Some kind of introduction to CMIP

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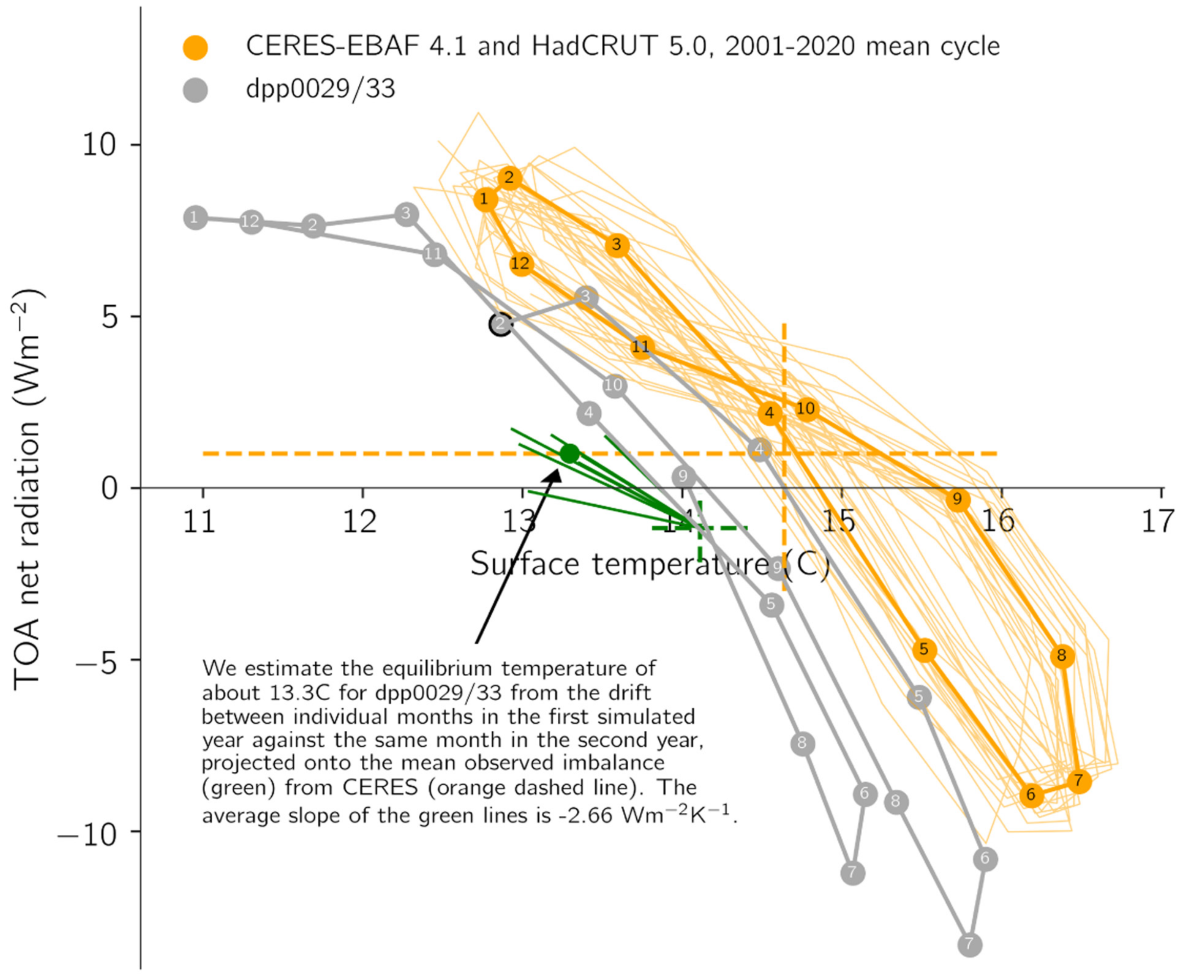
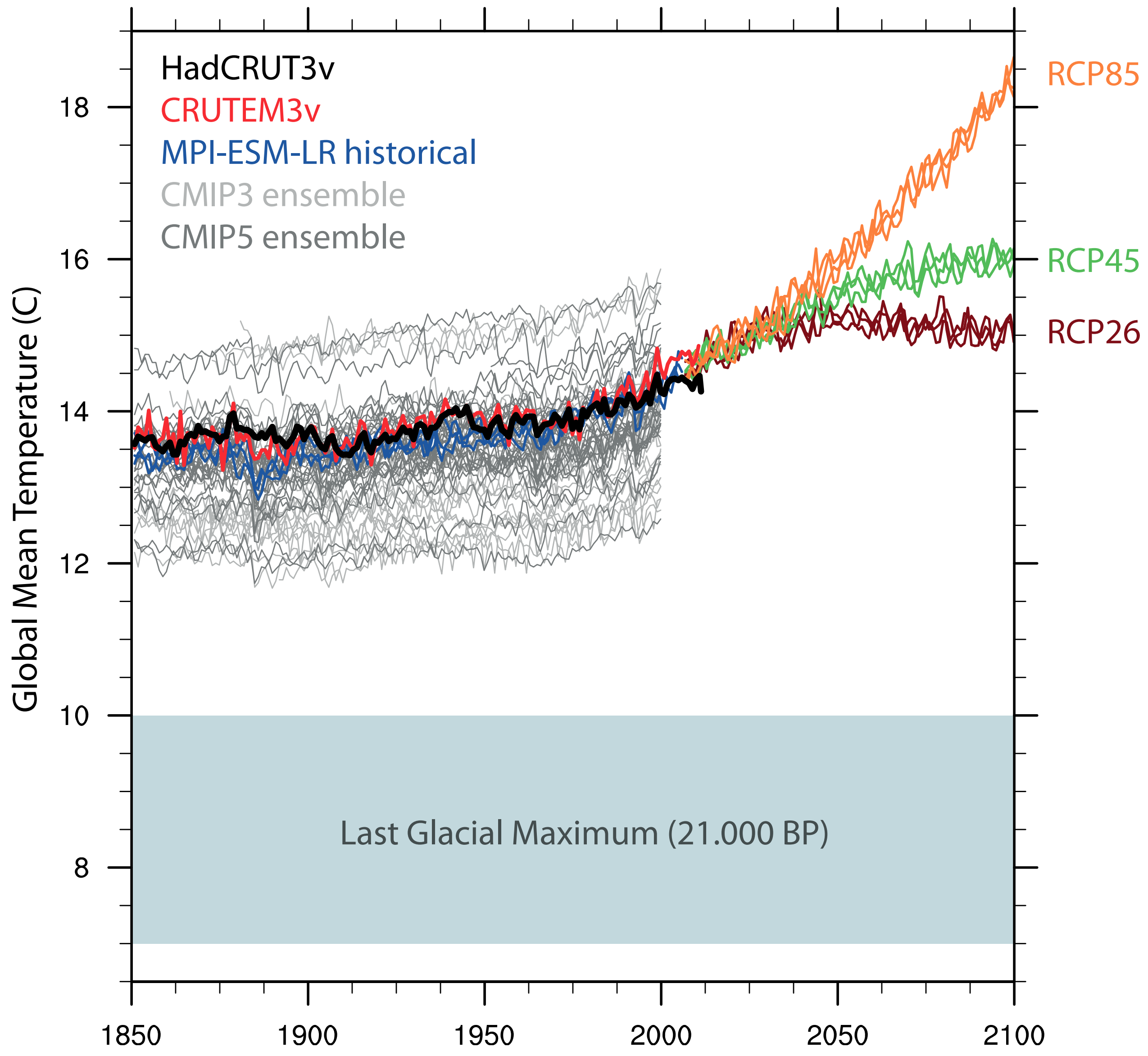
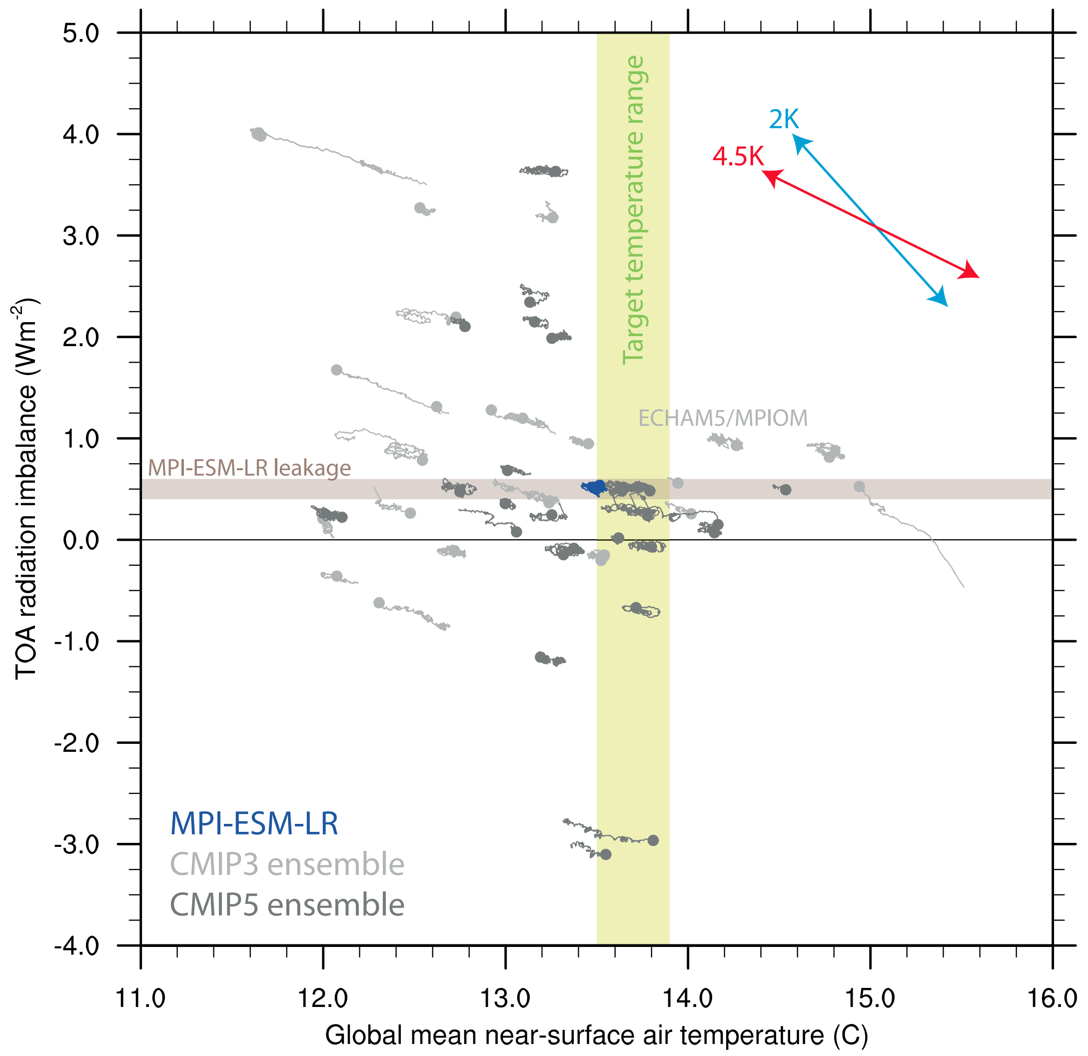
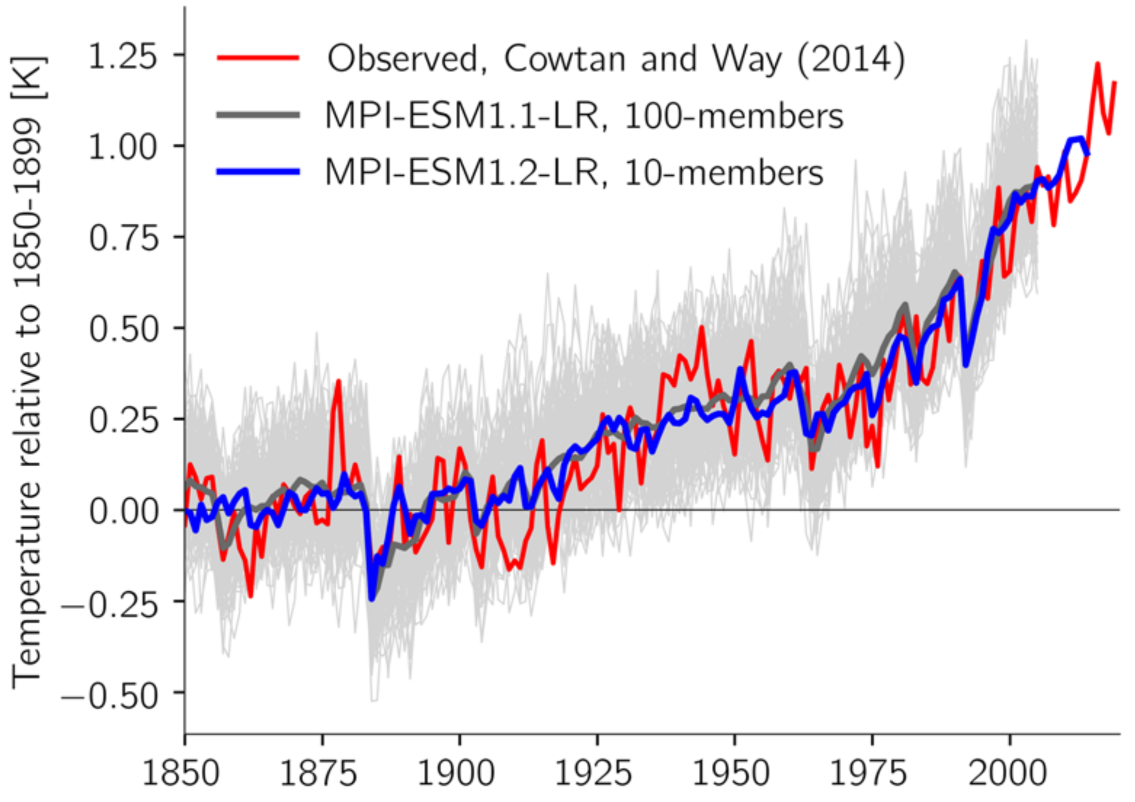
About me?

- I did Phd & post-doc at MISU on turbulence and Arctic climate
- Then moved to the Max Planck Institute in Hamburg, Germany (2009-2018)
- Got involved in climate model development and contributed to CMIP5 and CMIP6
- Wrote several papers about the developments with a focus on model tuning
- Also I participated in the IPCC AR6 report as expert on climate sensitivity









Mauritsen et al. (2012, 2019, 2020, 2022)

Bjerknes' and Richardson's model

$$\frac{\partial \vec{V}}{\partial t} = -\vec{V} \cdot \nabla \vec{V} - f\vec{k} \times \vec{V} - \frac{1}{\rho_0}\nabla p - \nabla \Phi + \vec{F}$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{V})$$

Equations of motion for the atmosphere, energy and mass conservation:

$$p = \rho R T$$

$$\frac{\partial \theta}{\partial t} = -\vec{V} \cdot \nabla \theta + K \nabla^2 \theta + Q^\theta$$

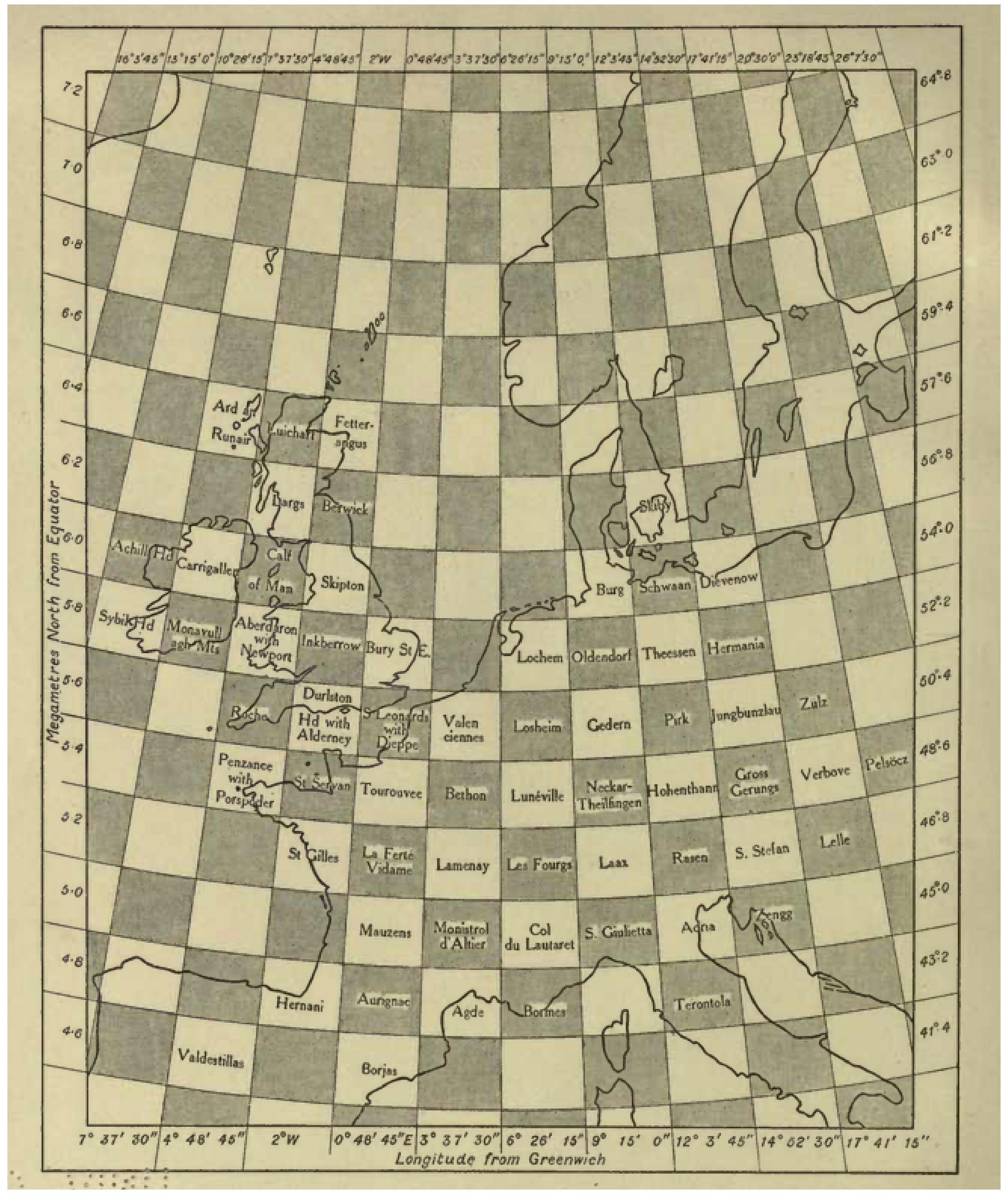
$$\frac{Dq}{Dt} = E - P$$

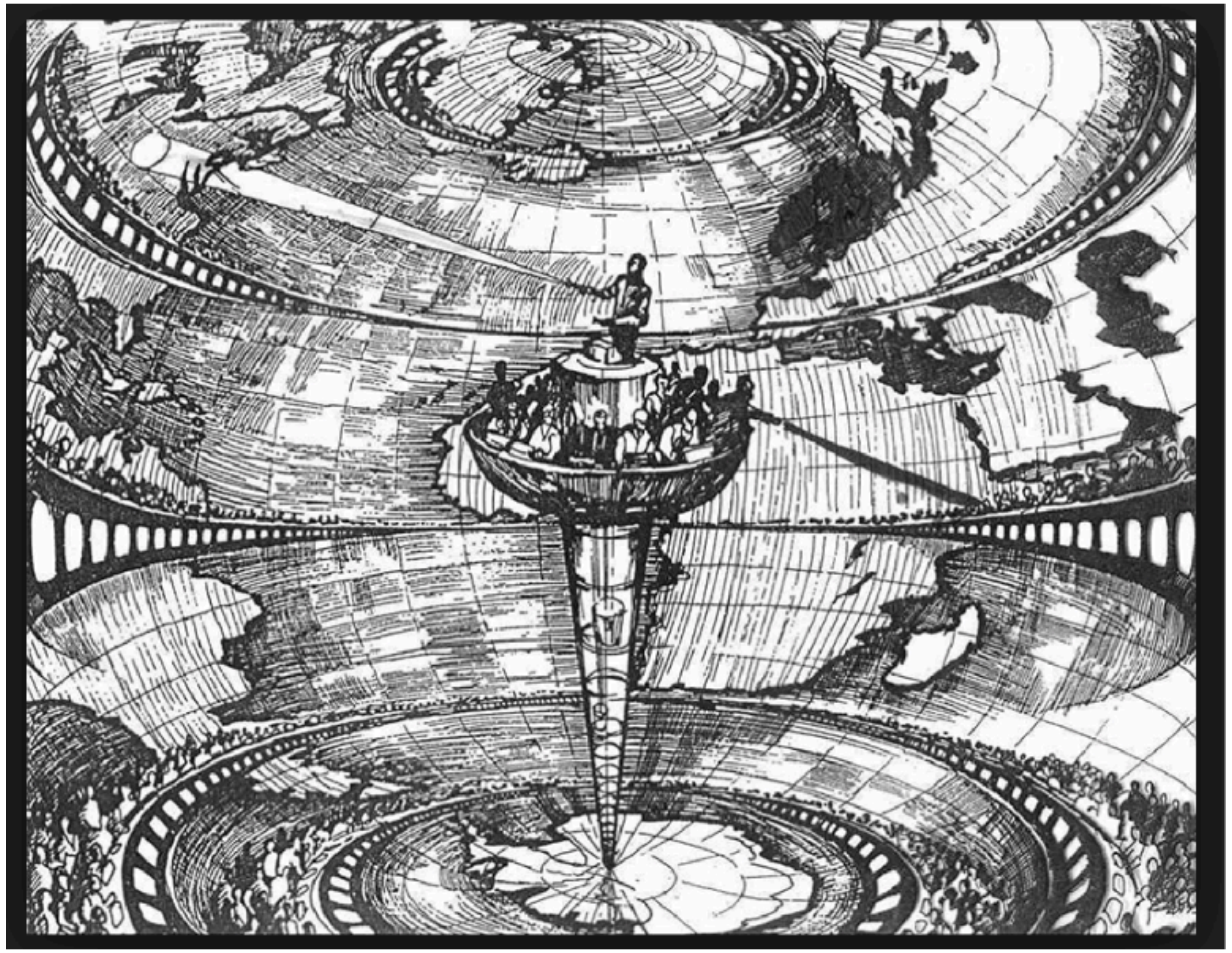
Bjerknes 1904, Richardson 1922, Charney et al. 1950, Rossby 1954

Bjerknes' and Richardson's model

$$\frac{\partial \vec{V}}{\partial t} = -\vec{V} \cdot \nabla \vec{V} - f\vec{k} \times \vec{V} - \frac{1}{\rho_0}\nabla p - \nabla \Phi + \vec{F}$$

- Use fundamental equations of motion to predict weather
- Richardson tried to solve them by hand, Charney later managed this with the advent of computers
- Carl Gustaf Rossby launched the worlds first operational forecasts in 1954
- The atmosphere models were applied to climate problems in the 1960s (Smagorinski, Manabe)





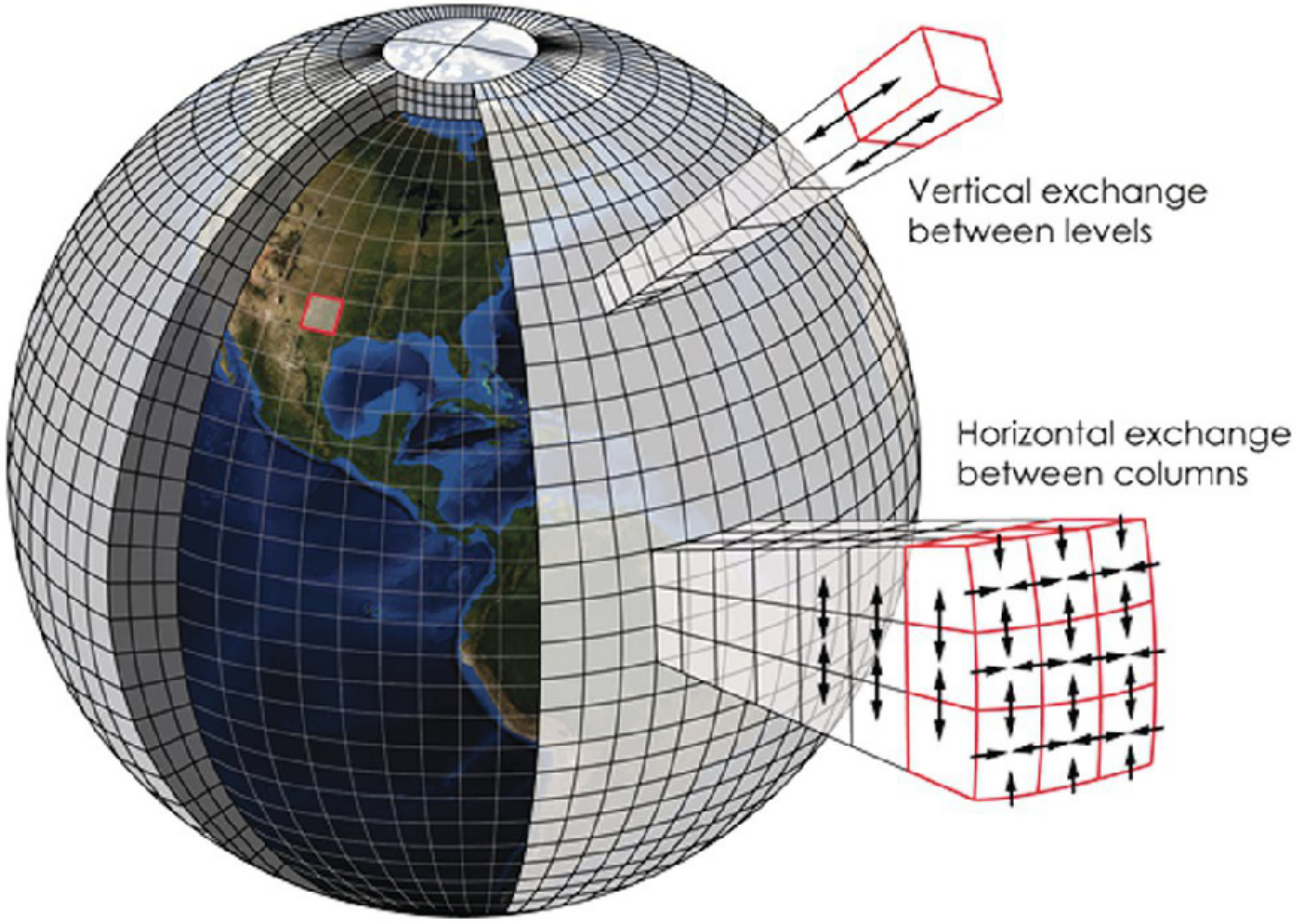
Bjerknes 1904, Richardson 1922, Charney et al. 1950, Rossby 1954

Same principle in modern climate models

$$\frac{\partial \vec{V}}{\partial t} = -\vec{V} \cdot \nabla \vec{V} - f\vec{k} \times \vec{V} - \frac{1}{\rho_0}\nabla p - \nabla \Phi + \vec{F}$$

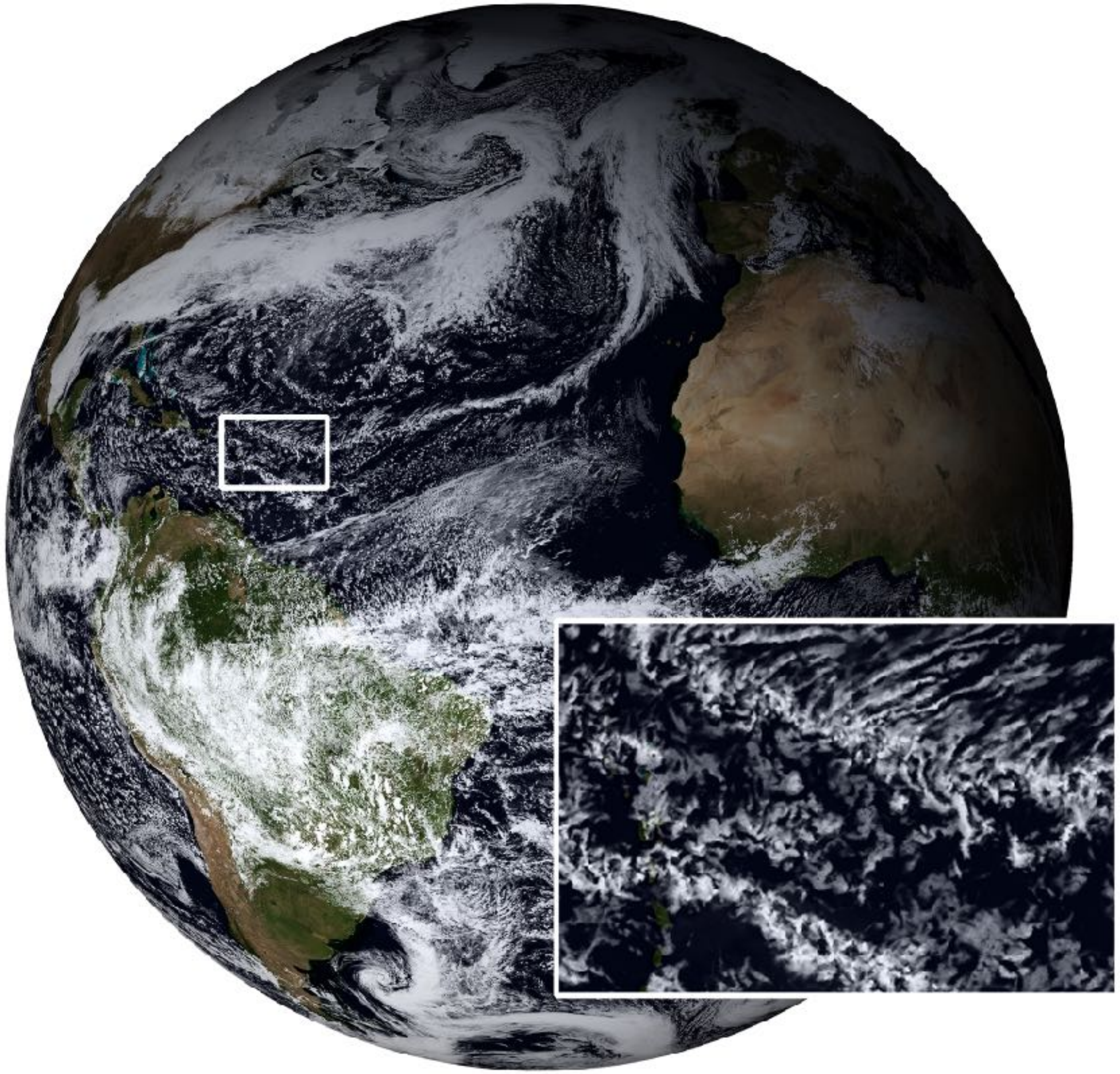
The atmosphere part of a modern climate model is not too different from a weather model

You can say that they **simulate** the weather according to an approximation of the laws of physics

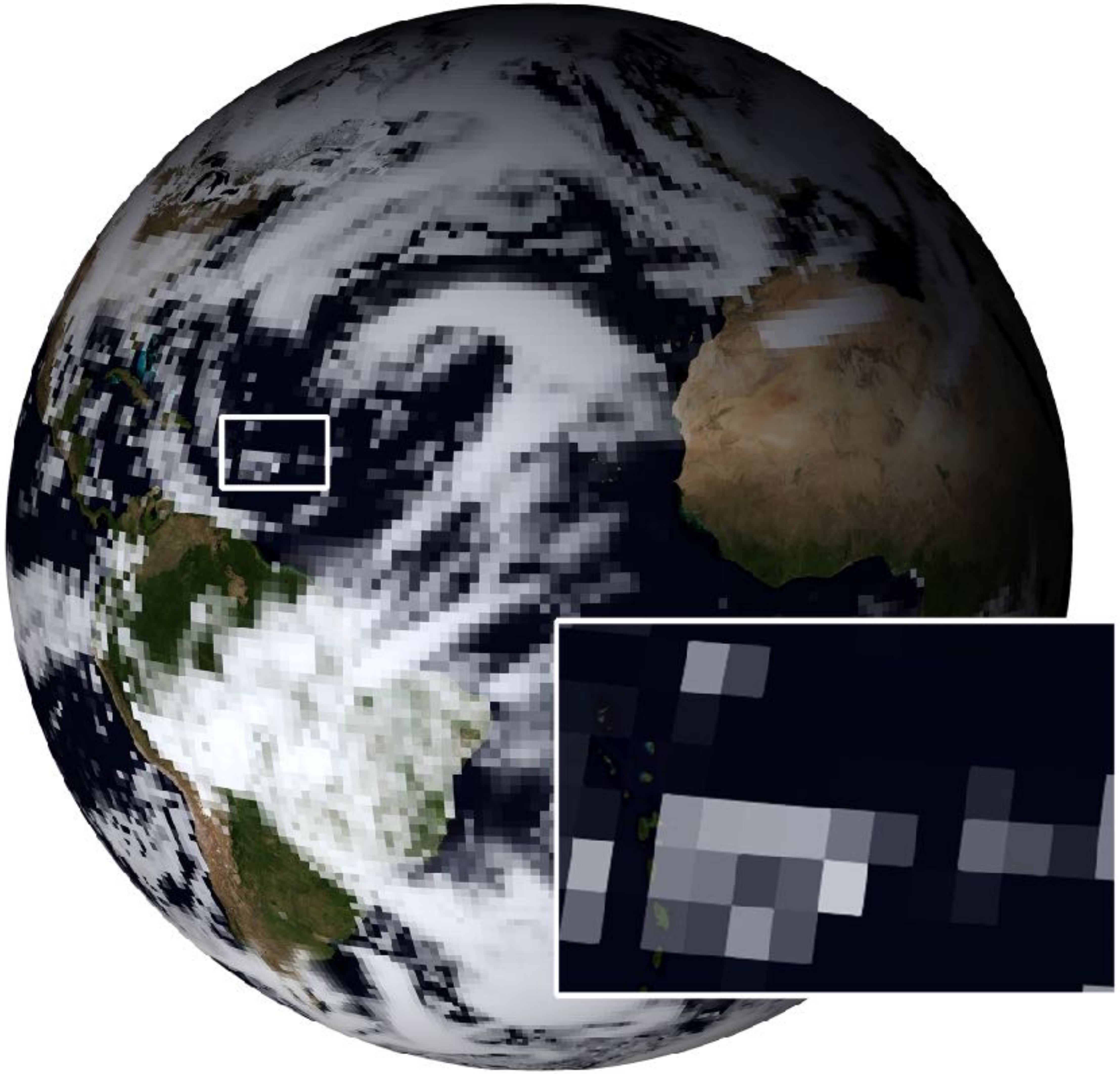


Kotamarthi et al. (2021)

Snap shot of clouds

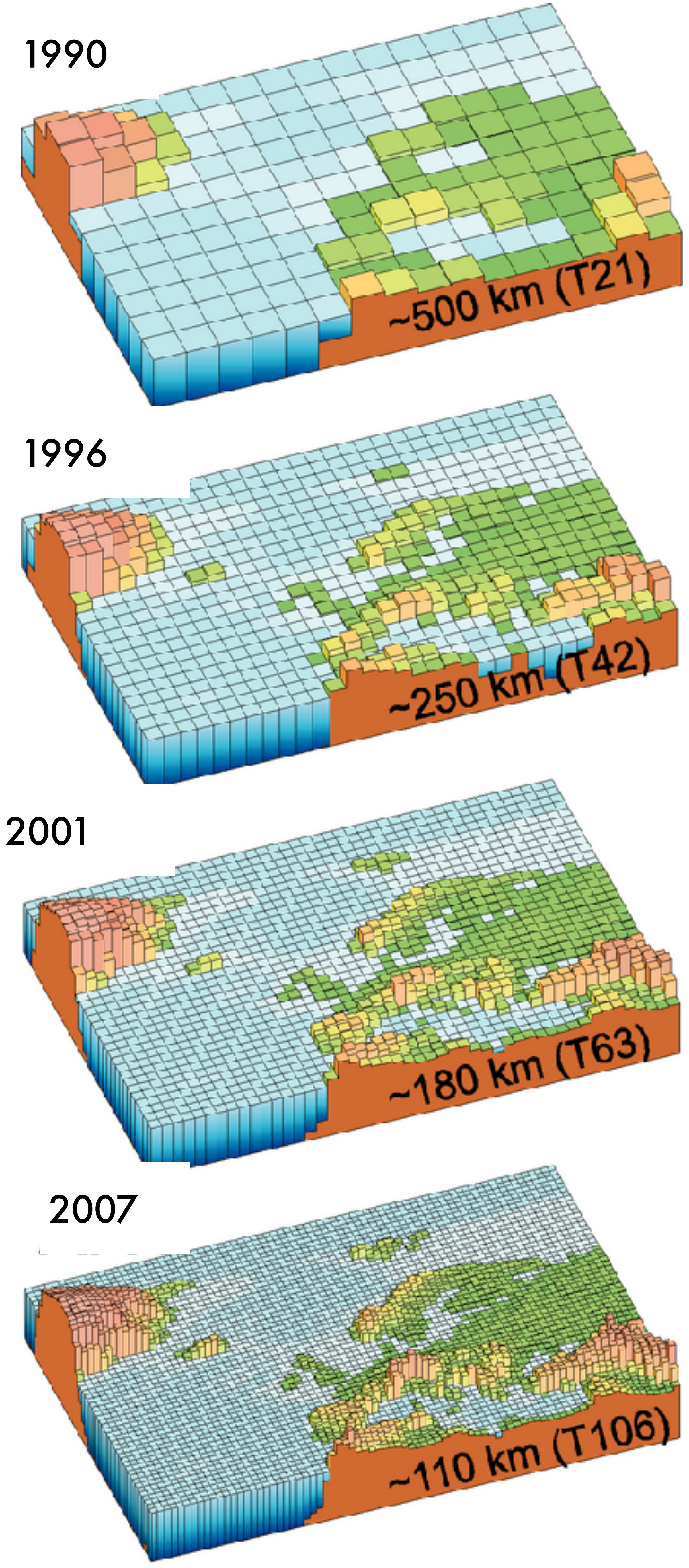


2.5 km resolution



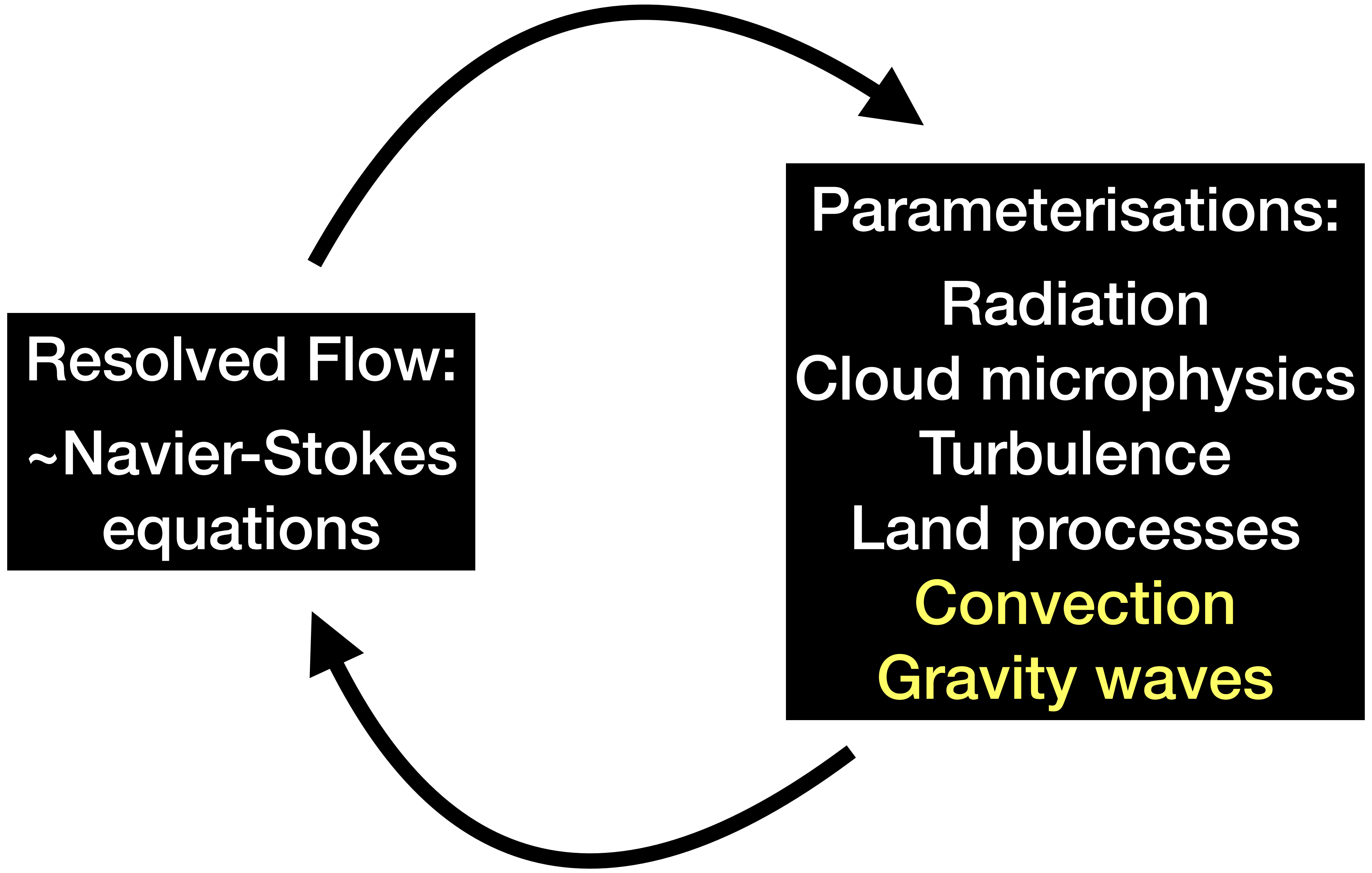
100 km resolution

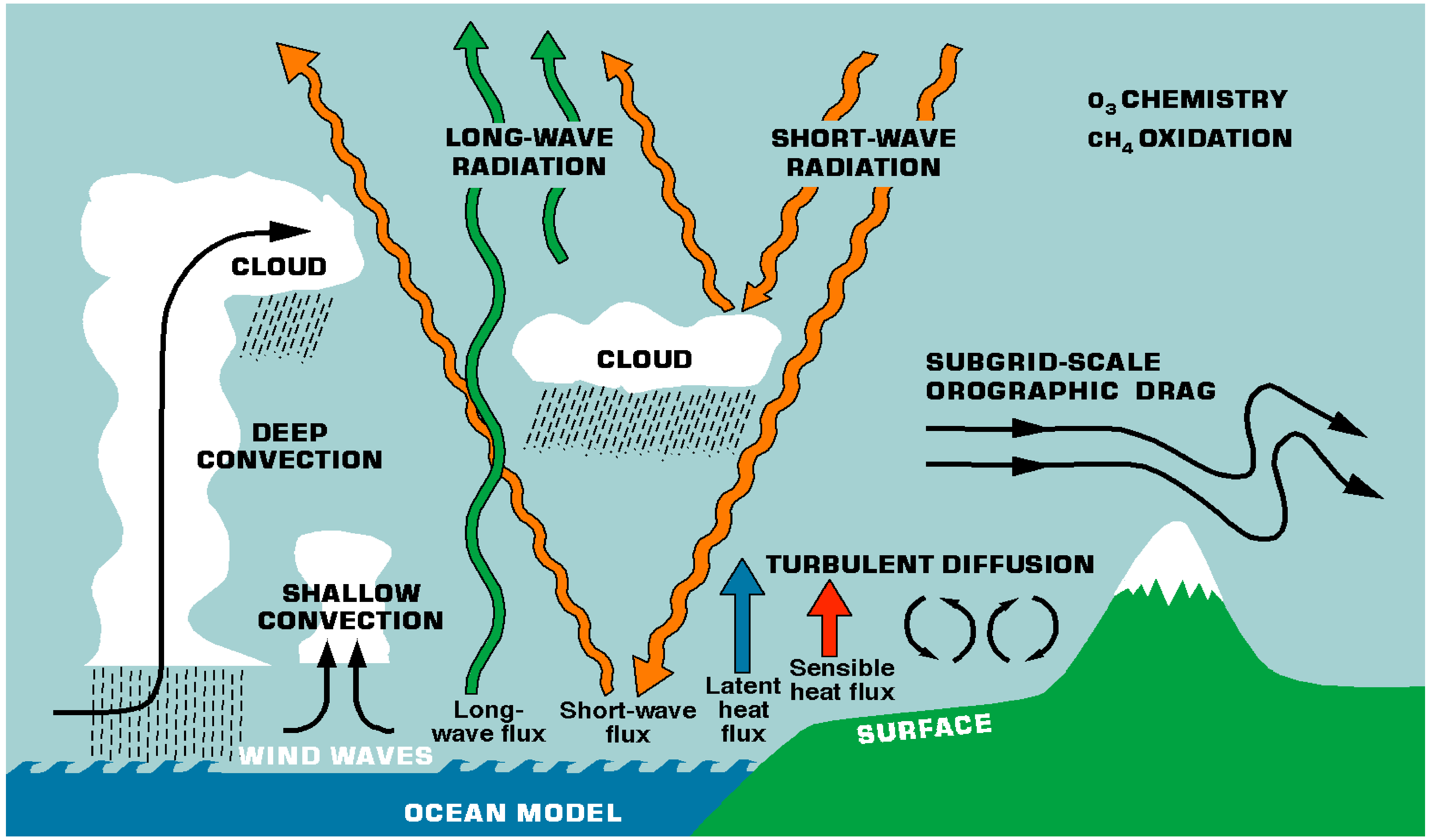
- Computational power limits the number of grid points and therefore grid spacing
- Doubling resolution increases cost 8 times
- Unresolved processes must be parameterised



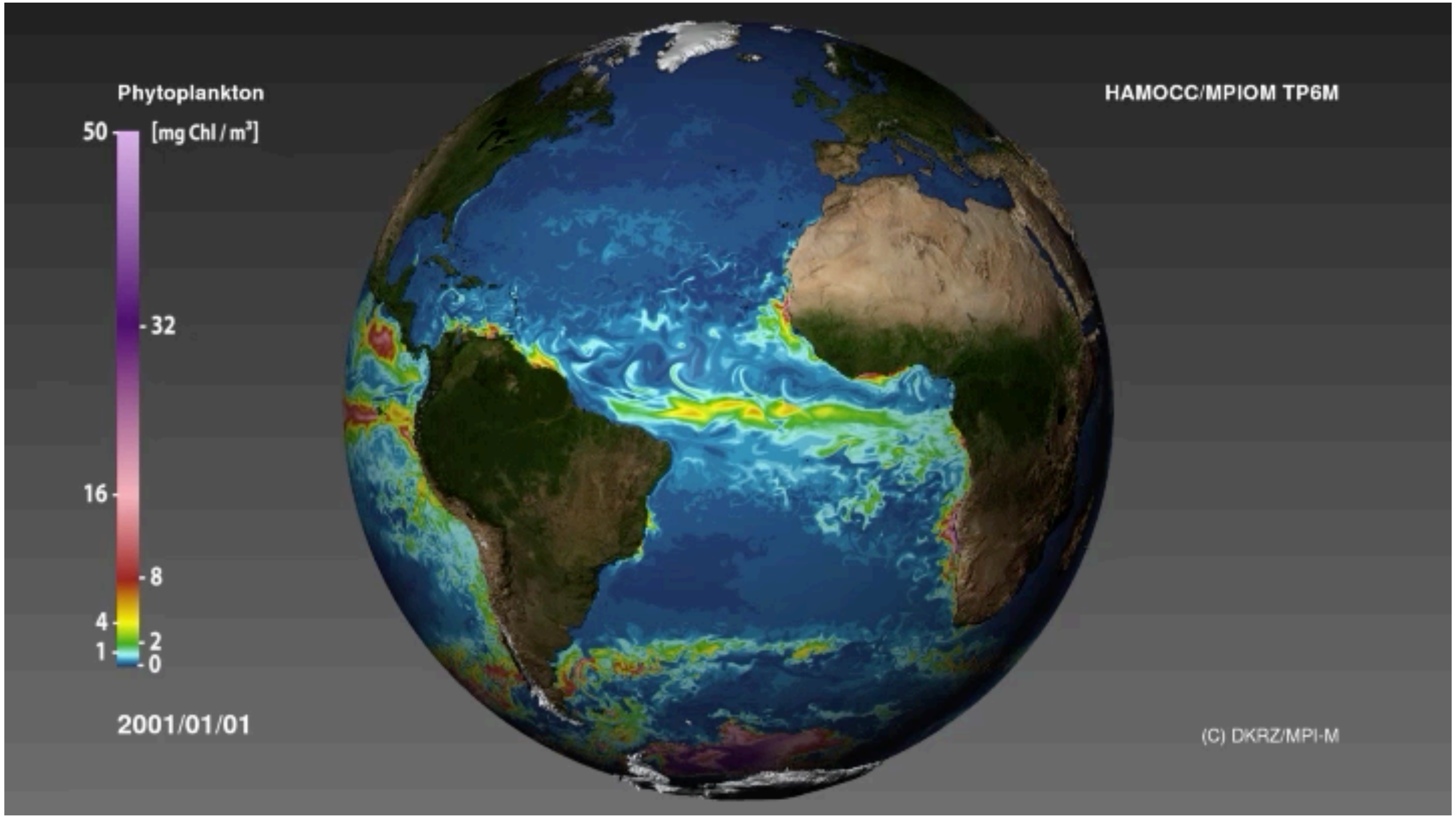
Illustration

It is not all fundamental!





The ocean is simulated in more or less the same way



From a 10 km resolution simulation

Model setups

Complexity

Atmosphere-only:

- Simulates the atmosphere and land processes
- Sea surface temperatures and sea ice are prescribed

[**Mixed-layer model**]

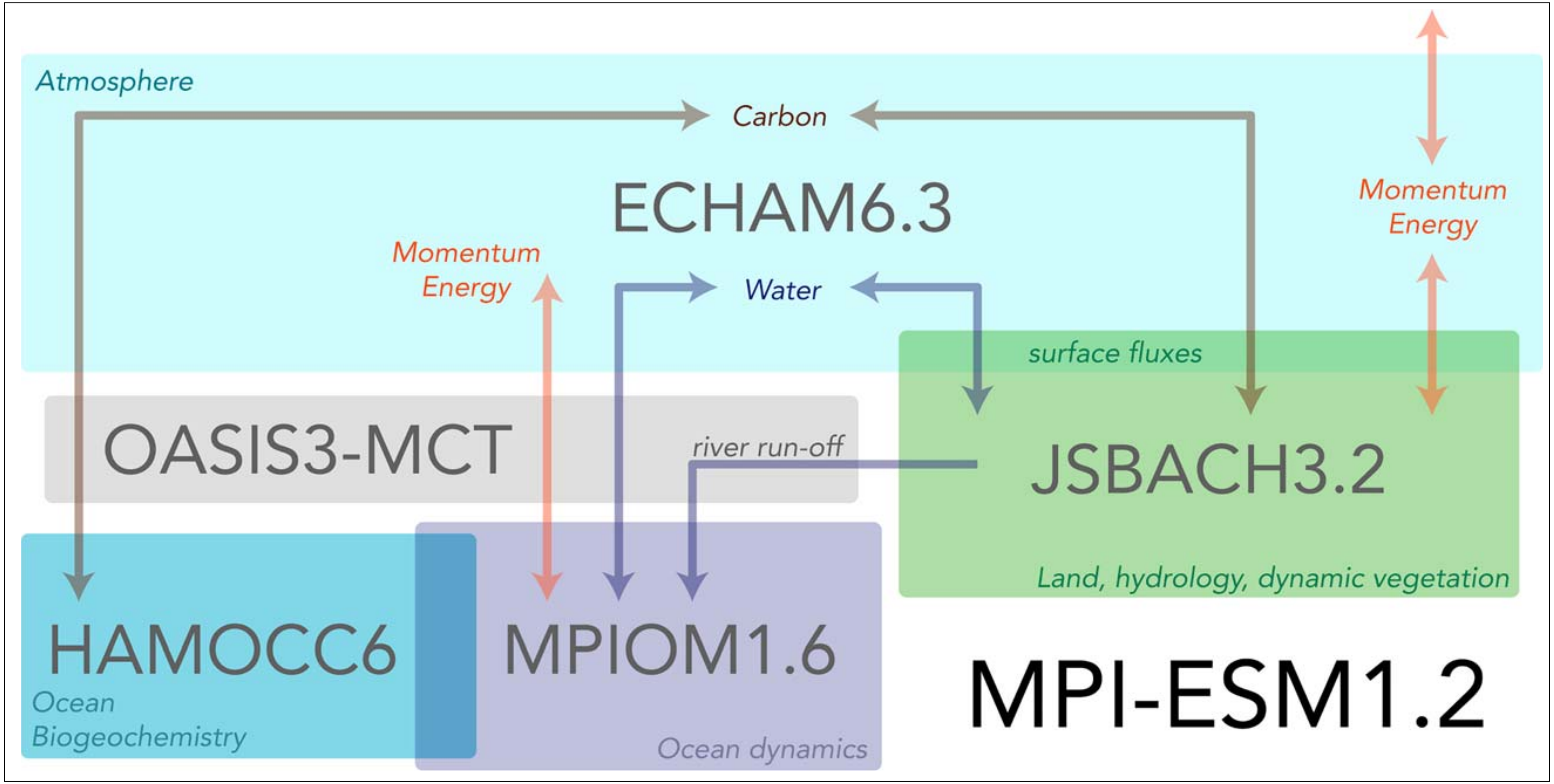
Coupled model:

- Ocean currents, temperatures, salinity etc. is simulated
- Connected to the atmosphere through a coupler software

Earth system model (ESM):

- Poorly defined category
- Usually simulates at least a carbon cycle
- Can therefore be driven by CO2 emissions rather than concentrations

Model setups



What is model intercomparison project, aka *MIP?

Essentially a *MIP consists of:

- Ideally, a good **idea**!
- Modellers **wanting** to participate with their models
- An experimental **protocol** and a **description** of the desired output
- A **facility** to share the output

Today, these elements have become a lot easier and faster to achieve, so you will see more and more autonomous MIPs arise

What is CMIP/AMIP

The first climate models were created in the 1960's and with time more and more interest in them emerged.

Two official MIPs took off in the 1990's:

- The Atmosphere Model Intercomparison Project (AMIP, Gates et al. 1999)
- The Coupled Model Intercomparison Project (CMIP, Meehl et al. 2000)

Came about as a bottom-up process, as modellers saw a need for and a scientific value in being able to compare their models with others.

In part they were inspired by successful model inter-comparisons led by Robert Cess looking at climate sensitivity and feedbacks in models (Cess et al. 1989, 1990, 1991).

What is CMIP/AMIP

Still today, CMIP is an independent activity that is not controlled by e.g. the United Nations Intergovernmental Panel on Climate Change (IPCC), unlike what many people think

Please don't call them "the IPCC models"

CMIP cycles

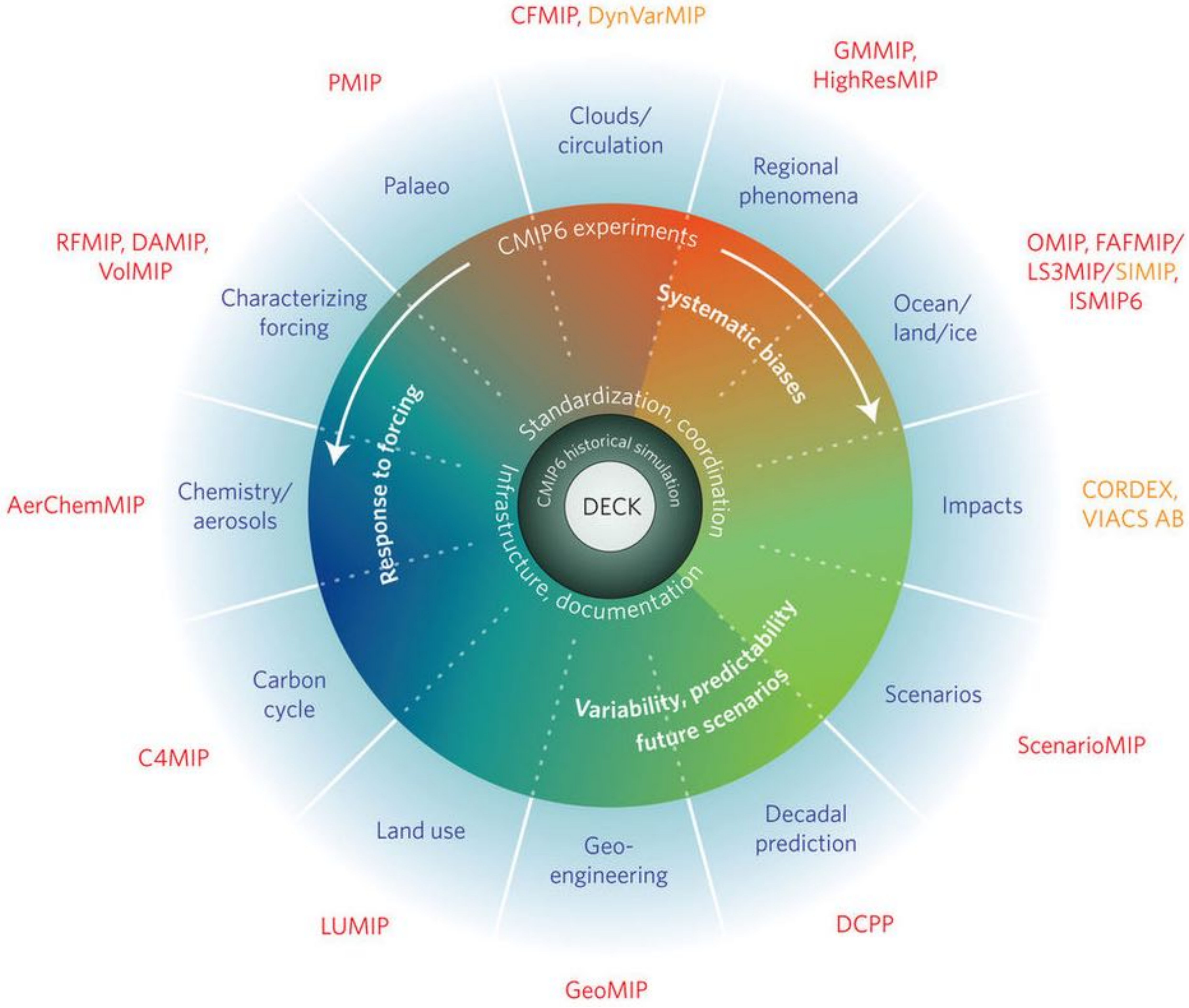
CMIP1: control simulations, flux corrections

CMIP2: gradually increasing CO2 at 1 percent per year to probe transient climate response (TCR)

CMIP3: historical and future scenarios, also included AMIP for evaluation, mixed-layer ocean models for climate sensitivity, and first open access to the public!

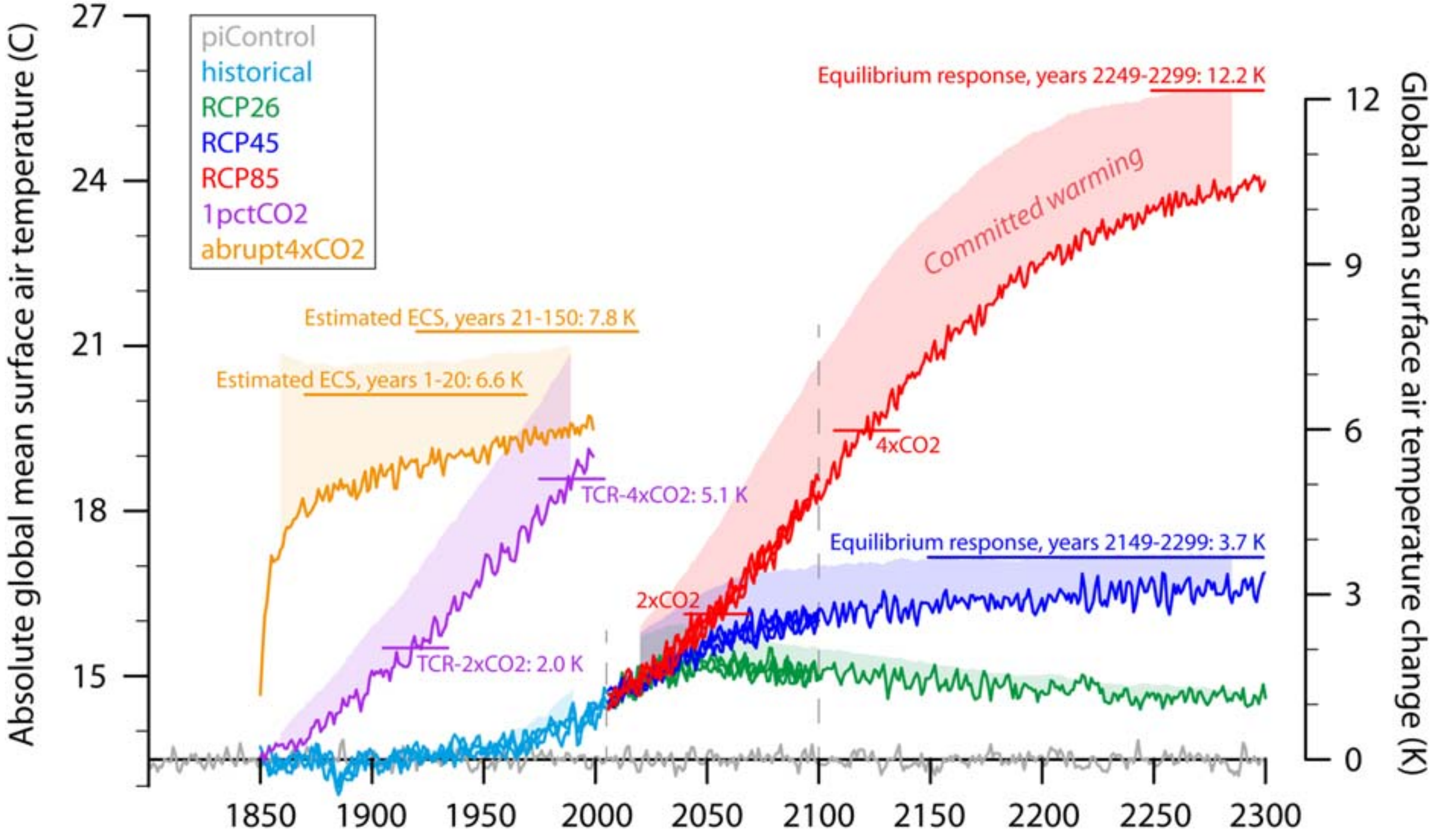
CMIP5: adds abrupt 4xCO2 and other idealised experiments, and also decadal predictions and carbon cycle models (ESMs)

CMIP6: more of everything, and a more distributed approach with endorsed sub-MIPs focused on specific questions



Experiments

- Pre-industrial control
- Historical simulation
- Future scenarios
- Idealised forcing experiments



Control simulation

CMIP1 models only conducted a control simulation:

- a long run with constant boundary conditions such as CO2 and other greenhouse gases

Ideally, a control simulation will be stable in time, but this was difficult to achieve

Some CMIP1 models also relied on flux-corrections, which is a method to stabilise climate and minimise biases, but this is no longer used

Model	Flux correction	Run length (yr)	Comments
*BMRC	none	105	no std dev or ocean data
*CCCMA	heat, water	150	
*CCSR	heat, water	40	
*CERFACS	none	40	
COLA	none	50	
*CSIRO	heat, water, momentum	100	
*DOE PCM	none	300	
ECHAM1+LSG	heat, water, momentum	960	temperature time series data only
*ECHAM3+LSG	heat, water, momentum	1000	no flux-correction fields
ECHAM4+OPYC3	heat, water (ann. mean)	240	
*GFDL	heat, water	1000	
GISS (Miller)	none	89	
*GISS (Russell)	none	98	no decadal std dev or barotropic stream function
*IAP/LASG	*sea surface salinity restored to obs*	50	
*LMD/IPSL	none	24	no decadal std dev
*MRI	heat, water	100	no ocean heat transports
*NCAR (CSM)	none	300	
*NCAR (Wash. & Meehl)	none	100	
*NRL	*sea ice prescribed to obs*	36	
*UKMO (HadCM2)	heat, water	1085	
*UKMO (HadCM3)	none	80	in CMIP2 only

Biases and drifts

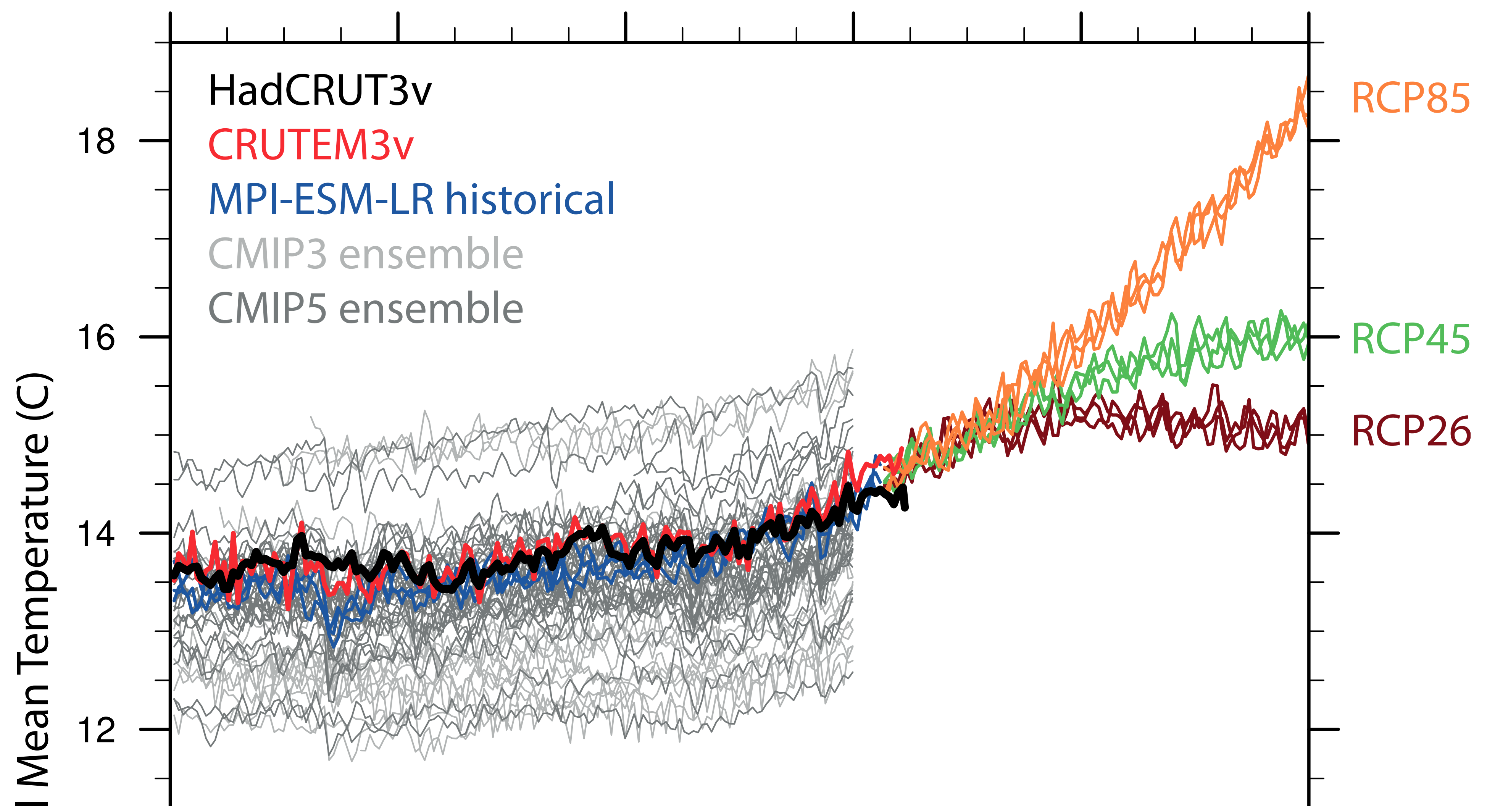
Something **you will have to deal with** is that models have both biases and drifts

Bias: a constant off set, e.g. the temperature is too high or too low all the time

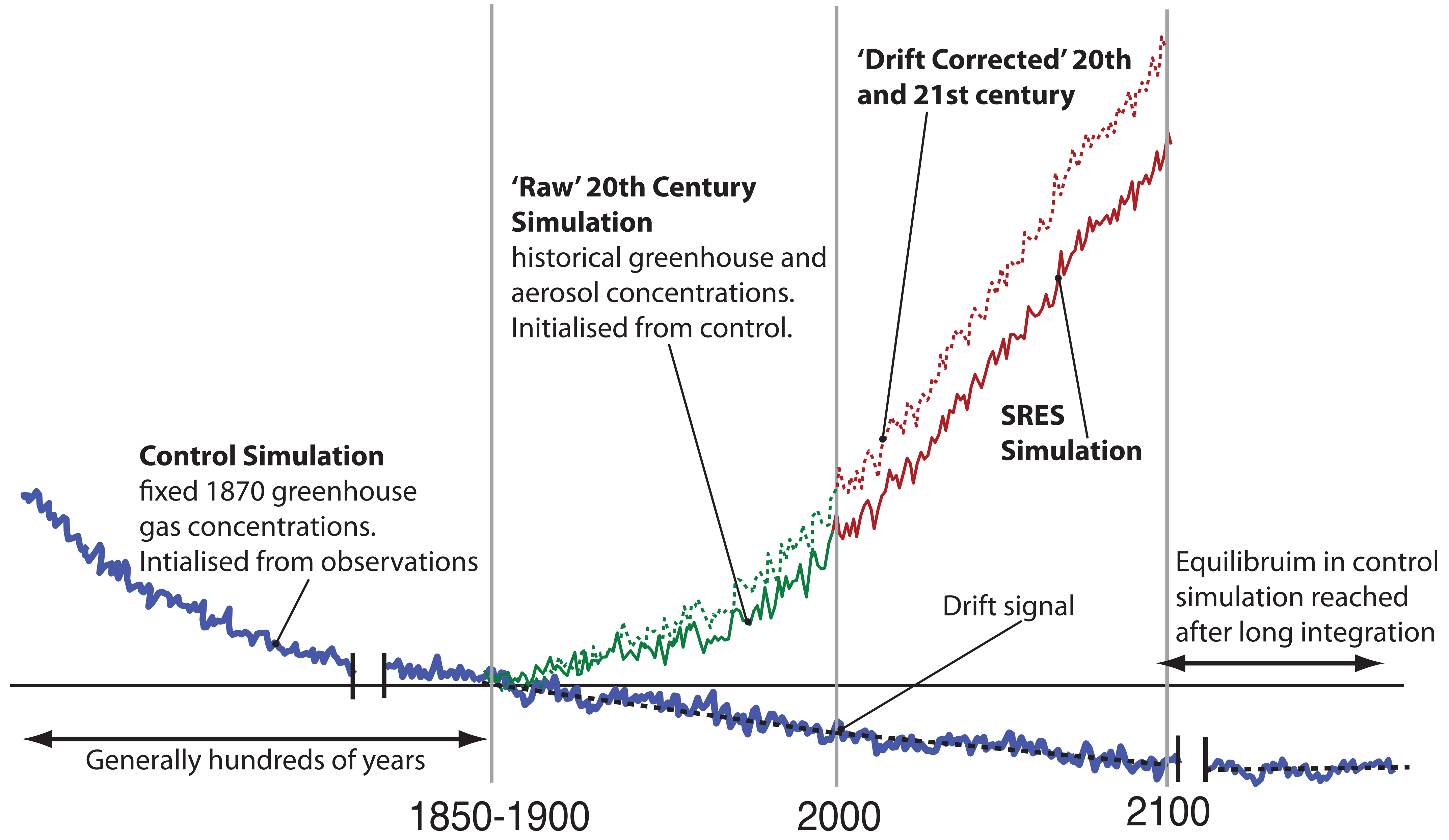
Drift: the system is somehow out of balance, such that the climate changes even if the boundary conditions don't change

Modelling centers will try to reduce both these issues, but are successful to different extents

Make sure to check the influence on your results!



Mauritsen et al. (2012)



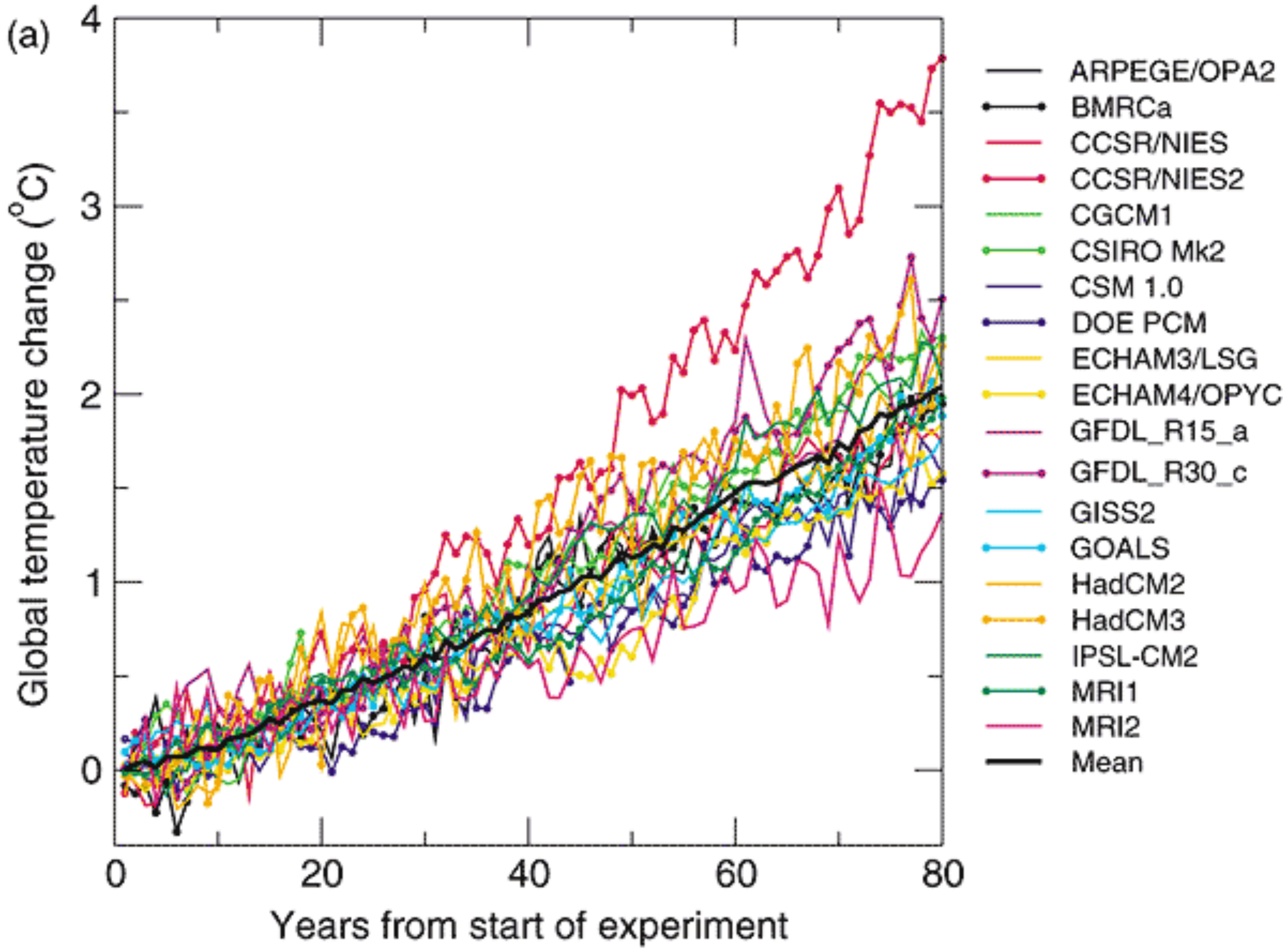
Sen Gupta et al. (2012)

CMIP2: Transient climate response (TCR)

The simplest kind of scenario is one where the CO2 concentration increases gradually

Here at 1 percent per year, such that after 70 years the concentration is doubled

The transient climate response (TCR) is then usually taken as the mean of years 60-80



IPCC (2001)

CMIP3/5/6 equilibrium climate sensitivity (ECS)

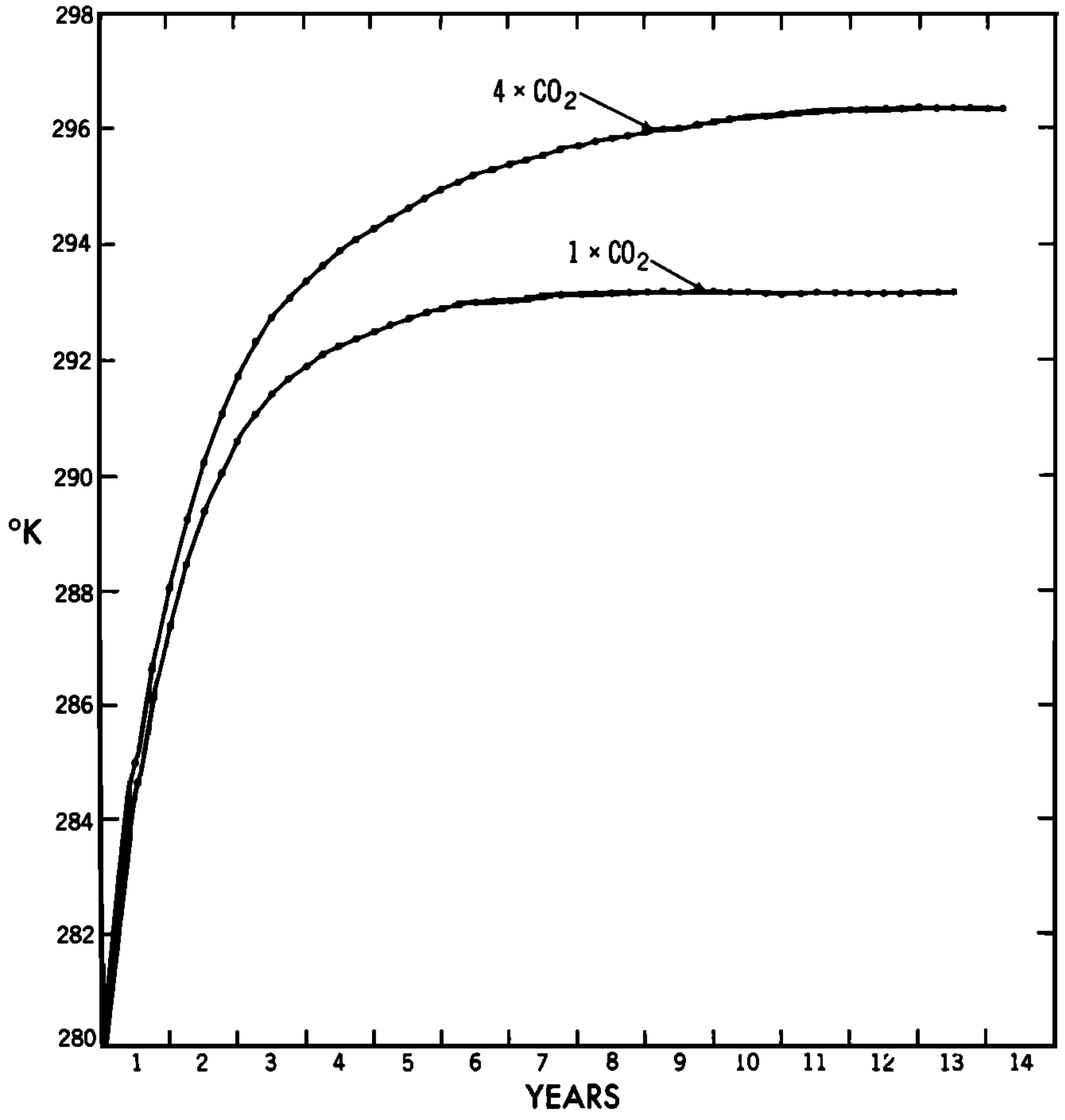
TCR: the transient warming to gradual increase of CO2 to doubled concentration

ECS: the long term global warming response to a doubling of CO2 over pre-industrial levels

TCR < ECS

In CMIP3 and earlier, ECS of a model was estimated with a mixed-layer ocean model that is about 50 m deep

Such a model can be run to equilibrium in a few decades



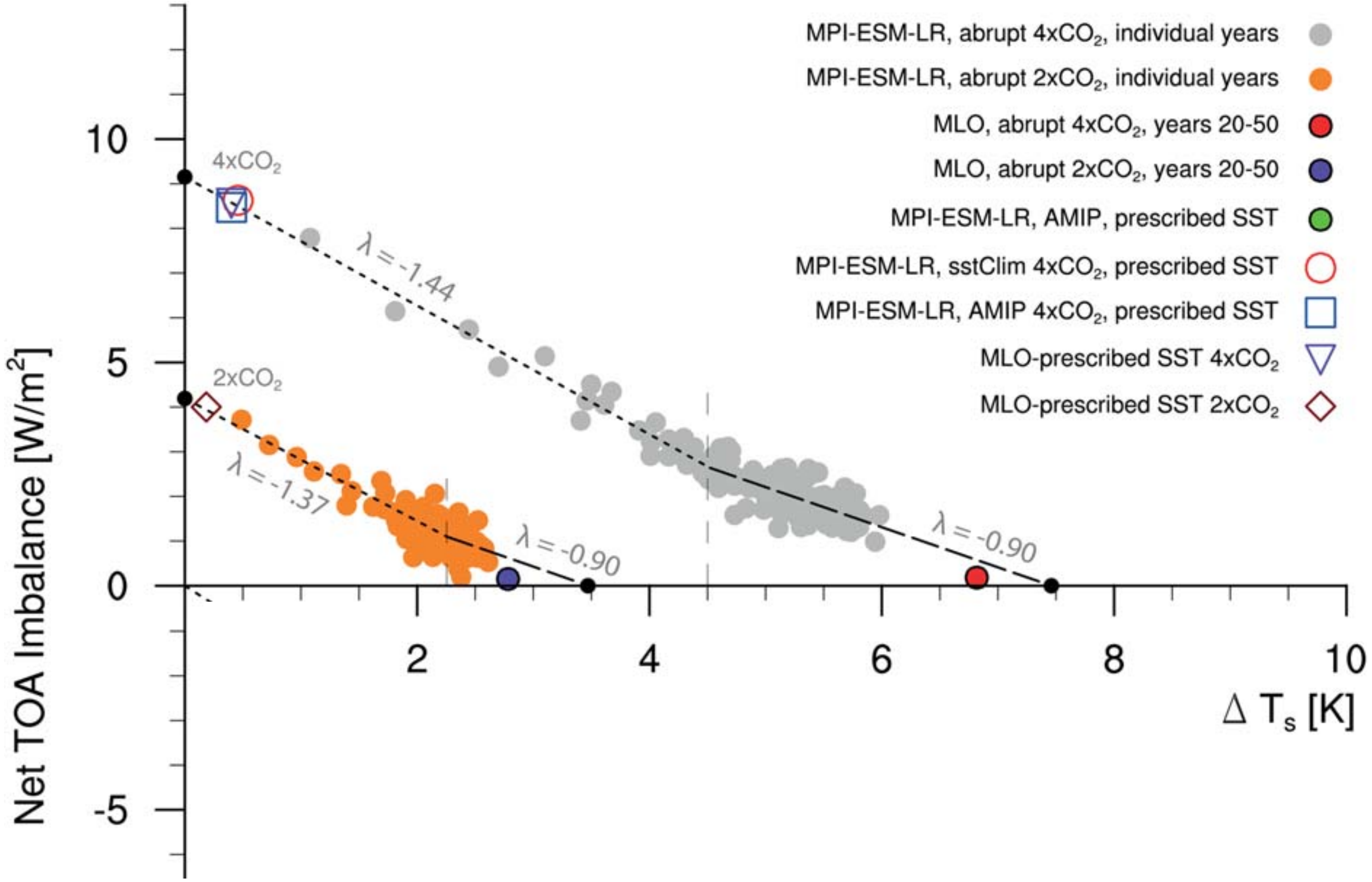
Manabe and Stouffer 1980

CMIP3/5/6 equilibrium climate sensitivity (ECS)

In CMIP5, and later, instead coupled models were being used

These will take about 4-6000 years to equilibrate due to the deep oceans heat capacity

Instead an abrupt increase in CO2 is applied and extrapolation is used according to the Gregory method (Gregory et al. 2004)



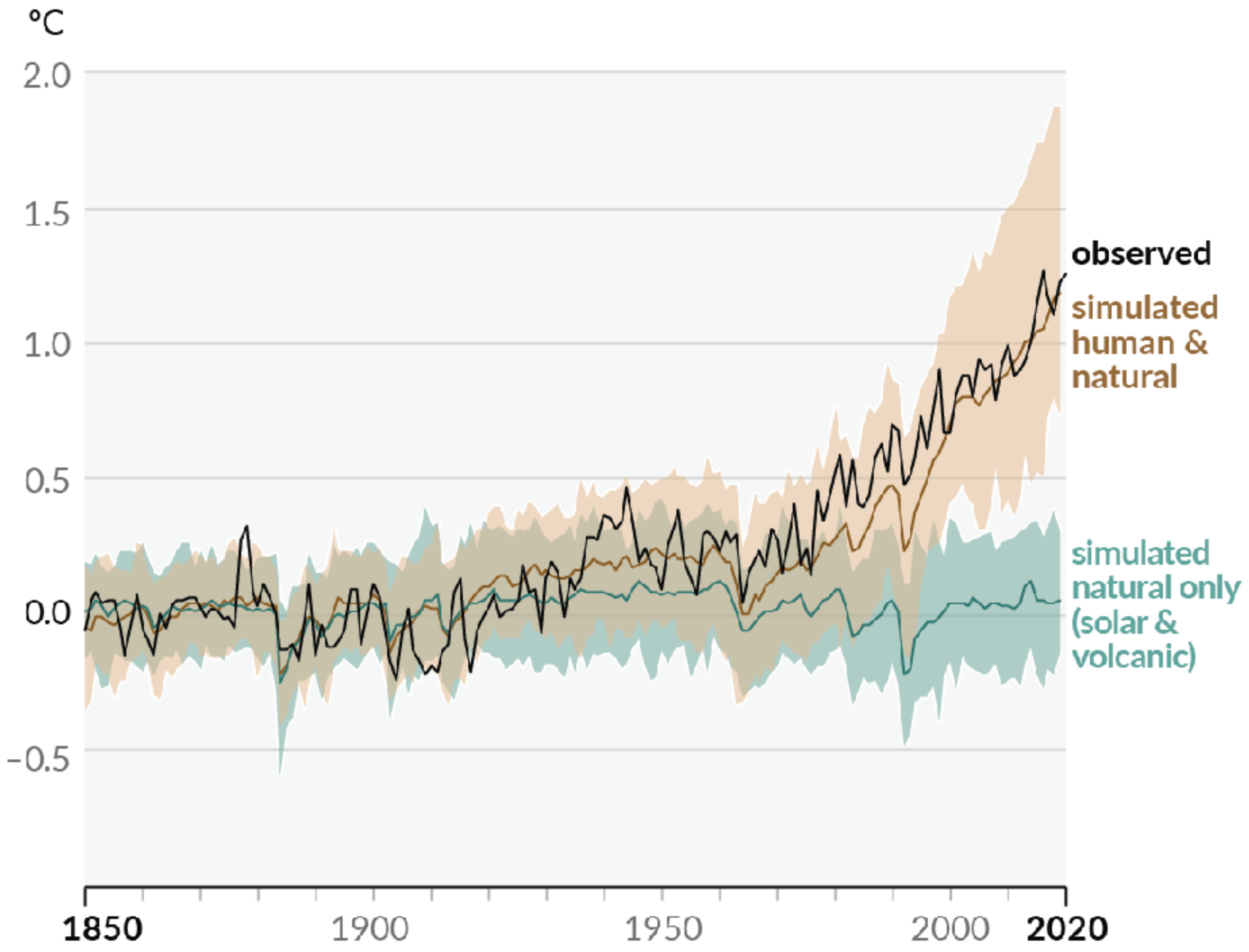
Block and Mauritsen (2013)

Historical and future scenarios

Historical simulations include as accurate as possible changes in:

- Greenhouse gases
- Ozone
- Aerosols
- Volcanoes
- Land use changes
- Solar forcing

They can be used for a range of things, for example illustrate how unlikely global warming would be without greenhouse gases



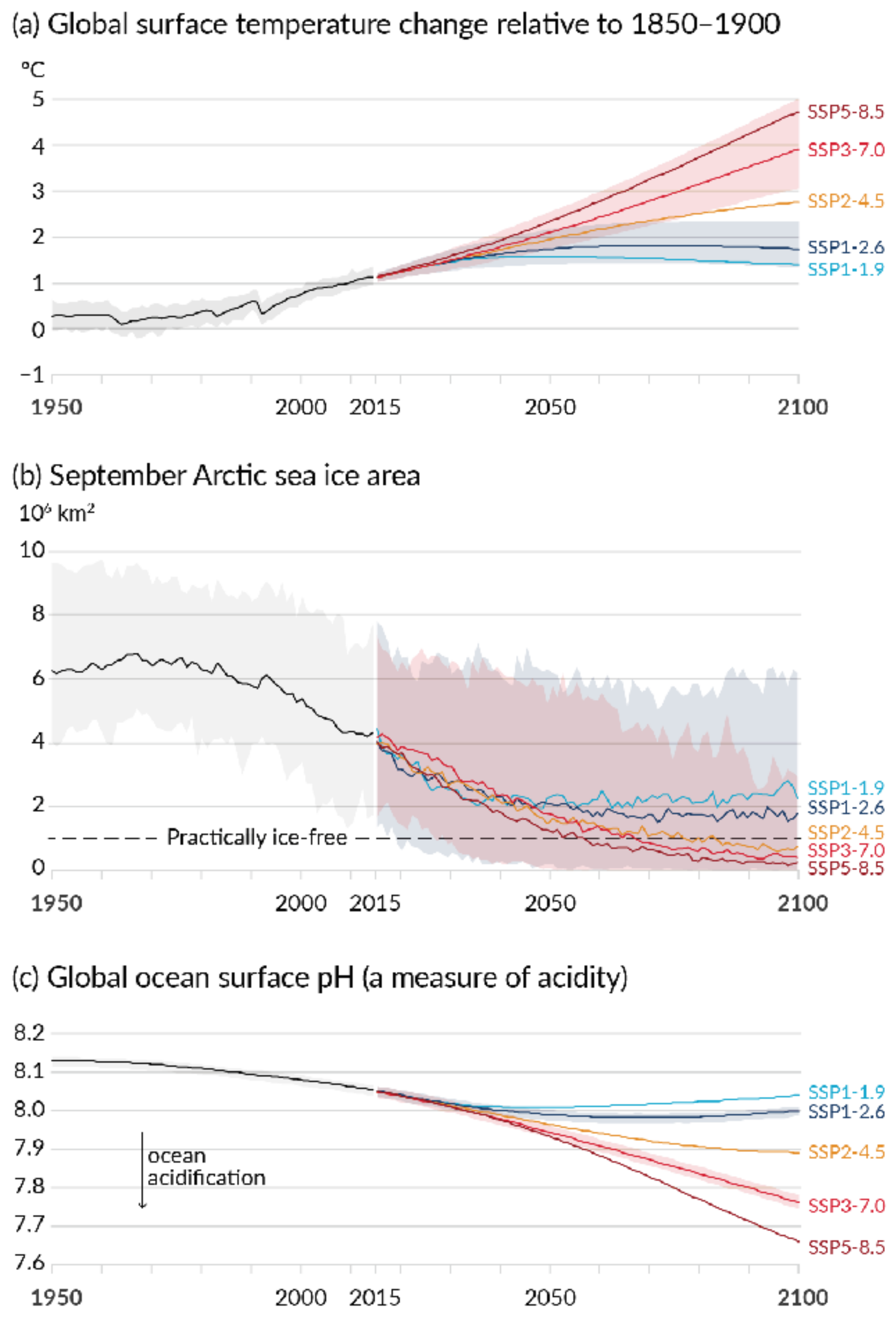
IPCC (2021)

Historical and future scenarios

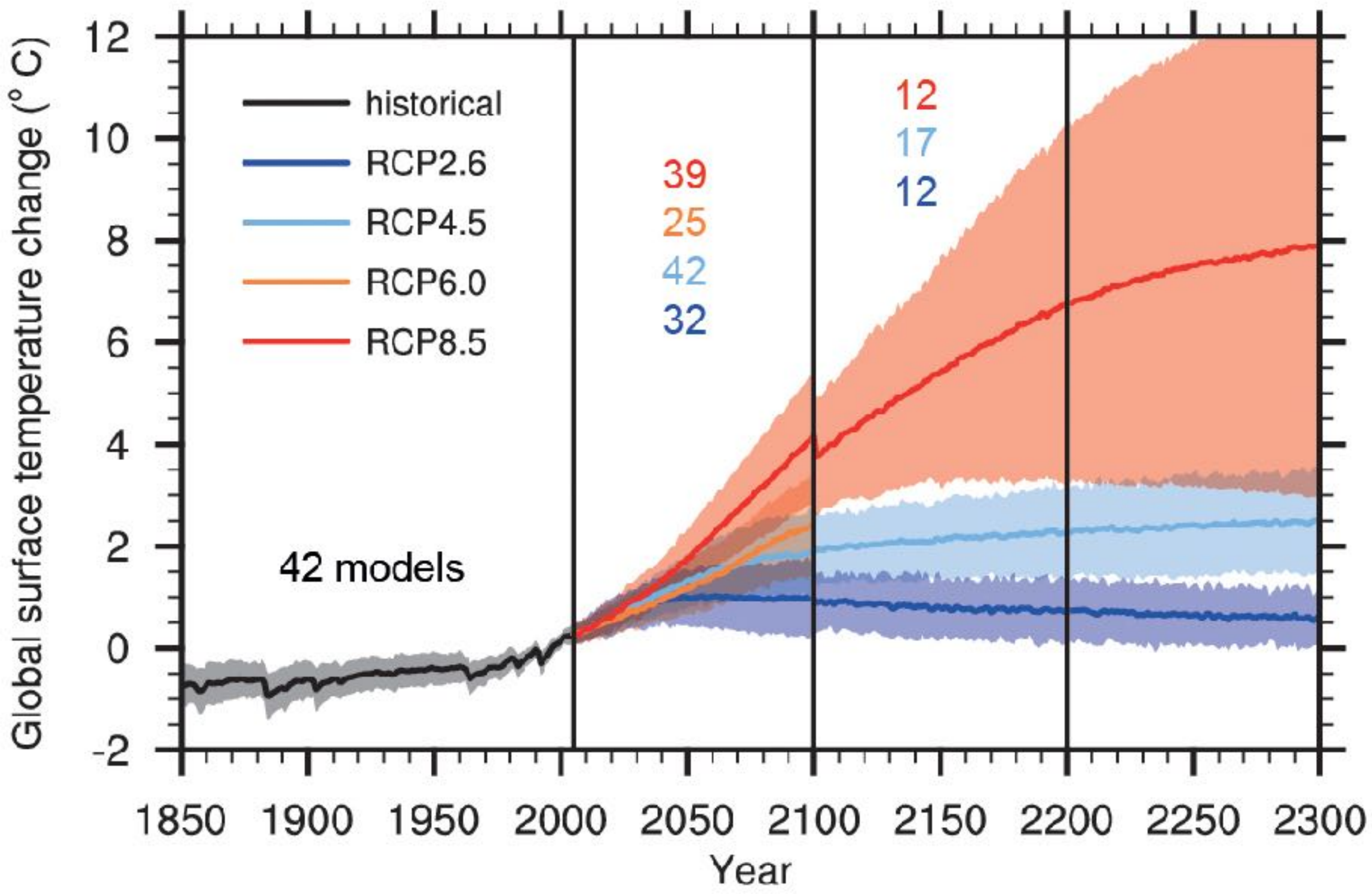
The historical simulations are continued forward to present and future using scenarios:

- SSP1-2.6, high mitigation 2-degree scenario
- SSP2-4.5, mid-range scenario
- SSP5-8.5, burn all that makes economic sense, sort of

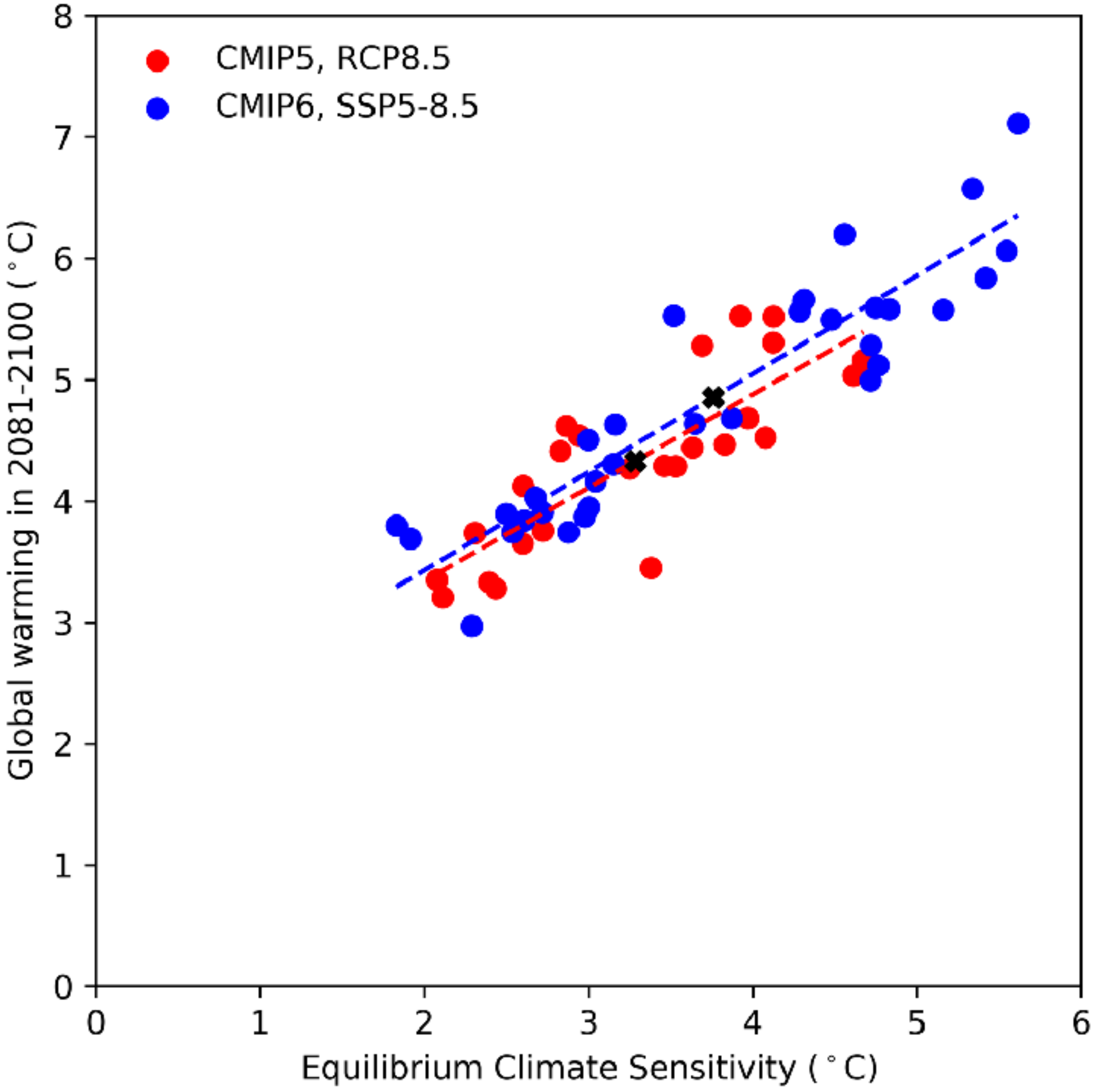
These make different economic and political assumptions to come up with emissions and concentrations in the future



IPCC (2021)



IPCC (2013)



Unpublished

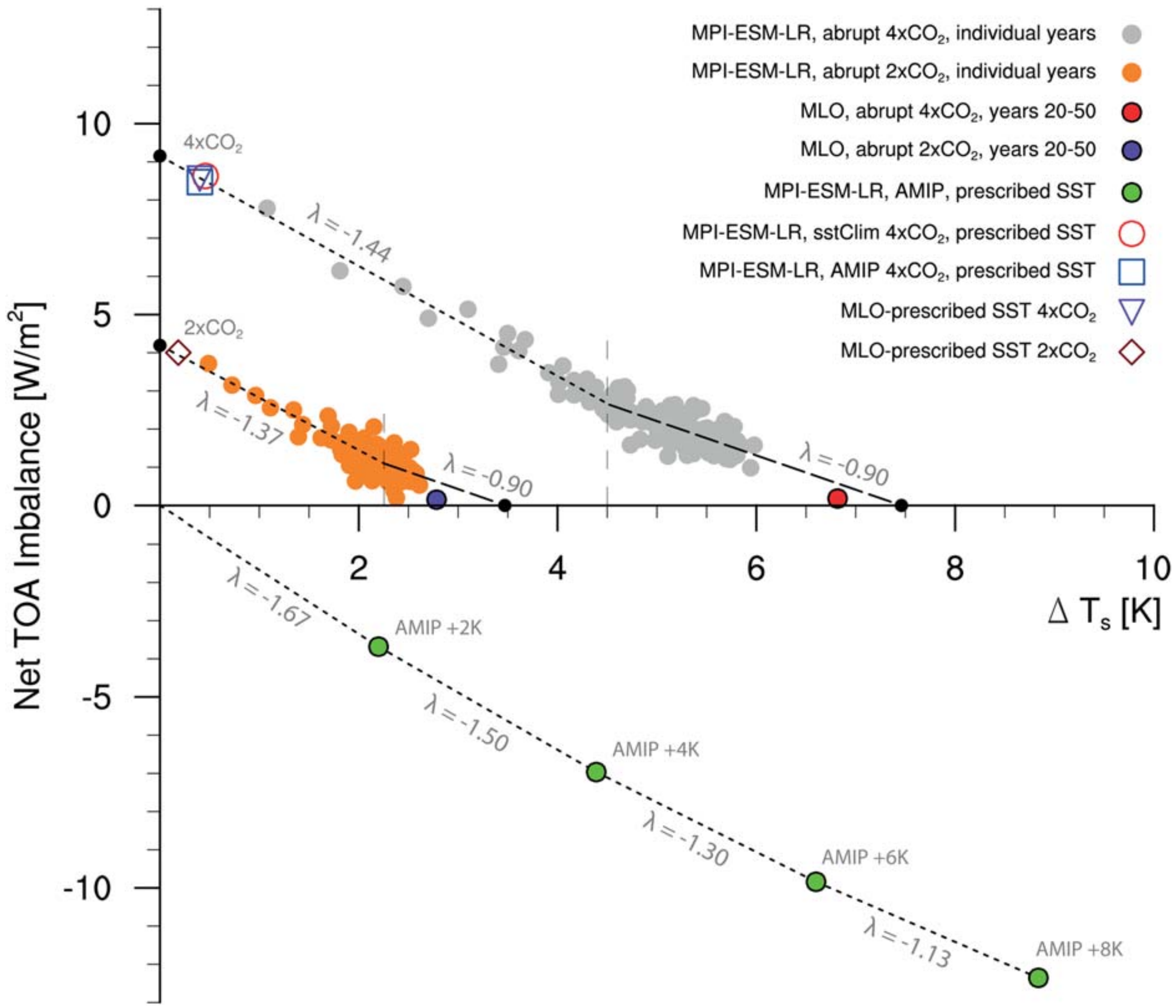
The AMIP and AMIP+4K experiments, honourable mention

The first climate change/impact experiments were orchestrated by Robert Cess in the 1980's

Here an atmosphere-only setup was used and sea surface temperatures, sea ice, etc. is prescribed

Then, to probe the effects of global warming, and also climate feedbacks, the ocean surface is simply warmed up uniformly, typically +4K

The advantage is that these runs don't need to be very long, and so can also be run at very high resolutions



Block and Mauritsen (2013)

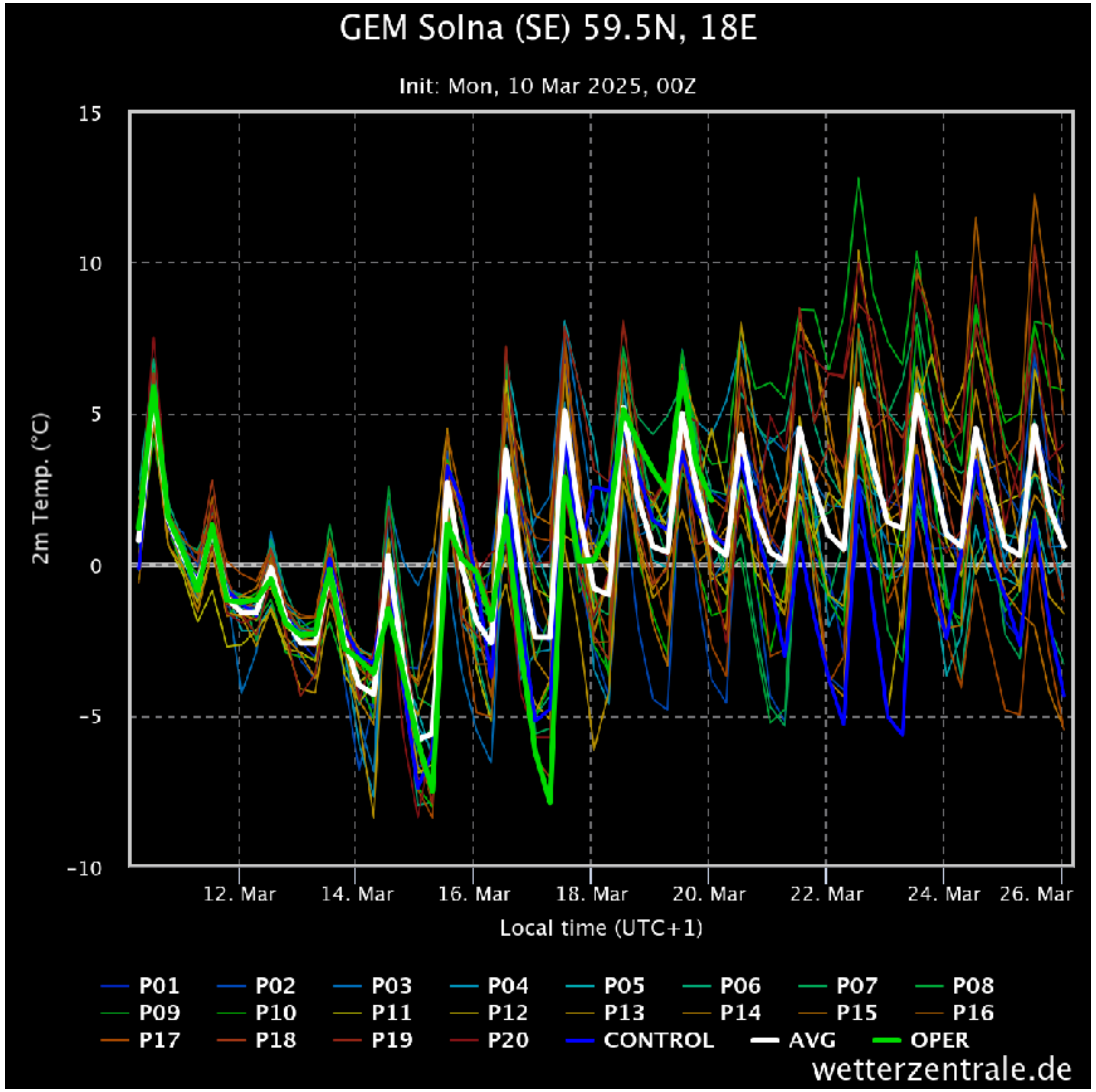
Ensembles, large ensembles and the grand ensemble

Weather can be predicted up to a point in the future, depending on what you are interested in

Caused by inherent chaos, a small error in initial state grows exponentially

In weather forecasts ensemble weather forecasting systems exploit this to explore forecast uncertainty

Ensemble forecasts consists of many runs with the same model, but starting from slightly different initial conditions



Ensembles, large ensembles and the grand ensemble

- It has become increasingly popular to produce ensembles with climate models
- NCAR first created their LENS1 ensemble with micro perturbations in 1920 (Kay et al. 2015)
- MPI conducted a 100 member ensemble, but instead initialised each from a different year in the control run (Maher et al. 2019)

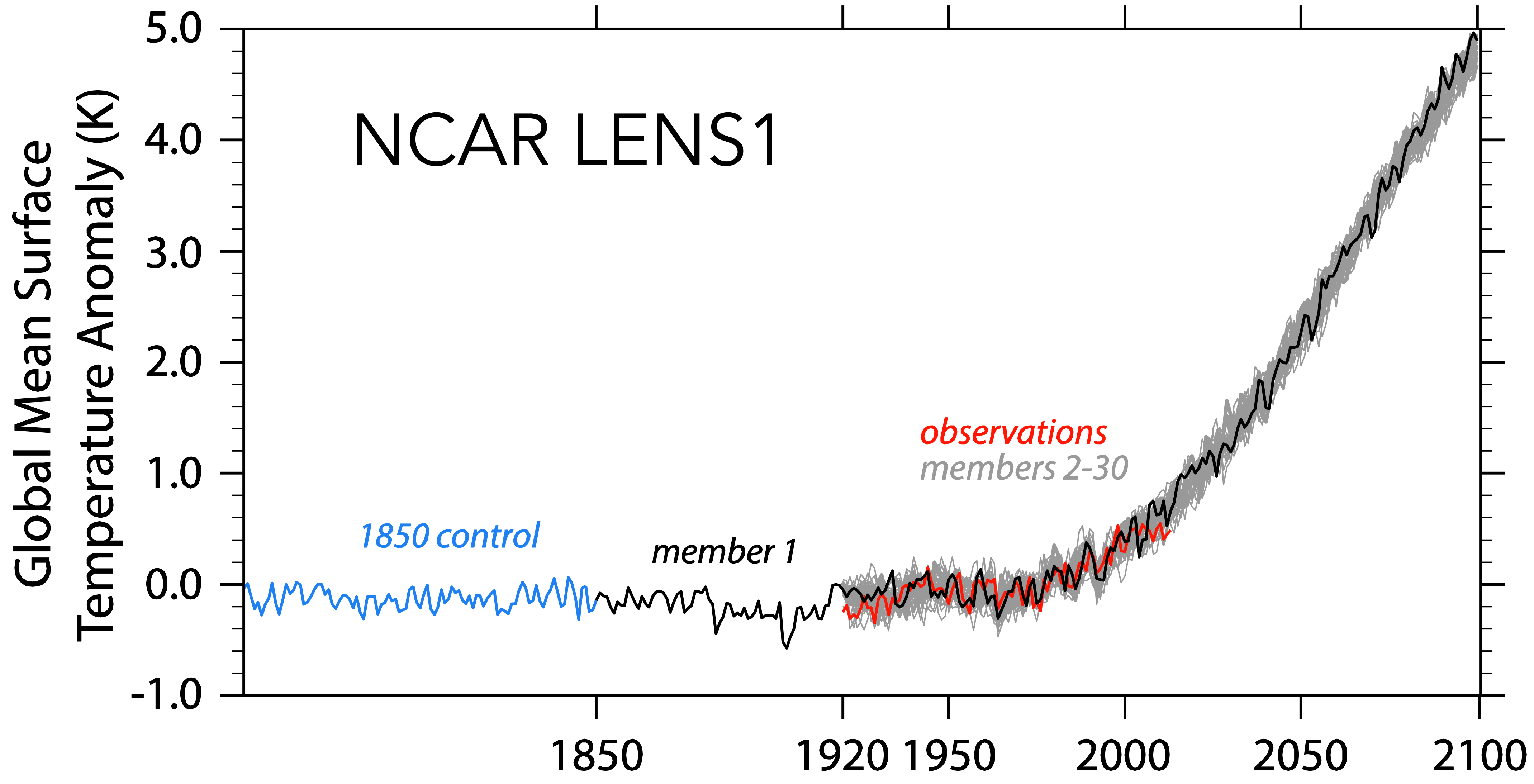


Table 1
Initialization Branching Times From the Preindustrial Control Run

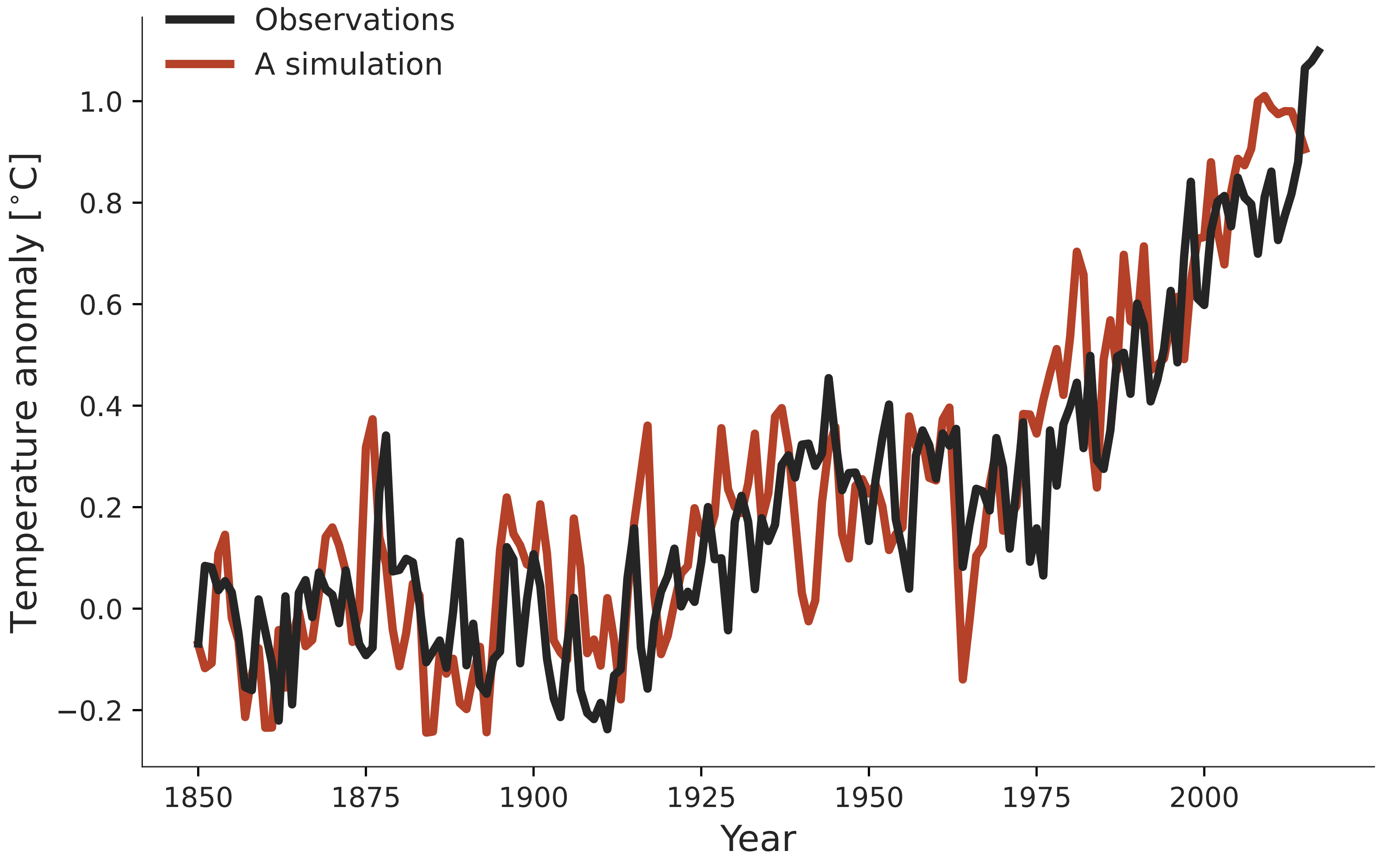
Ensemble member	Branch time	Ensemble member	Branch time
1	1898	51	3164
2	1946	52	3188
3	1994	53	3212
4	2042	54	3236
5	2090	55	3260
6	2138	56	3284
7	2186	57	3308
8	2234	58	3332
9	2282	59	3356
10	2330	60	3380

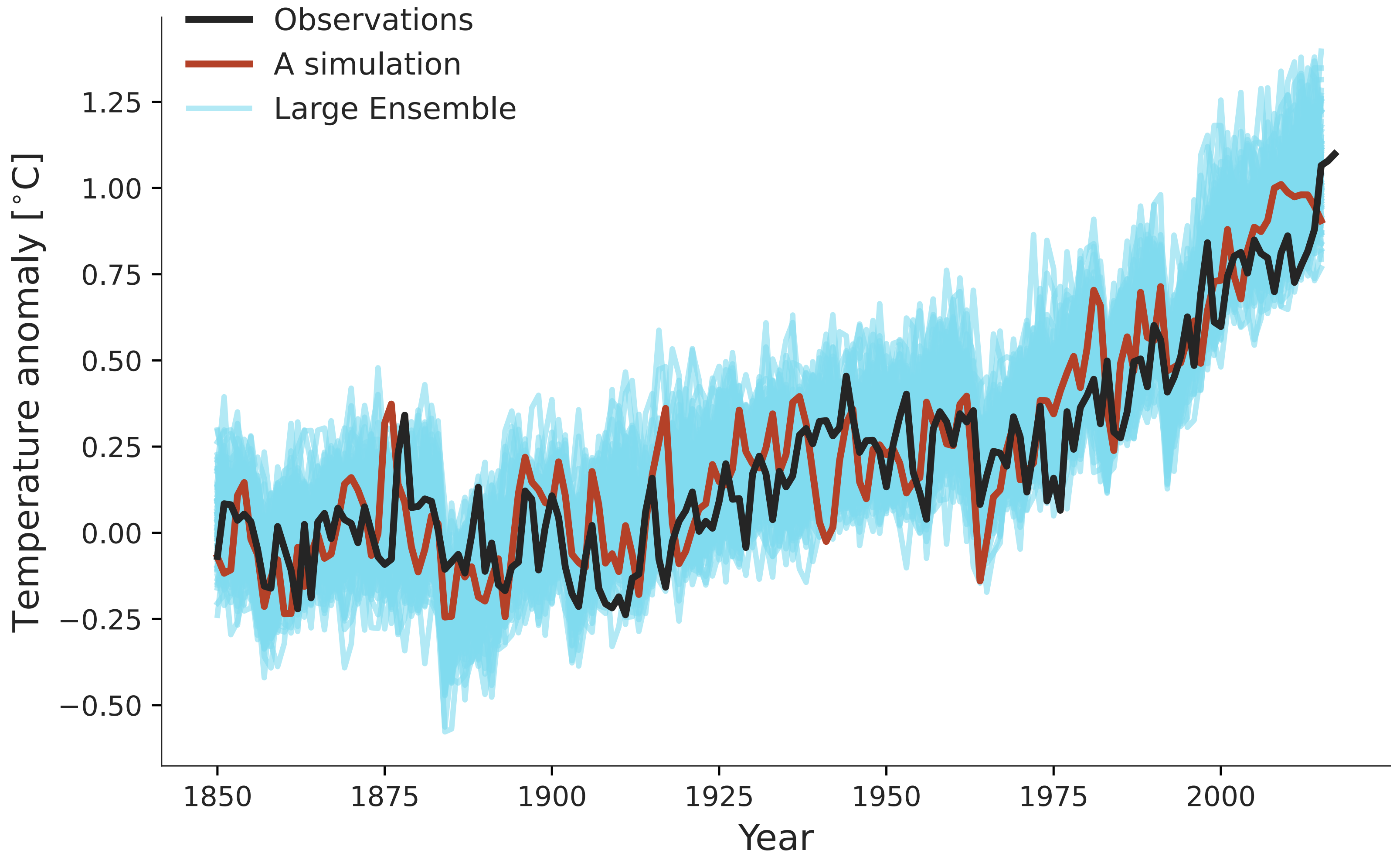
...

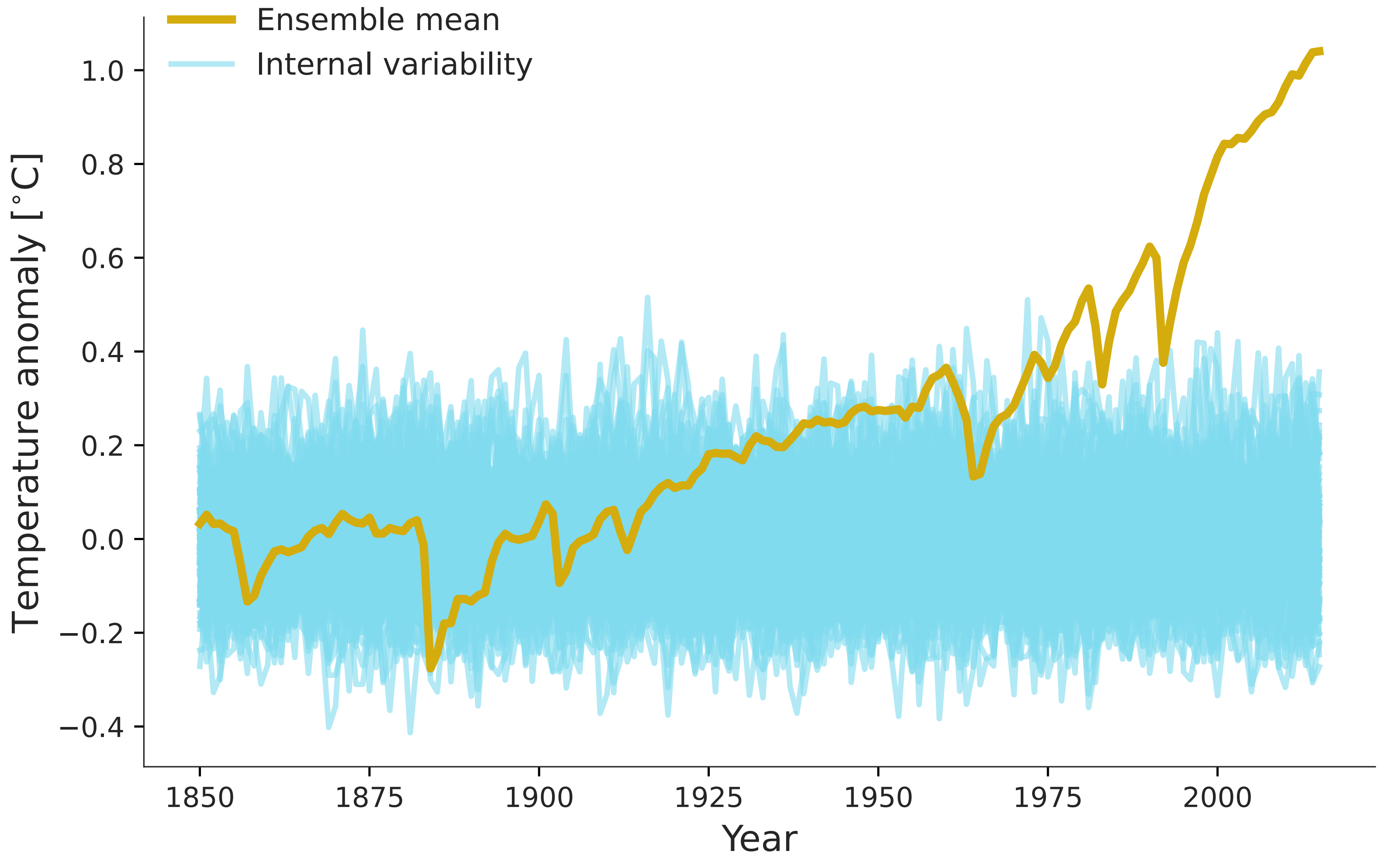
MPI-GE

Ensembles, large ensembles and the grand ensemble

With 100 member ensemble we can
say that observations are mostly
within the models variability:







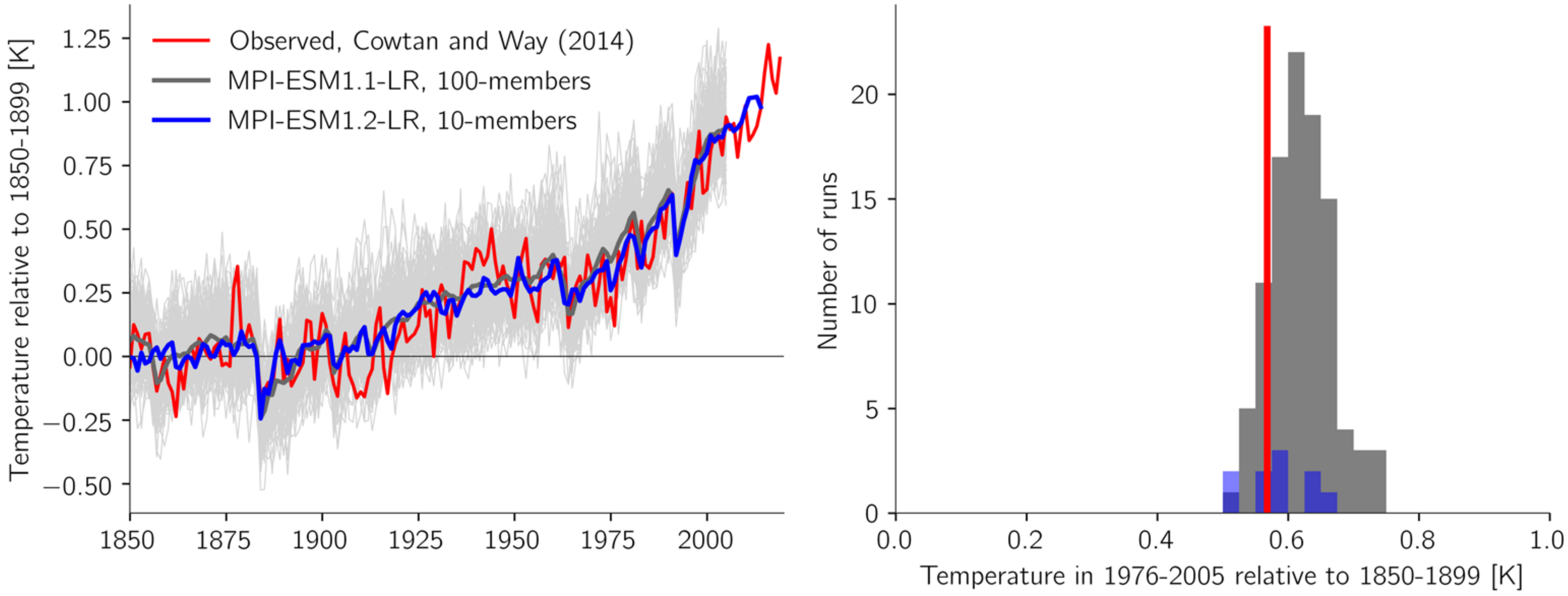
A single realisation, lucky strike?

We can also cleanly separate the
forced response (ensemble mean)
from the internal variability

Ensembles, large ensembles and the grand ensemble

Previously: how close is the model to observations?
And when is it close enough?

Now: is the model ensemble behaviour consistent
with observations, which is just one realisation?



Mauritsen and Roeckner (2020)

Ensembles, large ensembles and the grand ensemble

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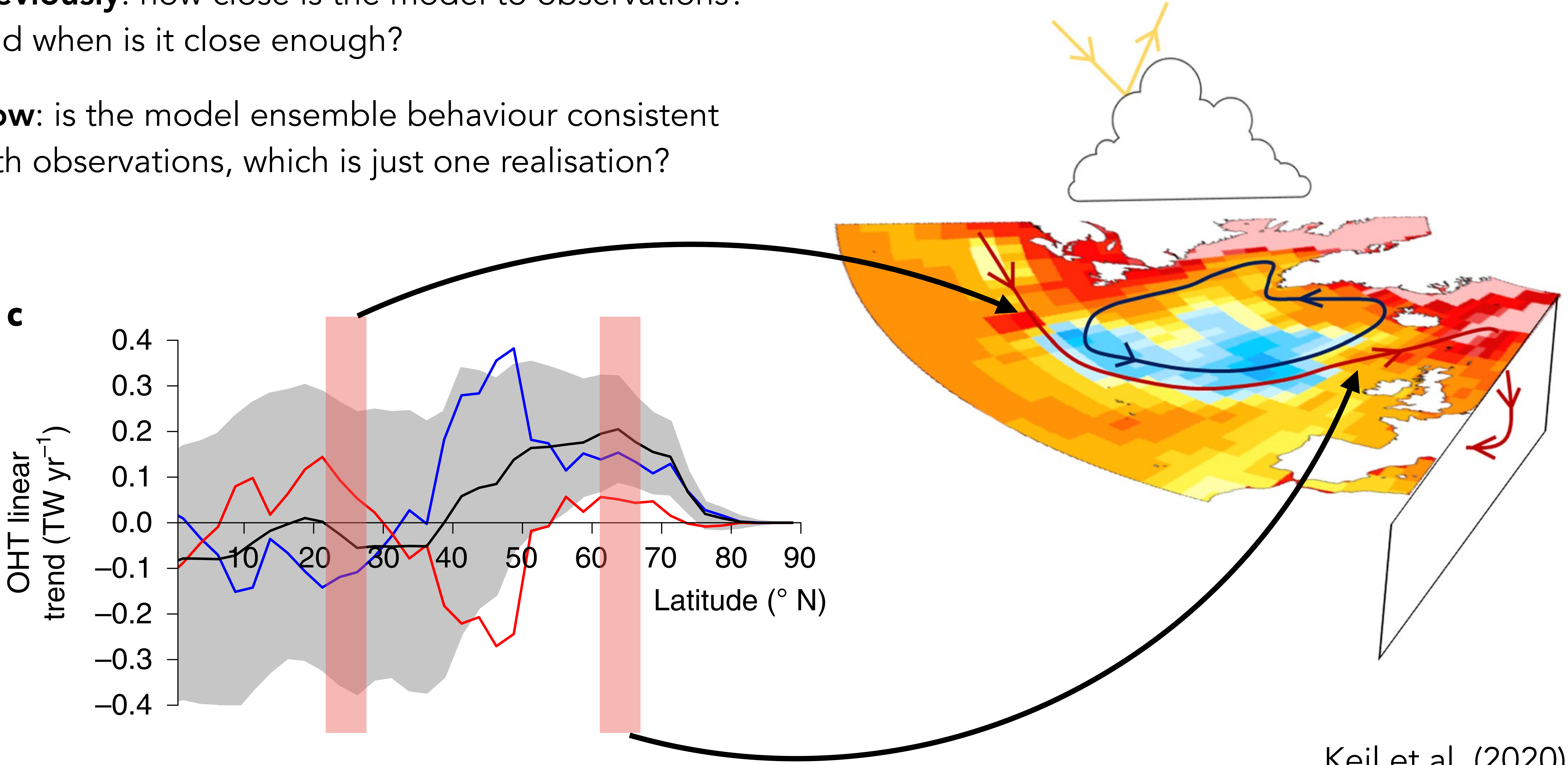

Keil et al. (2020)

The Multiverse (a bit philosophical)

Perhaps think of models as a kind of alternative universe with slightly different physical laws than our universe

Each of these alternative worlds can be realised as many times as we like through experimentation

But the real world is what we are trying to understand, and we only get to see a single experiment with that