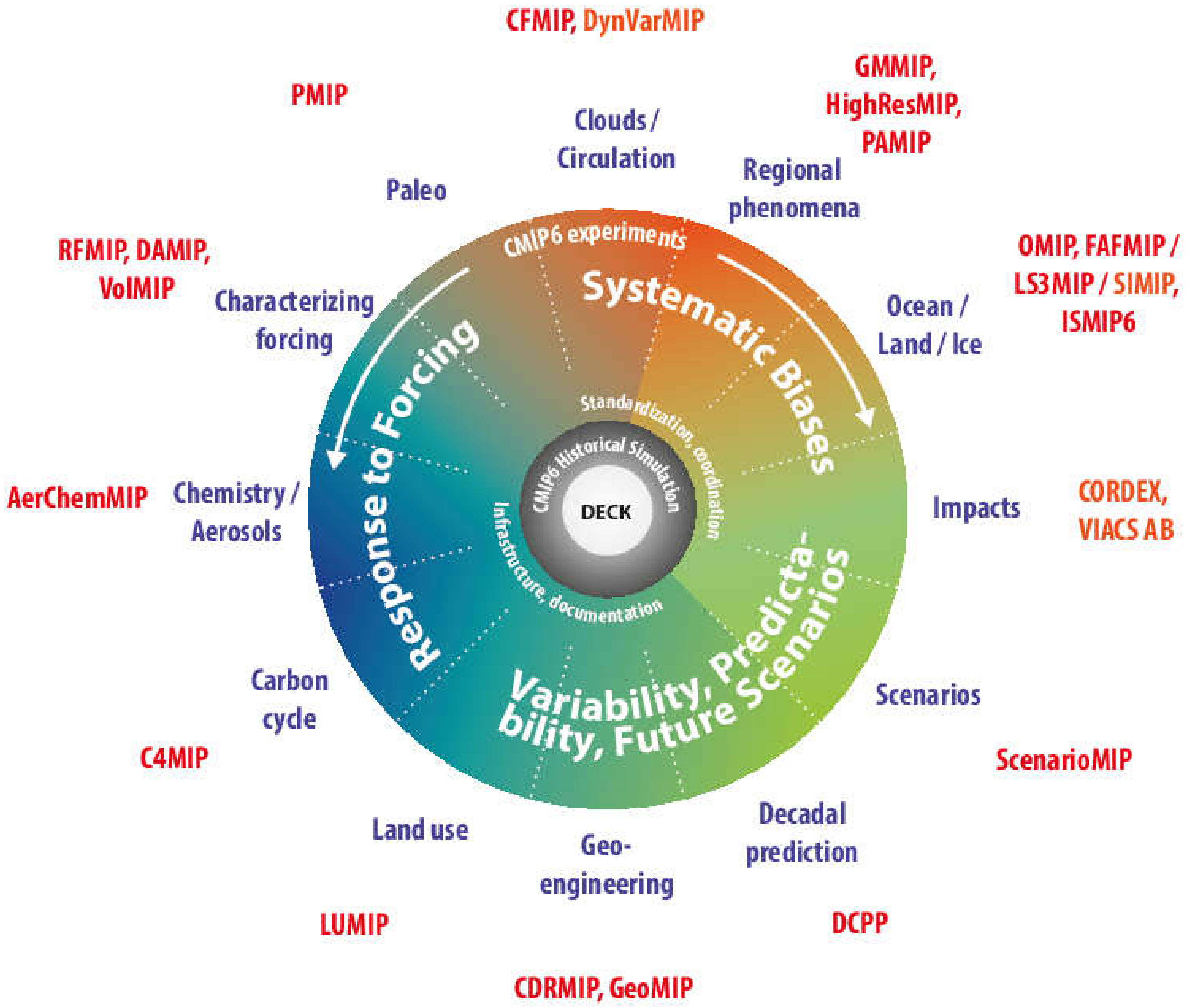
CMIP6 Historical Simulation (entry card for CMIP6)

v. Historical simulation using CMIP6 forcings (1850-2014)

2) Standardization, coordination, infrastructure, documentation

DECK (Diagnosis, Evaluation, and Characterization of Klima) & CMIP6 Historical Simulation to be run for each model configuration used in CMIP6-Endorsed MIPs

23 CMIP6-Endorsed MIPs



Community-based design with 10 agreed MIP criteria for Endorsement, e.g.

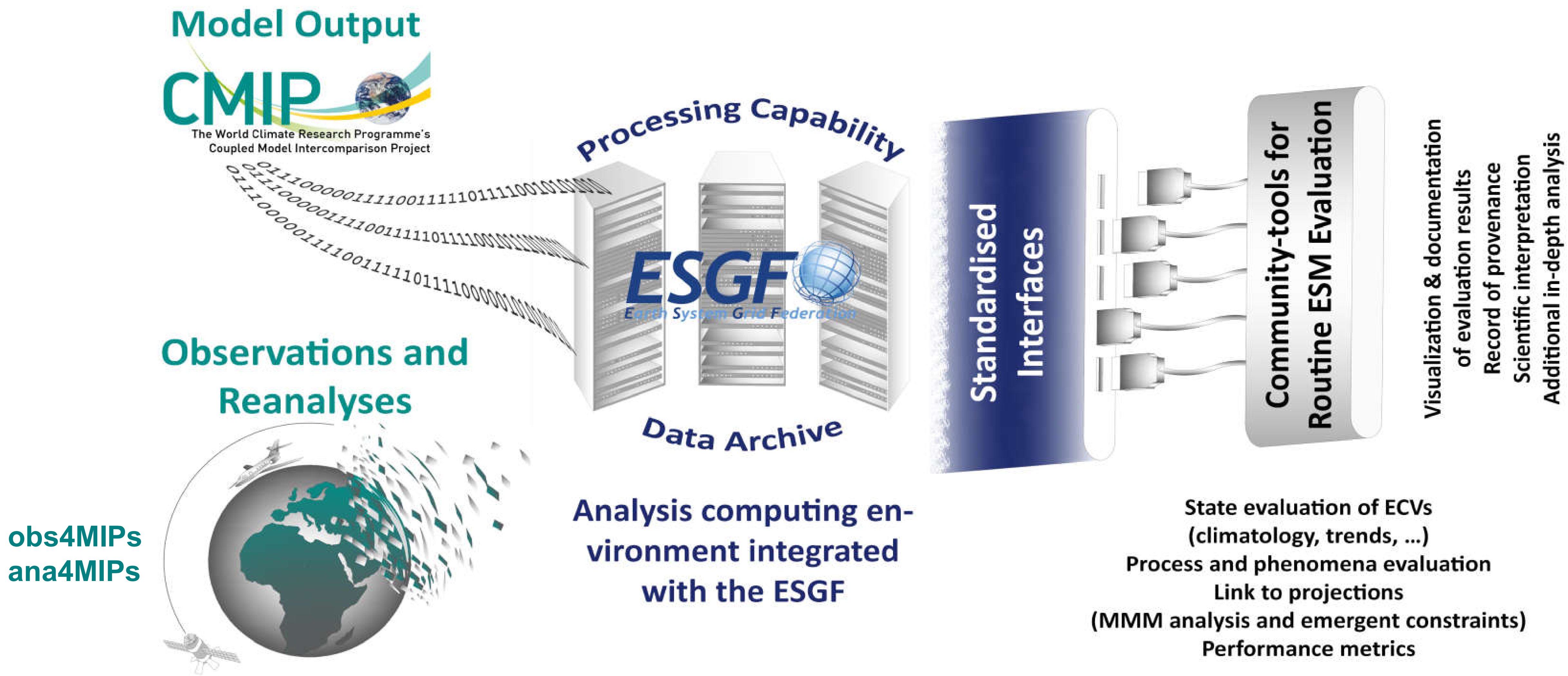
A sufficient number of **modelling centers (at least 8)** are committed to performing all of the MIP‘s Tier 1 experiments and providing all the requested diagnostics needed to answer at least one of its science questions.

Diagnostic MIPs

See Special Issue on the CMIP6 experimental design and organisation at https://www.geosci-model-dev.net/special_issue590.html for description of the CMIP6-Endorsed MIPs

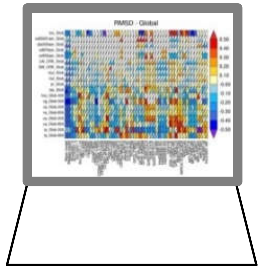
Routine Evaluation established in CMIP6

- Ensuring traceability and provenance of the results -



Eyring et al., ESD (2016)

ESMValTool Result-Browser:
https://cmip-esmvaltool.dkrz.de



ESMValTool
Earth System Model eValuation Tool

NCAR UCAR | CGD's Climate Analysis Section
Climate Variability Diagnostics Package

PCMDI Metrics Package (PMP)

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CMIP6 Design: Scientific Focus

- The **scientific backdrop** for CMIP6 is the **WCRP Grand Science Challenges**:
  1. Clouds, Circulation and Climate Sensitivity
  2. Changes in Cryosphere
  3. Climate Extremes
  4. Regional Sea-level Rise
  5. Water Availability
  6. Near-Term Climate Prediction
  7. Biogeochemical Cycles and Climate Change
- The specific experimental design is focused on **three broad scientific questions**:
  1. How does the Earth System respond to forcing?
  2. What are the origins and consequences of systematic model biases?
  3. How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?

Eyring et al., Overview CMIP6, GMD, 2016

General Model Evaluation of the DECK and the historical simulations

(more in the talk by Manuel Schlund)

ESMValTool

Earth System Model Evaluation Tool

CMIP

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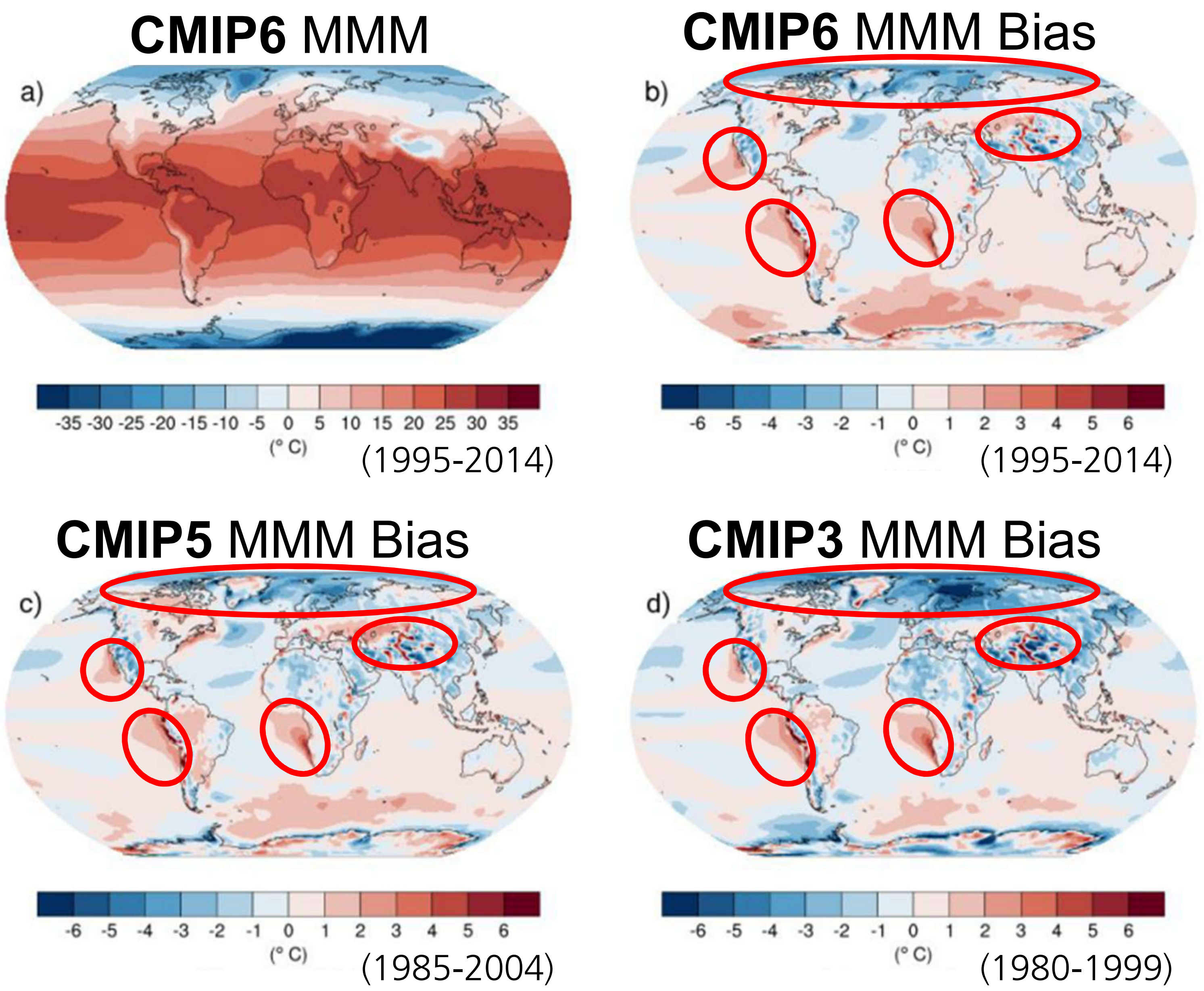
Near-surface temperature bias

- Annual climatological multi-model mean (MMM) -



Reference data set: ERA5

Systematic biases remain in CMIP6

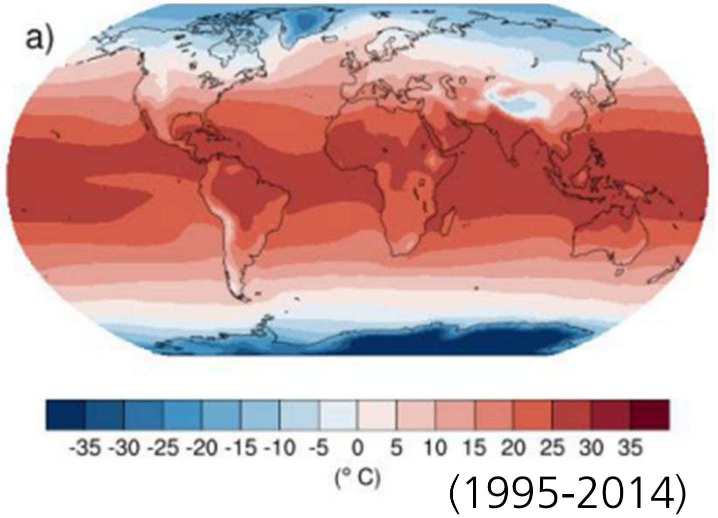
- In **high elevation** regions
- Near **ice edge** in the North Atlantic
- Over **ocean upwelling regions**
- Many reasons: errors in simulated **cloud properties**, errors in **oceanic circulation**, etc.

Bock et al., JGR: Atmospheres, 2020

Near-surface temperature bias

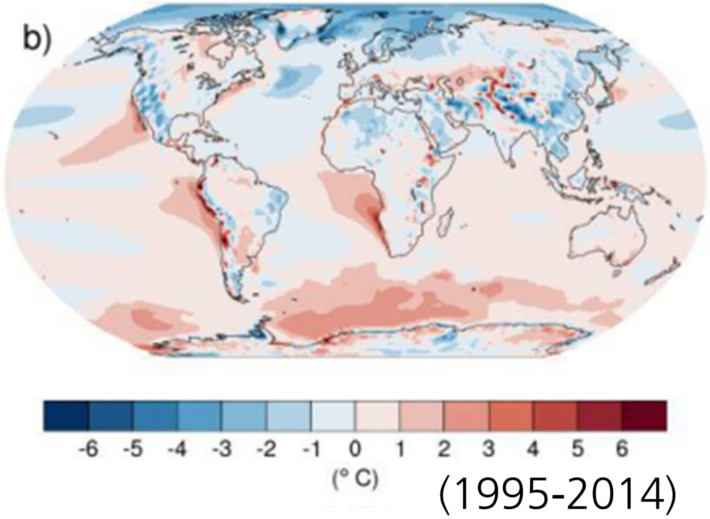
- Annual climatological multi-model mean (MMM) -

CMIP6 MMM



(1995-2014)

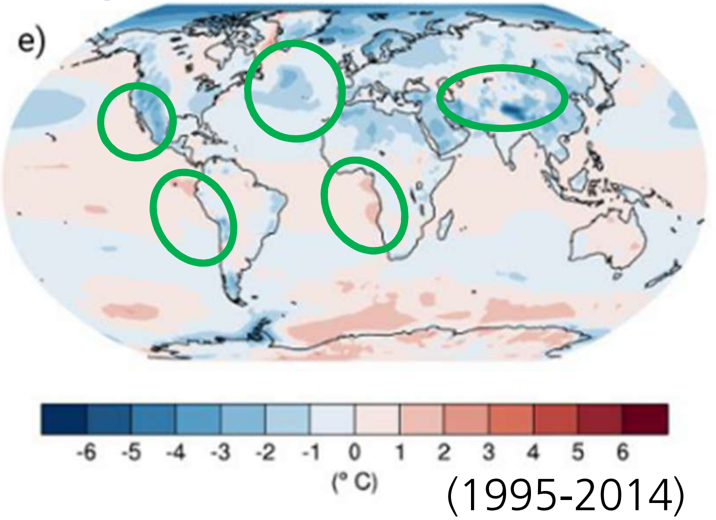
CMIP6 MMM Bias



(1995-2014)

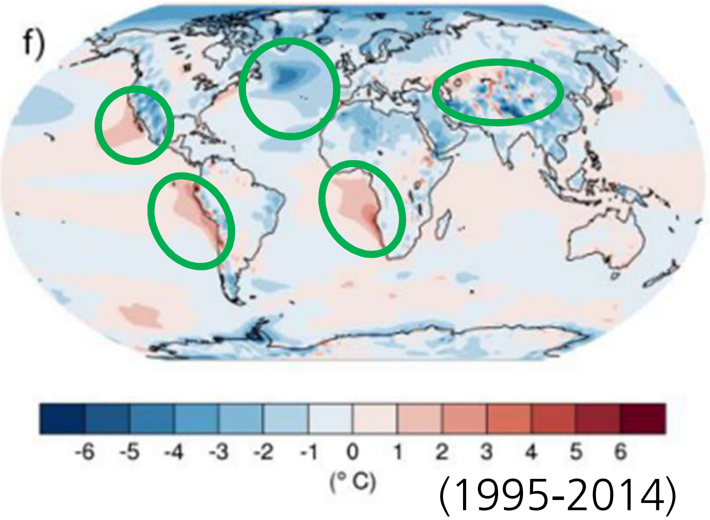
HighResMIP

High res MMM Bias



(1995-2014)

Low res MMM Bias



(1995-2014)

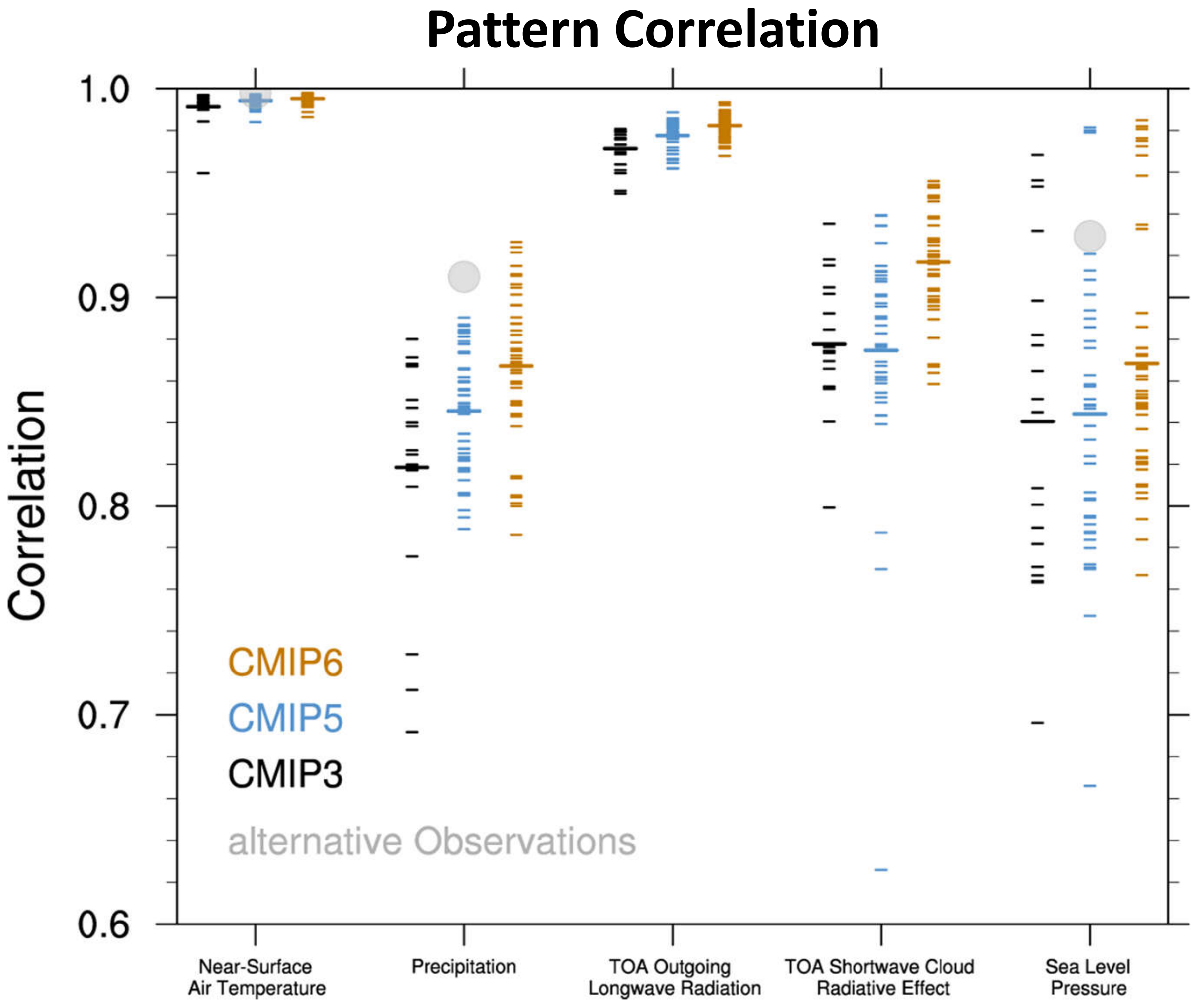
Reference data set: ERA5

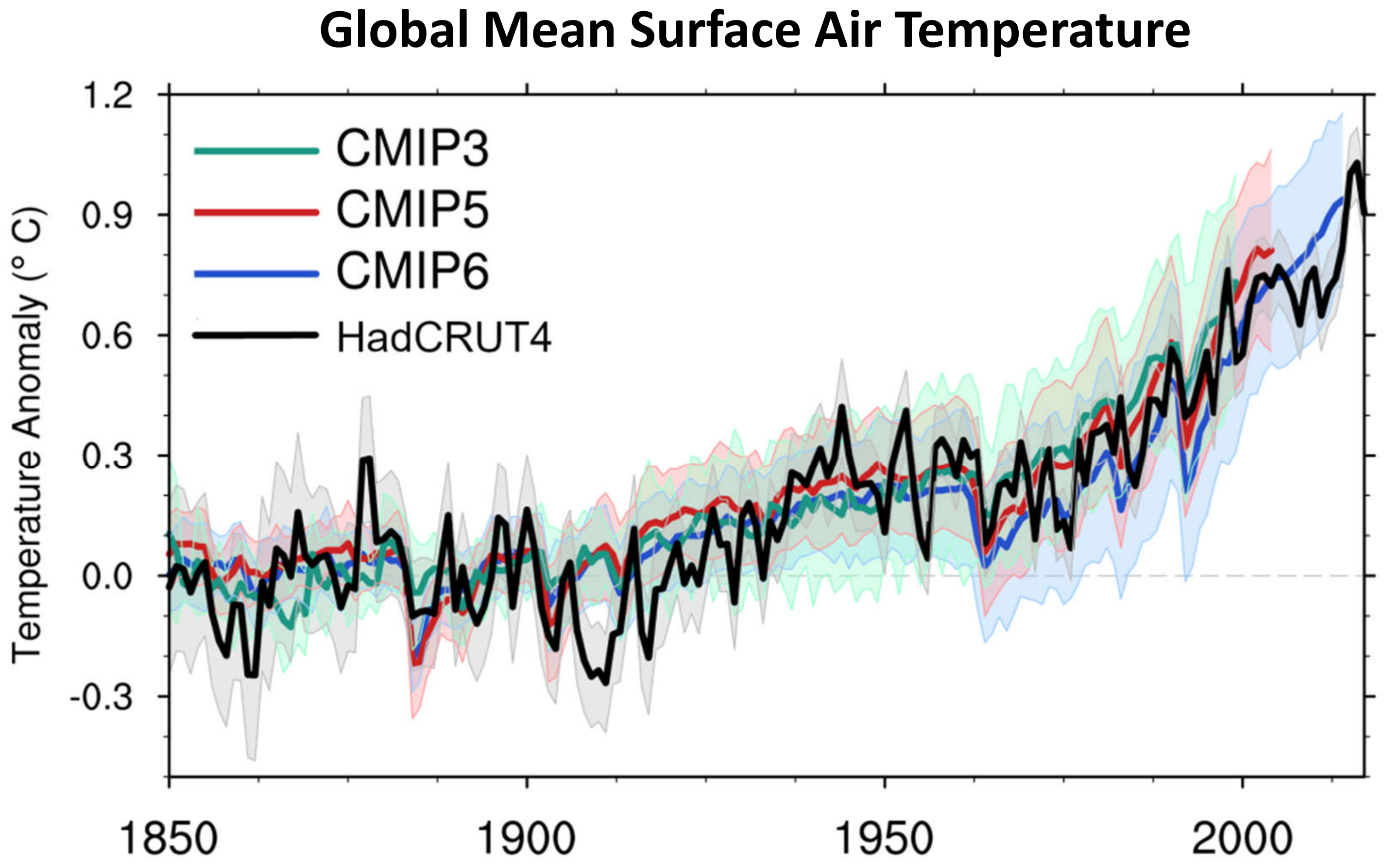
Related to horizontal resolution?

- Most biases **decrease** for HighResMIP model simulations (ocean upwelling regions, high elevations, etc.)
- Direct comparison to CMIP6 ensemble **not possible** due to different experiment setups

Bock et al., JGR: Atmospheres, 2020

Are Earth System Models Improving?





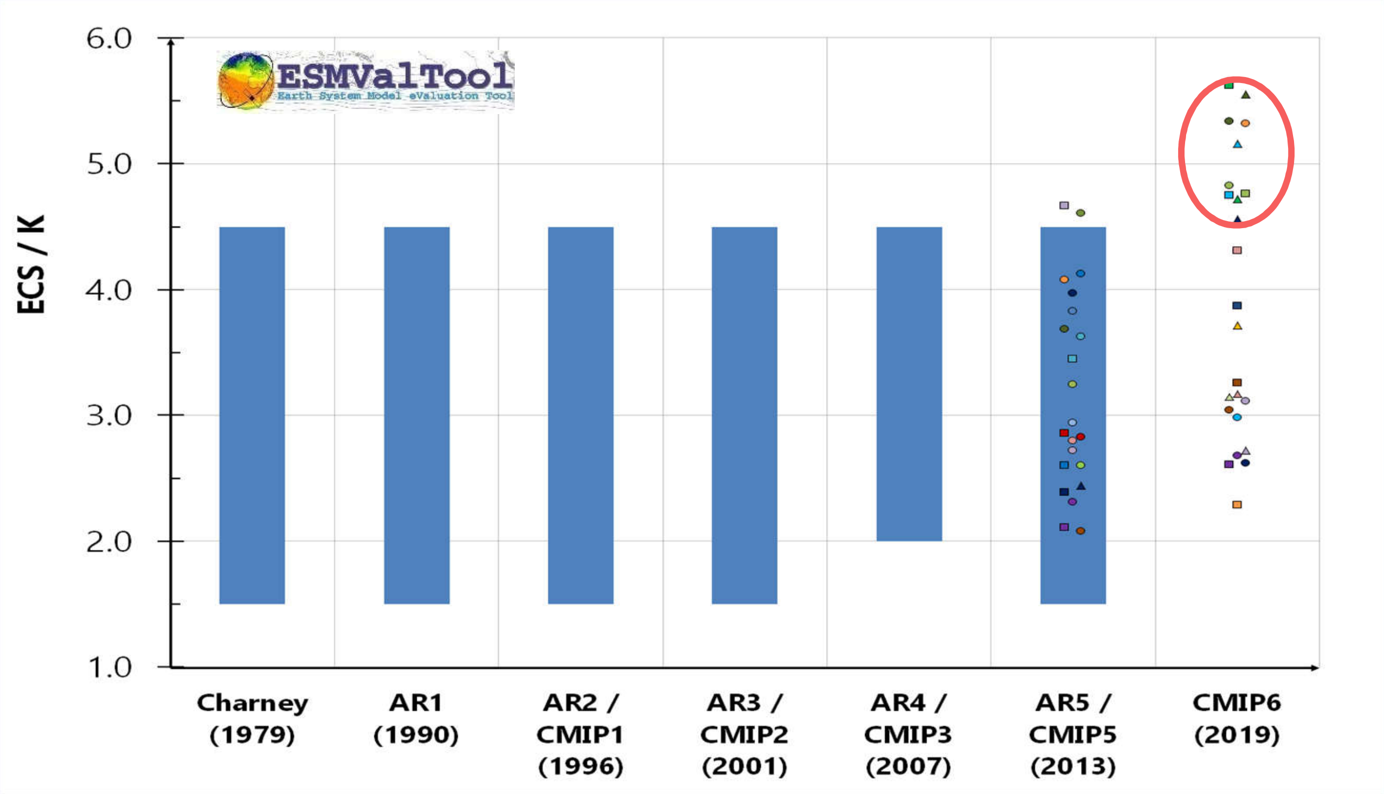
→ Significant improvements from CMIP3 to CMIP6 in **model performance of mean climate**

→ Overall **warming trend** similar than in observations
→ Stronger **reduction in warming** over the period 1950-1990 in CMIP6
→ Some CMIP6 models have **larger warming** in recent decades than observed

Bock et al., JGR, 2020

Large Uncertainties in Climate Projections Remain

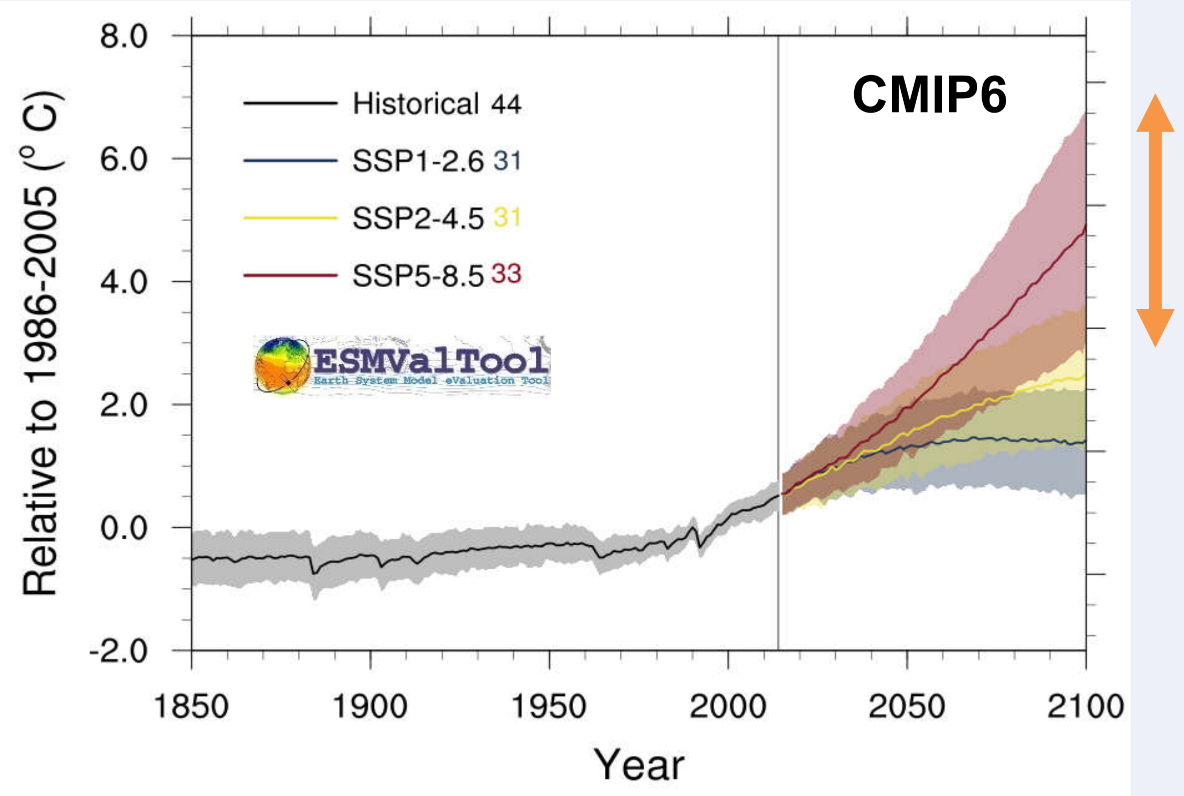
Effective Climate Sensitivity (ECS)



Uncertainty range (1.5 - 4.5°C) has not decreased

Meehl et al., Science Adv. (2020)

Global warming projections



Large Uncertainties: Clouds & Carbon Cycle

Tebaldi et al., ESDD (2020)

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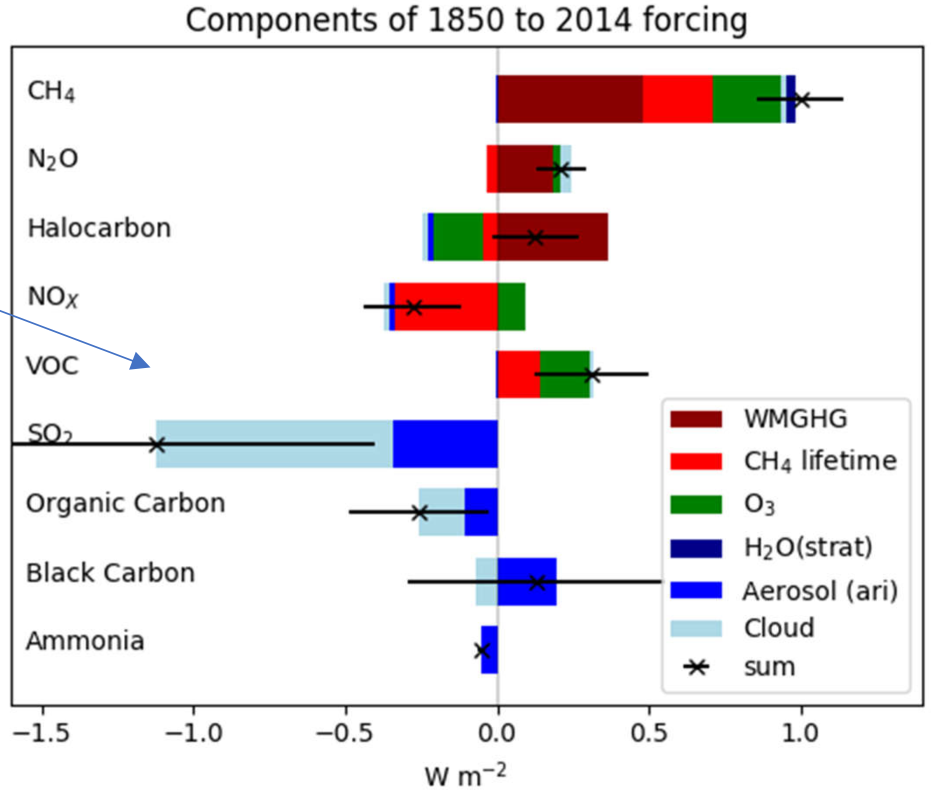
Scientific Highlights from CMIP6-Endorsed MIPs

CMIP

The World Climate Research Programme's
Coupled Model Intercomparison Project

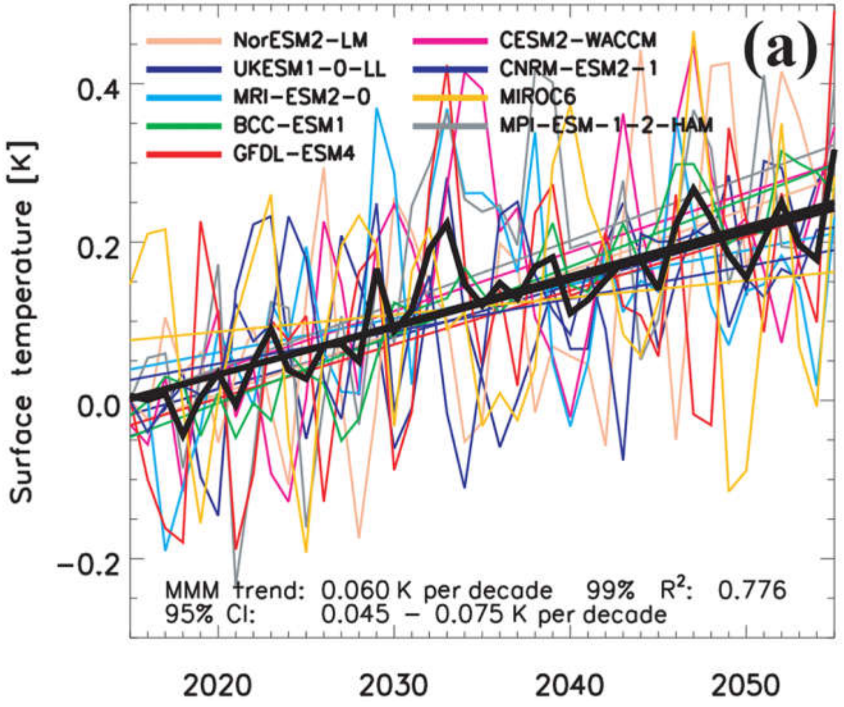
AerChemMIP- Aerosols and Chemistry MIP

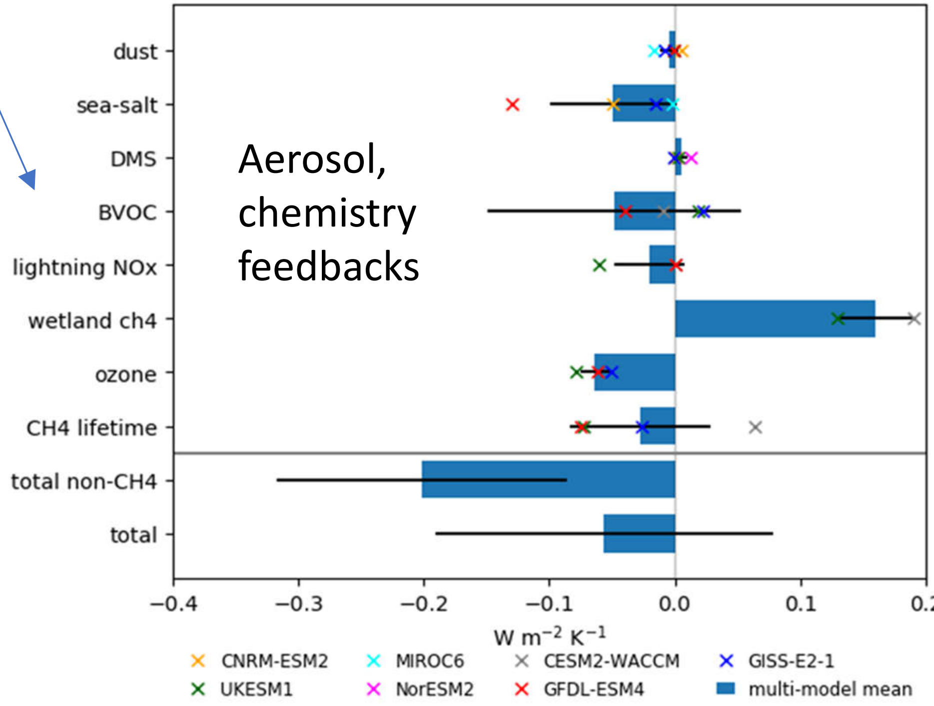
- Quantification of the additional **historical effective radiative forcing** caused by the WMGHGs through their impacts on methane lifetime, ozone, aerosols, and clouds
  - Species specific studies: Ozone, OH, ODSs, Aerosols.
  - Evaluation of trop ozone, strat ozone, aerosols
- **Future scenarios + with air quality controls:** gives warming effect => Impacts on ozone, PM, climate
- Aerosol and Chemistry contributions to model's **climate sensitivity:** overall negative feedback - increased natural aerosols, decreased ozone



Impact of air quality controls in SSP3-7.0

Non-methane controls lead to warming (Allen et al. ACP 2020)

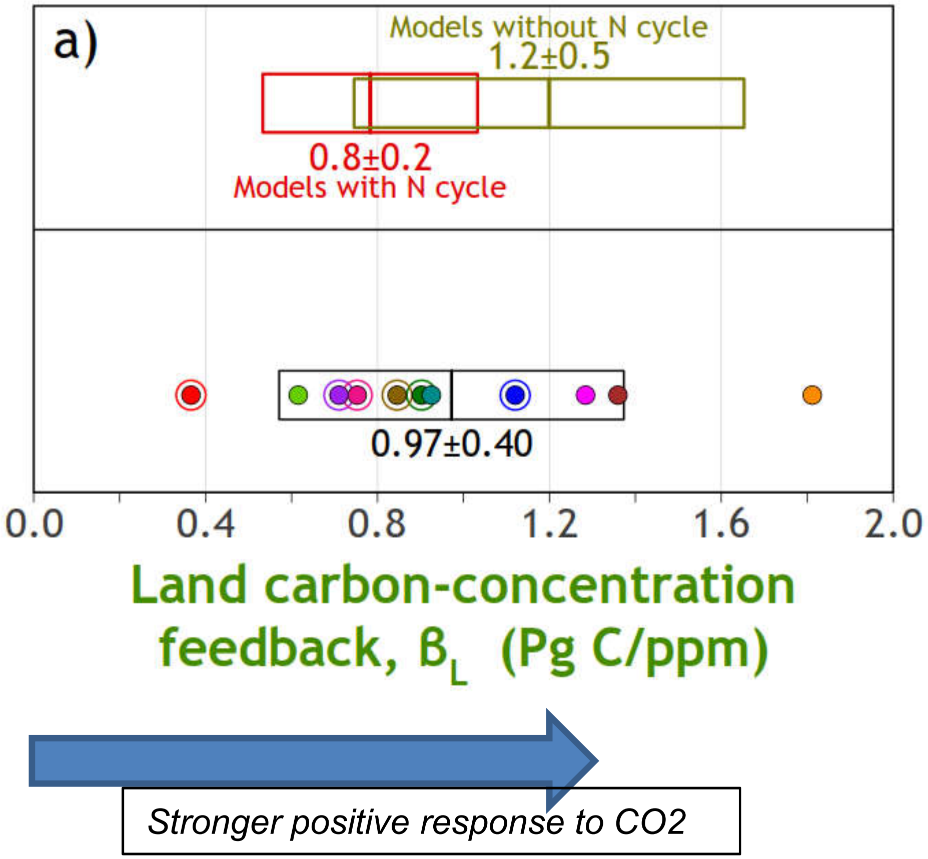




Thornhill et al. ACP 2020

C^4MIP - Coupled Climate Carbon Cycle Model Intercomparison Project

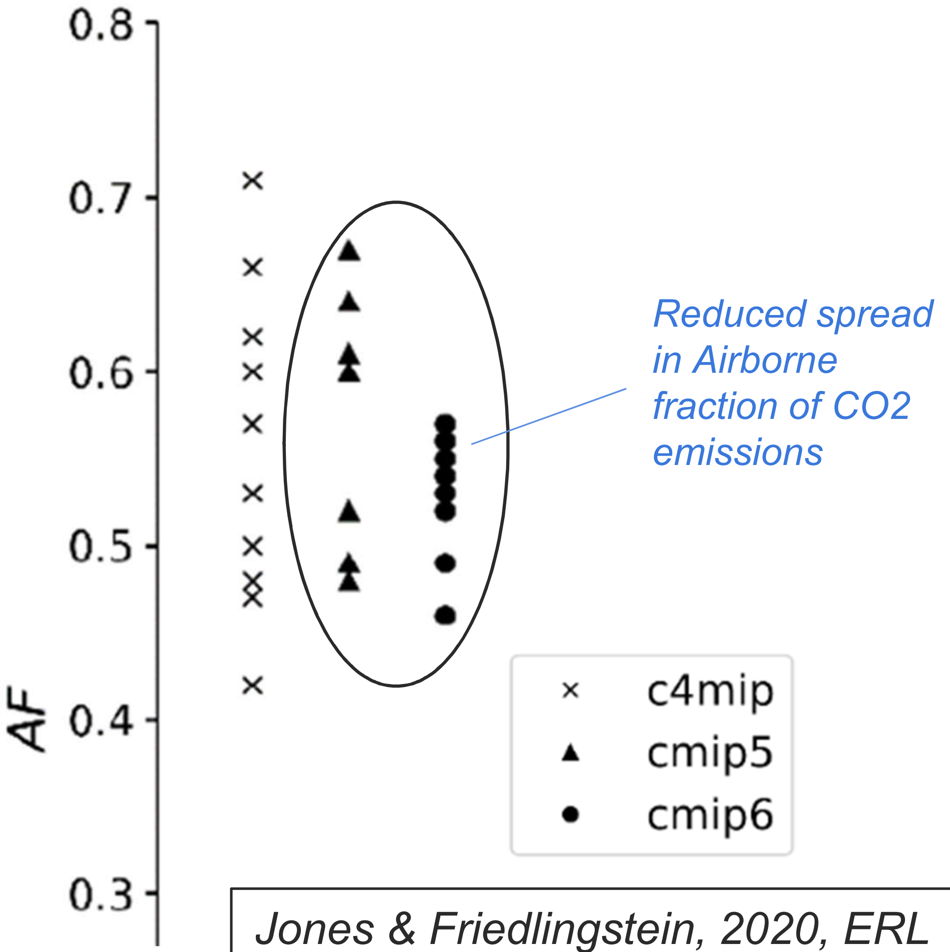
Carbon cycle feedback analysis



Biggest advance: Models with land nitrogen cycle exhibit **weaker strengths of the land carbon-concentration feedback** and a **narrower spread** across models.

Arora et al. (2020, Biogeosciences)

- This means - **Carbon cycle response** has been **constrained in CMIP6 (less spread),** relative to CMIP5, due to inclusion of terrestrial Nitrogen cycle



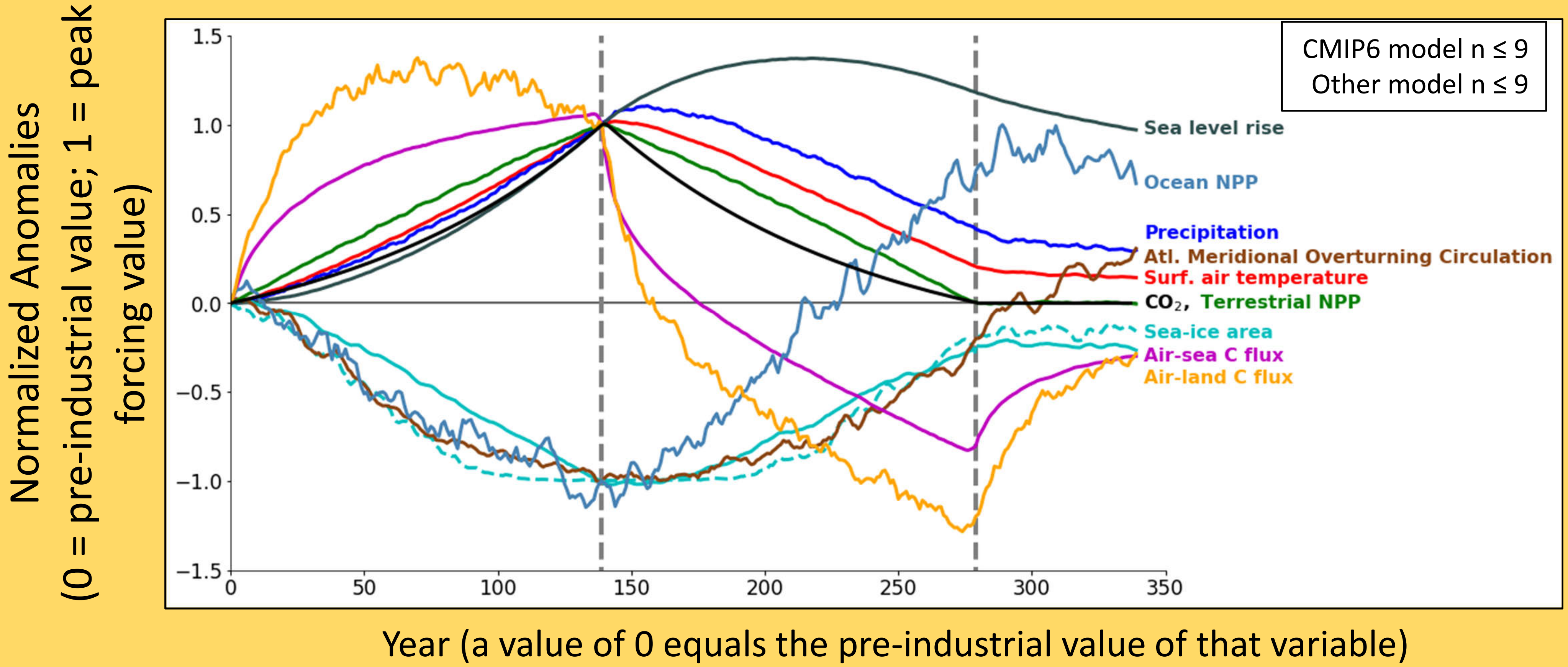
Jones & Friedlingstein, 2020, ERL

Leads to reduced uncertainty in TCRE and remaining carbon budgets

γ and β both decrease in magnitude (so γ becomes less negative). β is the bigger controller of the airborne fraction.

Is climate change reversible? CDRMIP - Carbon Dioxide Removal MIP: *cdr-reversibility* experiment results

Multi-model mean changes normalized to pre-industrial and peak CO_2 forcing



Keller et al., *in prep*

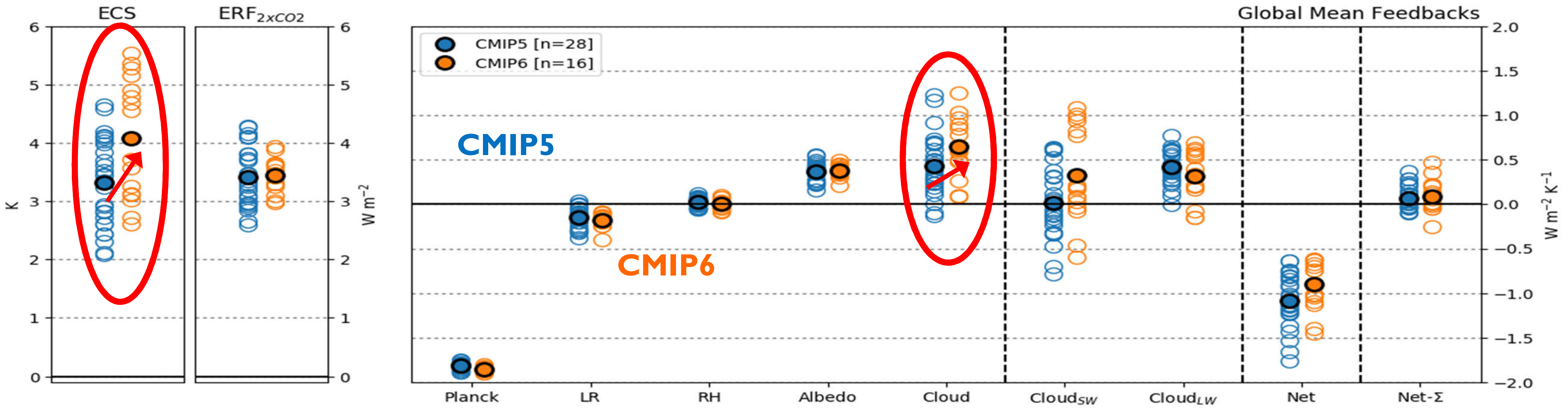
- For many modelled quantities climate change eventually **reversible** (at least at the global annual mean level).
- However, for most variables the response time-scales to the CO2 increase are very different than to the decrease in CO2 with many properties exhibiting **long time lags** before responding to decreasing CO2, and much longer again (many times greater than a human lifetime) to return to their unperturbed values (if this occurs).

Focuses on how the climate responds to a rapid and massive CO_2 increase (1% yr^{-1} to 4x pre-industrial) followed by a **decrease (1 % yr^{-1} back to pre-industrial) that implies large-scale carbon dioxide removal:**

- What components of the Earth's climate system exhibit "reversibility" when CO_2 increases and then decreases?
- On what timescales do these "reversals" occur?
- Which, if any, changes are irreversible? What role does hysteresis play in these responses?

CFMIP
Cloud Feedback Model Intercomparison Project

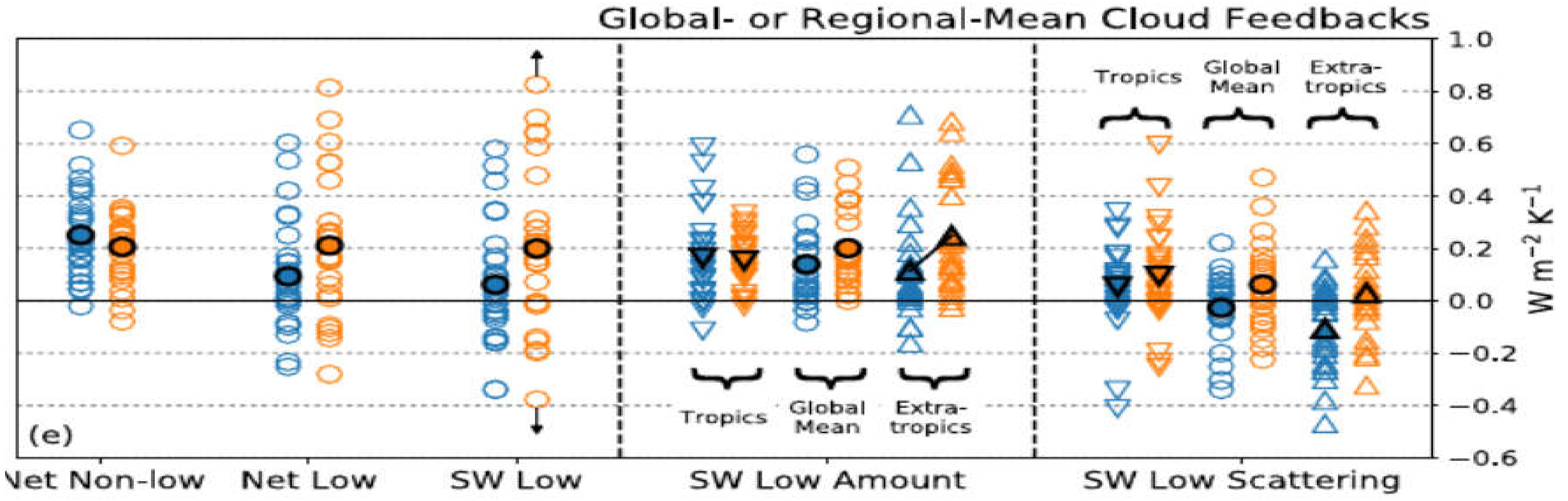
Zelinka et al. (2020 GRL)



A **stronger positive cloud feedback** is likely the major cause of higher CMIP6 ECS values

Breakdown of the cloud feedback into net non-low, net low, and SW low components.

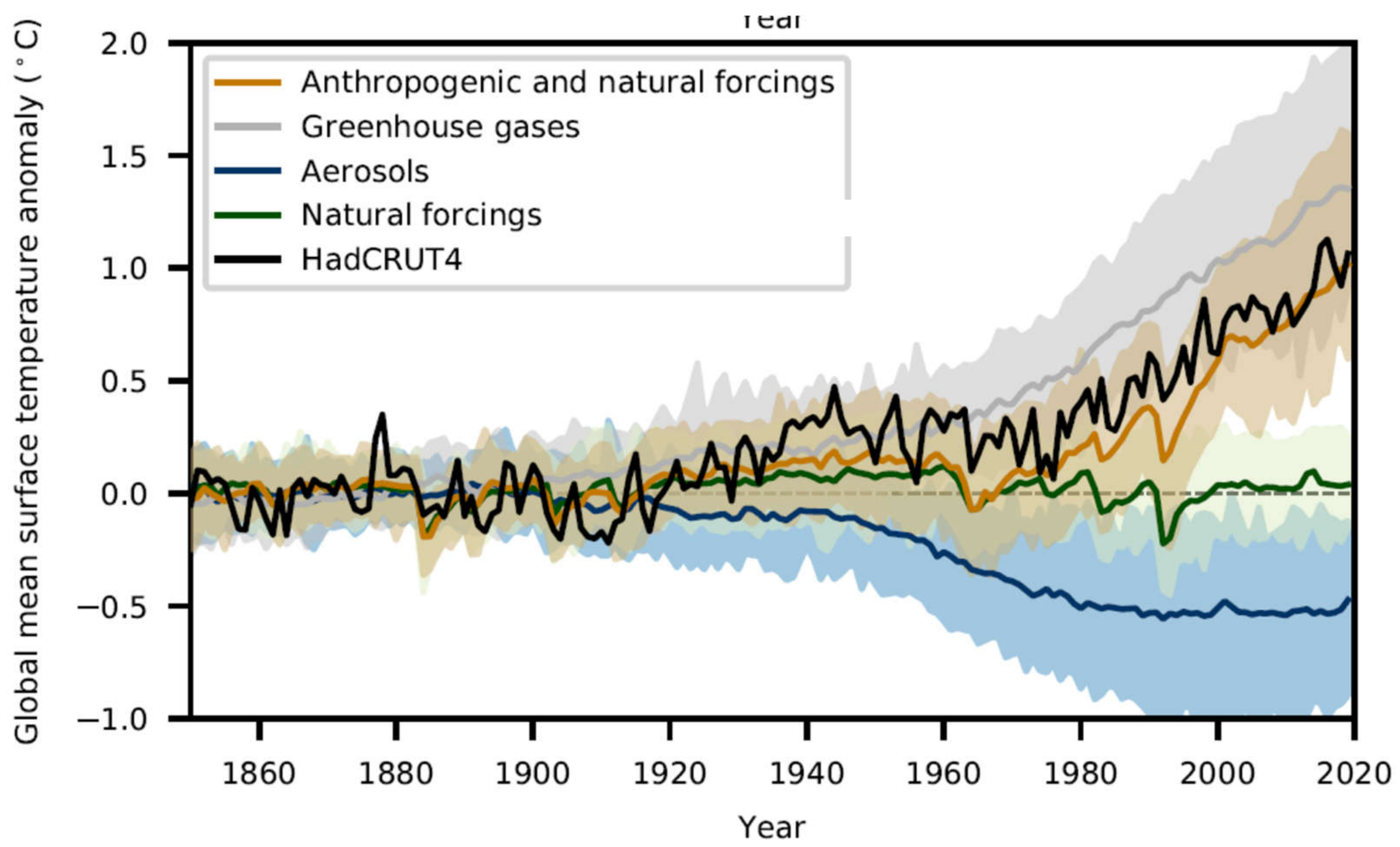
SW low component is further broken down into amount and scattering components



- **Increase in SW low cloud feedbacks** more dramatic & statistically significant in the extratropics.
- MMM **extratropical SW low cloud scattering feedback** changes from negative to positive
- MMM **low cloud amount feedback** is actually larger in the extratropics than in the tropics

DAMIP - Detection and Attribution Model Intercomparison Project

- DAMIP simulations from 13 CMIP6 models published on ESGF, and have been used in many studies to constrain anthropogenic contributions to observed changes in temperature and other variables.
- Extensions to DAMIP have been added to examine contributions of individual forcings to CMIP5 to CMIP6 differences, detectability of the response to COVID-19.

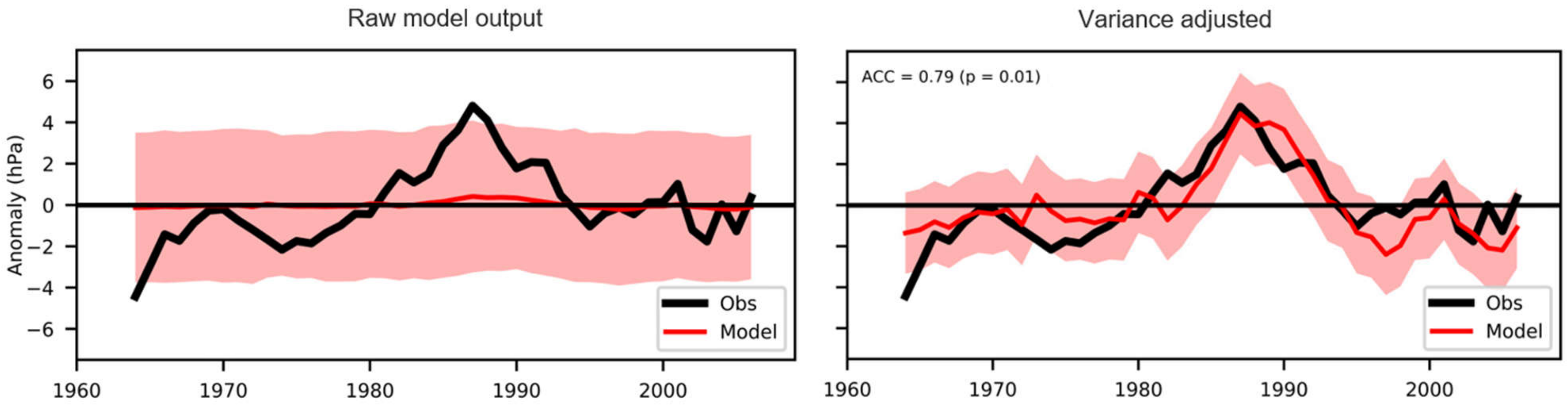


Model name	historical -ssp245	hist-nat	hist-GHG	hist-aer	hist-stratO3	hist-sol	hist-volc	hist-CO2
ACCESS-ESM1-5	3	3	2	3				
BCC-CSM2-MR	1	3	3	3				
CanESM5	50	50	50	30	10	50	50	10
CESM2	3	2	1	2				
CNRM-CM6-1	6	10	10	10				
FGOALS-g3	4	3	3	3				
GFDL-ESM4	3	3	1	1				
GISS-E2-1-G	10	5	5	5				
HadGEM3-GC31	4	4	4	4				
IPSL-CM6A-LR	11	10	10	10	10			
MIROC6	3	3	3	3	3	3	3	3
MRI-ESM2-0	5	5	5	5	3	5		
NorESM2-LM	2	3	3	3				

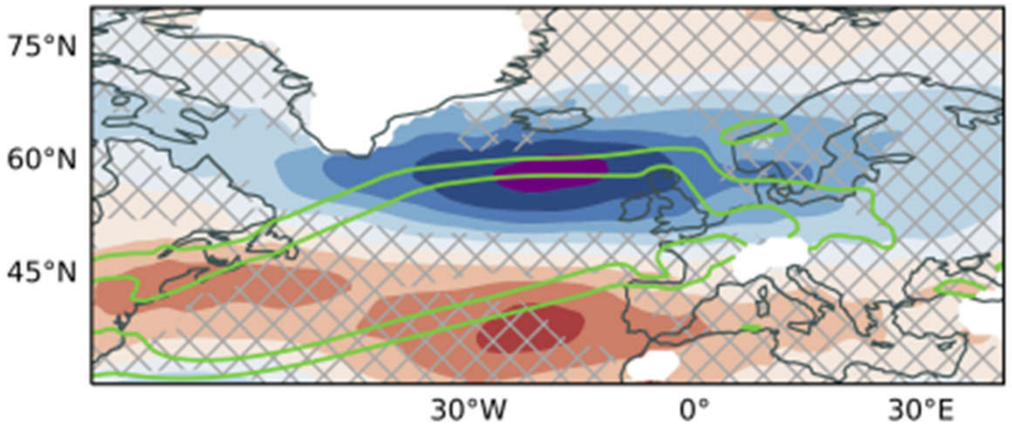
Benefits from additional single forcing simulations compared to CMIP5

Decadal Climate Prediction Project (DCPP)

NAO : Forecast years 2 to 9



U850 response to AMV



Decadal predictions (DCPP component A)

Taken at face value (left) models show very little signal and huge uncertainties in decadal predictions of the North Atlantic Oscillation (NAO)

But the predictable signal is 10 times too small in the models. Hence skill is much higher than thought, but post processing is needed (right)

- adjust the variance of the ensemble-mean NAO forecast to match observed variance of the predictable signal.
- use only the ensemble members with a North Atlantic Oscillation sufficiently close to the variance-adjusted ensemble-mean forecast NAO
- This approach greatly improves decadal predictions of winter climate for Europe and eastern North America

Understanding (DCPP component C)

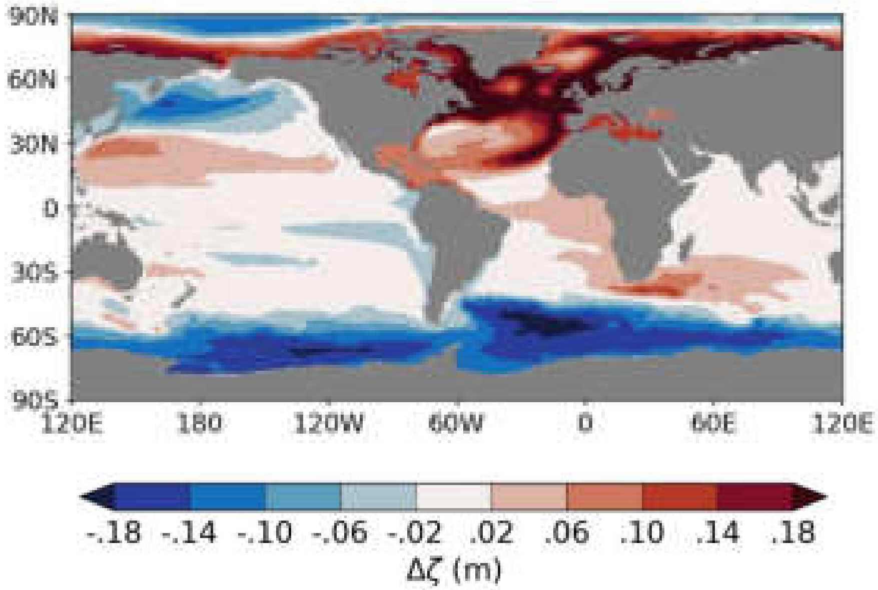
Atlantic Multidecadal Variability (AMV) drives an equatorward shift of the Atlantic storm track

The strength of the response depends on the ability of models to simulate jet regimes

Smith et al., Nature, 2020; Ruggieri et al., J Climate, 2020

FAFMIP (flux-anomaly-forced MIP)

- Addresses uncertainty in ocean heat uptake and sterodynamic sea level change. **AOGCM experiments with surface flux perturbations**, prescribed and typical of transient climate change at $2xCO_2$, to momentum, heat and freshwater.
- New process-based diagnostics of ocean d*T*/d*t* and d*S*/d*t*, also in DECK&OMIP.
- FAFMIP datasets from **8 CMIP6 AOGCMs** have been deposited on ESGF.
- Couldrey *et al.* (Clim Dyn, 2020) study FAFMIP data from 13 CMIP[356] AOGCMs.
- Todd *et al.* (JAMES, 2020) analyse **corresponding experiments with OGCMs**, not originally proposed because no workable method had previously been devised.



- **Multimodel-mean dynamic sea level change** is very similar in CMIP[56], primarily due to **heat flux change** (← shown), with a smaller contribution from **wind-stress change** in the Southern Ocean.
- The **model spread** is mostly due to redistribution of existing ocean heat content, due to AMOC change in the Atlantic, and probably to correlated eddy effects in the Southern Ocean.

Saenko *et al*. (J. Climate, in review) is the first multi-model study of heat uptake processes. It finds that OHU is dominated by **circulation and eddy transports** and almost entirely takes place along isopycnals.

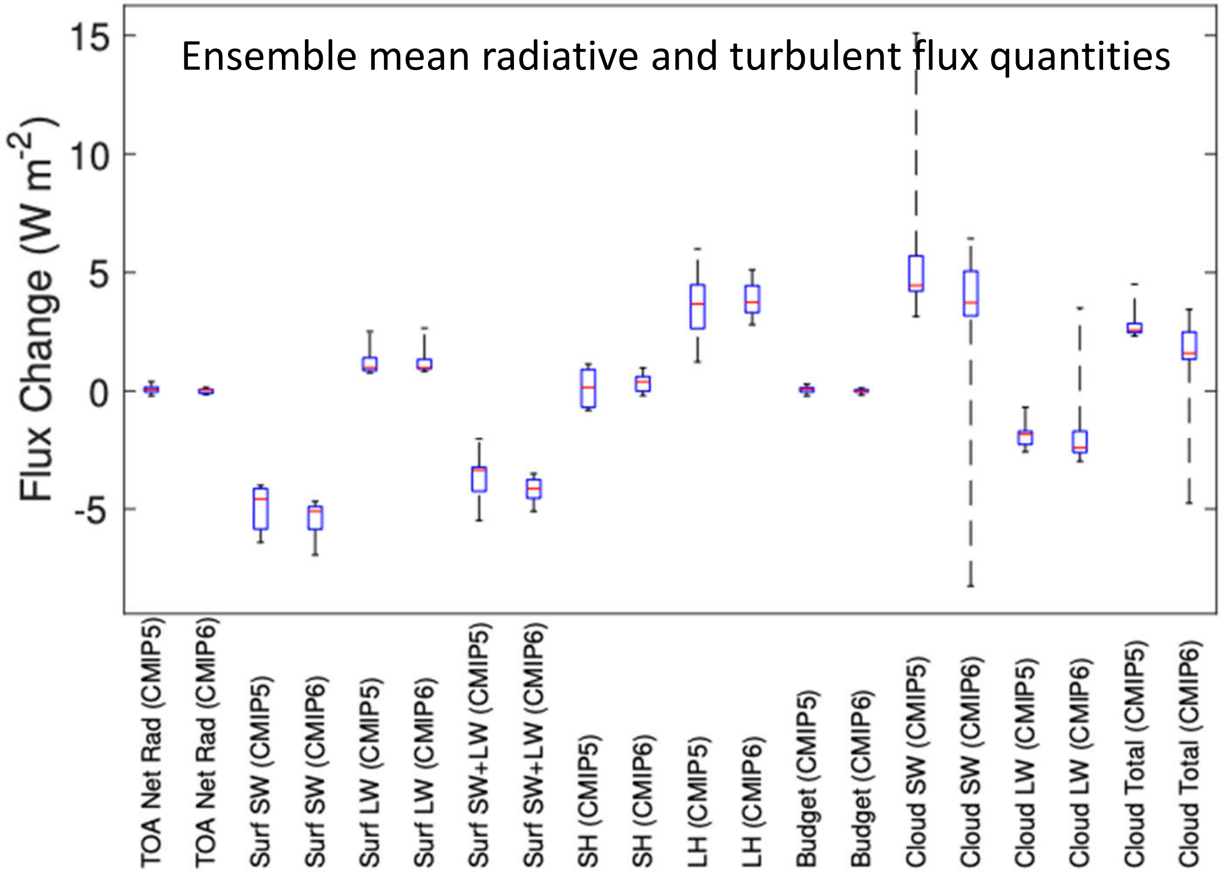
Geoengineering Model Intercomparison Project (GeoMIP)

- We have carried out standard experiments as part of CMIP5 and CMIP6 using identical global warming and geoengineering scenarios, to see whether our results are robust.
- Results from CMIP6 runs are now being analyzed and several papers have been submitted for publication in the 3rd GeoMIP special issue https://acp.copernicus.org/articles/special_issue1133.html.
- So far, 7 models have uploaded results for the G1 extended and 5 for the G6sulfur and G6solar experiments.
  - **G1**: starting from a preindustrial control (piControl) baseline, the atmospheric CO2 concentration is instantaneously quadrupled (the standard CMIP experiment abrupt4xCO2), and insolation is simultaneously reduced such that net top-of-atmosphere (TOA) radiative flux is approximately unchanged from the baseline in the first decade of simulation

Ensemble median (red lines), inter-quartile (blue boxes), and ranges (black whiskers) for global mean energetics quantities for both the CMIP5 and CMIP6 ensembles for the **experiment G1 minus piControl.**

No major differences between CMIP5 & 6 in how the models handle energy balance and energetics, with the exception of clouds => consistent with findings from Zelinka et al., 2020

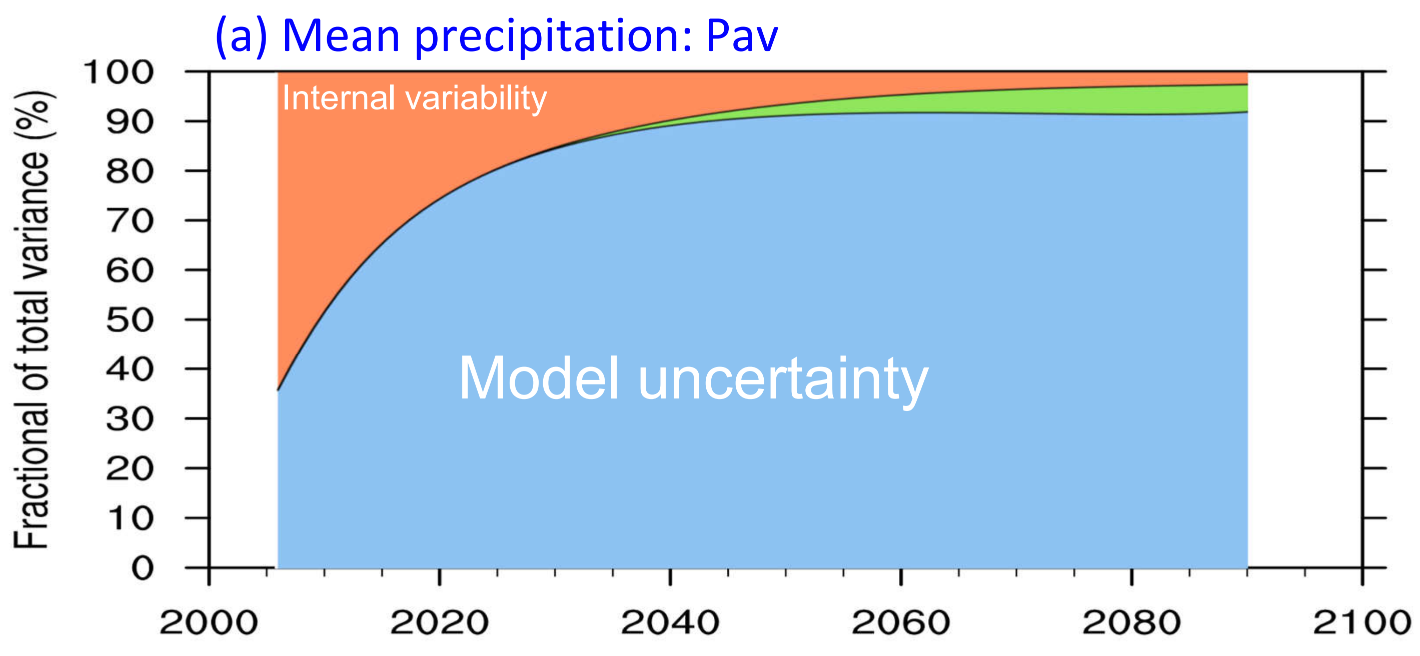
From Kravitz et al. (2020), in review for ACP
https://doi.org/10.5194/acp-2020-732

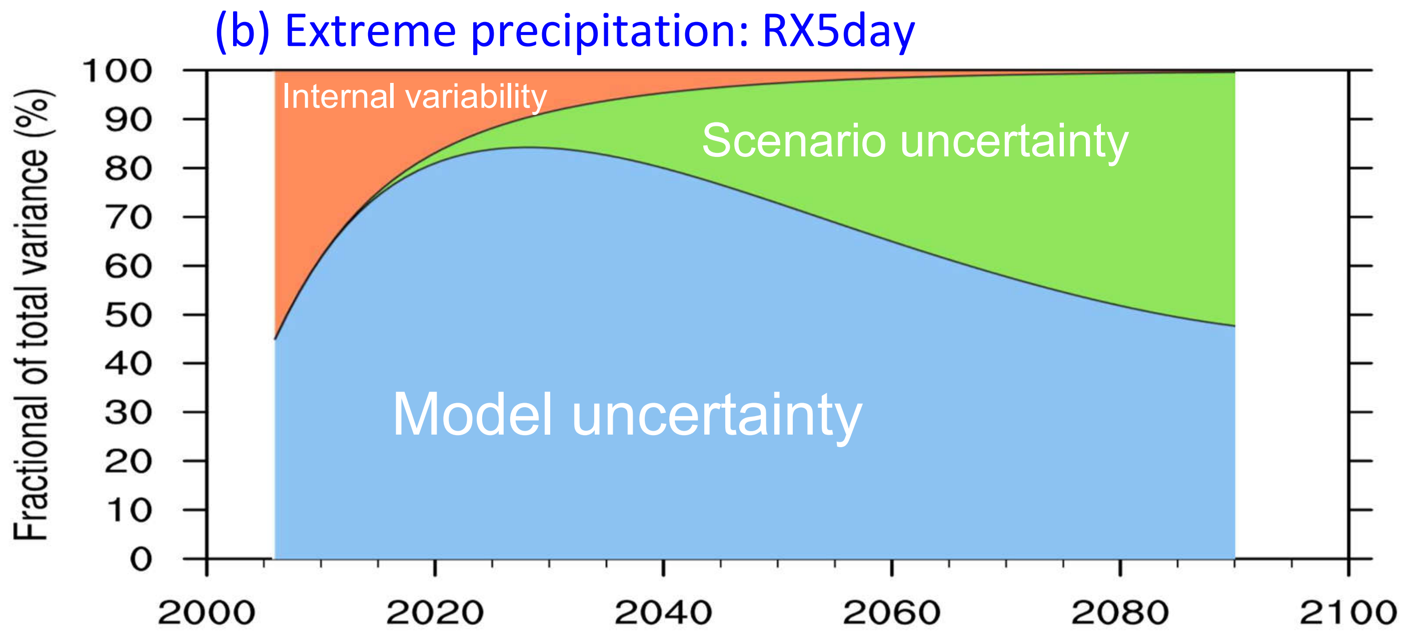


The World Climate Research Programme's Coupled Model Intercomparison Project

GMMIP - Global Monsoons Model Intercomparison Project

Quantify the uncertainty in the projection of global land monsoon precipitation





Fractions of total variance explained by **scenario uncertainty**, **model uncertainty** and internal variability in decadal mean global land monsoon precipitation projections

For **mean monsoon precipitation**

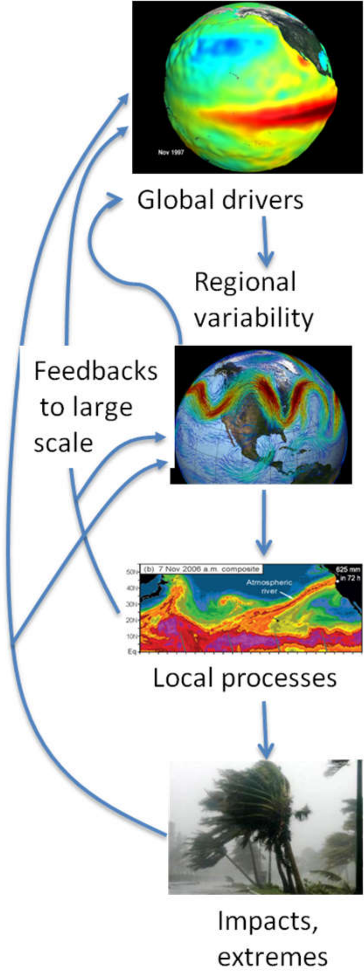
- more than **70% of variability** can be linked to **model uncertainty after 2020**, reaching 90% from ~2040.
- While internal variability is important, its influence is largely limited to the near-term, contributing ~30% variance in 2020 and diminishing thereafter as anthropogenic forcing strengthens.
- **Scenario uncertainty** consequently becomes a more important factor but contributes only ~10% variability by the end of the century.

In contrast, the contributions from **scenario uncertainty** are much larger for **extreme precipitation**, the influence of which is comparable to that of **model uncertainty** in the long term.

Zhou T., J. Lu, W. Zhang, Z. Chen,2020: The Sources of Uncertainty in the Projection of Global Land Monsoon Precipitation. *Geophysical Research Letters*, 47, e2020GL088415. https://doi.org/10.1029/2020GL088415

HighResMIP

Rein Haarsma KNMI (co-lead)
Malcolm Roberts Met Office (co-lead)



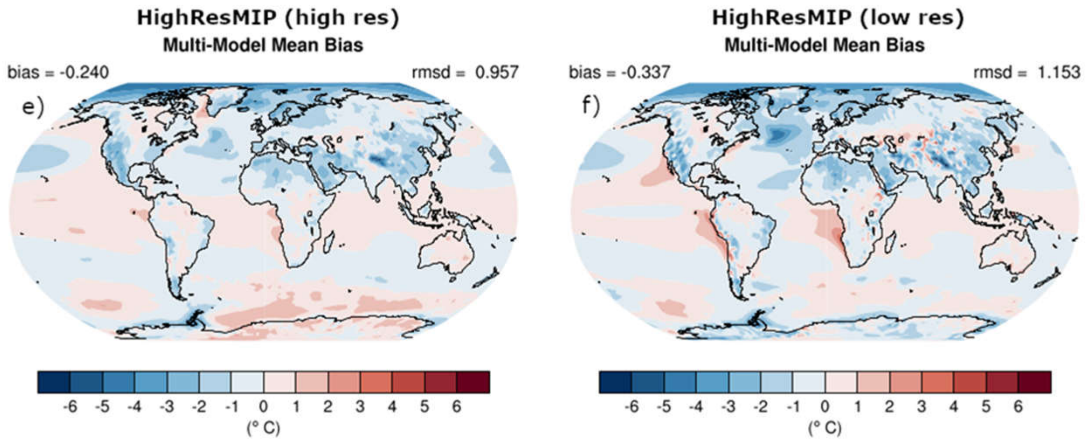
Goal of HighResMIP:

- to investigate the robustness across a multi-model ensemble of changes to the representation of climate processes as model horizontal resolution is increased
- To find out if there is any convergence with resolution across models

CMIP6 main science question: What are the origins and consequences of systematic model biases

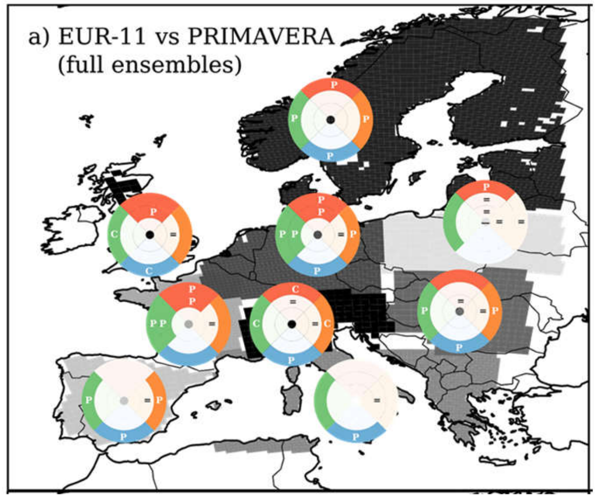
HighResMIP data from 16 models now available on ESGF
90+ papers published, 50+ submitted from PRIMAVERA, many other HighResMIP papers appearing
https://www.primavera-h2020.eu/output/scientific-papers/
https://hrcm.ceda.ac.uk/research/cmip6-highresmip/highresmip-papers/

Model biases



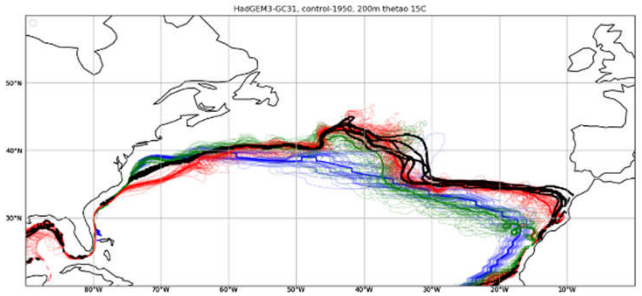
SST and precipitation biases
Bock et al. 2020

Linking global to regional

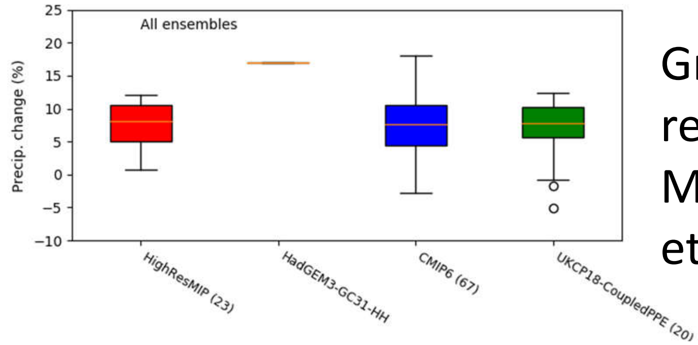


HighResMIP vs CORDEX
Demory et al. 2020

Regional change



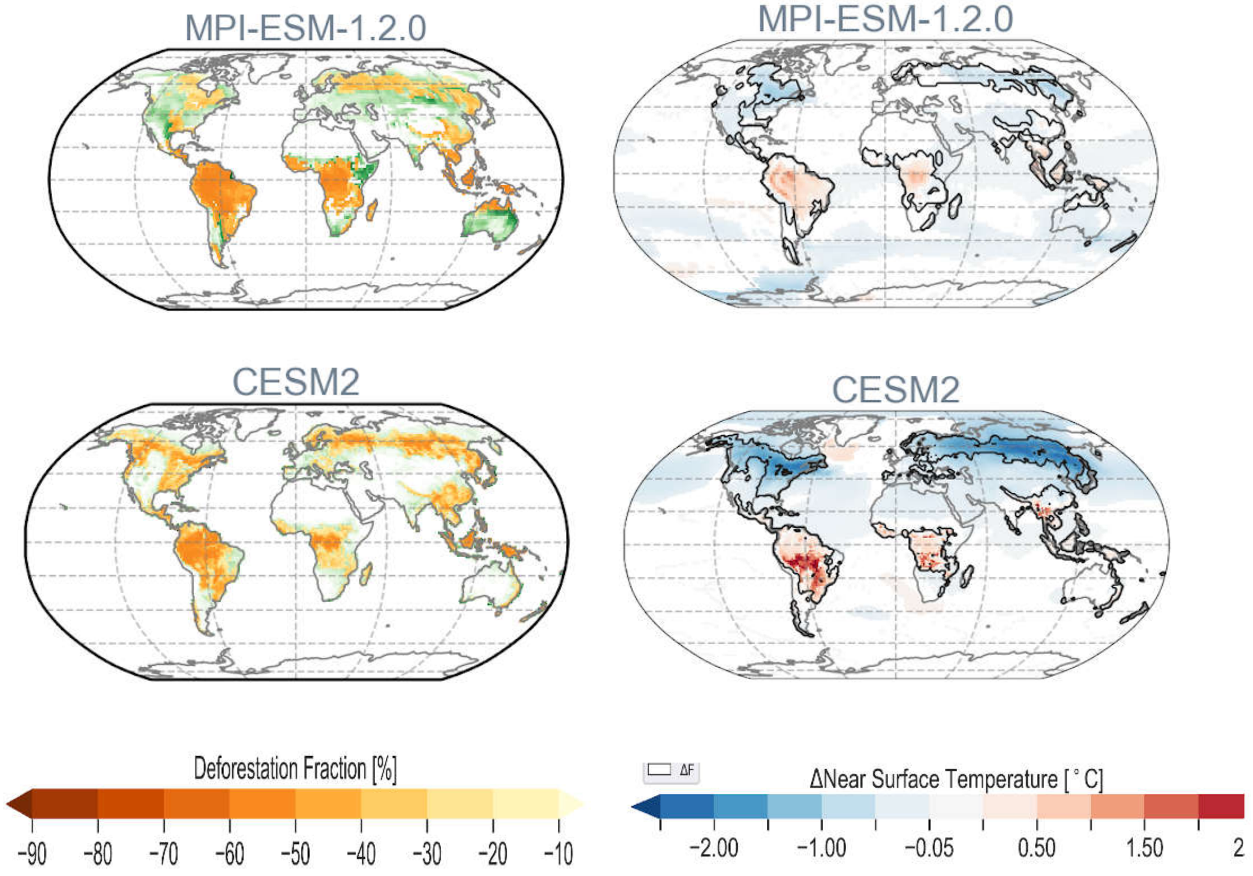
Eddy-rich ocean enables different Gulf Stream separation, and enhanced future rainfall over Europe



Grist et al., GRL, revised
Moreno-Chamarro et al., ERL, submitted

LUMIP - Land Use MIP: Climate response to Idealized Deforestation

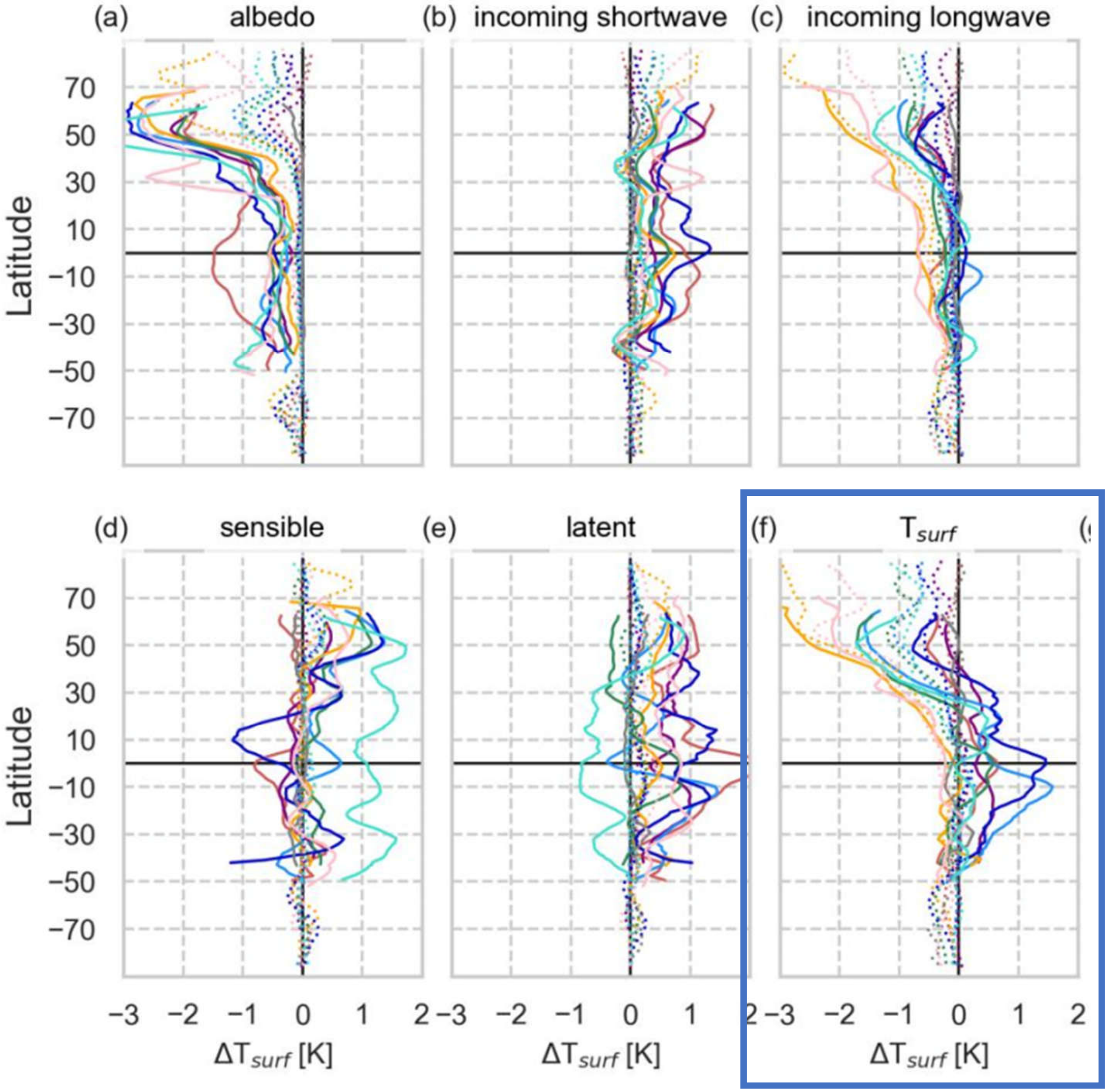
deforest-globe: Remove 20 million km^2 of forest over 50 years from top 20% forested cells



- Broad agreement of cooling across boreal forests
- Most (but not all) models show warming in the Tropics

Boysen et al., Biogesciences, 2020

Surface energy balance decomposition of deforest impact on T_{surf}



High lats: Cooling due to ↑ albedo, reinforced by ↓ incoming longwave, offset by ↑ LH and ↑ shortwave

Tropics: Warming due to ↓ LH combined with ↑ shortwave, offset by small ↑ albedo

- 7 papers published
- Several more in progress
- Analysis plans at cesm.ucar.edu/projects/CMIP6/LUMIP/

OMIP: Building Better Oceans

Supporting simulations, evaluation, and development of global ocean models

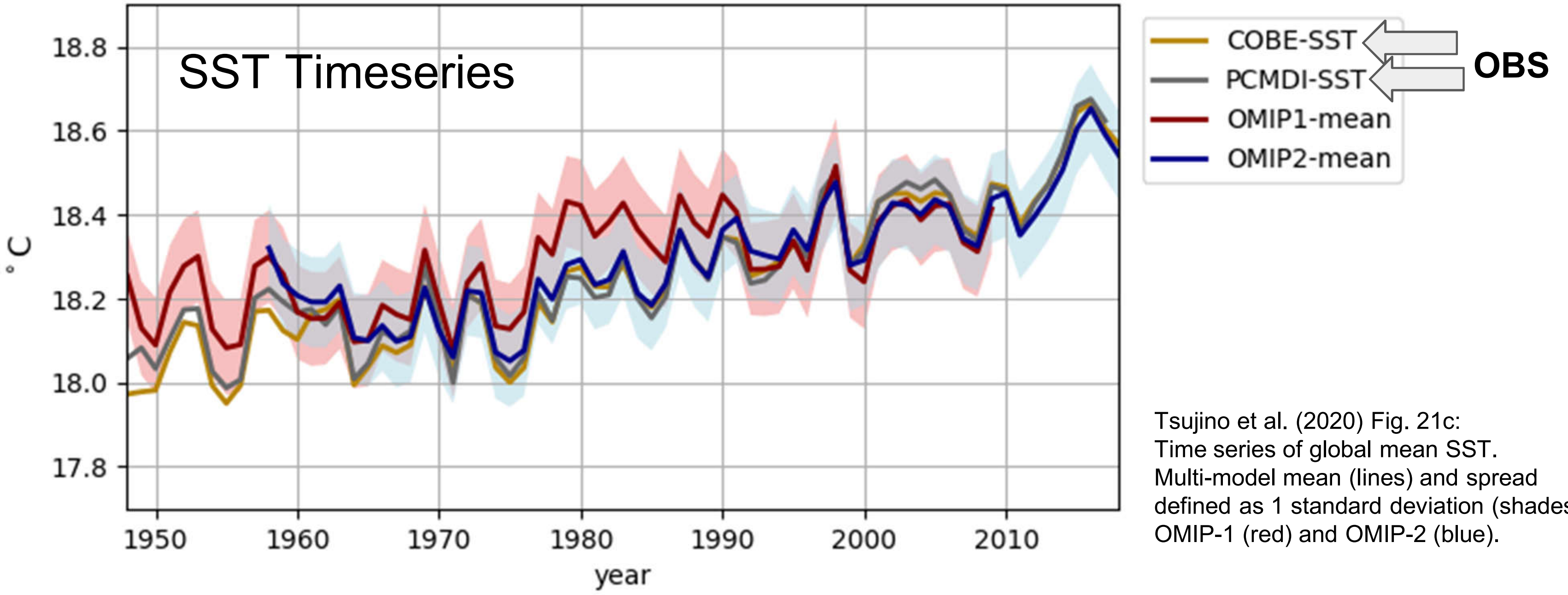
- Defines the standard diagnostics and protocols (Griffies et al. 2016).
- Provides a new forcing dataset (JRA55-do, Tsujino et al. 2018) through input4MIPs.

Two state-of-science papers:

- Tsujino et al. (2020): Impact of **atmospheric forcing** (OMIP-1/CORE *vs* OMIP-2/JRA55-do)
- Chassignet et al. (2020): Impact of **horizontal resolution** (OMIP-2)

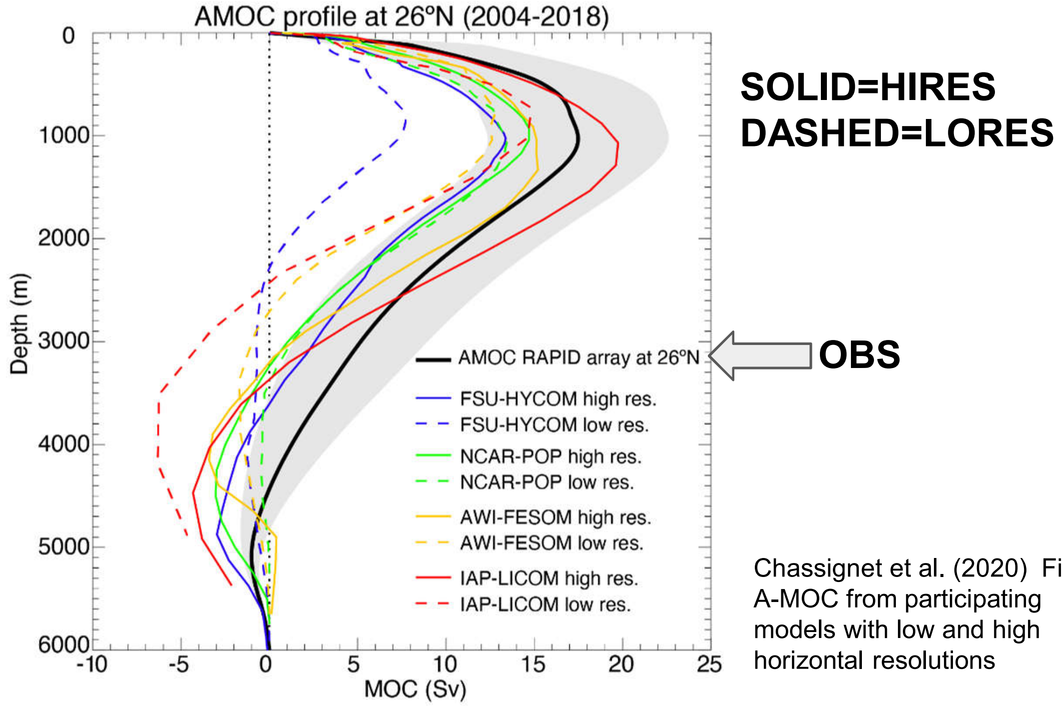
Forcing datasets regridded for ease of use. **Infrastructure** supports **CMIP/FAMIP. Diagnostics** used for **CMIP, ScenarioMIP,** and all **MIPs**.
Wide use: Dataset downloads (in millions) from CMIP6 dashboard: http://esgf-ui.cmcc.it/esgf-dashboard-ui/index.html

Atmospheric forcing may cause larger errors than ocean model ensemble spread



Tsujino et al. (2020) Fig. 21c:
Time series of global mean SST.
Multi-model mean (lines) and spread defined as 1 standard deviation (shades) of OMIP-1 (red) and OMIP-2 (blue).

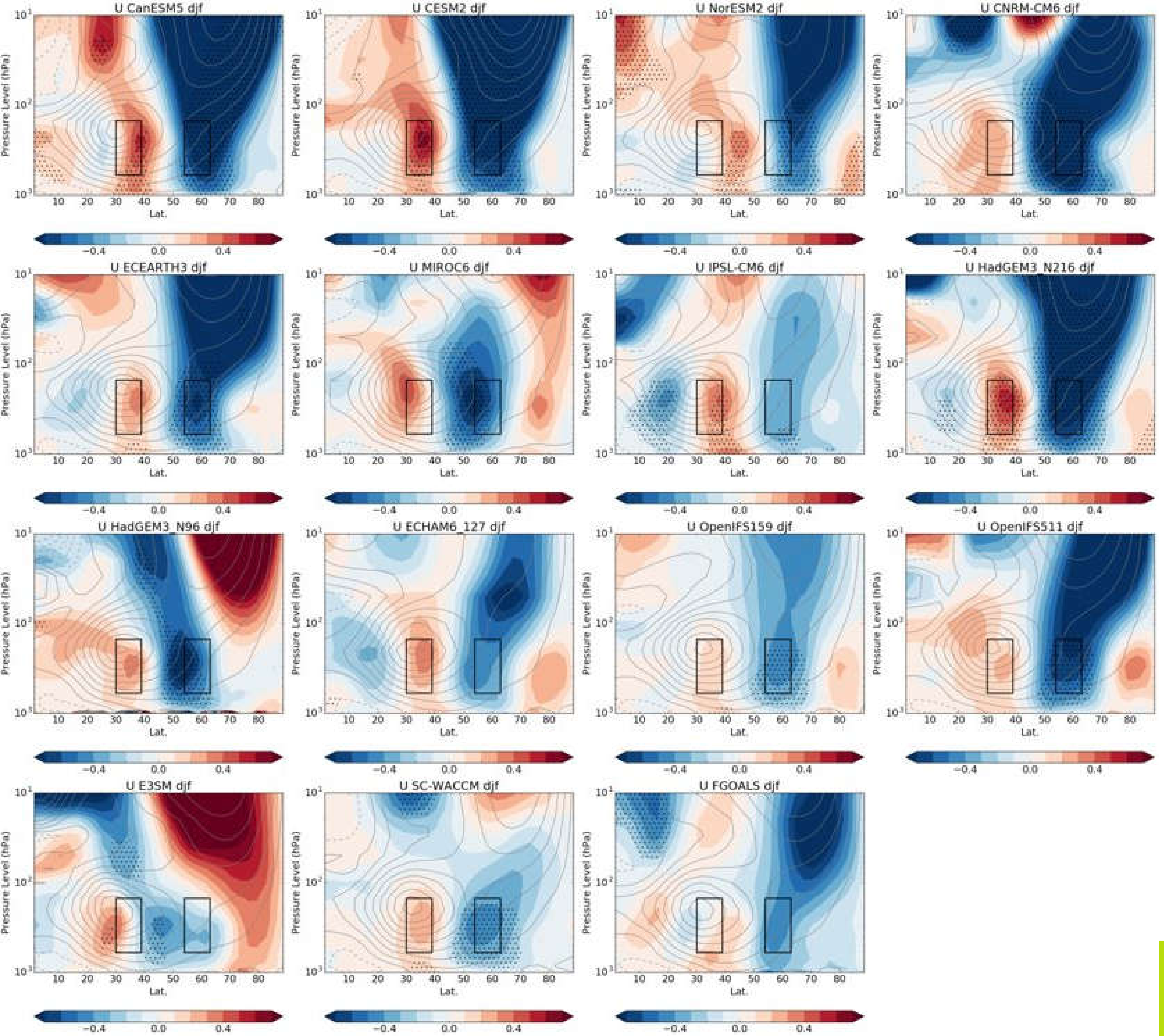
AMOC more consistent and less biased in high-resolution model ensemble



Chassignet et al. (2020) Fig. 27.
A-MOC from participating models with low and high horizontal resolutions

Polar Amplification MIP (PAMIP)

Zonal mean zonal wind response



Atmospheric response to future Arctic sea ice loss
(Future Arctic – Present Day)

Experiments completed by 15 models

Robust **equatorward shift of the tropospheric jet and storm track**

Stratosphere response not robust

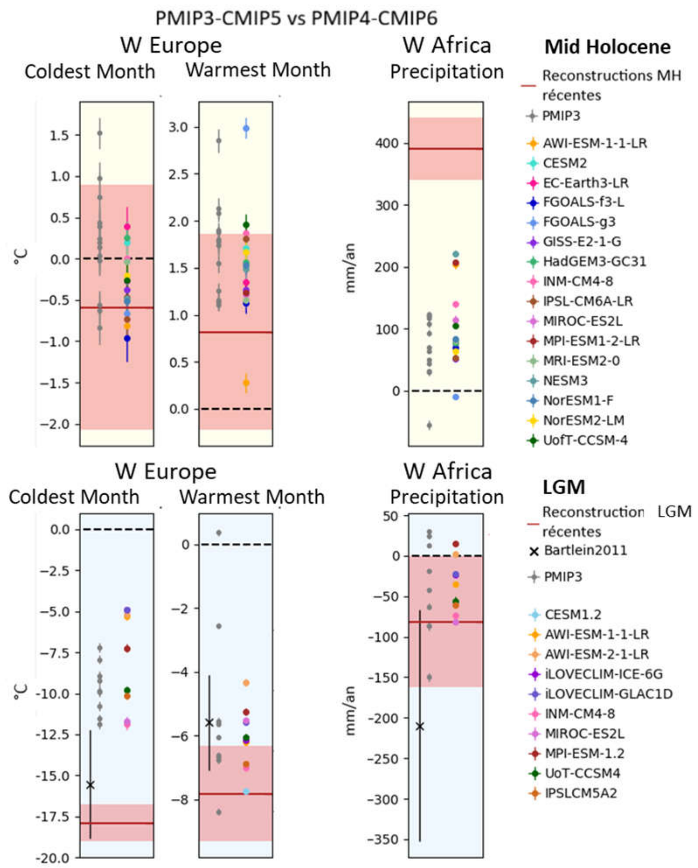
Large model spread

Working to define an emergent constraint and diagnose the real world response

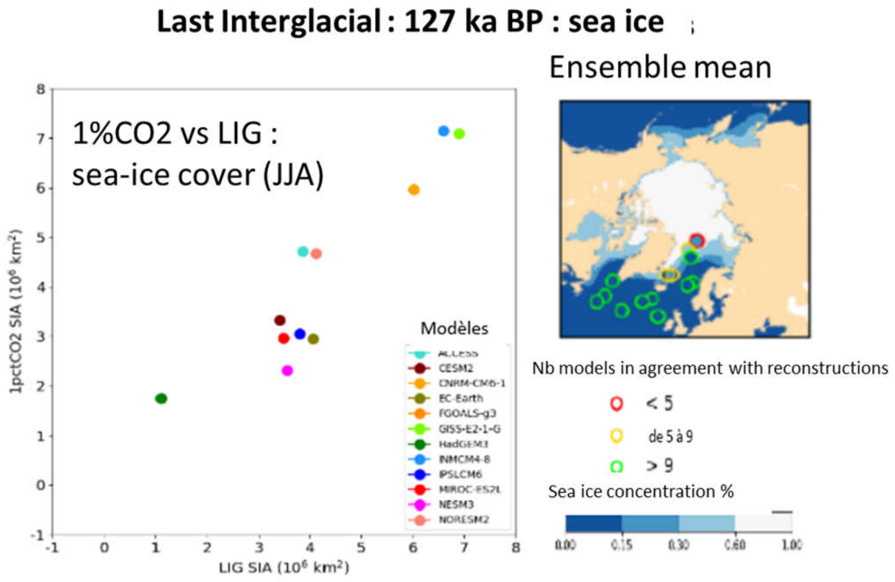
Smith et al, in prep

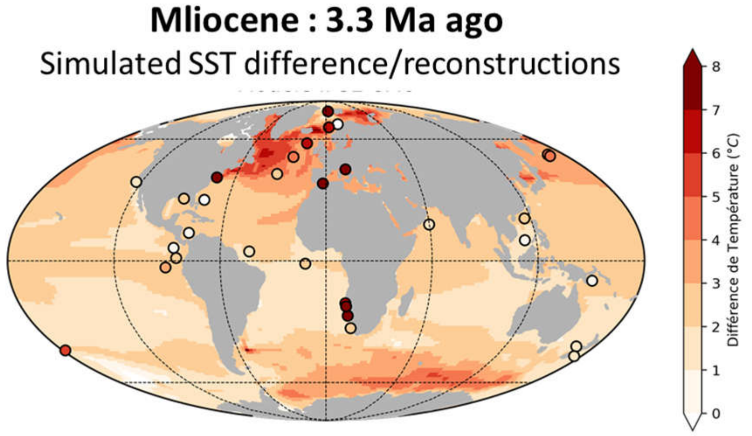
PMIP - Palaeoclimate Modelling Intercomparison Project

- Late delivery of simulations on ESGF
- 5 key reference simulations in CMIP6
  - Entry cards : **Last Glacial Maximum** (21ka BP) and **mid Holocene** (6ka BP)
  - **Past 1000 , Last Interglacial (127 ka), Pliocene (3.3 Ma)**
- Contribution to WCRP climate sensitivity paper (Sherwood et al. 2020)
- PMIP GMD-CP special issue : about 17 published papers now, including 5 papers of PMIP4-CMIP simulations
- New results on climate sensitivity, monsoon, sea-ice and ENSO (cf special issue)
- Need time for other in depth analyses within PMIP MIPs and working groups, and across CMIP6 MIPs
- Need to reduce the « burden » and « multiple requests » for rush in the analyses for IPCC



Brierley et al 2020
Kageyama et al. 2020





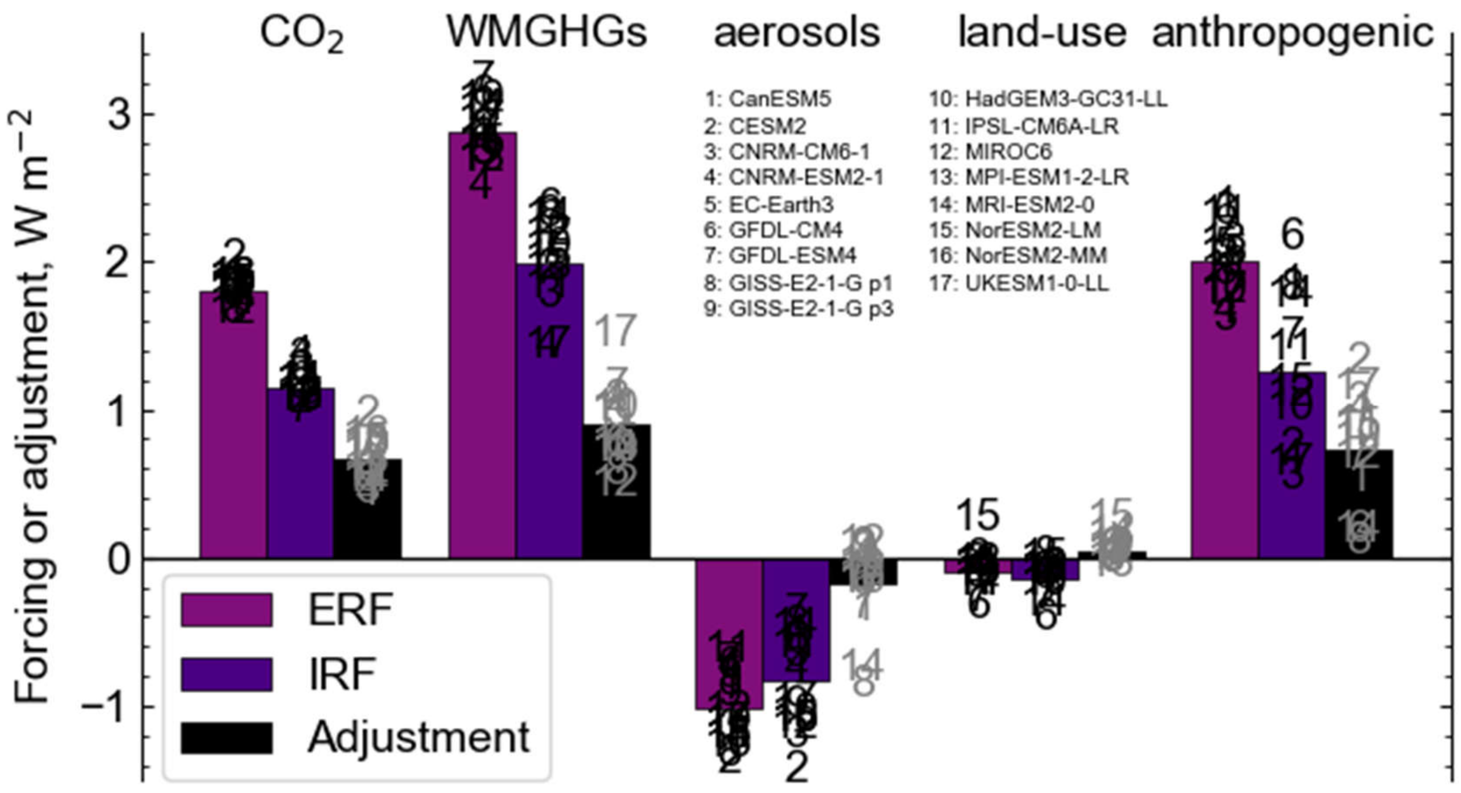
Otto-Bliesner et al 2020
Kageyama et al. 2020b

Haywood et al. 2019

See also Brown et al. 2020 for ENSO and different periods

RFMIP: Effective Radiative Forcing in CMIP6 models

- **Radiative Forcing Model Intercomparison Project (RFMIP)** tier 1 provides: **Effective Radiative Forcing (ERF)** from 4×CO_2 and present-day GHGs, aerosols, land use and total anthropogenic forcing using 30-year time slice experiments with climatological SSTs
- Radiative kernels allow decomposition of **ERF** into **instantaneous RF (IRF)** and **adjustments**

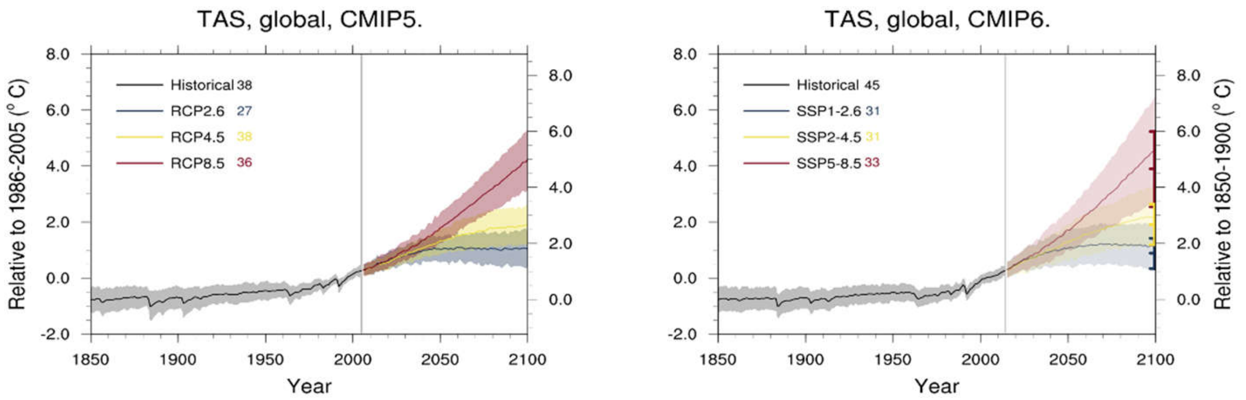


Forcing	**ERF ± s.d. (W m^{-2})**
4×CO_2	+7.98 ± 0.39
[Present-day CO_2]	[+1.81]
Well-mixed GHGs	+2.88 ± 0.19
Aerosols	-1.01 ± 0.23
Land-use change	-0.09 ± 0.13
Anthropogenic total	**+2.01 ± 0.23**
[Residual, interpreted as O_3]	[+0.23]

C.J. Smith et al. 2020, doi:10.5194/acp-20-9591-2020

ScenarioMIP (O'Neill et al. 2016 https://doi.org/10.5194/gmd-9-3461-2016)

GSAT change: CMIP5 vs. CMIP6 for the three 'comparable' scenarios

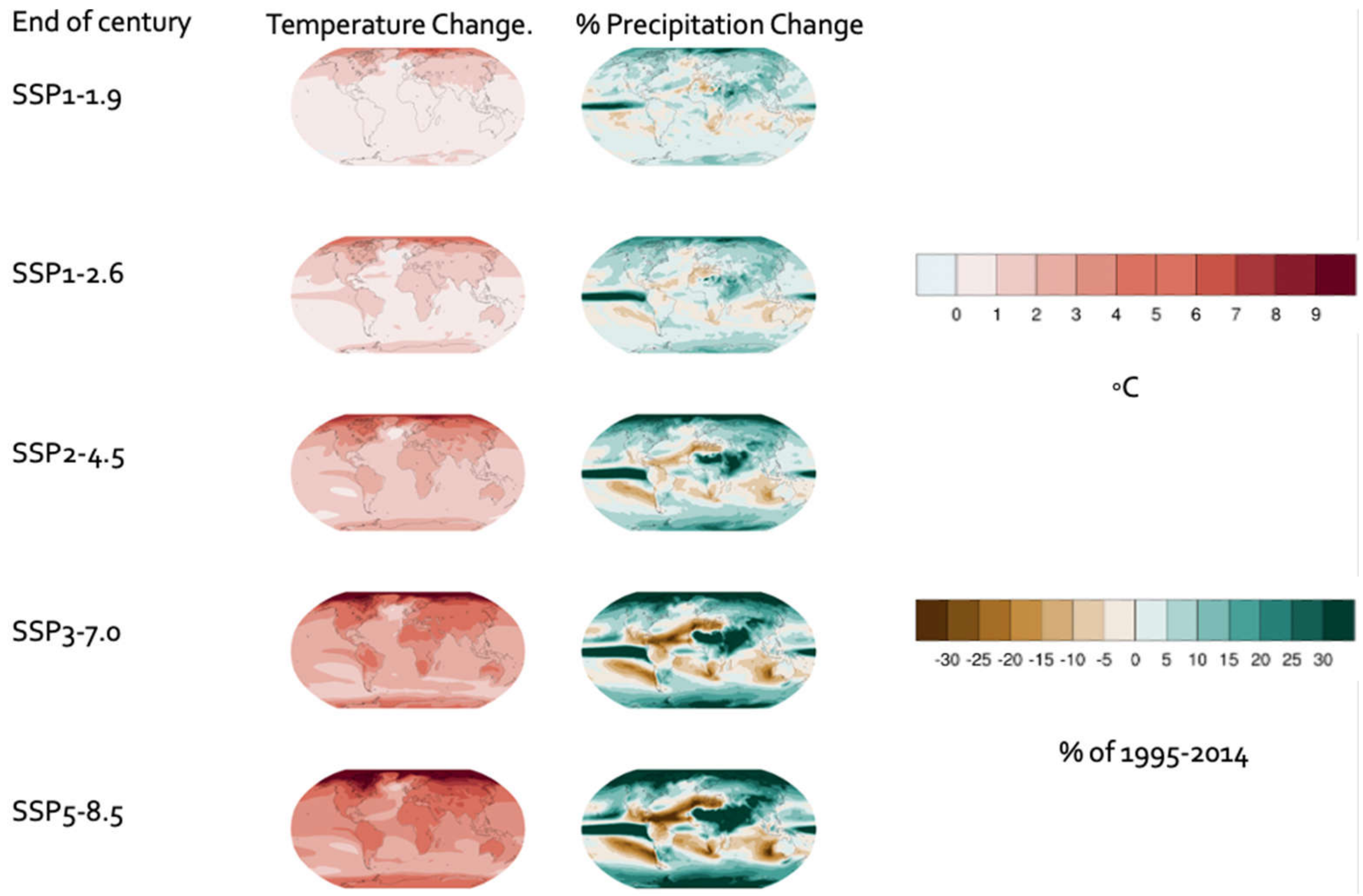


Times of crossing warming thresholds

	SSP1-2.6	SSP2-4.5	SSP5-8.5	RCP2.6	RCP4.5	RCP8.5
1.5°C	2026 (2020,NA) 32/33	2027 (2020,2048) 33/33	2025 (2020,2040) 33/33	2034 (2020,NA) 20/23	2031 (2022,2049) 32/32	2027 (2020,2037) 33/33
2.0°C	2058 (2030,NA) 18/33	2044 (2029,2085) 33/33	2038 (2028,2055) 33/33	NA (2041,NA) 6/23	2053 (2039,NA) 27/32	2041 (2033,2054) 33/33

When do scenarios separate? (results shown for GSAT)

	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
SSP1-1.9	2042 [2070]	2036 [2052]	2036 [2048]	2026 [2043]
SSP1-2.6		2037 [2071]	2035 [2056]	2027 [2048]
SSP2-4.5			2040 [2074]	2034 [2055]
SSP3-7.0				2036 [2076]



Summary

- **Time series:** covering a wide(r) range of warming, esp. reaching higher levels than CMIP5 if not constrained.
- **Geographically:** familiar patterns, stable in time, similar across scenarios.
- **Comparison with CMIP5** complicated by differences in forcing composition and resulting differences in effective radiative forcings.
- **Threshold crossing** earlier than projected by RCPs/SR1.5.

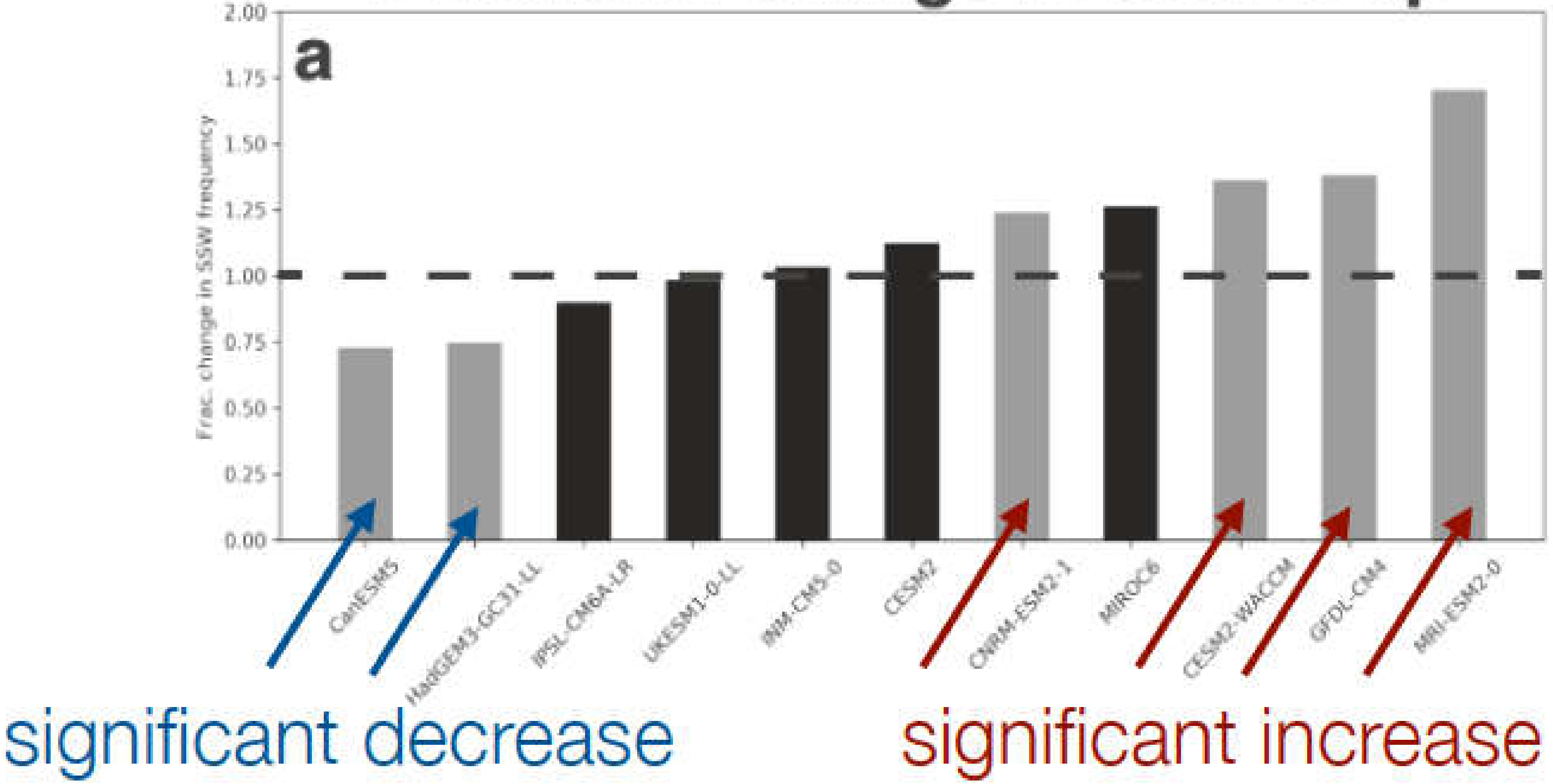
More results in **Tebaldi and 48 co-authors, 2020 ESD**https://esd.copernicus.org/preprints/esd-2020-68/

Dynamics and Variability MIP

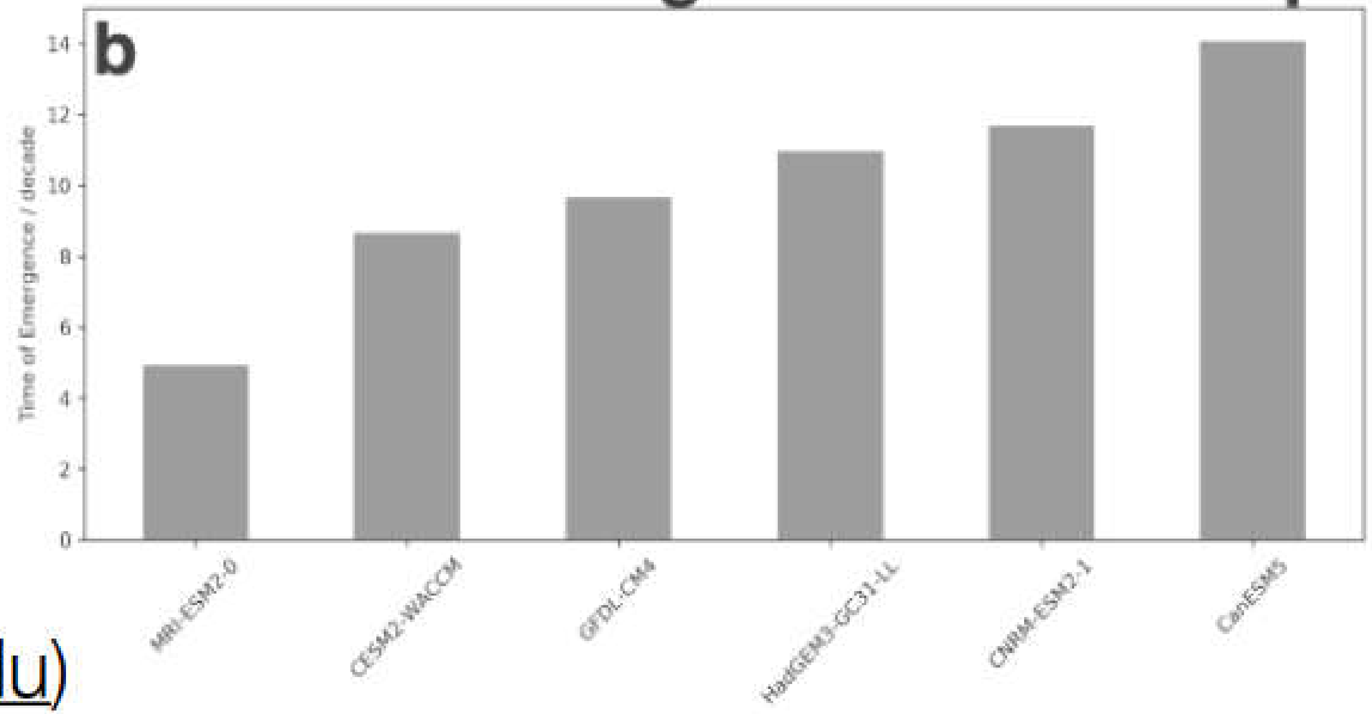
DynVarMIP

- Uncertainty in the response of sudden stratospheric warmings and stratosphere-troposphere coupling to quadrupled CO2 concentrations in CMIP6 models *(Ayarzagüena et al. JGR-Atmospheres, 2020)*
  - tropospheric impact of Sudden Stratospheric Warmings (SSW) does not change under 4x CO2 forcing
  - models disagree on changes in SSW frequency: some show significant increase, other significant decrease
  - robust change in seasonal cycle: a longer polar winter, associated with active stratosphere-troposphere coupling, is observed
- Work in progress: The Brewer-Dobson circulation in CMIP6 models *(Abalos et al. , in prep.)*, expected to be submitted this year.

Fractional change in SSW freq.



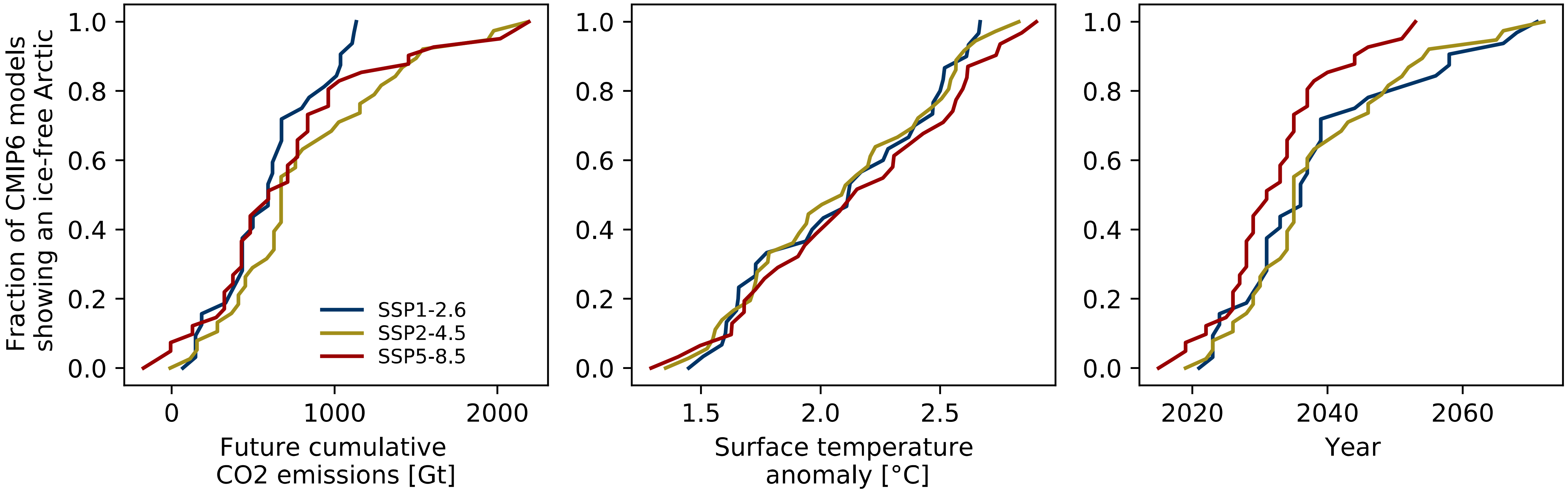
Decade of emergence of SSW freq.



Questions: Contact Ed Gerber (epg2@nyu.edu)

SIMIP - Sea Ice Model Intercomparison Project

Fraction of CMIP6 models that have lost their September sea ice cover at least once as a function of CO_2 emissions, GSAT rise and time



- The Arctic will likely become sea-ice free in September before 2050 in all scenarios
- **Main conclusion:** We can likely no longer prevent the Arctic summer sea ice to disappear in summer at least occasionally.

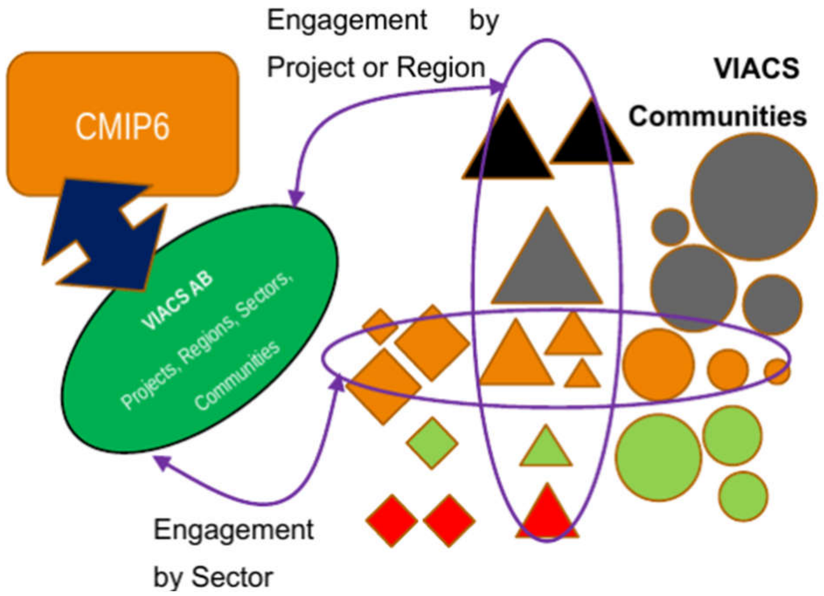
SIMIP Community, Arctic sea ice in CMIP6, GRL, https://doi.org/10.1029/2019GL086749, 2020

CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project

VIACS AB - Vulnerability, Impacts, Adaptation & Climate Services Advisory Board: Phase 2

Claas Teichmann and Alex Ruane, co-chairs

Reconstituting new phase in early 2021 with increased diversity across regions and VIACS communities



Envisaged Objectives and Activities

Phase 2 will focus on the use of CMIP6 outputs and findings relevant to model performance and improvement needs.

(Specific objectives and activities will be determined by the entire VIACS Advisory Board upon its initial convening.)

- *Identify* key VIACS-relevant evaluation metrics for CMIP models in DECK & historical experiments.
- *Highlight* and share successful or novel VIACS applications using CMIP MIP outputs.
- *Recognize* common challenges or unmet requests from VIACS applications of CMIP outputs that may be addressed through closer interaction with CMIP modeling groups (leading toward CMIP7).
- *Inform* the creation of guidance documents on best practice use of CMIP outputs for VIACS.
- *Foster* demonstrations of VIACS applications using MIP outputs that are suited to particular applications sectors or climate services (e.g., HighResMIP and agricultural applications; LUMIP and ecosystem applications; ScenarioMIP and Climate Services).
- *Engage* VIACS representatives from Earth System Modeling groups participating in CMIP.
- *Represent* the VIACS perspective at international workshops and conferences.
- *Develop* a stronger web presence for the VIACS Advisory Board.

ISMIP6 - Ice Sheet Model Intercomparison Project for CMIP6

LS3MIP - Land Surface, Snow and Soil Moisture

VolMIP - Volcanic Forcings Model Intercomparison Project

CORDEX - Coordinated Regional Climate Downscaling Experiment

=> Analysis started and ongoing

Summary and Outlook

CMIP
The World Climate Research Programme's
Coupled Model Intercomparison Project

Summary

- More than **40 climate modelling centers worldwide** are expected to participate in CMIP6
- ***Many improvements*** have been made to models from CMIP5 to CMIP6, including
  - changes in the **representation of physics** of the atmosphere, ocean, sea-ice, and land surface,
  - **increases in spatial resolution**,
  - inclusion of **additional Earth system processes and new components**.
- Current results suggest emerging topics like
  - ***High resolution models improved*** *realism of model-simulated weather variability, such as tropical and mid-latitude cyclones and blocking anticyclones*
  - ***Models with nitrogen cycle*** *over land exhibit weaker strengths of the feedbacks and a narrower spread across models*
  - ***Increased Effective Climate Sensitivity:*** *related to cloud feedbacks, process studies underway across CMIP6-Endorsed MIPs and model groups*
  - *Some CMIP6 models exhibit* ***more mid- & late-century warming*** *compared to their CMIP5 counterparts.*
- The climate science community is actively investigating these important topics

=> We expect CMIP6 to continue CMIP's tradition of major scientific advances

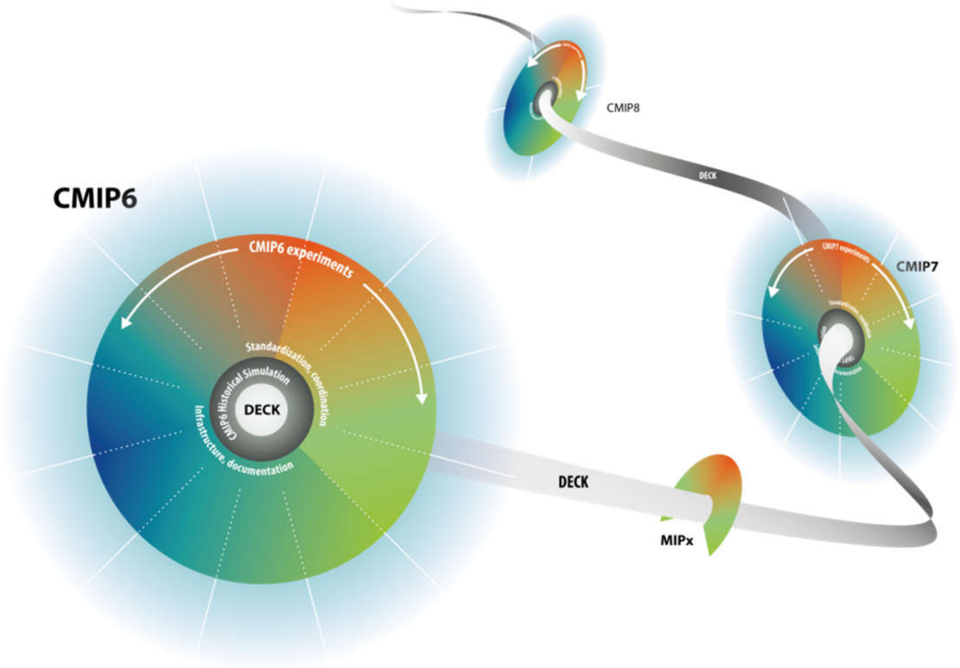
What's next?

CMIP6:

- Many CMIP6 model simulations still underway
- Analysis will continue for several more years
- CMIP Analysis Workshops will be held every 2 years (once COVID situation is getting better)
- CMIP6 scientific review by CMIP Panel (tbd)
- Establishment of a CMIP-IPO will help with some of the key issues faced during CMIP6

Beyond CMIP6:

- Planning has started
- See talks by Jean-Francois, Robert Pincus and others in next session



High priority issues for CMIP

- **The growing dependency on CMIP products** by a broad research community and by climate assessments means that basic CMIP activities, such as the creation of **forcing datasets**, **the provision and archiving of CMIP products**, and **model development**, require substantial efforts that must be better supported
  - Increasing number of experiments and other demands causes **heavy load for model groups => reduce!**
  - Most of CMIP coordination occurs through volunteered time of climate scientists **=> CMIP-IPO**
  - **Ensure timely delivery and enhanced quality control for the forcings** and **data request**
- **Continue to providing critical underpinning to IPCC Assessment Reports**.

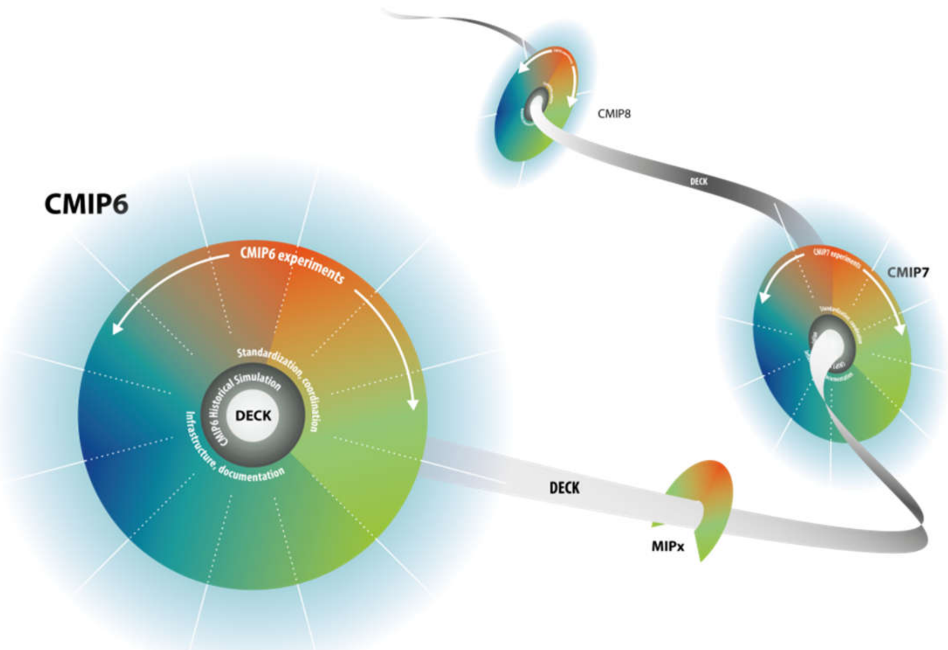
- Make use of the **CONTINUOUS structure & DECENTRALIZED structure** we have set up in CMIP6

  "CORE EXPERIMENTS" REQUIRED FOR USERS (DECK, historical + possibly others)
  - Can go on faster timescales
  - **More automatic infrastructure in place through program level support**

  (e.g. for forcings), also at the modelling centers (to reduce the burden)

  RESEARCH (CMIP-Endorsed MIPs) Could go on longer timescales

  Infrastructure critical - needs to support the CMIP Research Activities
  - Decentralize documentation (300 experiments cannot be defined by 1 person)

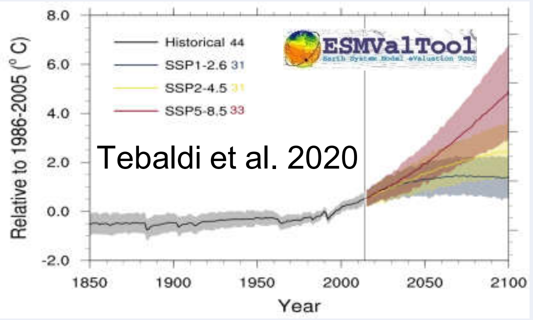


=> CMIP Panel will be actively working with the community, WGCM & the WIP

High priority issues for CMIP

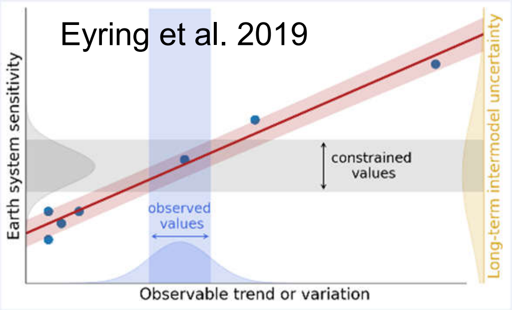
=> Targeted Observations and innovative methods required to Constrain Climate Projections and Feedbacks
- Large uncertainties due to **clouds** and the **carbon cycle**
- **Policy relevant** information

Global Warming Projections

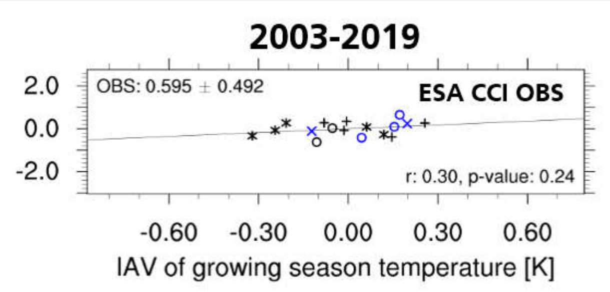


Obs.

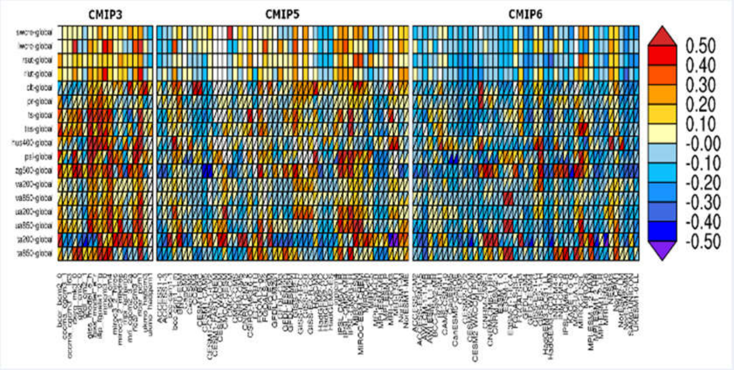
Emergent Constraints



=> Routine model evaluation with CMIP evaluation tools
- Great progress in CMIP6
- Multi-year long-term quality controlled time series from obs
- Further align with observational community (obs4MIPs!)
- Further development of the CMIP evaluation tools that are now well-tested tools that facilitate model evaluation and enhance science



Gier et al. 2020



Bock et al 2020

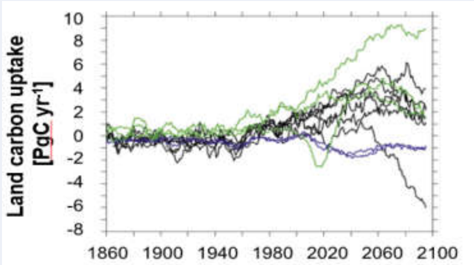
=> Earth System Model Developments
- **Higher resolution** (clouds, extreme events / precipitation)
- **Complex ESMs** (e.g. carbon, CH4 & N cycles, ice sheets, permafrost)
- Develop methods to **bridge** between these two developments

Cloud Resolving Models

Stevens et al. 2019

&

Complex Earth System Models

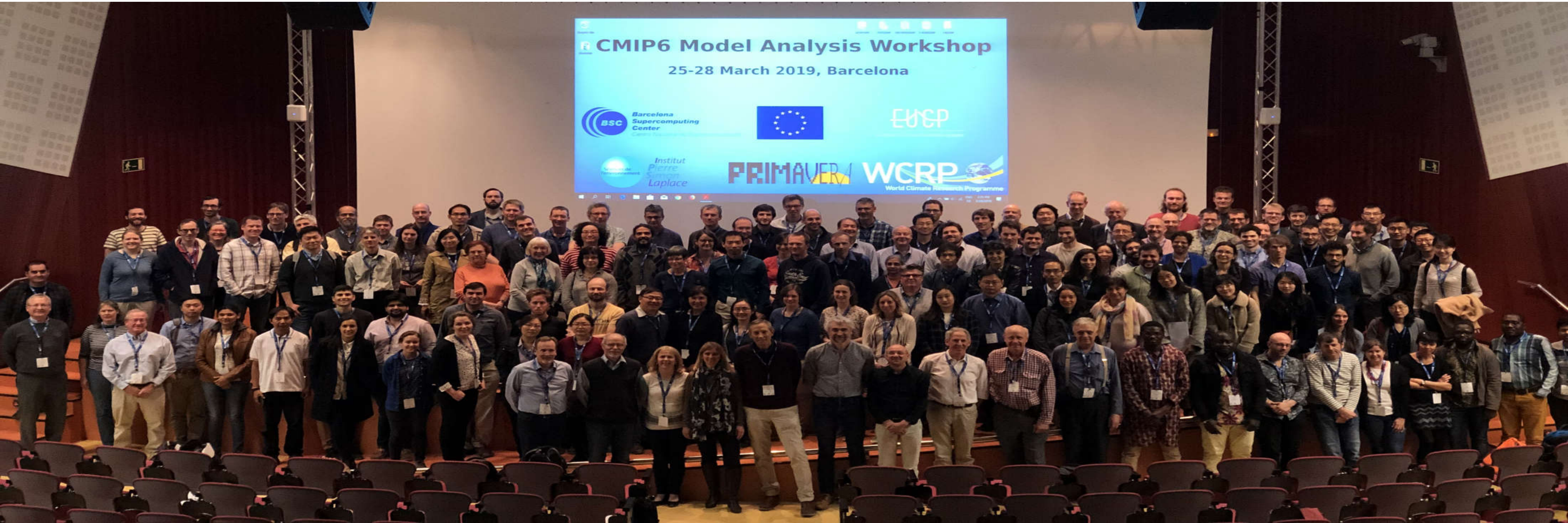


Friedlingstein et al. 2014

DLR

THANKS to…

- CMIP6 Model Groups
- CMIP6-Endorsed Model Intercomparison Projects
- WIP (for a well working infrastructure)
- ESMValTool, NCAR CVDP & PMP Teams
- Broader CMIP community



Thanks to the CMIP Panel!

… and to Jean-Francois!

…I recommend to keep the CMIP Panel really small!

Good luck!