Earth System Model Evaluation with Observations to Constrain Future Climate Projections

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Math colloquium

College of Engineering, Mathematics and Physical Sciences

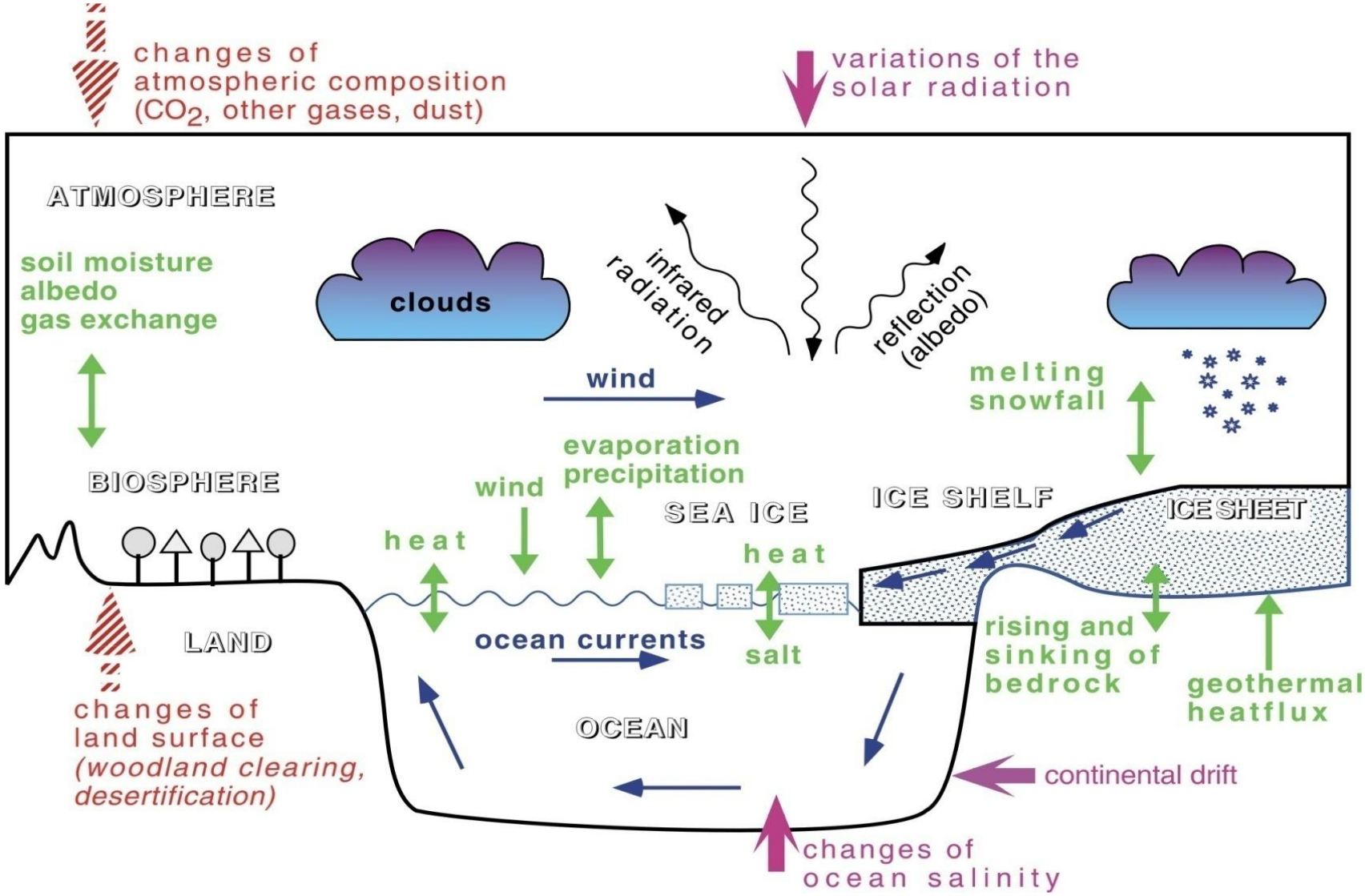
University of Exeter, UK

Outline

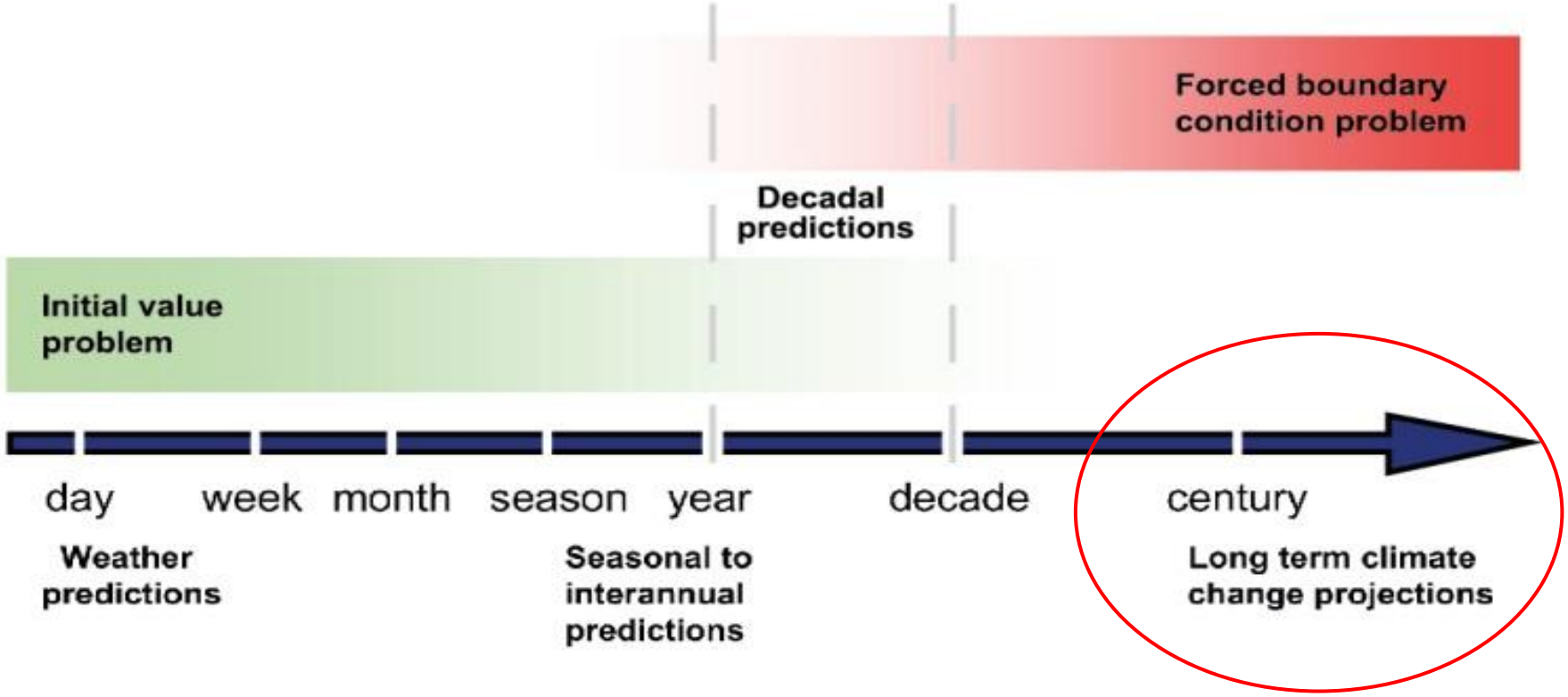
1. **Introduction**
2. **How do we gain confidence in climate model projections?**
3. **Brief overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) design**
4. **Opportunities for CMIP6**
   - More routine evaluation of Earth system models with observations
   - Better consideration of internal variability and more process-oriented evaluation
   - Emergent constraints: Use of observations to constrain a simulated future Earth system feedback
5. **Summary**

1. Introduction

The Climate System

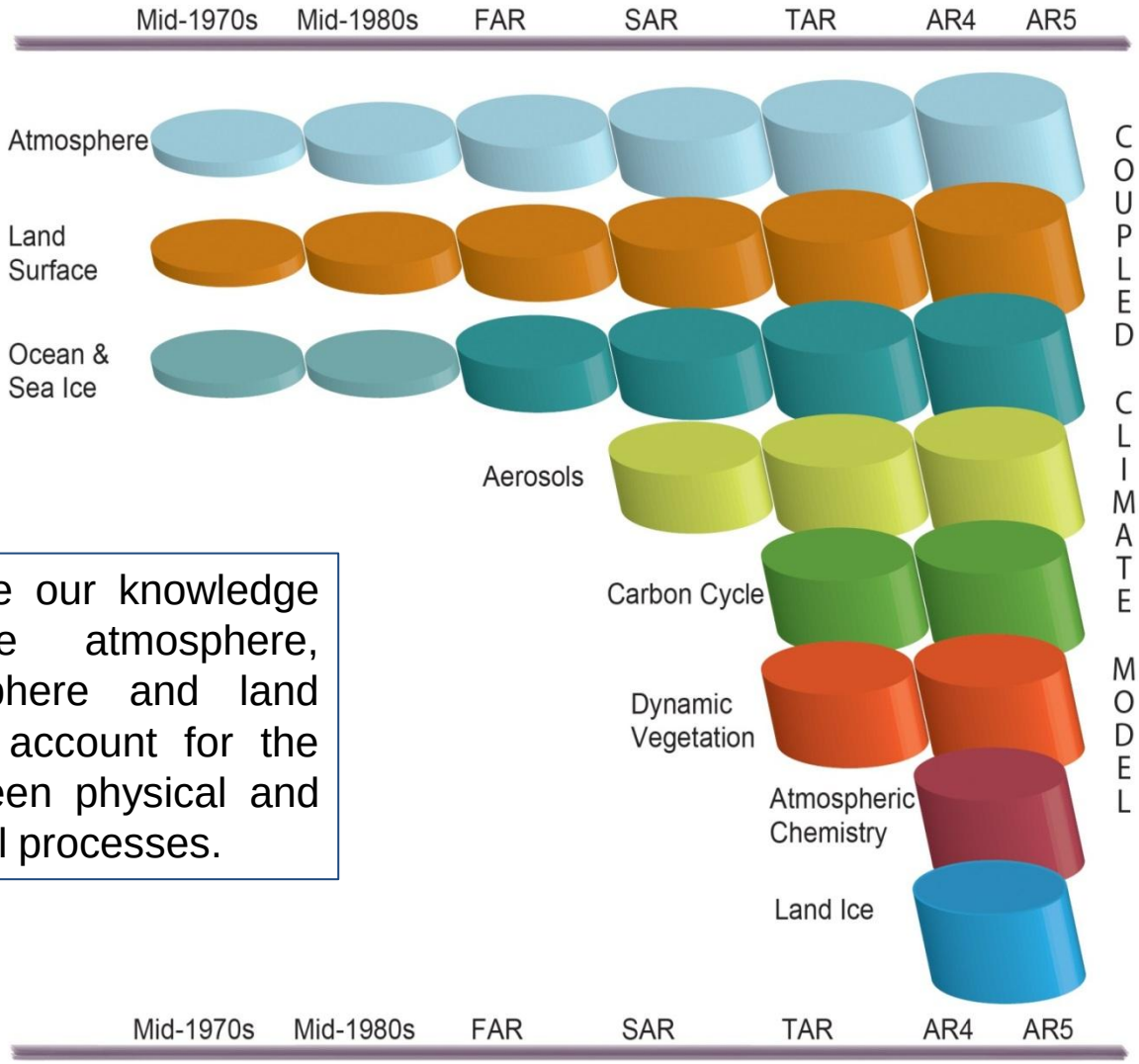


How to improve long-term climate projections?



Historical Evolution of Climate Models

- From Atmosphere-Ocean General Circulation Models (AOGCM) to Earth System Models (ESMs) -



ESMs integrate our knowledge regarding the atmosphere, ocean, cryosphere and land surfaces, and account for the coupling between physical and biogeochemical processes.

Figure 1.13
IPCC, AR5

Coupled Model Intercomparison Project (CMIP)

- Understanding past, present and future climate -

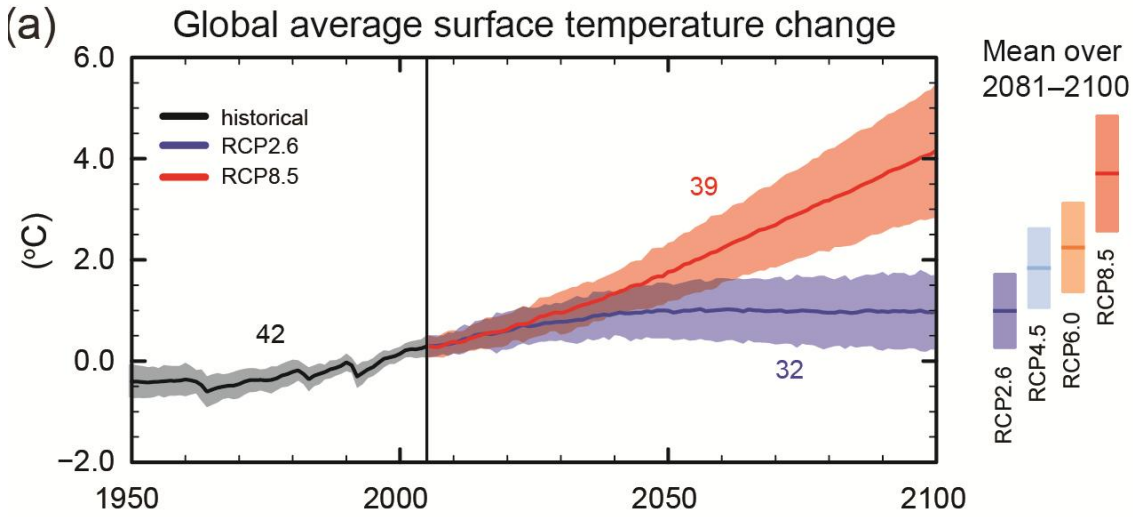
- CMIP is a project of the World Climate Research Programme (**WCRP**)'s Working Group of Coupled Modelling (**WGCM**).
- Since 1995, **CMIP** has coordinated climate model experiments involving multiple international modeling teams worldwide.
- CMIP has led to a better understanding of past, present and future climate change and variability in a **multi-model framework.**
- CMIP defines **common experiment protocols, forcings and output.**
- CMIP has developed in phases, with the simulations of the fifth phase, CMIP5, now completed, and the planning of the sixth phase, i.e. CMIP6, well underway.

- CMIP's central goal is to advance scientific understanding of the Earth system.
- CMIP model simulations have also been regularly assessed as part of the IPCC Climate Assessments Reports and various national assessments.

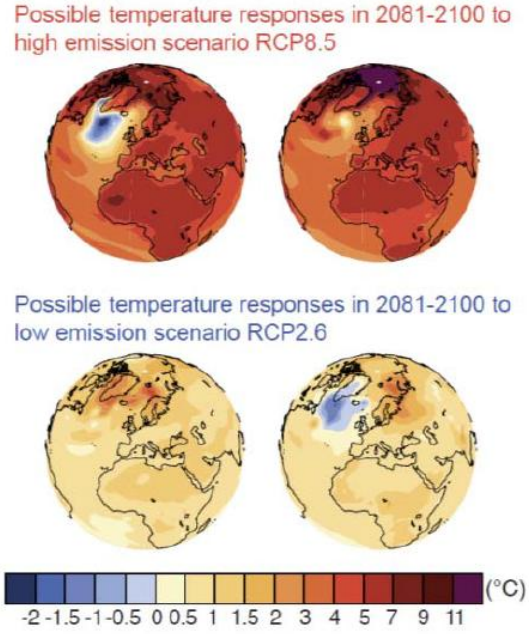
Why using an Ensemble of Model Simulation?

The multi-model approach is now a standard technique to **assess projections of specific variables** and to **derive robust process understanding of the Earth's climate system** in combination with observations**.**

1. Assessing the mechanisms responsible for model differences in poorly understood feedbacks
2. Estimating projection uncertainty
3. Determining why similarly forced models produce a range of responses.



IPCC, Figure SPM.7a, 2014



IPCC FAQ 12.1, Figure 1

Human influence on the climate system is clear

Evidence of human influence has grown since the AR4.

It is *extremely likely* that human influence has been the **dominant cause of the observed warming since the mid-20th century**.

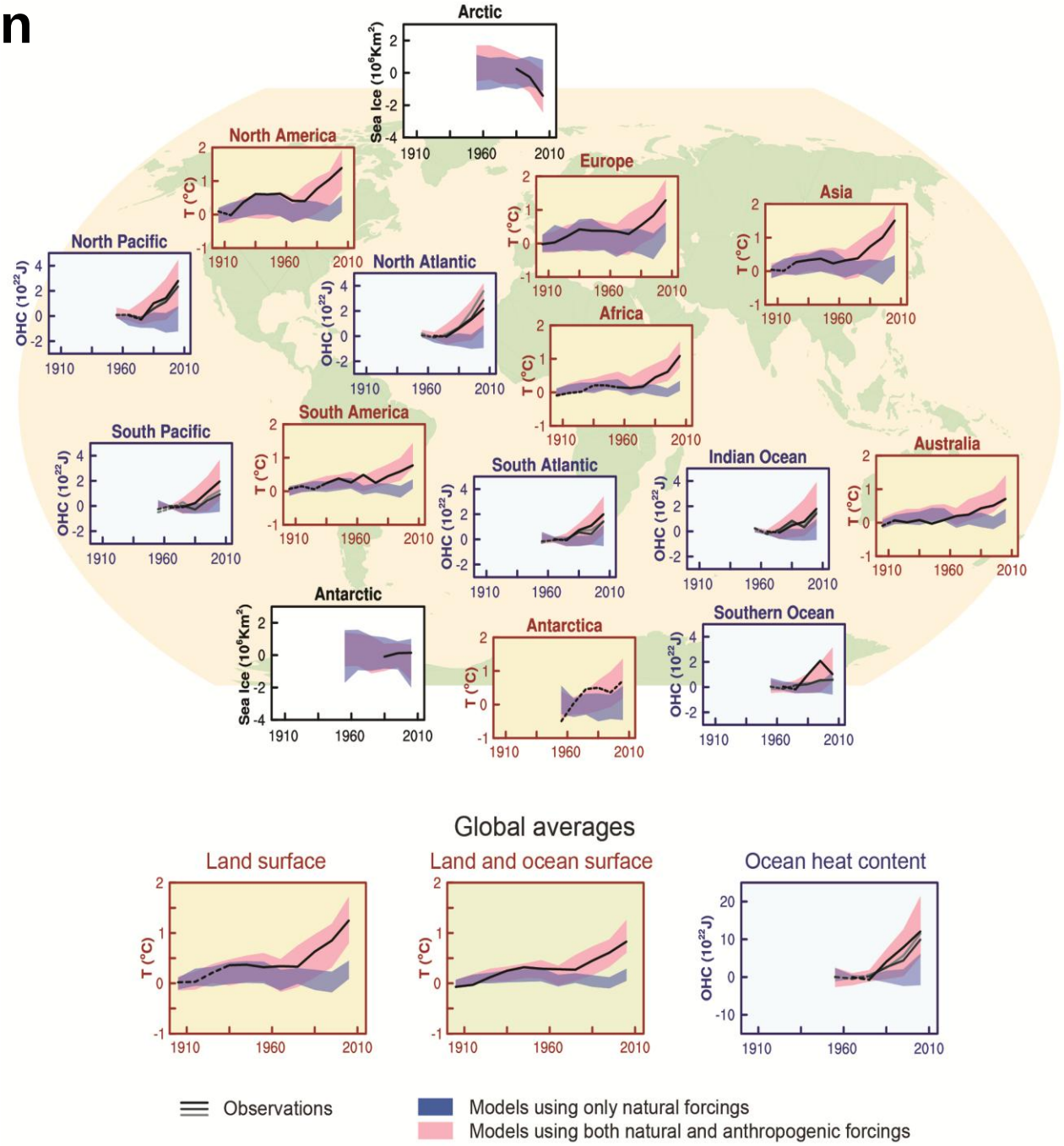
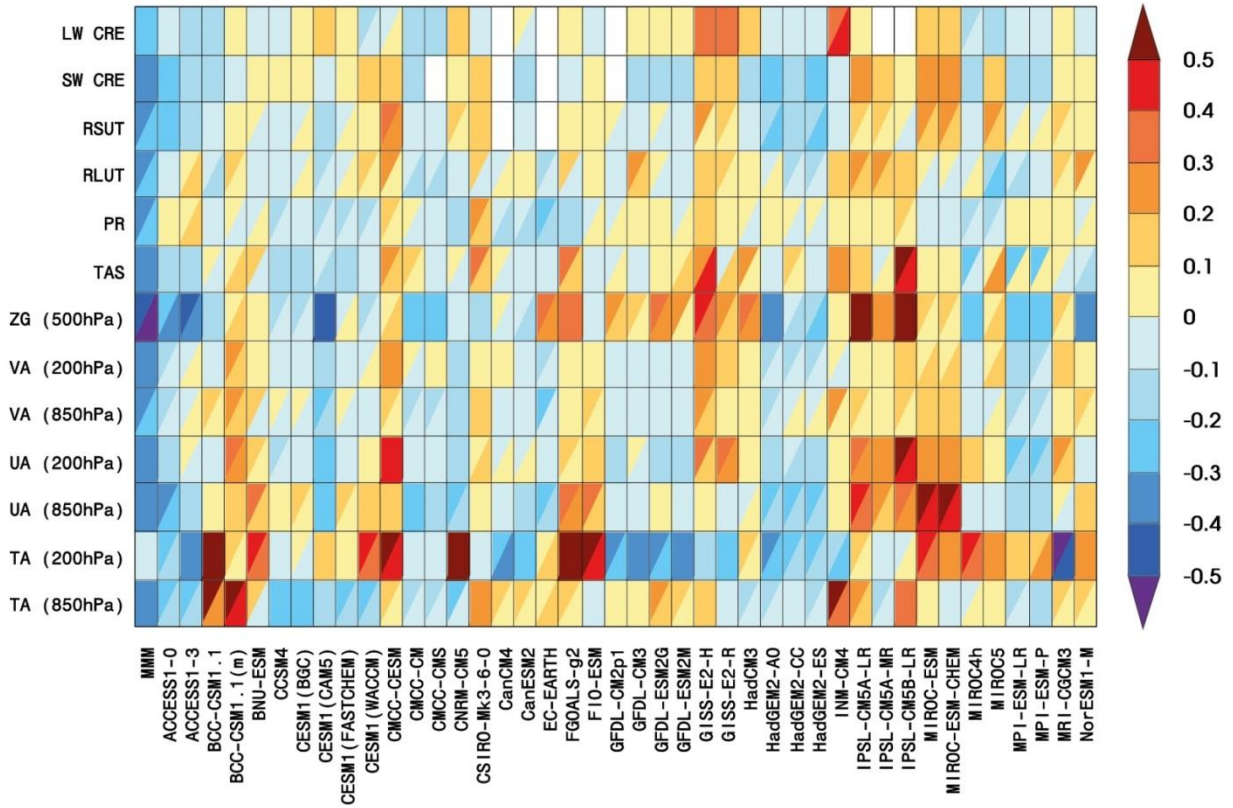


Figure SPM.6

2. How do we gain confidence in climate model projections?

How do we gain confidence in climate model projections?

- Based on physical understanding of the climate system and its representation in climate models, and
- On a demonstration of how well models represent a wide range of processes and climate characteristics on various spatial and temporal scales



Relative error measures of CMIP5 model performance (normalized by the median error of all model results), based on the global seasonal-cycle climatology (1980–2005)

- **Climate models have continued to be developed and improved since the AR4.**

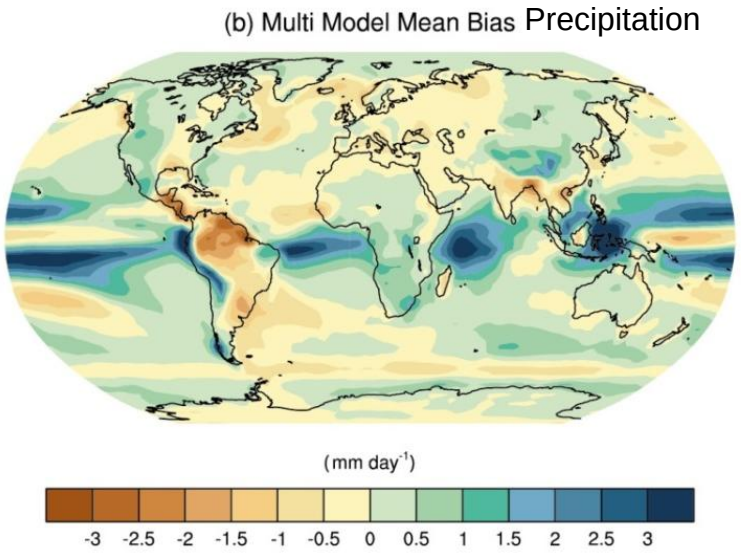
Chapter 9, Fig. 9.7
Following Gleckler et al. (2008)

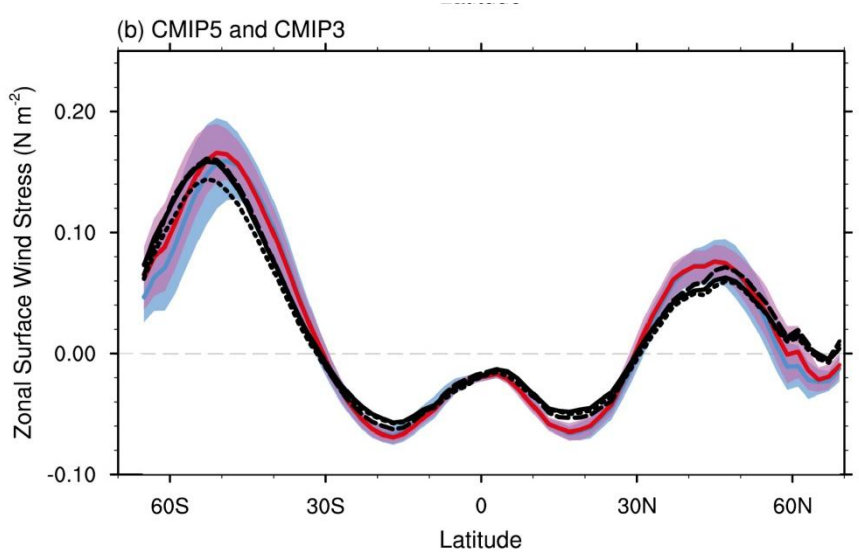
A lot of progress has been made, but…

Observations:

- In many cases the lack or insufficient quality of long-term observations or observations for process evaluation remains an impediment.
- For many observational datasets formal error estimates are lacking.
- Disagreement in observations complicate model evaluation (e.g. in cloud property trends), and upper tropospheric / lower stratosphere (UTLS) temperature trends

Systematic Biases: e.g., Double Intertropical Convergence Zone (ITCZ), i.e. spurious ITCZ in the SH associated with excessive tropical precipitation or the equatorward bias in the SH atmospheric jet location





Equilibrium Climate Sensitivity Remains Uncertain

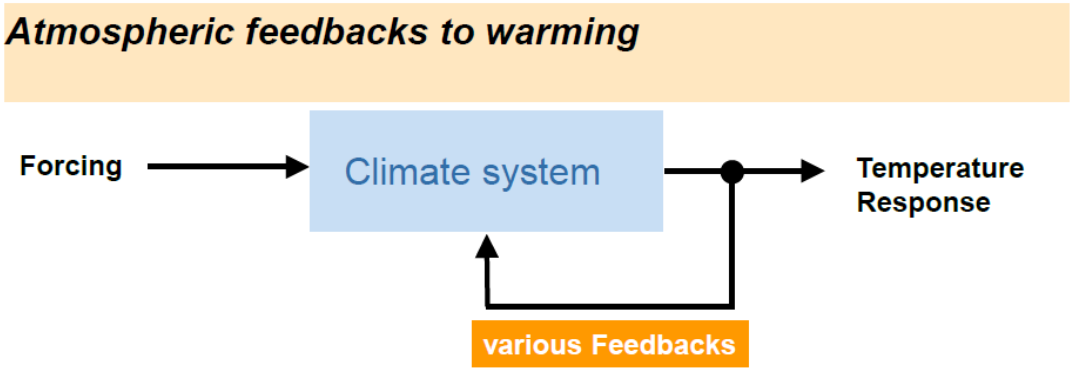
Equilibrium climate sensitivity (ECS):

- Response of the climate system to constant RF on multi-century time scales.
- Defined as the change in global mean surface temperature at equilibrium that is caused by a doubling of the atmospheric CO2 concentration.

	TAR	AR4	AR5
ECS	Likely range: 1.5 to 4.5°C	*likely* range: 2.0 to 4.5°C *very unlikely* <1.5°C – best estimate about 3°C	***likely* range: 1.5 to 4.5°C** ***extremely unlikely* <1.0°C** ***very unlikely* >6.0°C** –

The model spread in ECS ranges from **2.1°C to 4.7°C** and is very similar to the assessment in AR4.

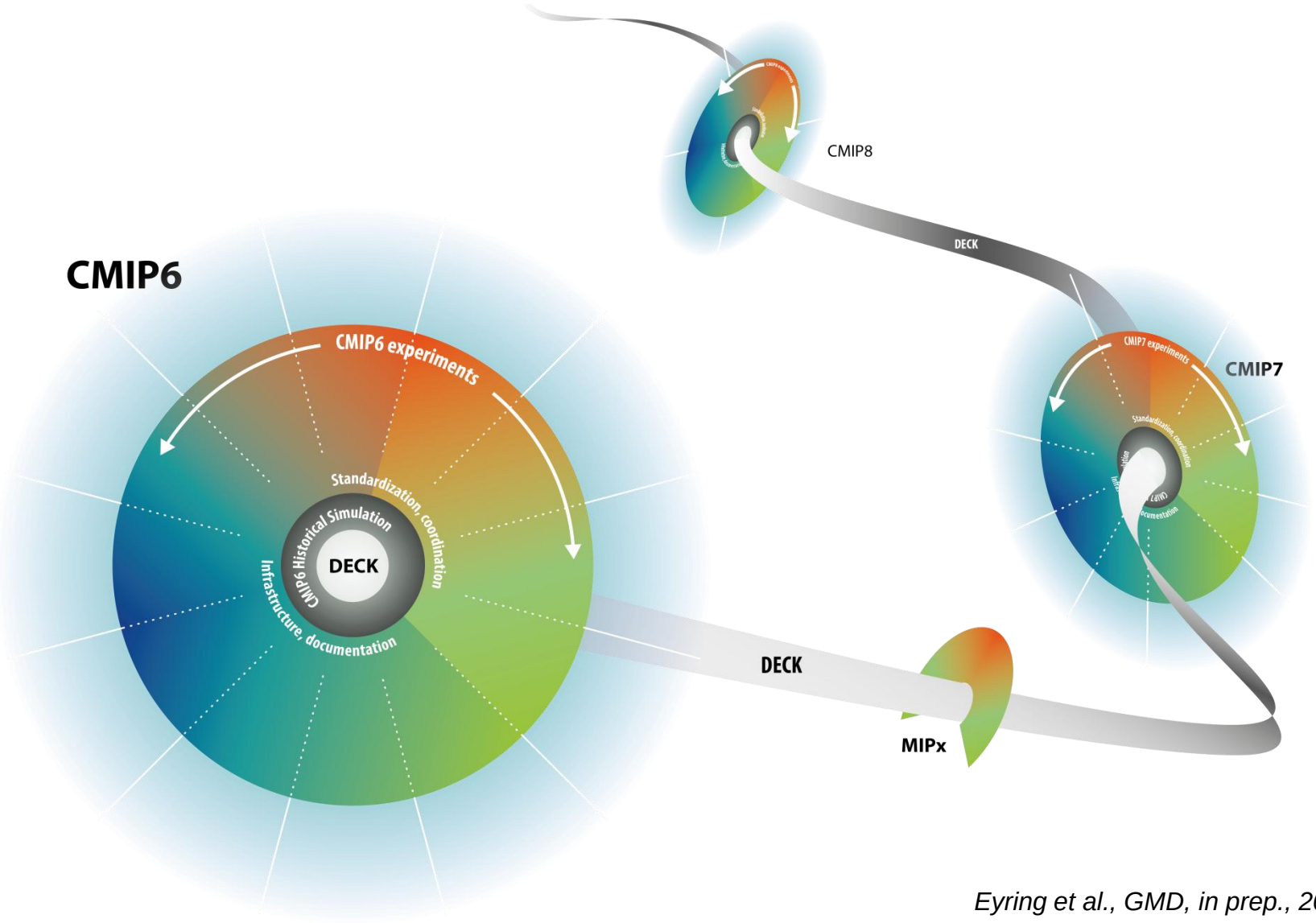
=> Due to uncertainties in climate feedbacks



3. CMIP6 Design

CMIP Continuity

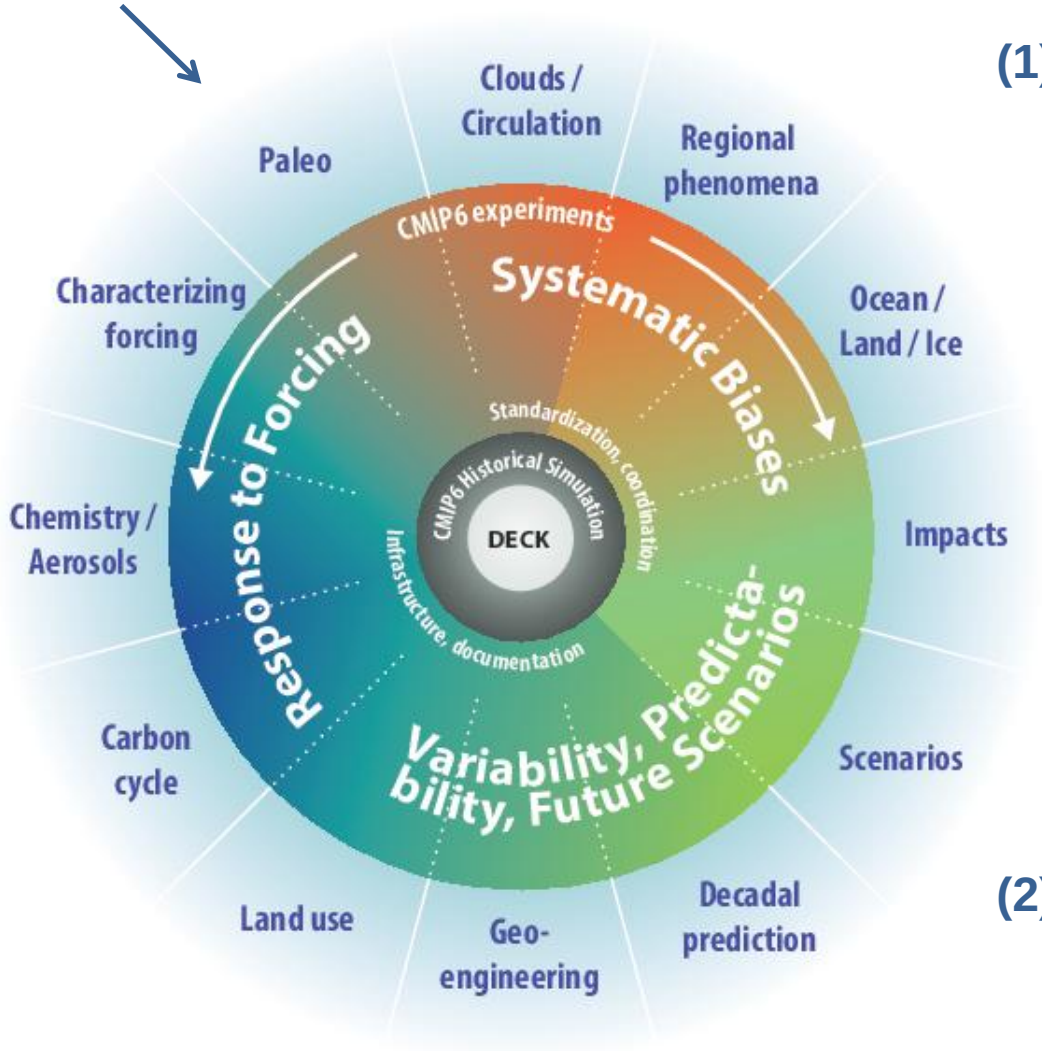
A common suite of experiments for each phase of CMIP provides an opportunity to construct a multi-model ensemble using model output from various phases of CMIP



Eyring et al., GMD, in prep., 2015

CMIP: a More Continuous and Distributed Organization

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



Eyring et al., GMD, in prep., 2015

(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)

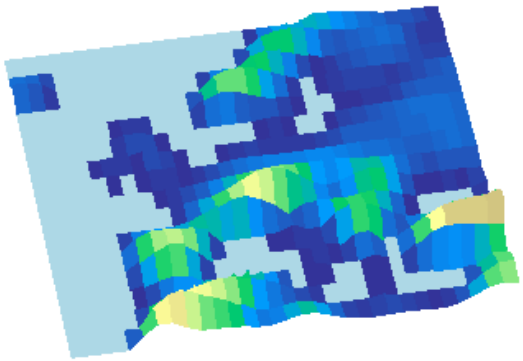
(2) Standardization, coordination, infrastructure, documentation

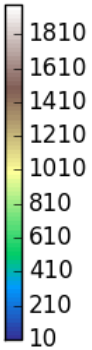
DECK (Diagnosis, Evaluation, and Characterization of Klima Experiments) & CMIP6 Historical Simulation to be run for each model configuration used in CMIP6-Endorsed MIPs

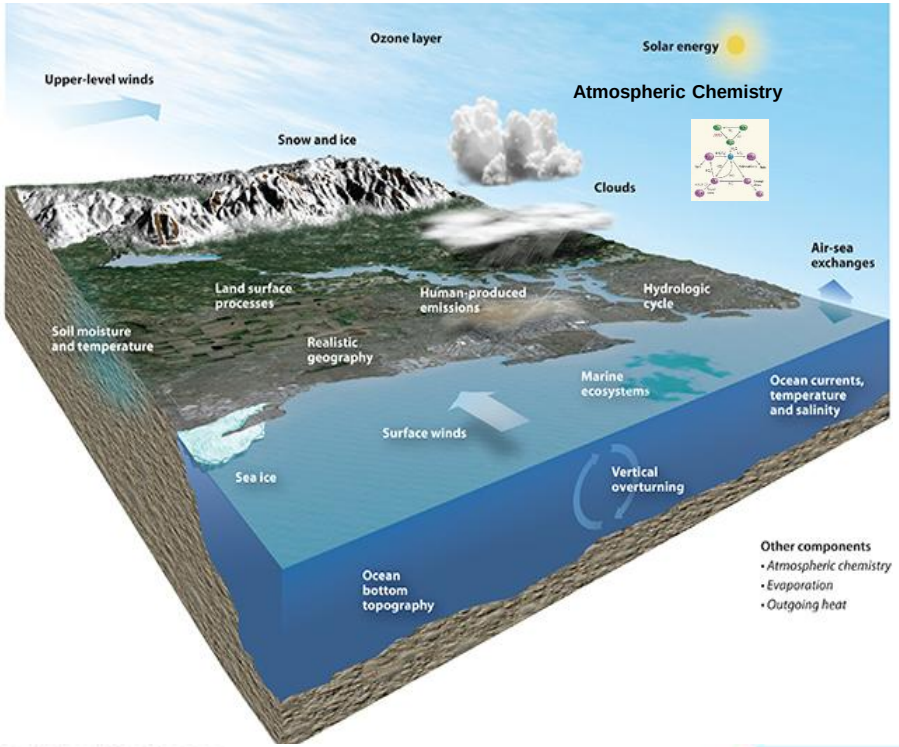
Models are increasing in complexity and resolution

From AOGCMs to Earth System Models with biogeochemical cycles, from lowres to highres

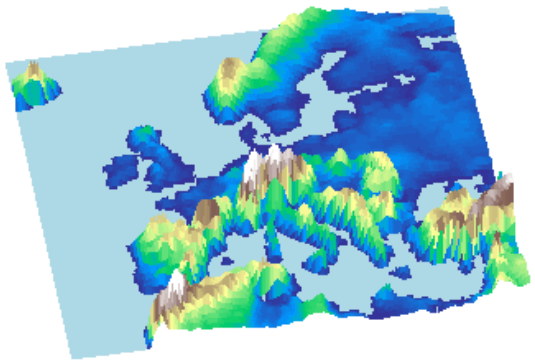
130 km resolution orography

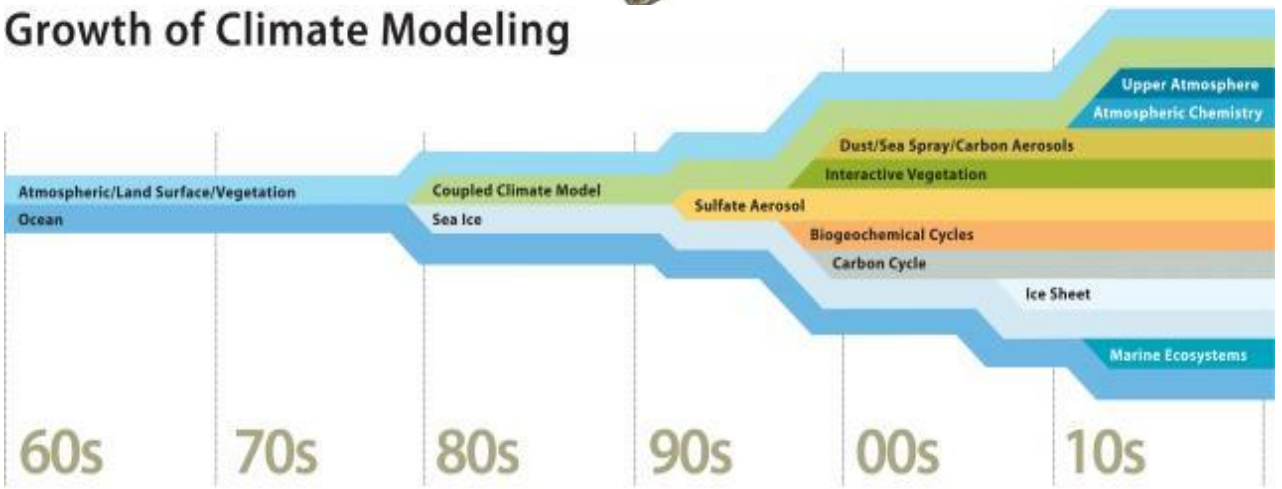






25 km resolution orography





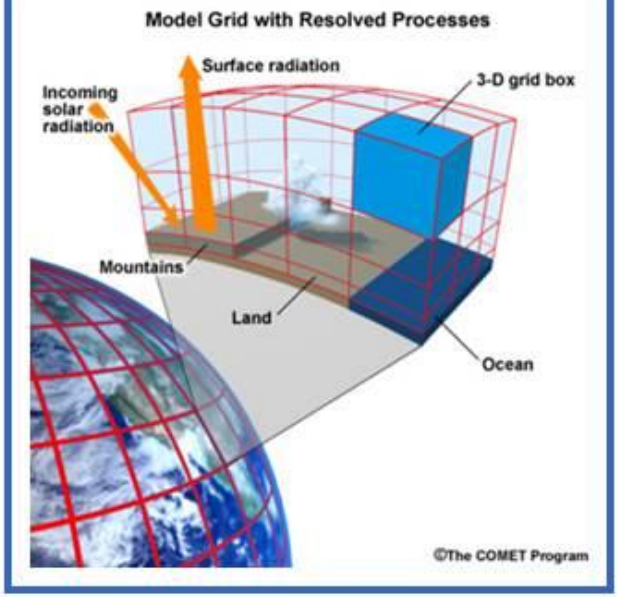
https://www2.ucar.edu/news/understanding-climate-change-multimedia-gallery

4. Opportunities for CMIP6

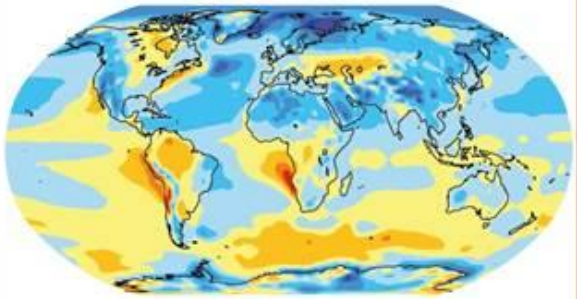
(A) More routine evaluation of Earth system models with observations

Earth System Model Evaluation

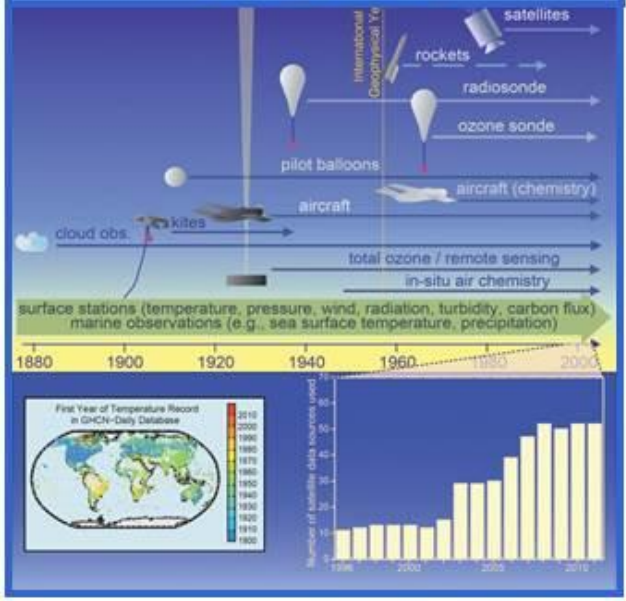
Earth System Models (ESMs)



ESM Evaluation



Relevant Earth System Observations



Evaluation of Simulated Climate

Do we get the right answer?

Evaluation of Processes & Phenomena

For the right reasons?

Link to Projections: Emergent Constraints

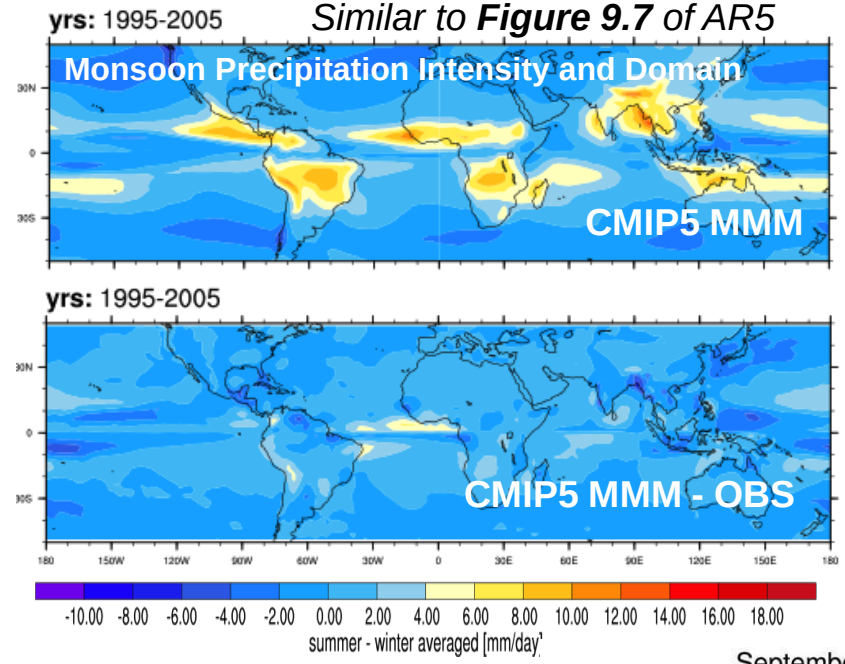
How is model performance related to projections?

DLR

Routine Benchmarking and Evaluation Central Part of CMIP6

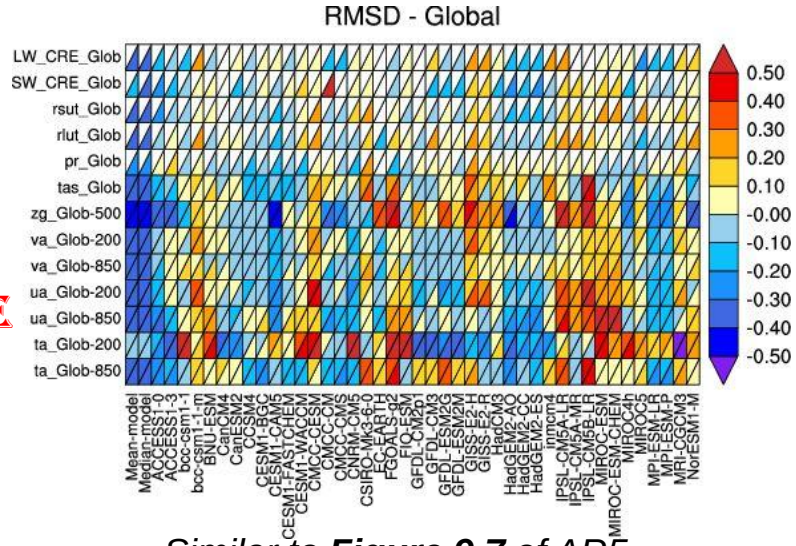
CMIP evaluation tool to produce well-established analyses as soon as model output becomes available
e.g., Community-developed ESMValTool (Eyring et al., GMDD, 2015) and PCMDI metrics package
(Gleckler et al., EOS, in press) - *Link to WGNE/WGCM Climate Model Metrics and Diagnostic Panel*

*Similar to **Figure 9.7** of AR5*



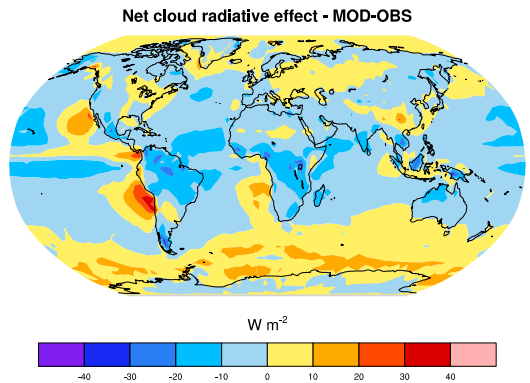
RUNNING ALONG-SIDE THE ESGF

AR5 CHAPTER 9

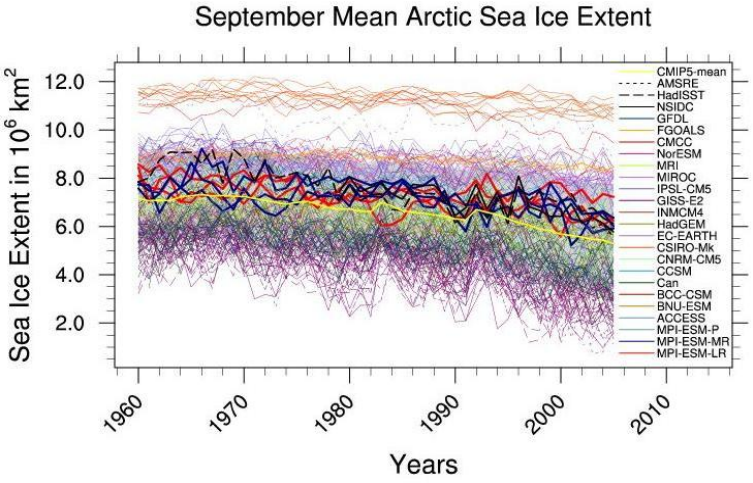


*Similar to **Figure 9.7** of AR5*

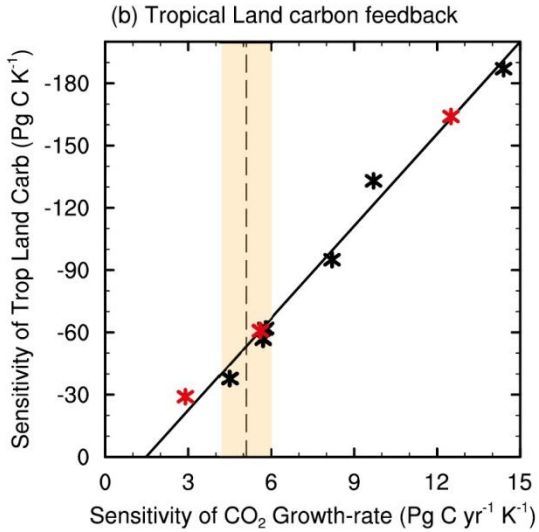
LINK TO PROJECTIONS



*Similar to **Figure 9.5** of AR5*



*Similar to **Figure 9.24** of AR5*



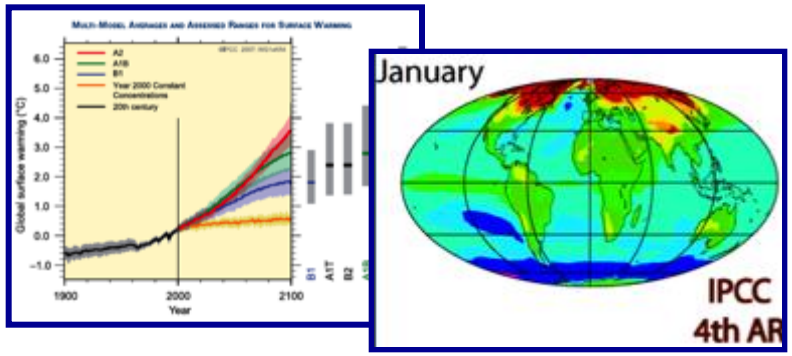
*Similar to **Figure 9.24** of AR5*

Under-Exploited Observations for Model Evaluation

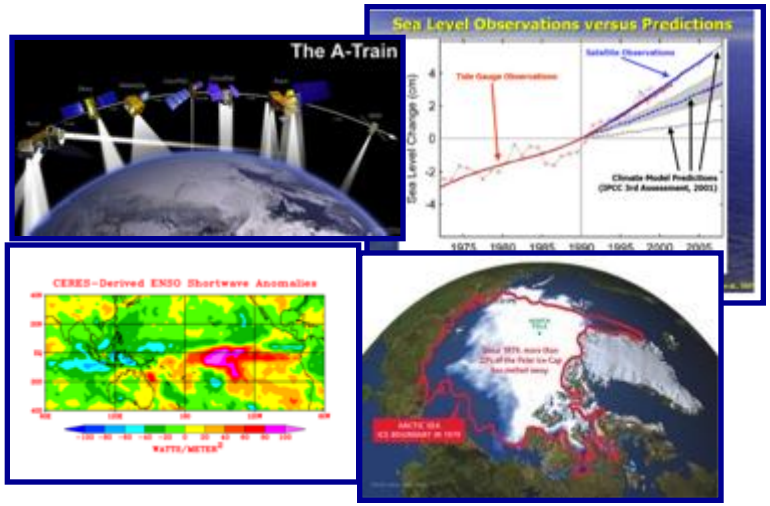
Observations for Model Intercomparison Projects (obs4MIPs)

WDAC Task Team on Observations for Model Evaluation

CMIP6



How to bring as much observational scrutiny as possible to the CMIP/IPCC process?

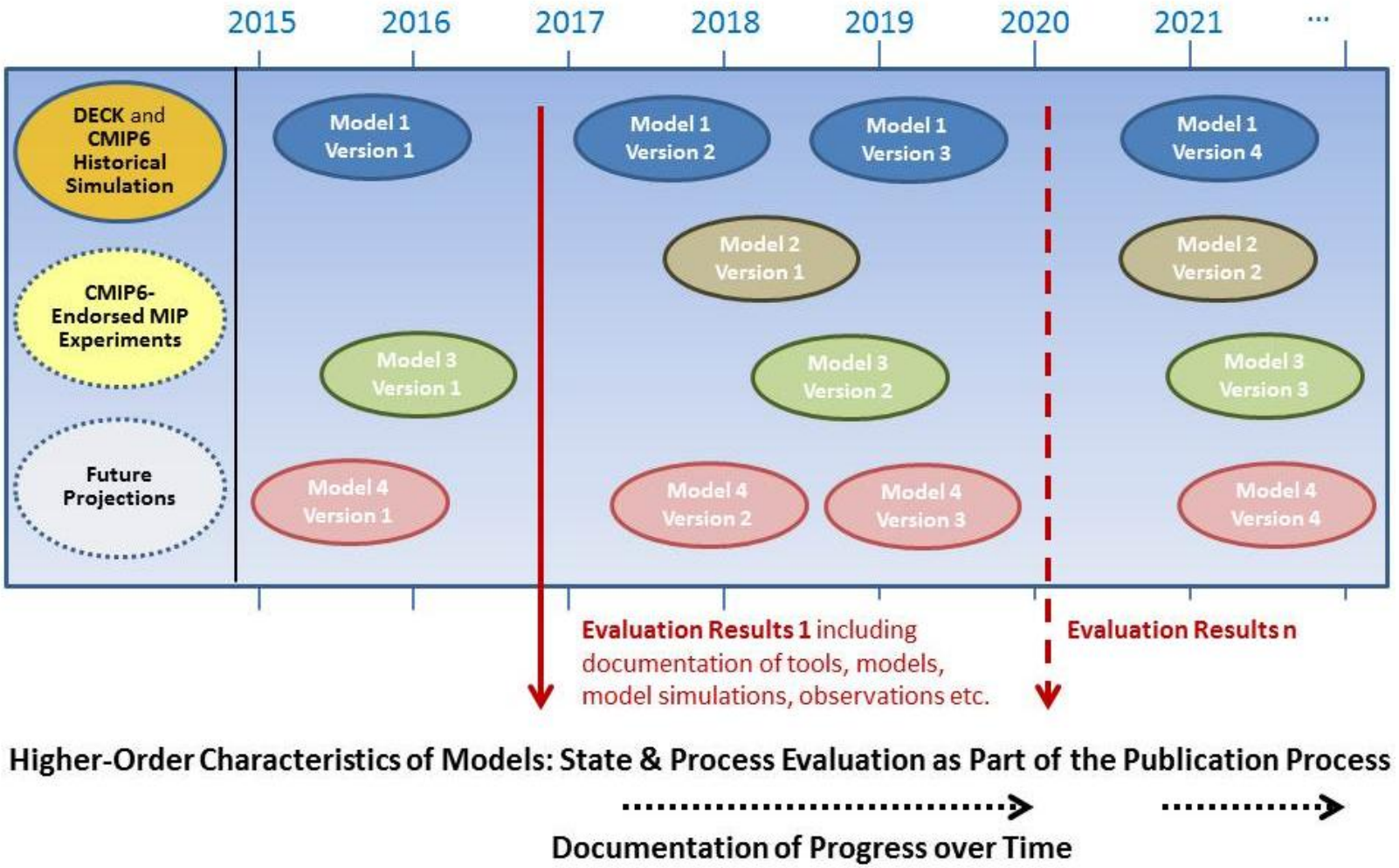


How to best utilize the wealth of satellite observations for the CMIP/IPCC process?

- Obs4MIPs has defined a set of technical specifications and criteria for developing observational data sets that are technically aligned with CMIP model output (with common file format, data and metadata structure).
- Over 50 datasets that conform to these standards are now archived on the ESGF alongside CMIP model output (Teixeira et al., 2014), including ESA CCI data
- Data users have enthusiastically received Obs4MIPs

Routine Benchmarking and Evaluation Central Part of CMIP6

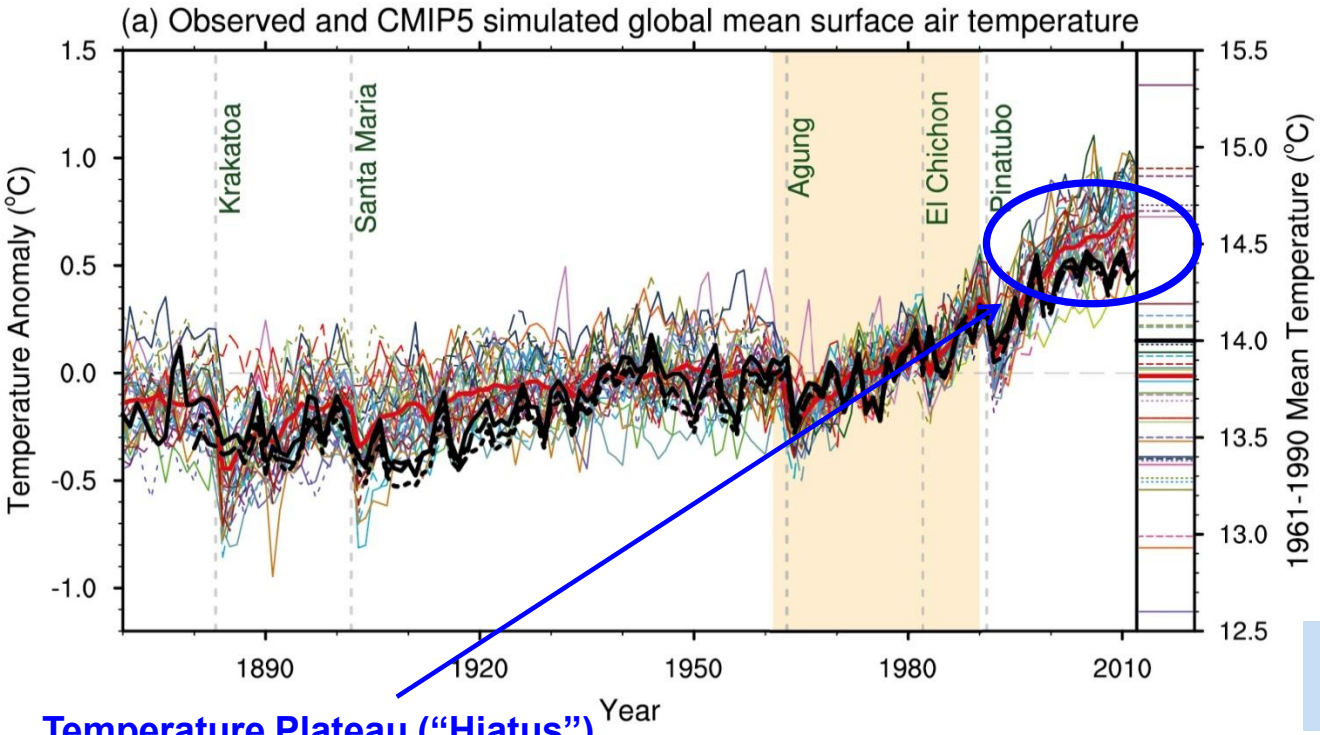
- The objective is to enable routine model evaluation and to aid the individual modelling groups in their model development process by providing feedback concerning their model errors, particularly the systematic model errors.
- Building such a community-based capability is not meant to replace how CMIP research is currently performed but rather to complement it.



4. Opportunities for CMIP6

(B) Better consideration of internal variability and more process-oriented evaluation

Evaluation of Climate Models: Temperature trends



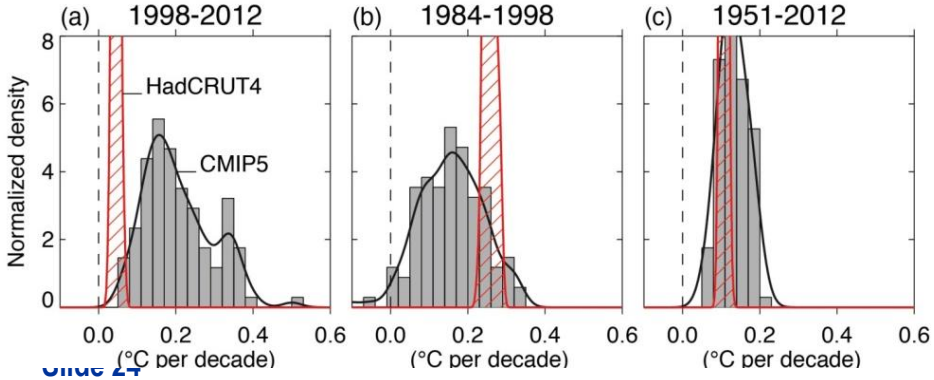
Models reproduce observed temperature trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*).

Chapter 9, Fig. 9.8

1998–2012: 0.04 ºC/decade
1951–2012: 0.11 ºC/decade

Temperature Plateau ("Hiatus")

Internal decadal variability causes to a substantial degree **the difference between observations and the simulations**. There may also be a contribution from forcing inadequacies and, in some models, an overestimate of the response to increasing GHGs and other anthropogenic forcing (dominated by aerosols).



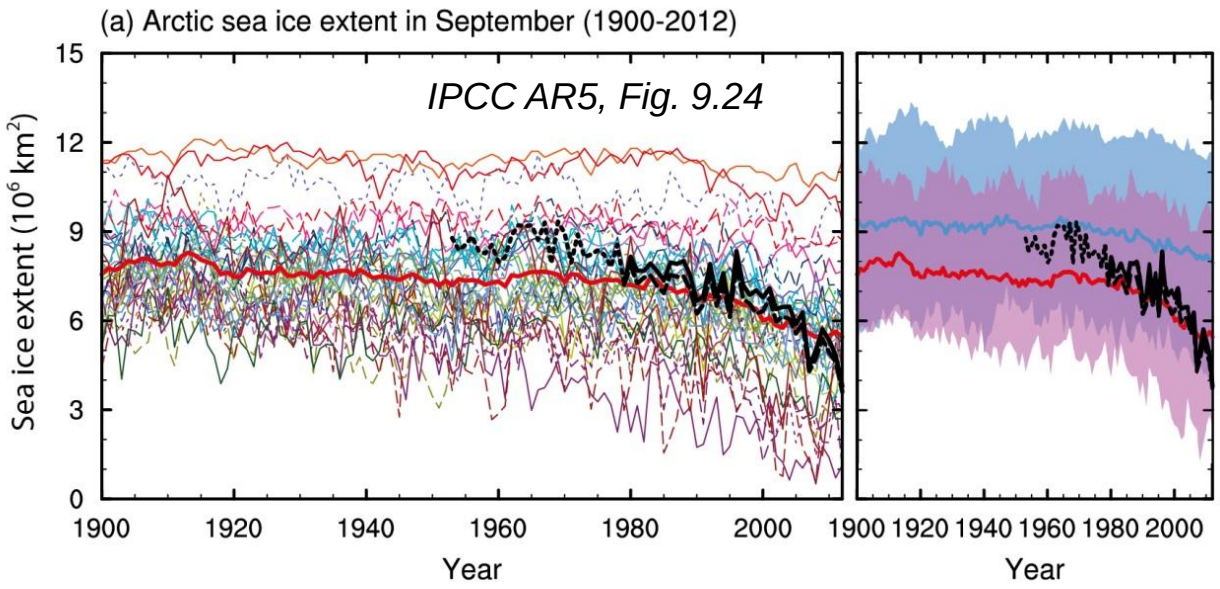
Observed and simulated GMST trends in ºC per decade

Box TS.3, Figure 1
Box 9.2, Figure 1

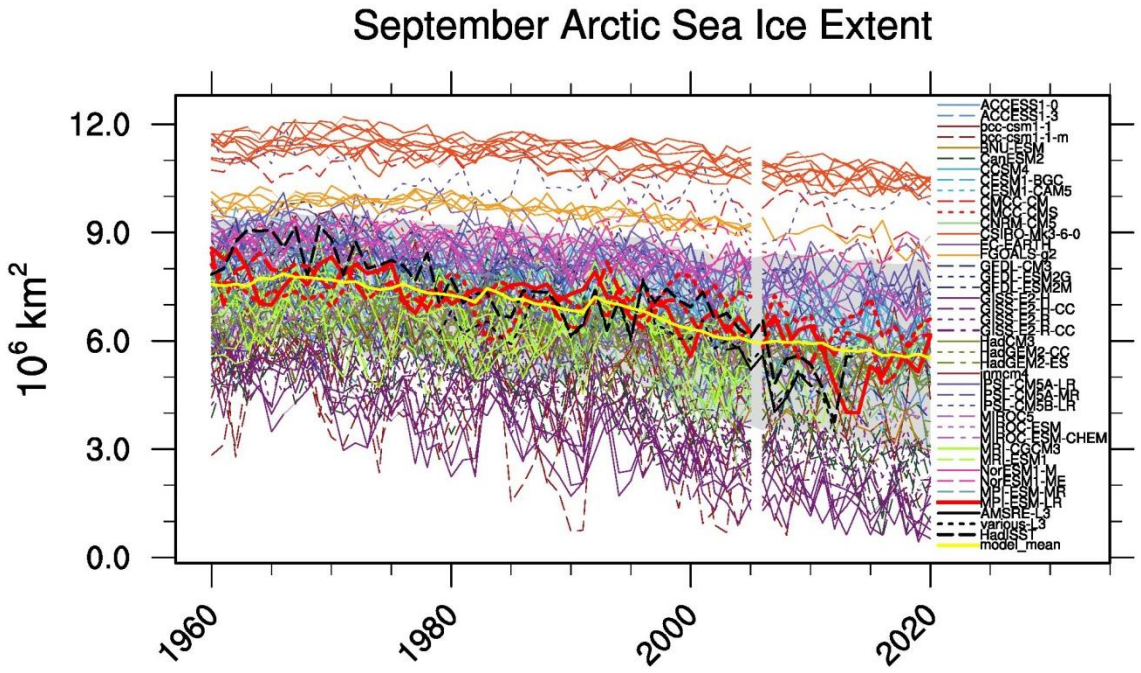
Noting Karl et al., 2015 and Trenberth. 2015

ipcc INTERGOVERNMENTAL PANEL ON climate change
WMO UNEP

Evaluation of Climate Models: Sea-Ice



Robust evidence that the **downward trend in Arctic summer sea-ice extent** is better simulated than at the time of the AR4, with about one-quarter of the simulations showing a trend as strong as, or stronger, than in observations over the satellite era (since 1979).



IPCC AR5, Fig. 9.24
redone with ESMValTool

More than one ensemble member required to make robust assessments of model performance for a single model,

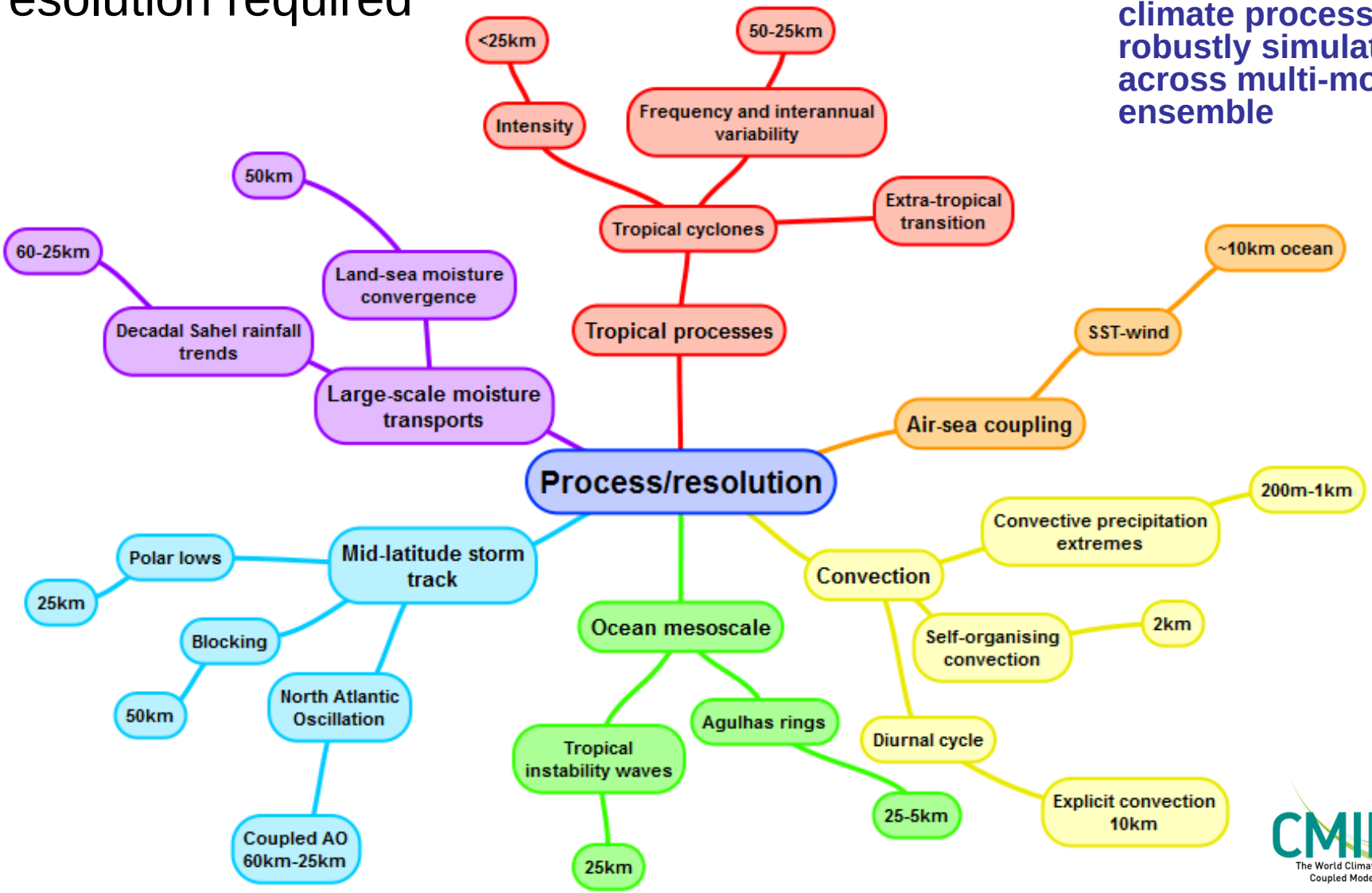
ipcc
ITERGOVERNMENTAL PANEL ON climate change
WMO UNEP

CMIP6-Endorsed Model Intercomparison Project HighResMIP

Co-chairs: Rein Haarsma & Malcolm Roberts

Example map of climate process and model resolution required

Aim: to discover at what resolution climate processes are robustly simulated across multi-model ensemble



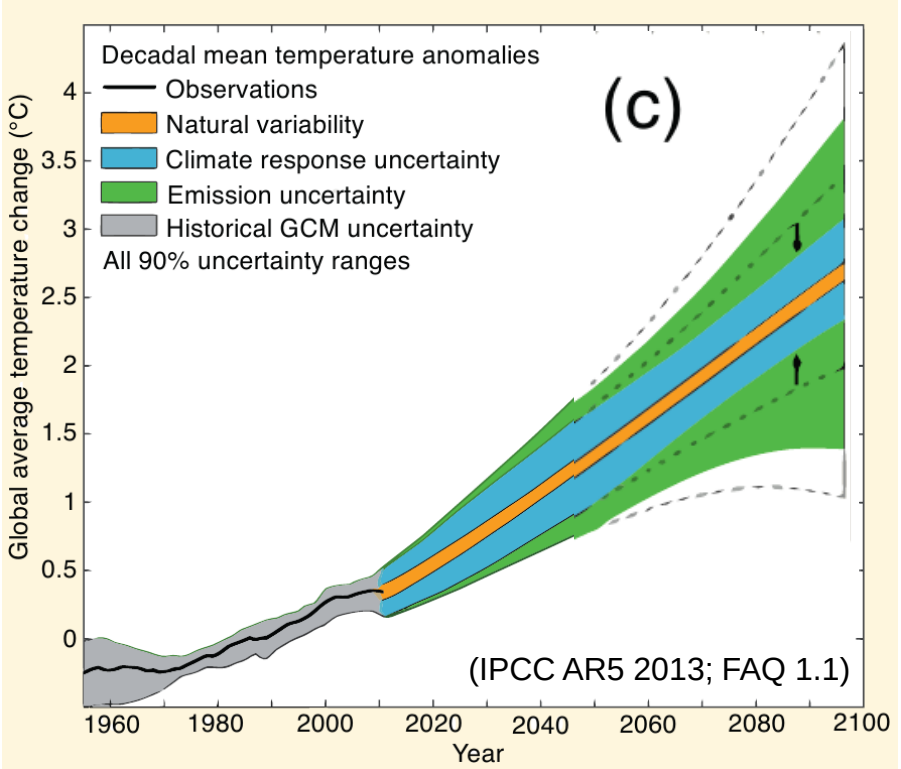
CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project

4. Opportunities for CMIP6

(C) Emergent constraints: Use of observations to constrain a simulated future Earth system feedback

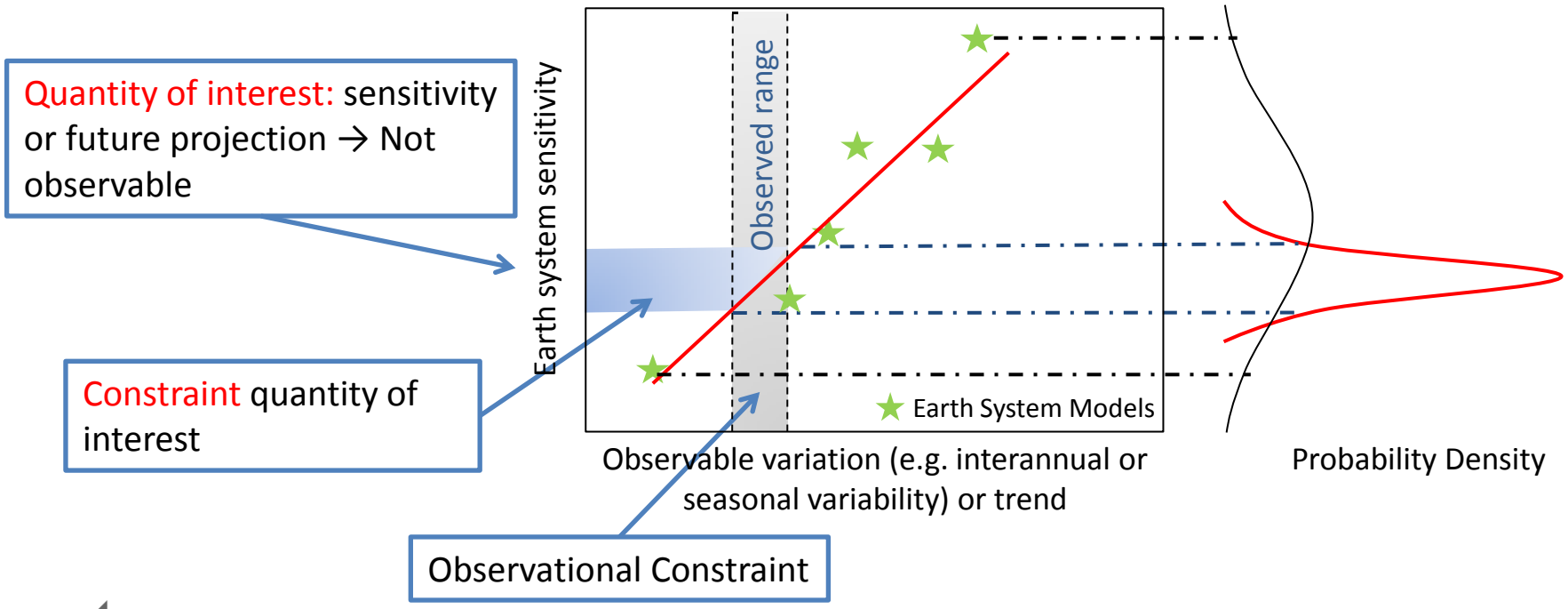
Uncertainties in Projections of Future Climate

1. **Internal Variability**
   - Due to the chaotic nature of climate system
   - Noise of climate record is constant with time
2. **Emission Uncertainty**
   - Dominant uncertainty for long term projections estimated as mean of different scenarios
   - Varying greenhouse gas emissions
   - Land use change
3. **Climate Response Uncertainty**
   - Models are build on same principles but parametrizations are needed
   - Increases when process become more relevant
   - Decreases with **model improvements** and **observational constraints**



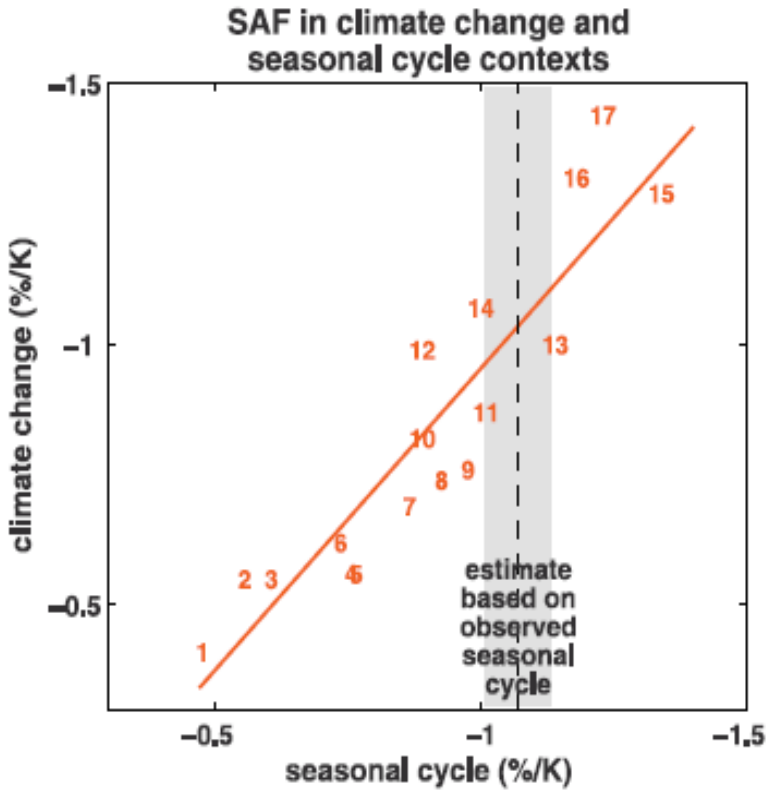
Emergent Constraints (ECs)

- **ECs** are a relationship across an ensemble of models, between some aspect of **Earth system sensitivity and** an **observable trend or variation** in the current climate
  - ➢ Emergent because it emerges from the ensemble of ESMs.
  - ➢ Constraint because it enables an observation to constrain the estimate of the Earth System sensitivity in the real world.
- The goal is to find a observable physical explanation to constrain the unobservable Earth system sensitivity



Emergent Constraint: Seasonal Cycle Physical Climate

1900-2200 April



20th century Apr-May

$$SAF \propto \Delta\alpha_s / \Delta T_S$$

- Large intermodel variations in the strength of **snow albedo feedback (SAF)** in **climate change** in the NH in April are nearly perfectly correlated with comparably large intermodel variations in feedback strength in the context of the **seasonal cycle**.

Hall and Qu, GRL, 2006

- Feedback strength in the real seasonal cycle can be **observed** and compared to models.
- These mostly fall outside the range of the observed estimate, suggesting many models have an **unrealistic snow albedo feedback** in the seasonal cycle context.

DLR

How will the carbon cycle change with climate change?

Long-term change in land carbon uptake ΔC_{Land} [GtC] (Friedlingstein et al., 2006):

$$\Delta C_{Land} = \gamma_{Long\,Term} \Delta T + \beta_{Long\,Term}\, \Delta C_{Atm}$$

ΔC_{Atm}: change in atm. CO_2 concentration
ΔT: change in temperature
γ, β : Feedback parameter

- **Response to increasing temperatures?** Climate warming reduces the efficiency of CO_2 absorption by the land and ocean => more emitted carbon stays in the atmosphere leading to additional warming, representing a positive climate-carbon cycle feedback

The **carbon cycle-climate feedback** γ_{LT} quantifies the difference of (tropical) land carbon storage between coupled and uncoupled simulations due to climate change in terms of carbon loss per degree [GtC/K]; ("LT" = long term) :

$$\gamma_{LT} = \frac{\Delta C^{c}_{LT} - \Delta C^{u}_{LT}}{\Delta T^{c}_{T}}$$

Study 1 constrains γ_{LT}
Cox et al., 2013; Wenzel, Cox, Eyring, Friedlingstein, JGR, 2014

- **Response to increasing atmospheric CO2 concentrations?** elevated CO2 will enhance Gross Primary Productivity (GPP)

The **carbon cycle-CO_2 concentration feedback** β_{LT} quantifies the change in land carbon due to the change in atmospheric CO_2 in the uncoupled simulation: $\beta_{LT} = \frac{\Delta C^{u}_{LT}}{\Delta C^{u}}$

Study 2 constrains β_{LT}
Wenzel, Cox, Eyring, Friedlingstein, in rev., 2015

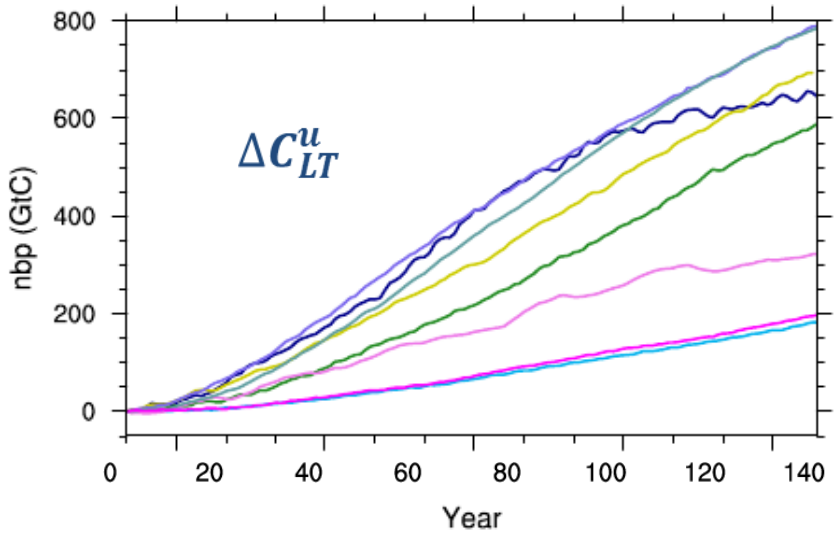
Diagnosing the Carbon Cycle-Climate Feedback (γ_{LT})

Coupled (*1%COU*) and uncoupled (*1%BGC*) 1%/yr simulations to estimate ΔC_L

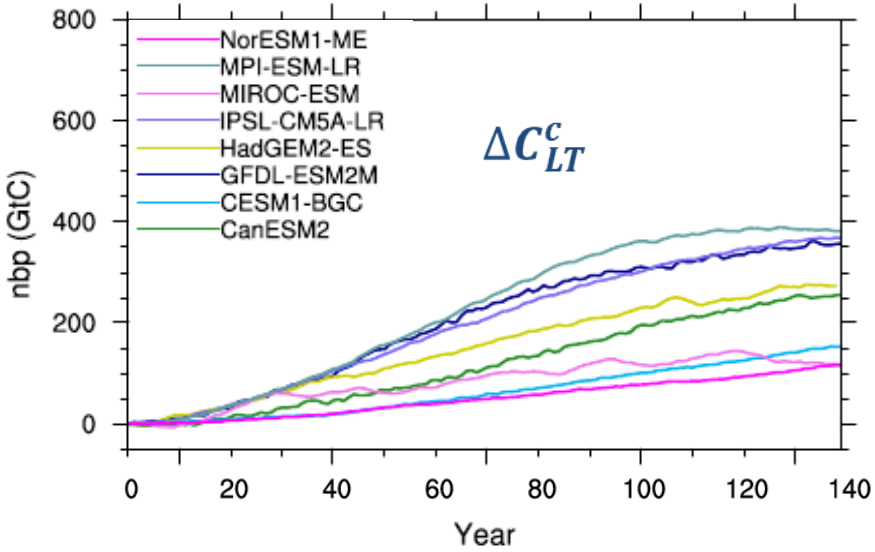
$$\gamma_{LT} = \frac{\Delta C^c_{LT} - \Delta C^u_{LT}}{\Delta T^c_T}$$

Net carbon flux from land to atmosphere (Net Biome Productivity - NBP)

Climate change is uncoupled to the carbon cycle



Climate change is coupled to the carbon cycle

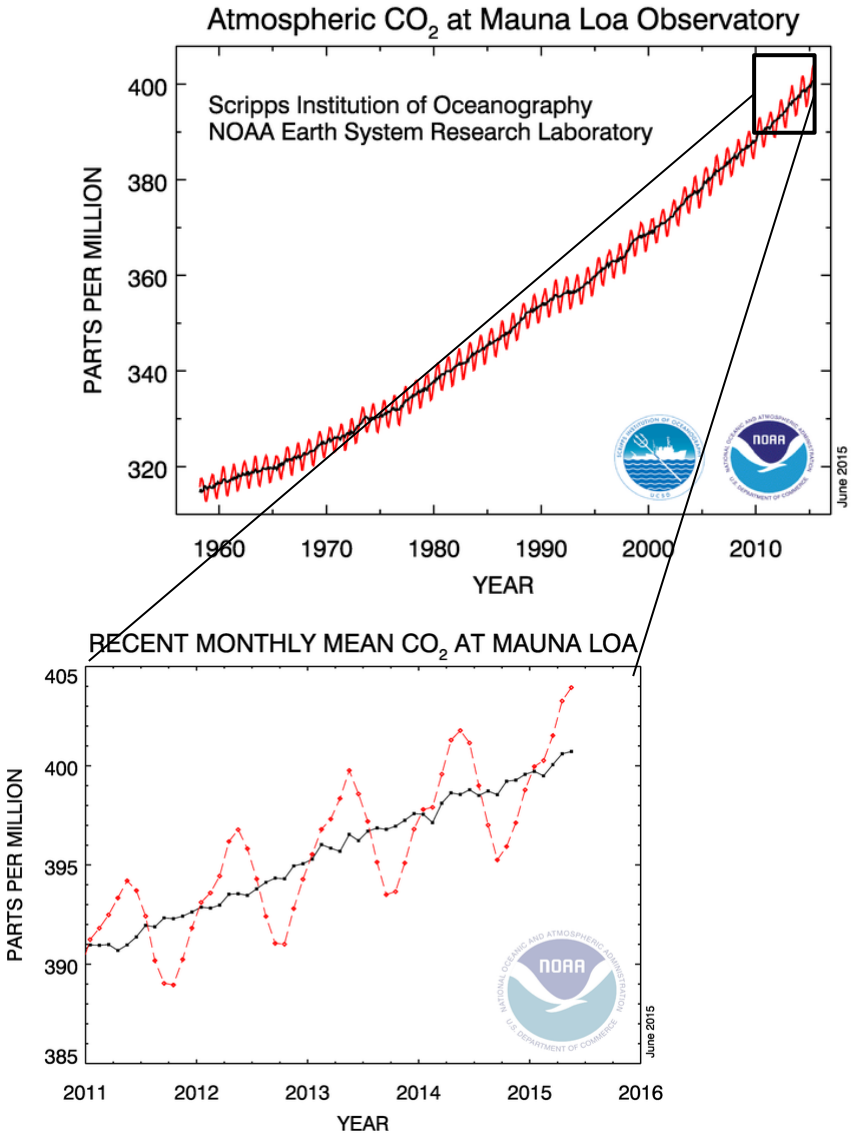


- Increasing temperature leads to decreased uptake of land carbon uptake
- Leads to higher CO_2 concentrations in the atmosphere
- Large uncertainties in the amount of future tropical land carbon uptake

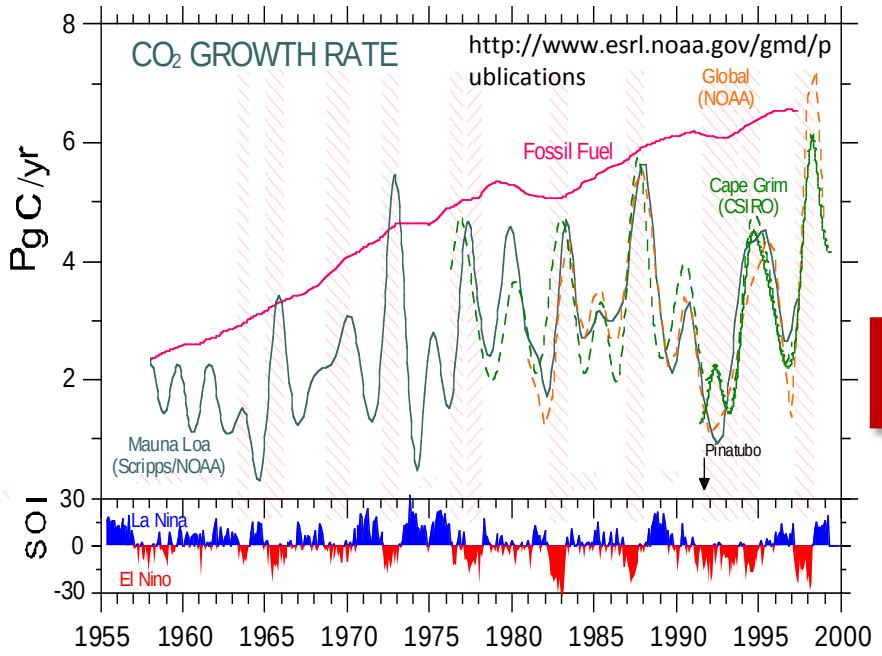
Wenzel et al., JGR, 2014

Atmospheric CO_2 Measurements

- Atmospheric CO_2 concentration increased over the last 50 years by approx. 100 ppmv
- Increasing atmospheric CO_2 concentration (black) mainly due to anthropogenic CO_2 emissions
- Seasonal variability (red) due to seasonal carbon cycle
  - Summer: more photosynthesis => atmospheric CO_2 decreases stored in terrestrial ecosystem
  - Winter: CO2 release by decomposition of soil organic matter

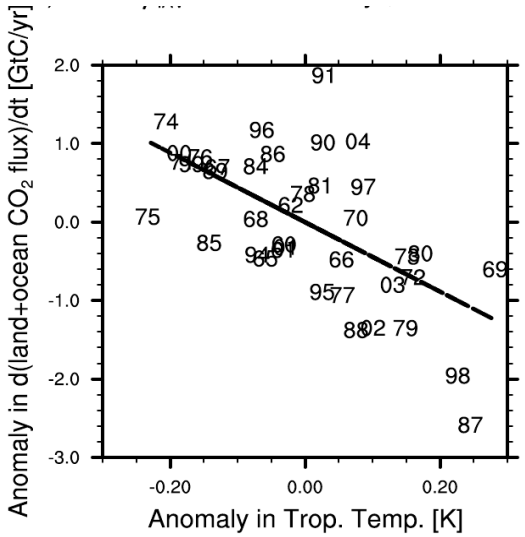


Relationship Interannual Variations in Temperature & CO_2 Growth Rate



Carbon flux estimates from: Global Carbon Project Surface temperature from NOAA-NCDC

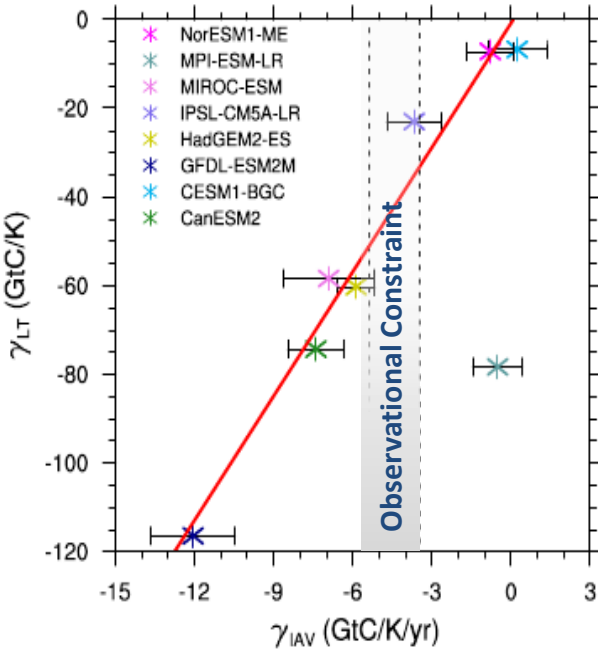
Observed relationship

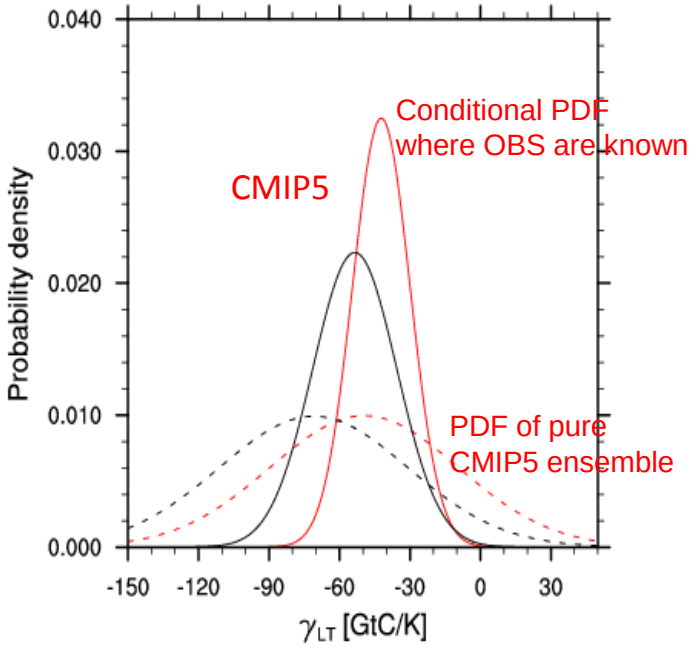


- Responses of the carbon cycle to climate anomalies are mirrored in the interannual variability (IAV)
- Especially valid in the tropics, where strong variability caused by El Niño gives a spatially coherent pattern of warmer and colder years
  - Decomposition is mainly controlled by climate, warming for example increases microbial activity and therefore decomposition.
- **Observed relationship: γ_{IAV} = - 4.4 ±0.9 GtC/yr/K**
- Same analysis for the CMIP5 ESMs using historical simulations

Wenzel et al., JGR, 2014

Constraining the Carbon Cycle-Climate Feedback (γ_{LT})





- EC between the **long-term sensitivity of tropical land carbon storage to climate warming (γ_{LT})** and the **short-term sensitivity of atmospheric carbon dioxide (CO2) to interannual temperature variability (γ_{IAV})**
- Constrained carbon cycle-climate feedback parameter: **-44 ± 14 GtC/K** (unconstr. -49 ± 40 GtC/K)

➢ Less carbon will be stored as a result of increasing of temperature

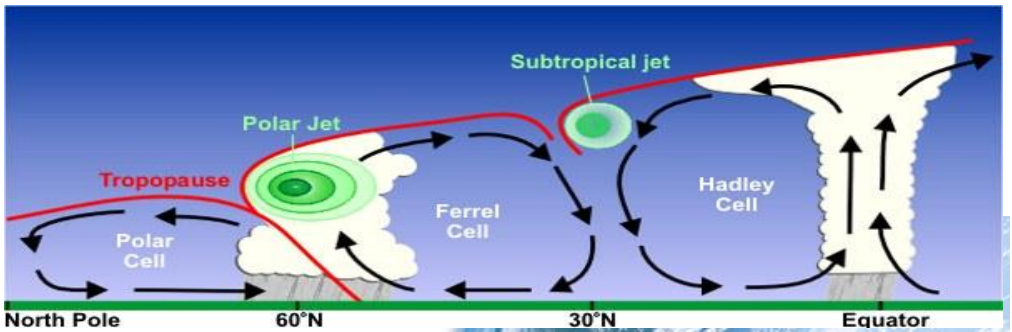
➢ This leads to higher CO_2 concentrations in the atmosphere

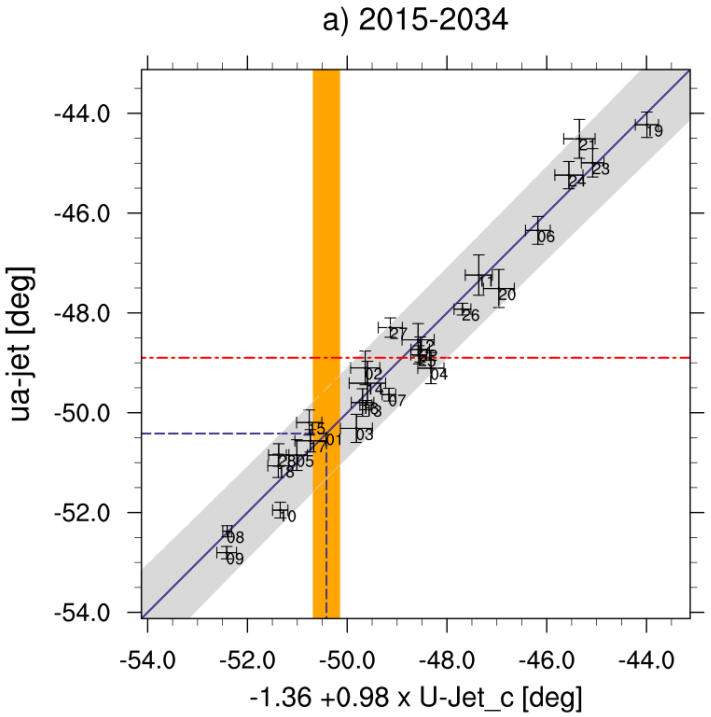
Wenzel et al., JGR, 2014

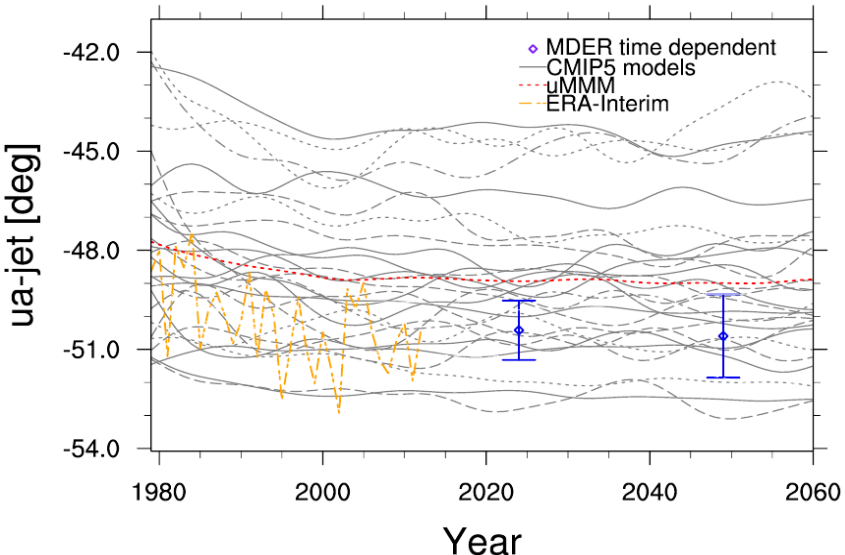
Applying MDER to future Austral Jet Stream Positions

- **Multiple Diagnostic Ensemble Regression (MDER**, Karpechko et al., 2013)
  - Uses process-oriented present day diagnostics to constrain future austral jet stream positions
- Equatorward bias of the CMIP5 models austral jet positions with a spread of 10˚
- MDER is targeted to constrain near-term (2015-2034) projections of the austral jet position, and selects the **historical jet position** as the most important of 20 diagnostics.
- The method essentially recognizes the equatorward bias in the past jet position, and provides a bias correction of about 1.5˚ southward to future projections.

Wenzel et al., J. Clim., in press

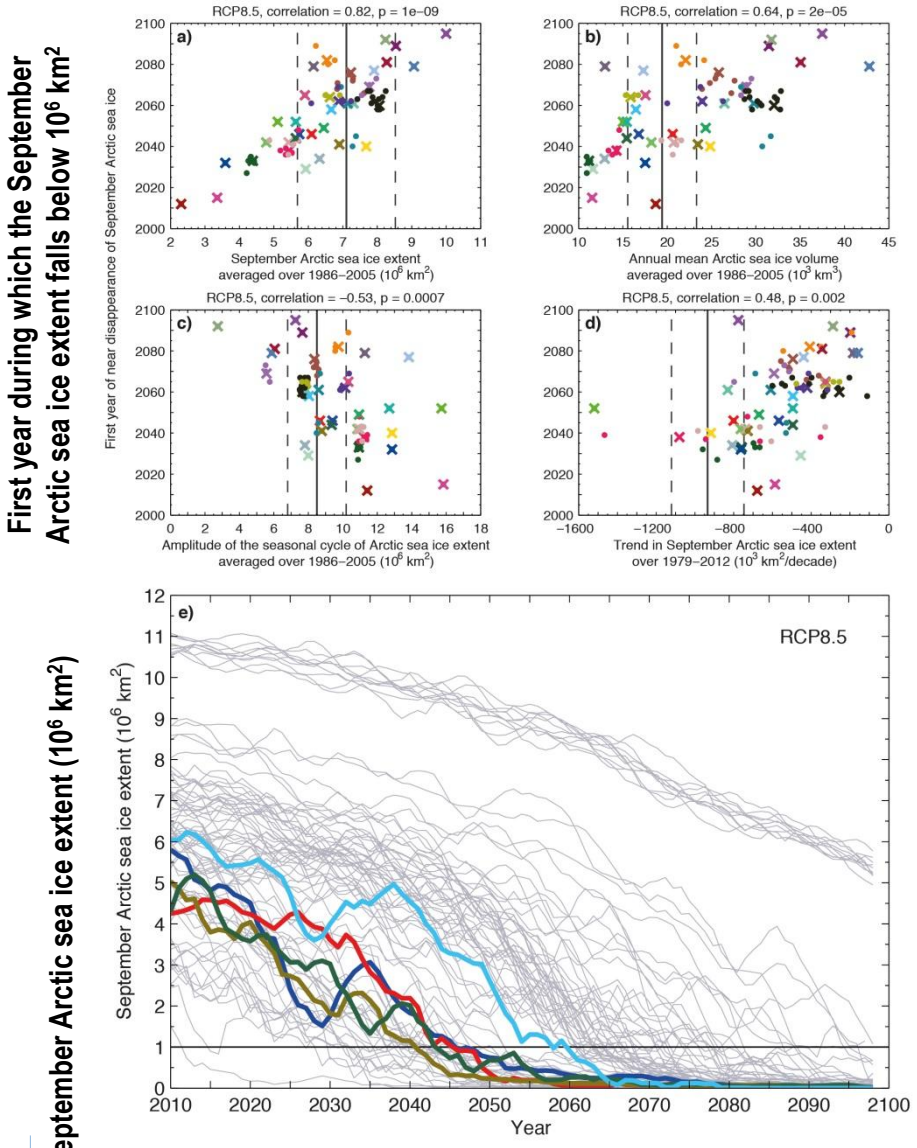






Weighting Model Projections: Arctic Sea-Ice

Process-based constraints can be used to reduce the spread of model projections



- **First year during which the September Arctic sea ice extent falls below a certain threshold** is highly correlated with the **September sea ice extent and annual mean sea ice volume averaged over the past.**
- **First year during which the September Arctic sea ice extent falls below a certain threshold** are correlated with the **past trend in September Arctic sea ice extent and the amplitude of the mean seasonal cycle of sea ice extent.**
- Suggests a faster rate of summer Arctic sea ice decline than the multi-model mean
- A model is retained if, for each diagnostic, either this interval overlaps a ±20% interval around the observed/reanalysed value of the diagnostic or at least one ensemble member from that model gives a value for the diagnostic that falls within ±20% of the observational/reanalysed data.

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Massonnet et al., 2012

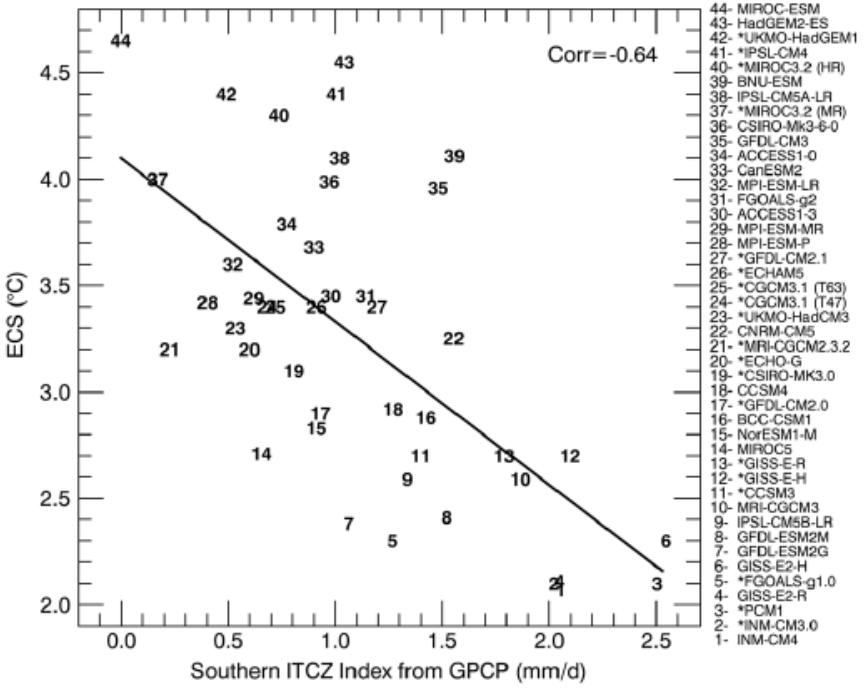
Figure 12.31

Other Examples on Selected Feedbacks and ECS

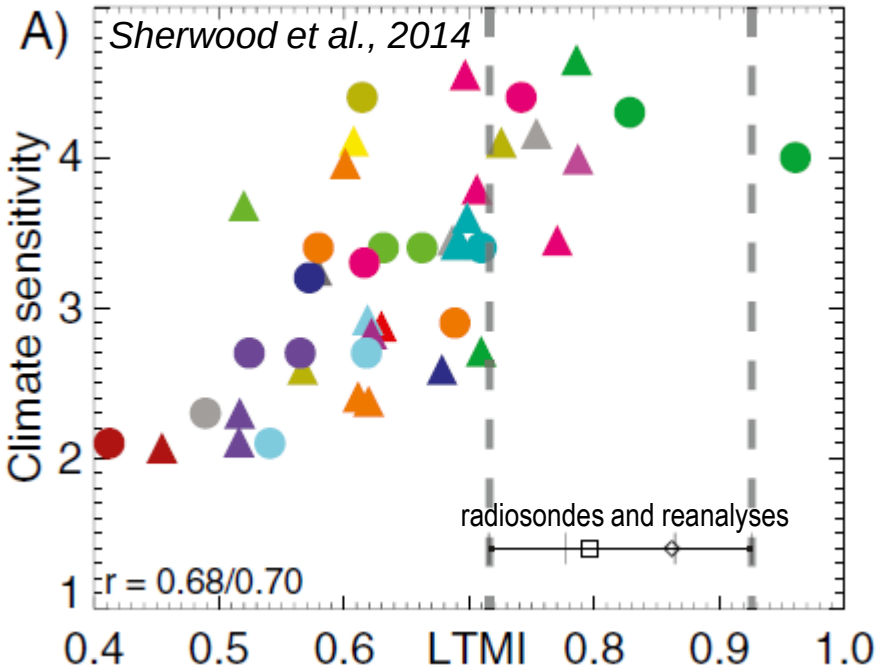
- The extratropical **surface cryosphere feedback** was constrained by Crook & Forster (2014) using variations in the seasonal cycle of the cryosphere. Models were found to largely underestimate this feedback (0.4 – 1.2 W m^{-2} K-1 compared to 3.1 ± 1.3 W m^{-2} K^{-1}) under warming despite their comparable seasonal sensitivity to observations.

- Gordon et al. (2013) related the **water vapor feedback** to observed variability (2002-2009)
  - Demonstrated the physical explanation of the relation between short and long-term forced changes in models under warming.
  - However, relative weak relation combined with large uncertainties in the observations.
  - Suggested an observational record of 25 years or longer could significantly improve the demonstrated observational constraint.

- Tian (2015) shows that show that the **double-ITCZ bias and ECS** in 44 GCMs from CMIP 3/5 are negatively correlated
  - **Southern ITCZ index**: model climatological annual mean precip bias over southeastern Pacific
  - Low sensitivity models having problems in representing its southern branch.
  - ECS might be in the higher end of its range (~4.0°C) and most CMIP3/5 models might have underestimated ECS.

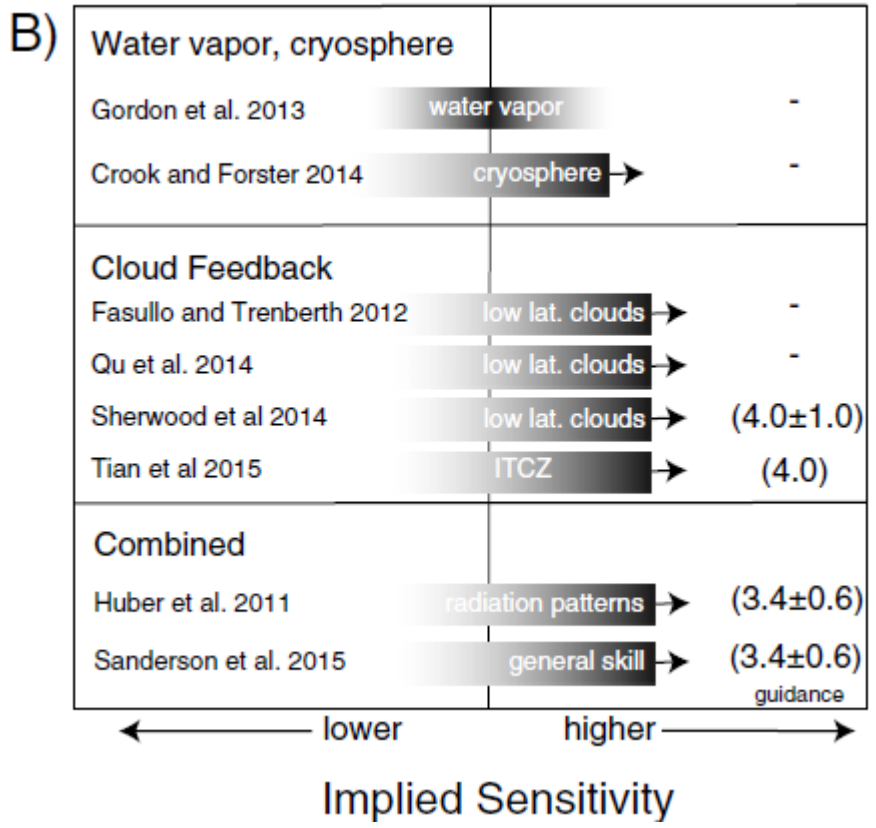


Constraining Equilibrium Climate Sensitivity



- Spread in ECS arises largely from low clouds
- Relates ECS to the strength of mixing in the lower troposphere over warm tropical oceans (lower-tropospheric mixing index LTMI)
- Higher-sensititivity models simulate certain cloud-relevant phenomena better.
- However, the metric suffers from large uncertainties in the observed estimates.

- No final conclusions can be made yet, but the results of EC studies generally suggest an underestimation of ECS by models due to cryospheric and cloud feedbacks.



Summary

While progress has been made in ESM evaluation over the last decades, there are important opportunities and challenges for CMIP6, with simulations starting in 2016

- In many cases the lack or insufficient quality of long-term observations or observations for process evaluation remains an impediment, but improvements can be made by **fully exploiting existing observations** and by **taking into account observational uncertainty**.
- Make the evaluation of CMIP models with well-established diagnostics and performance metrics **more routine** (by developing and applying diagnostic tools such as the ESMValTool) to leave more time for innovative research.
- Part of the difference between model results and observations can be attributed to **unforced variability**, originating from the nonlinear nature of the variable climate system. An accurate assessment of model performance therefore has to take into account internal climate variability in addition to observational uncertainty.

Summary Emergent Constraints

- While evaluation of the evolving climate state and processes can be used to build confidence in model fidelity, this does not guarantee the correct response to changed forcing in the future.
- **Emergent constraint analysis** refers to the use of observations to constrain a simulated **future Earth system feedback** offers the potential to reduce uncertainty in climate projections.
- Studies have been published that focus both on constraining ECS more generally, but also on constraining individual key feedbacks at a process level.
- ECs studies can help guiding model development onto processes crucial to the magnitude and spread of future Earth system change. This can also be used to prioritize future observations activities.
- A necessary property of emergent constraints is a physical basis for the relation.
- There are many open questions and issues, but emergent constraints remain a promising approach that should be fully exploited in CMIP analysis.