



Climate model basics

ASP Modelling Winter School

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Antarctica
New Zealand



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Te Pūtahi Rangahau i te Kōpakatanga ki te Tonga

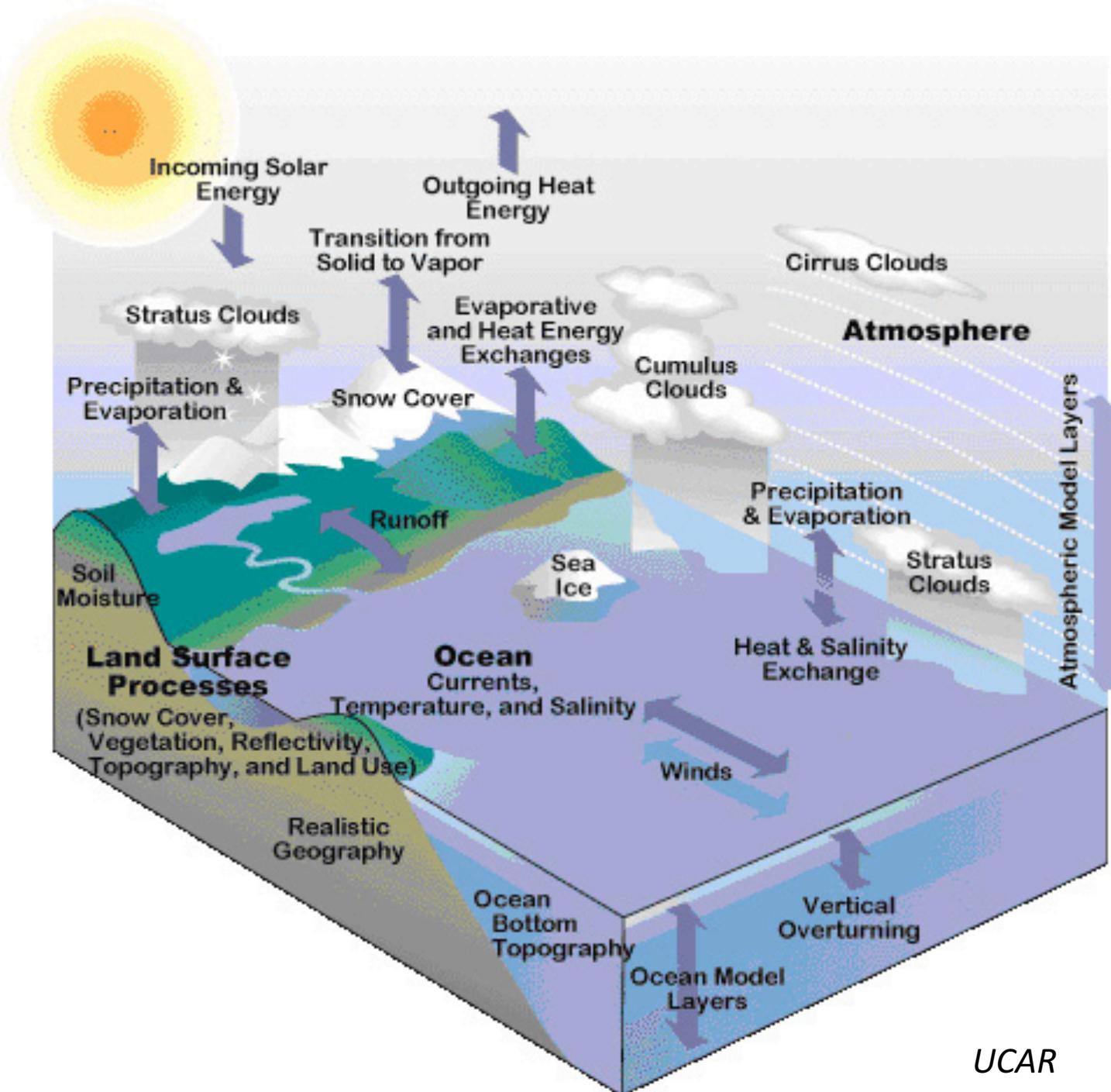


Topics covered

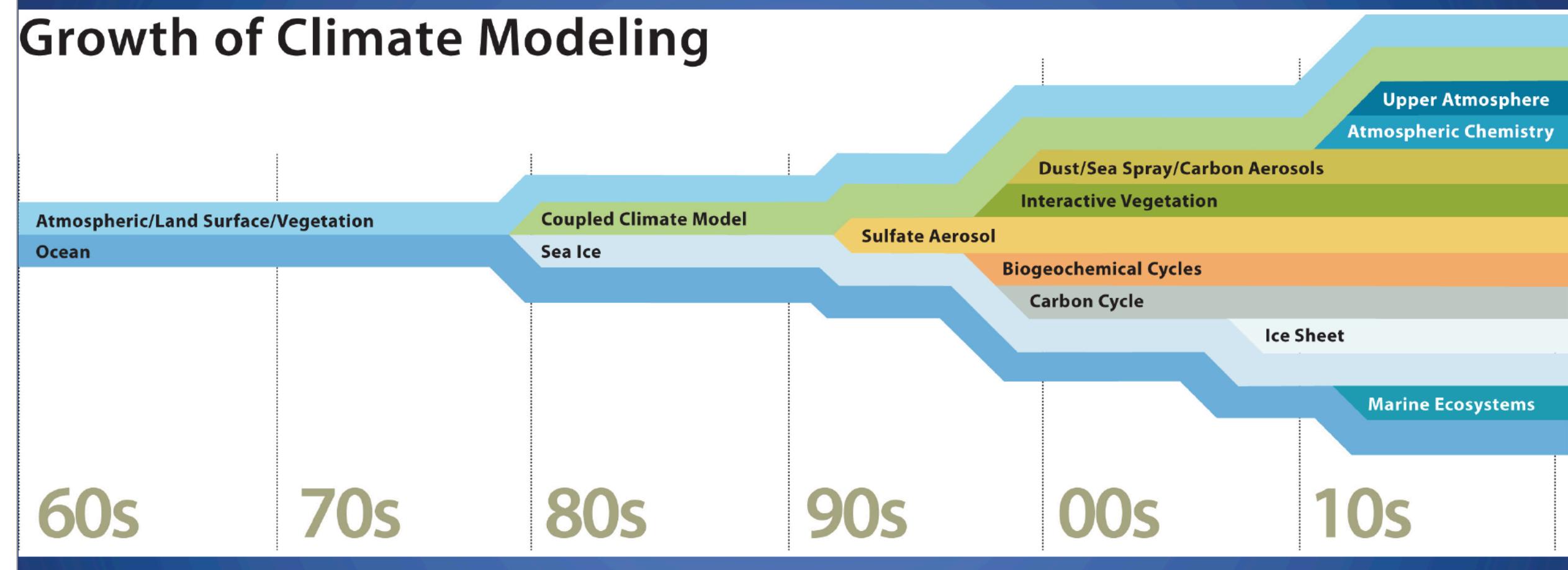
- Climate model components & types
- The carbon cycle & climate sensitivity
- CMIP and other MIPs
- IPCC AR6 interactive

Climate Model Components

- Various levels of complexity
- Atmosphere (dynamics, physics)
- Land surface
- Ocean



Growth of Climate Modeling



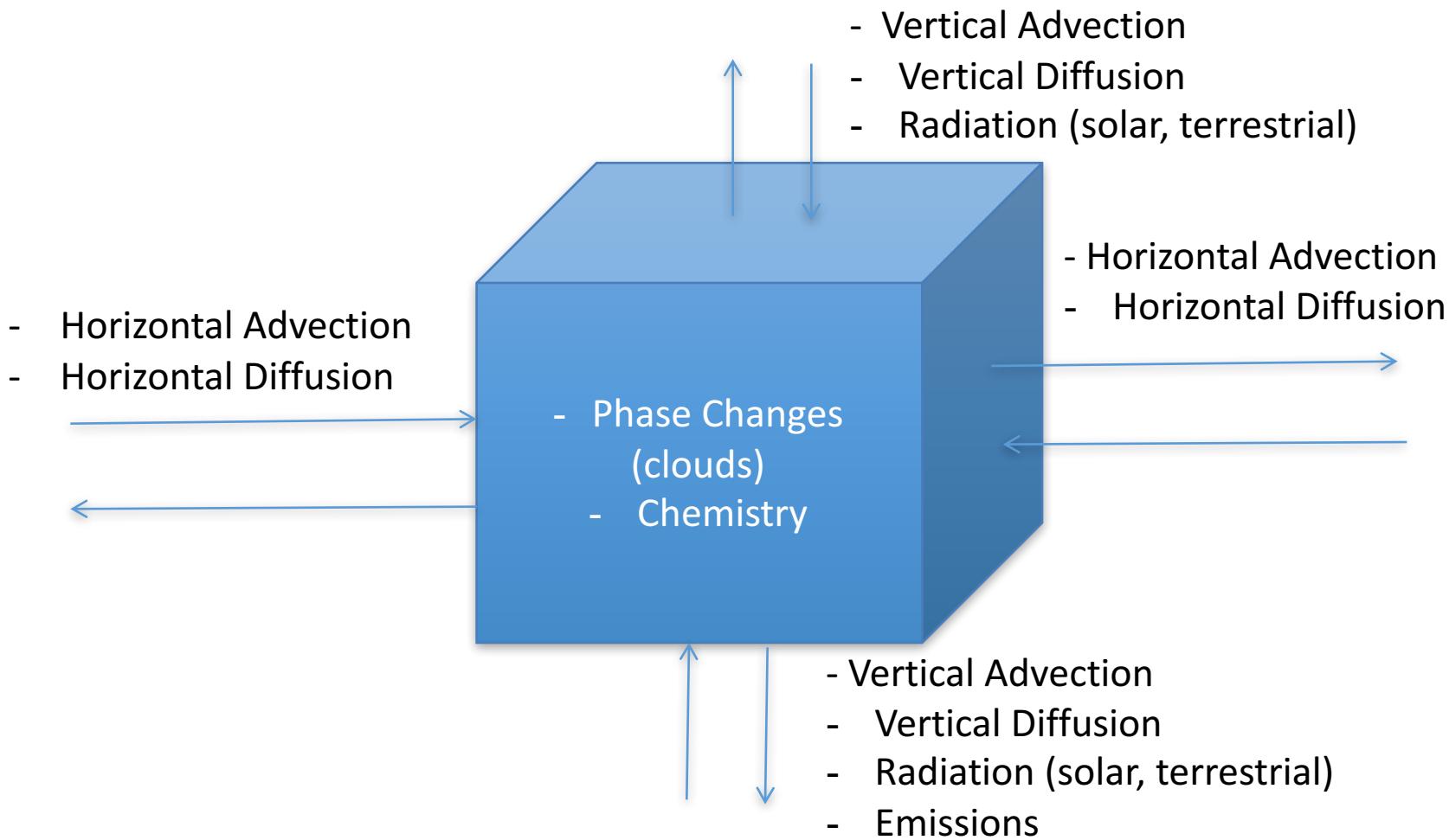
Inputs to a climate model

- Boundary conditions:
Orography/bathymetry, land/sea
mask, land surface properties
(vegetation, ice, lake, etc.), orbital
configuration
- Forcings: Solar radiation, volcanic
aerosols, greenhouse gases, ice
sheet meltwater



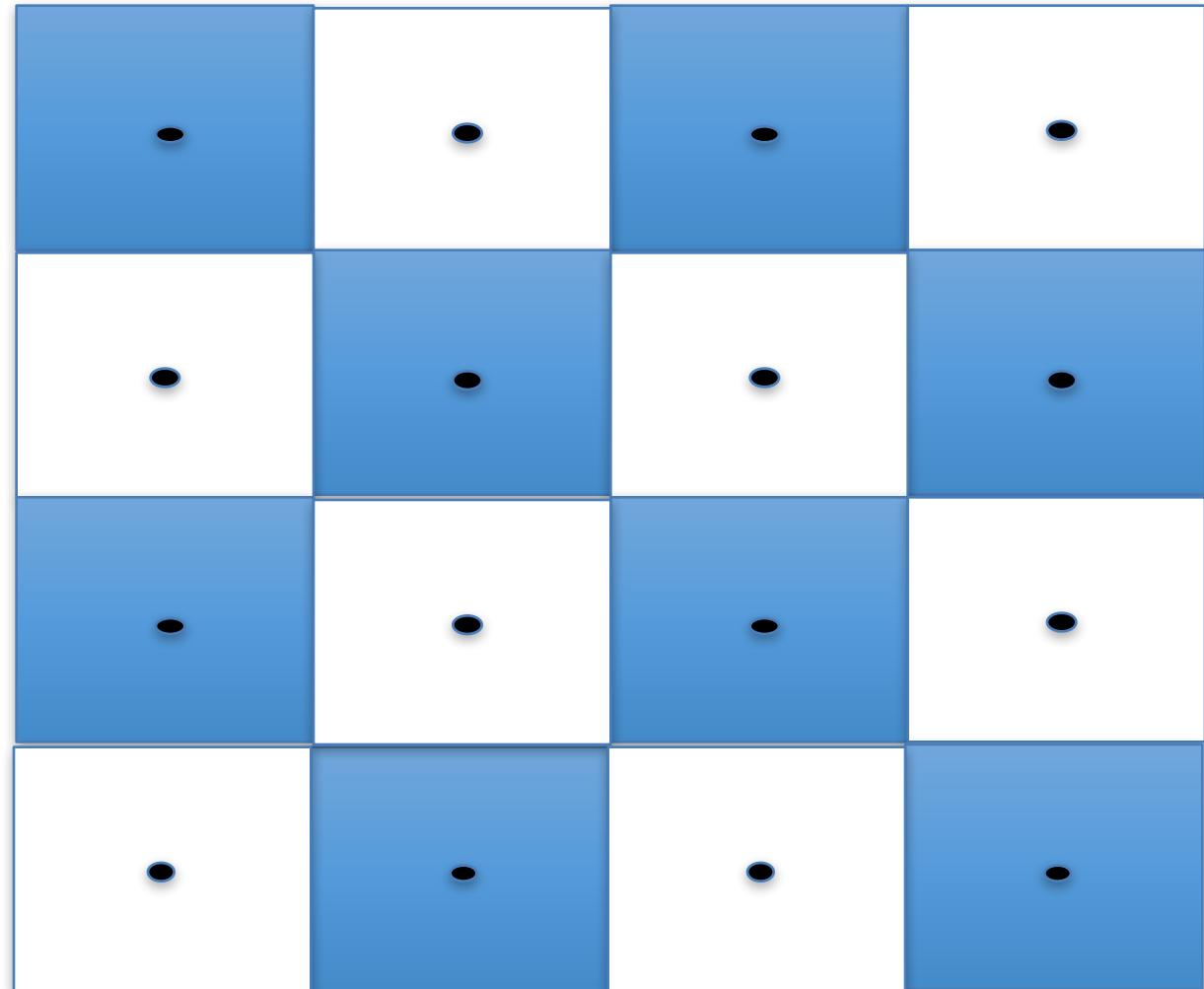
Atmospheric Models

- Keep track of these processes in each grid box for energy, mass and momentum



Atmospheric Models

- Model resolution: Horizontal and vertical scales that can be resolved or reproduced by the model
- Perform calculations one time for each grid cell at the dot – represents all processes in that grid cell
- Any processes at scales smaller than the grid box are called “sub-grid processes”

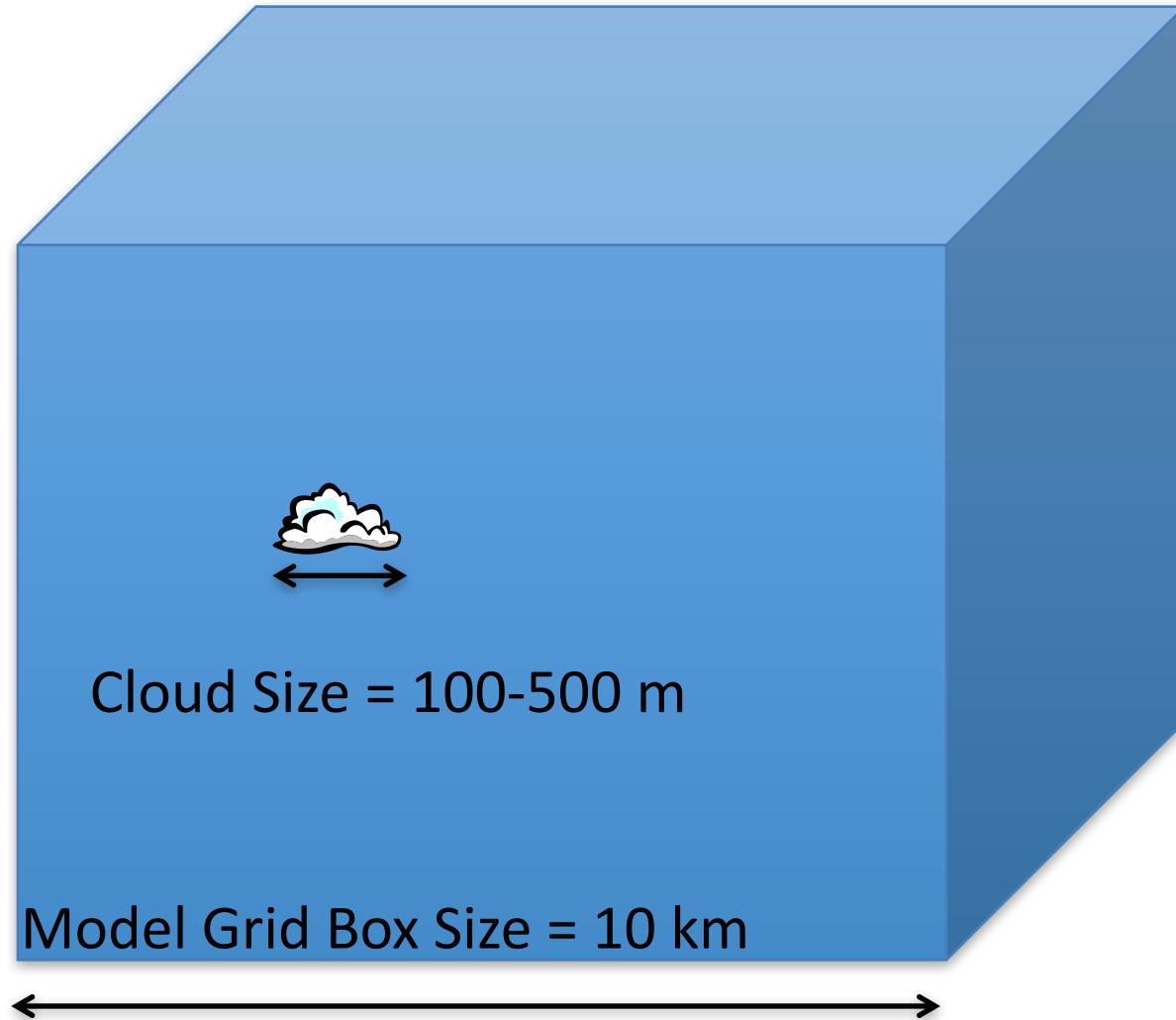


What is a parameterization?

- A set of physically-based equations to represent sub-grid scale processes
- Examples of sub-grid scale processes:
 - Circulation: Land-sea breezes
 - Precipitation: Thunderstorm, snow bands
 - Surface energy balance: heterogeneity (vegetated/urban)

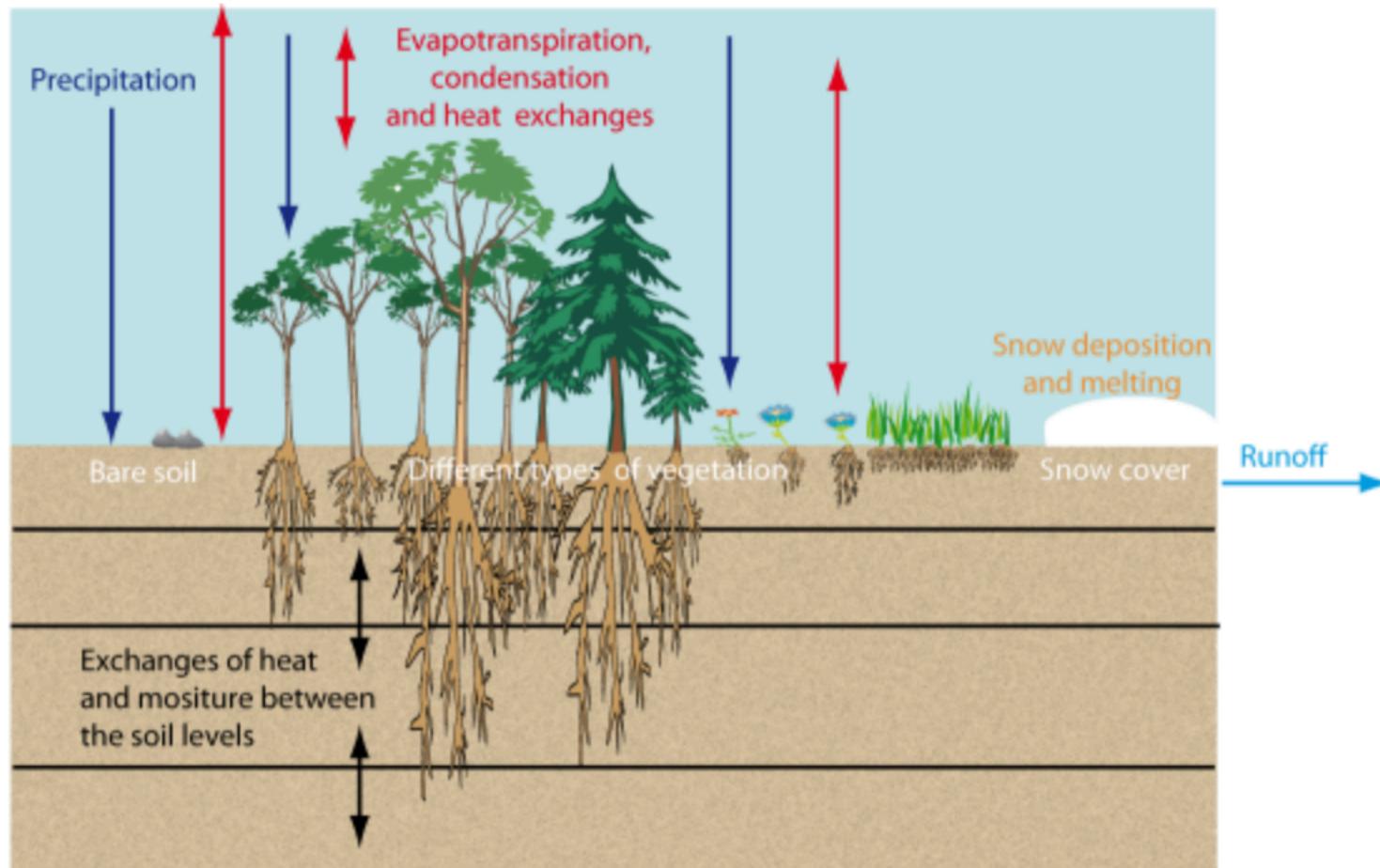
Parameterization example

- Example: Clouds are about 10-20 times smaller than the size of “high-resolution” model grid cells
 - Clouds are a sub-grid process
 - Need a parameterization to explain their formation



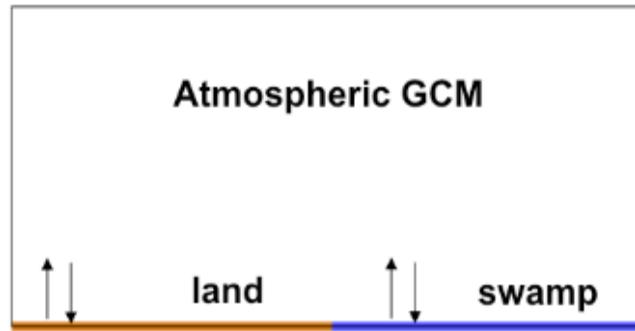
Land-Surface Parameterization

- The lower boundary condition to the atmosphere
- Gives inputs and outputs to the atm thru the Surface Energy Budget
- Plants grouped into plant functional types (PFTs)



Oceans: Simple Parameterization

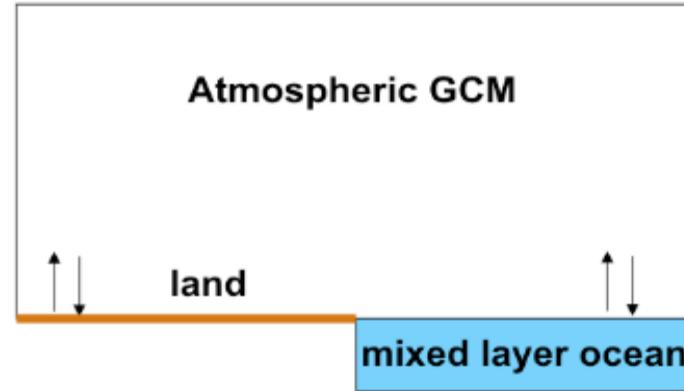
- Used in some regional models to reduce computation time
- Sometimes called a “swamp” ocean model: ocean has no heat capacity
- Force the model with SSTs (either observed or from a GCM) or calculate from SE balance



$$S_{\downarrow}(1-\alpha) + F_{\downarrow} - F_{\uparrow} - SH - LH = 0$$

Oceans: Slab Ocean Model

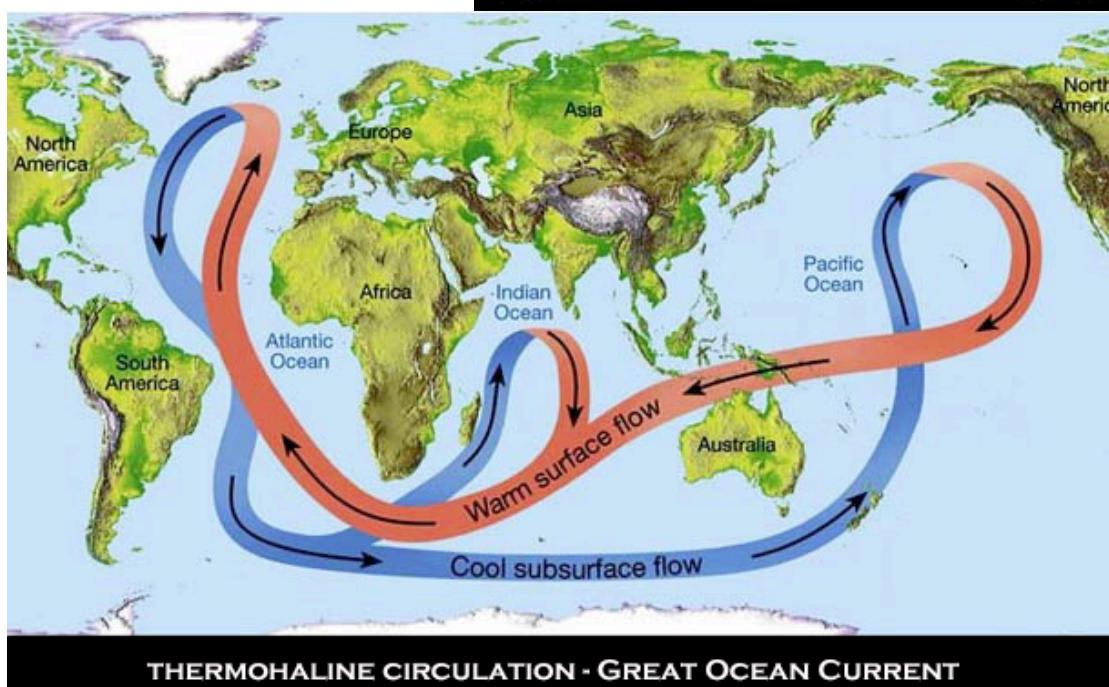
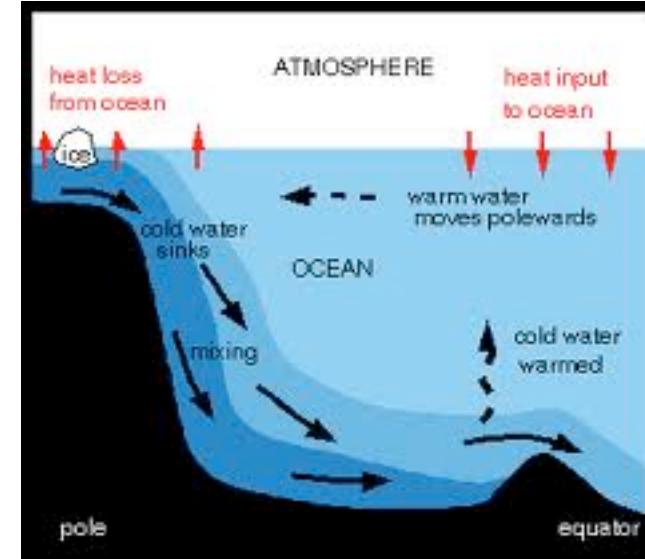
- Simplified version of an ocean model
- Slab (~50 m) can act as heat source or sink and simple currents, but no deep ocean current
- Can store heat in the “slab”
- Very common approach for climate runs



$$\rho c_p h \frac{\partial T}{\partial t} = S_{\downarrow} (1 - \alpha) + F_{\downarrow} - F_{\uparrow} - SH - LH$$

Oceans: Full Ocean Model

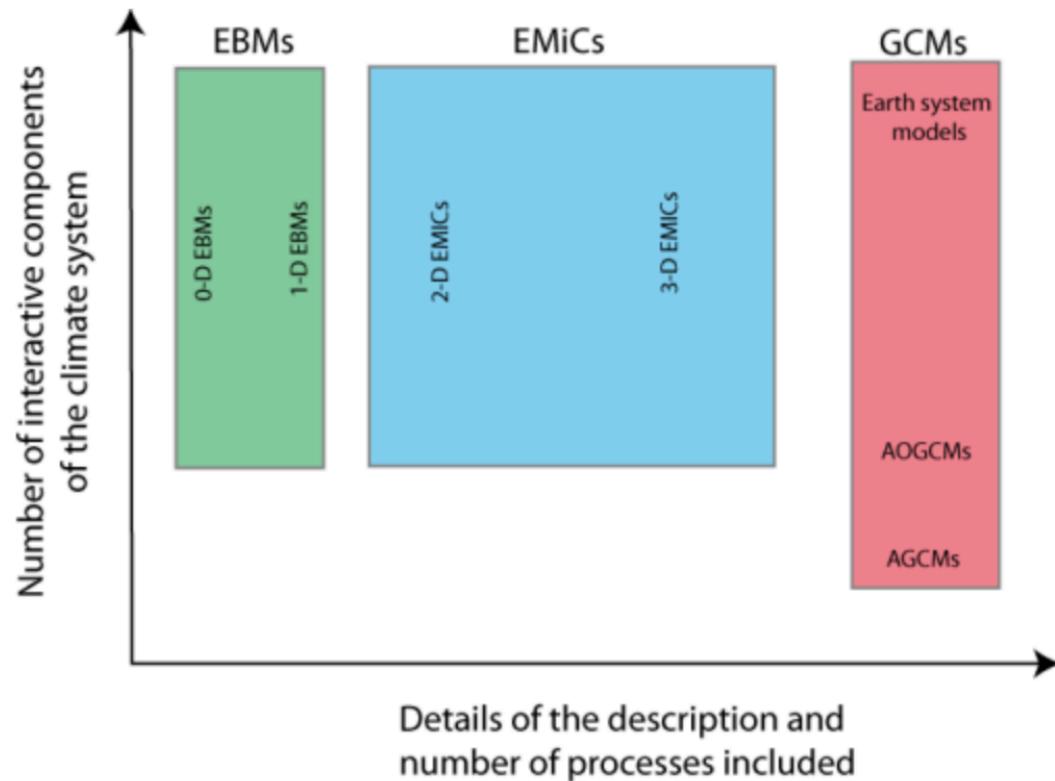
- More computationally expensive
- Includes advection, diffusion & heat storage
- Good representation of ocean-atm feedbacks
- Usually need to run for long time periods to get the ocean to equilibrate (e.g., deep ocean can take 1000+ years to truly equilibrate)



THERMOHALINE CIRCULATION - GREAT OCEAN CURRENT

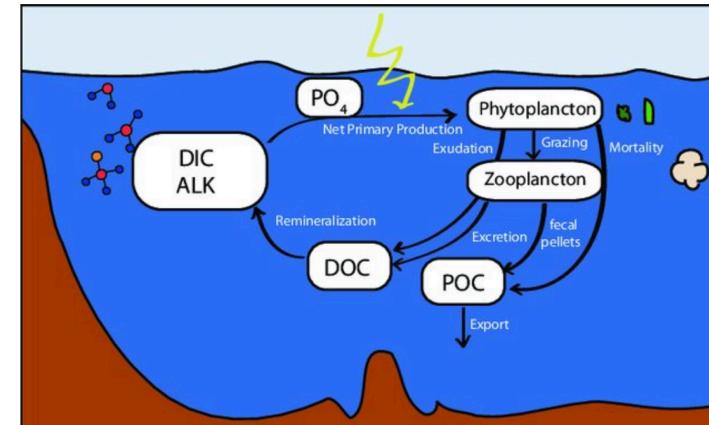
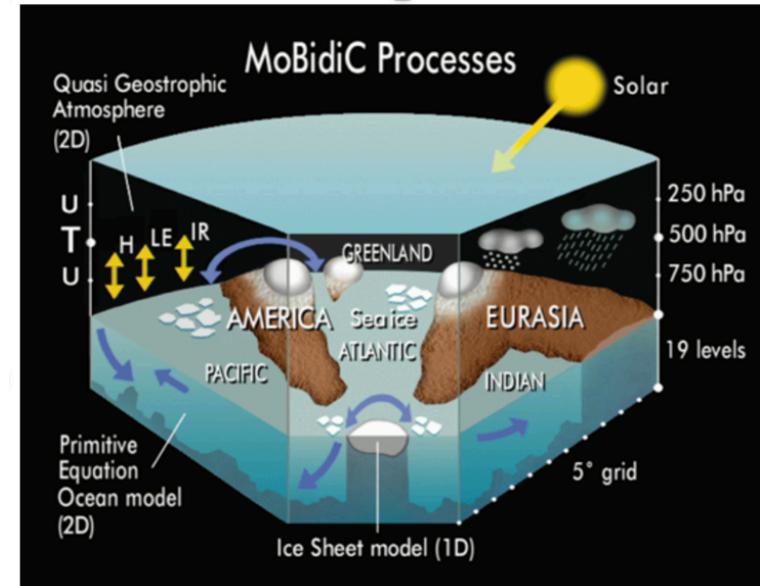
Levels of complexity

- Different models for different applications
- More processes included mean more computationally expensive to run



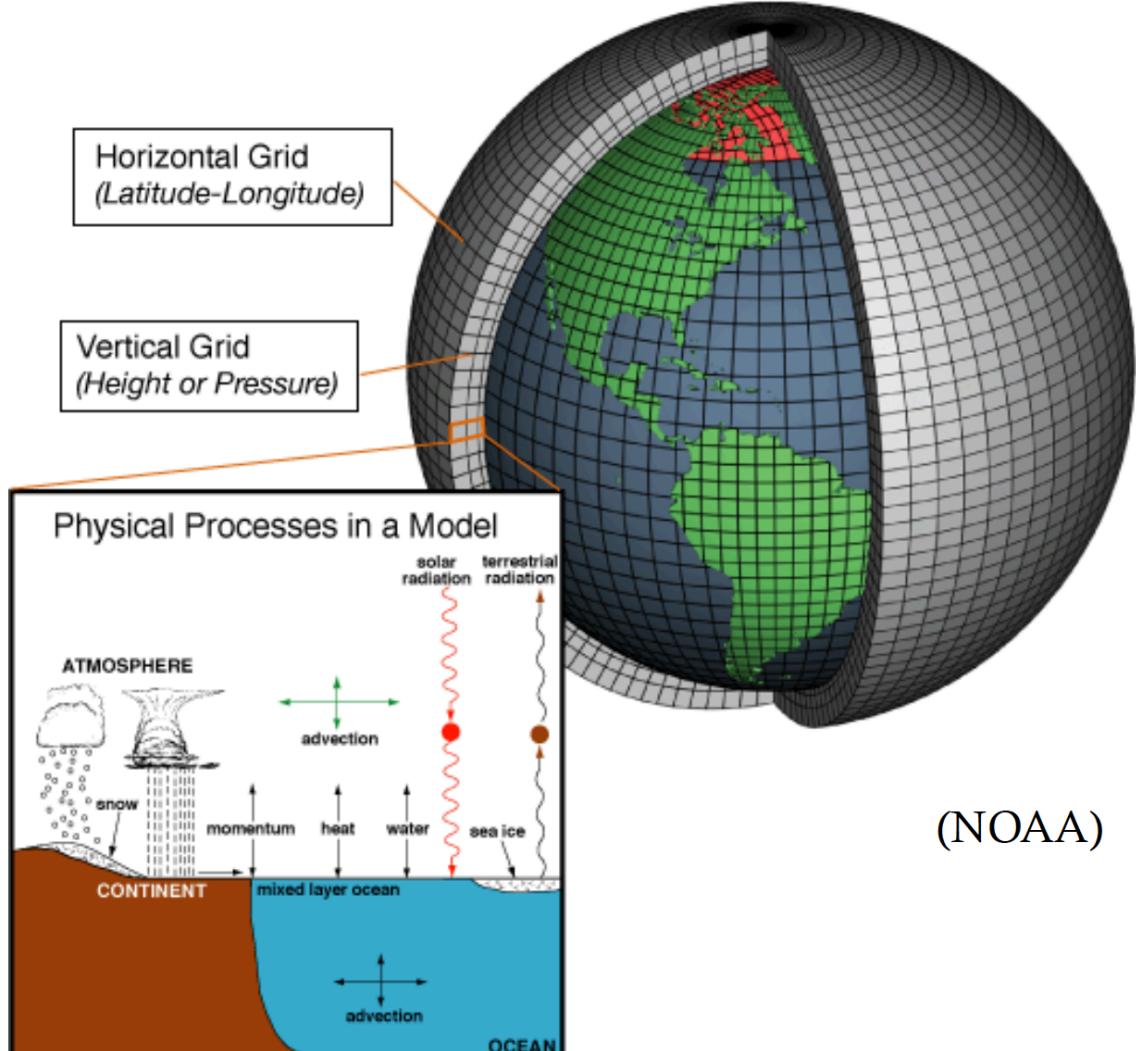
Levels of complexity: Intermediate complexity models

- EMICs include representation of Earth's geography
- Some components simplified/low resolution
- Other components similar to higher-res models
- Efficient to run for very long timescales



Levels of complexity: General circulation models

- More levels in ocean and atmosphere than EMICs, higher horizontal resolution
- More detailed information on regional scale
- More computationally intensive



Dynamical downscaling

- Simulating climate with a Regional Climate Model (RCM) or Limited Area Model (LAM)
- Selecting a specific region and running a separate climate model for that region
- Need to account for lateral boundary conditions (One-way or two-way nesting)

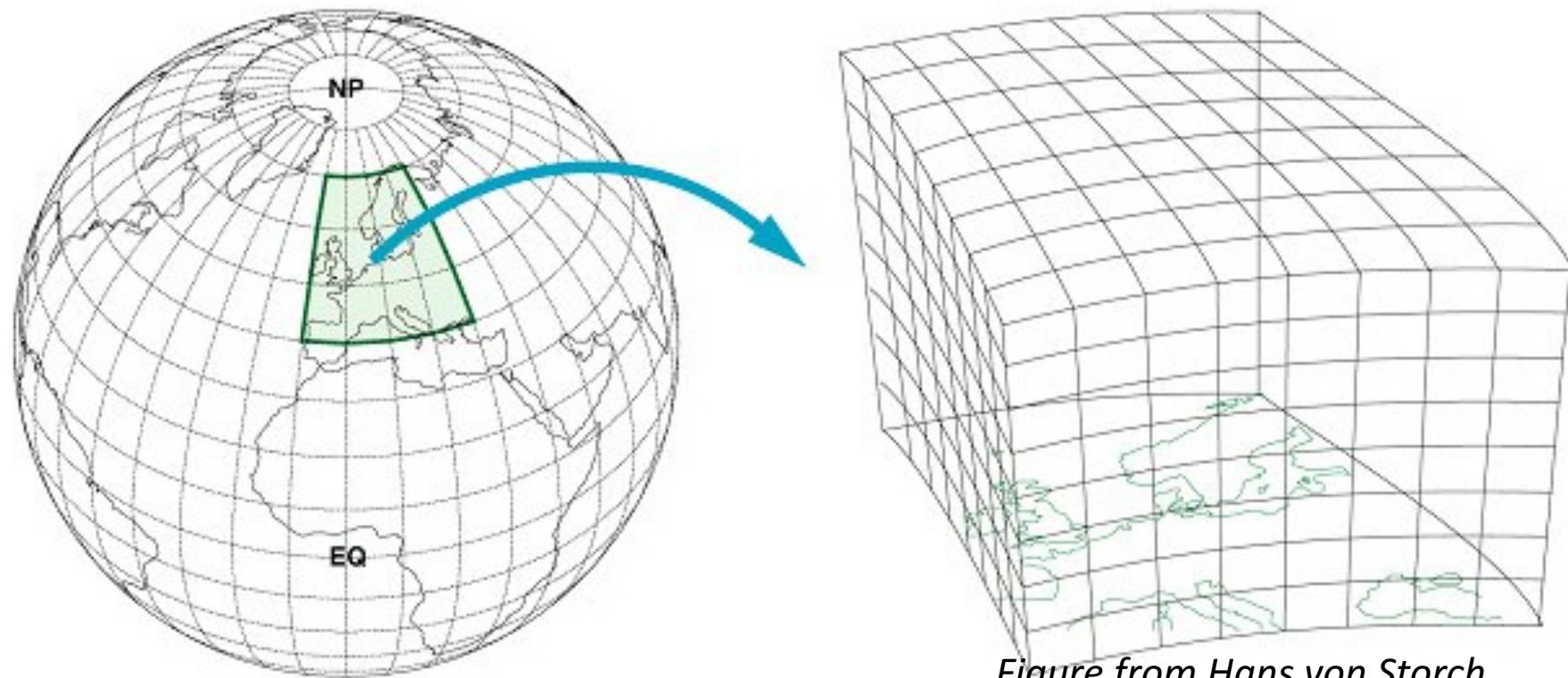
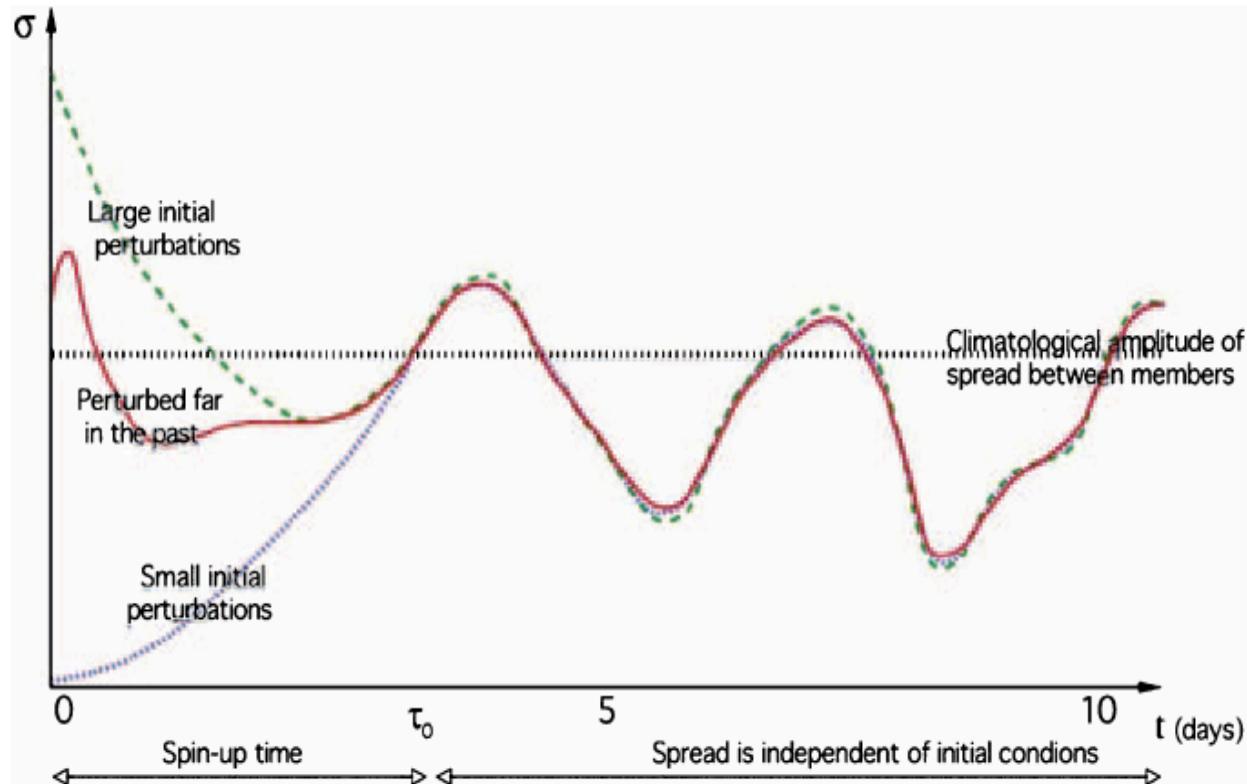


Figure from Hans von Storch

Climate model spinup

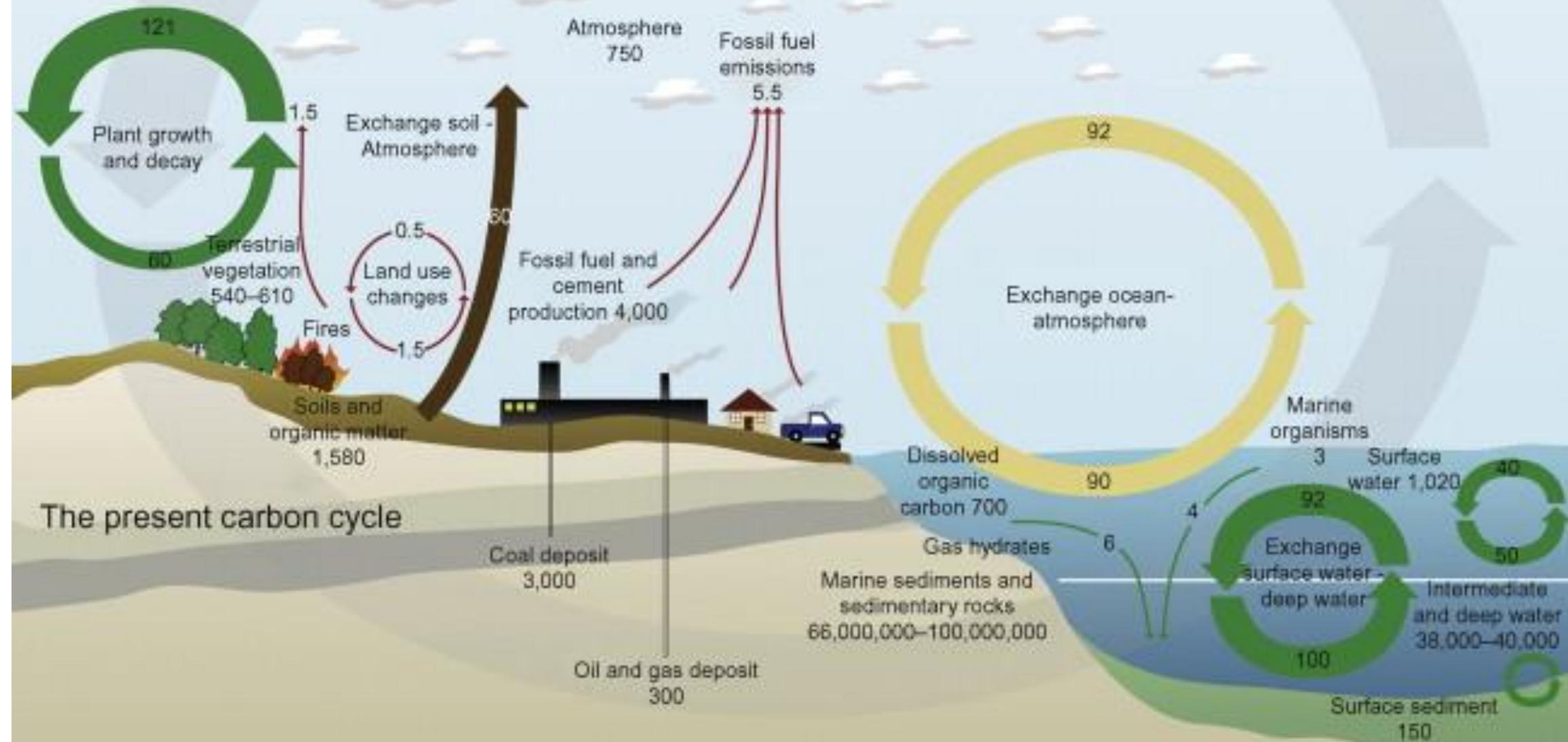


- Time taken to approach climatology after starting from other initial conditions
- Atmosphere has short “memory”: little spin-up required to equilibrate (~ 1 year)
- Ocean has long “memory”: need full overturning if using full ocean model (centuries to 1000 years)

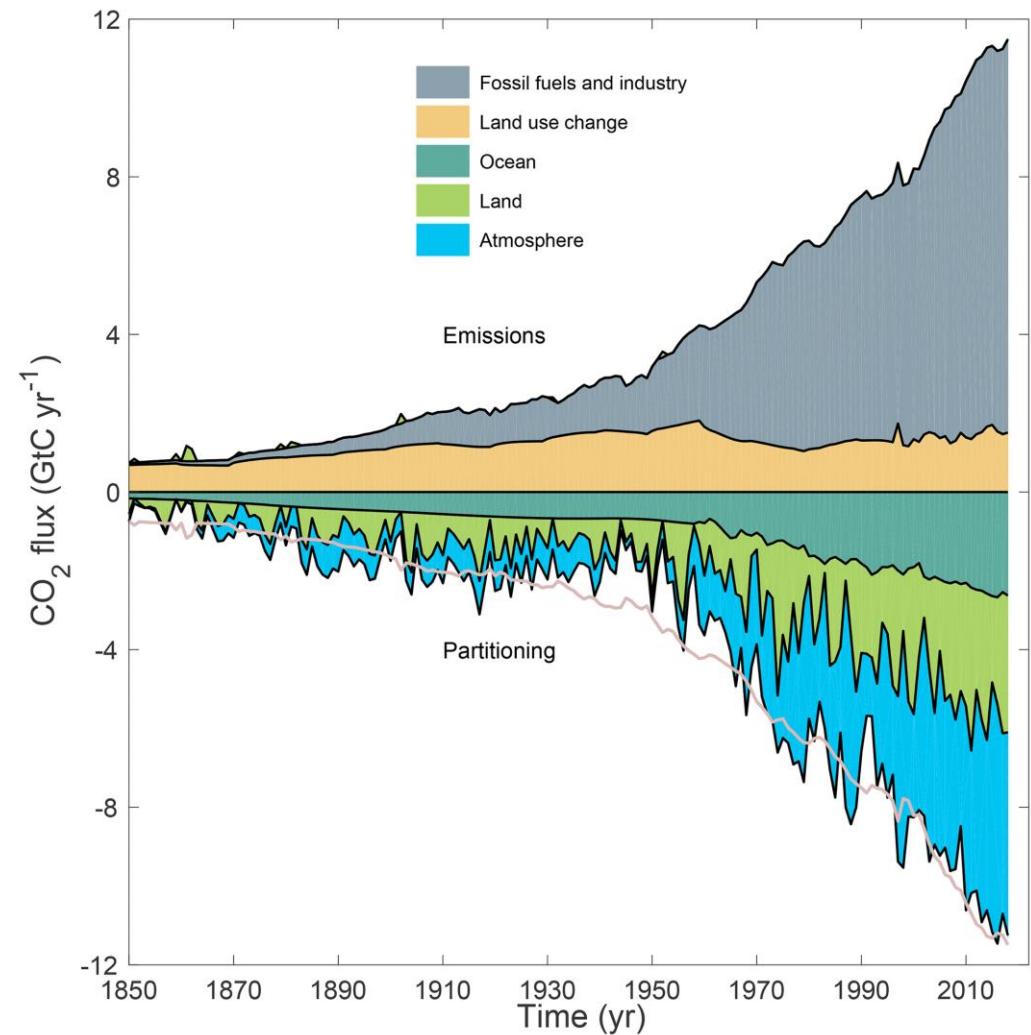
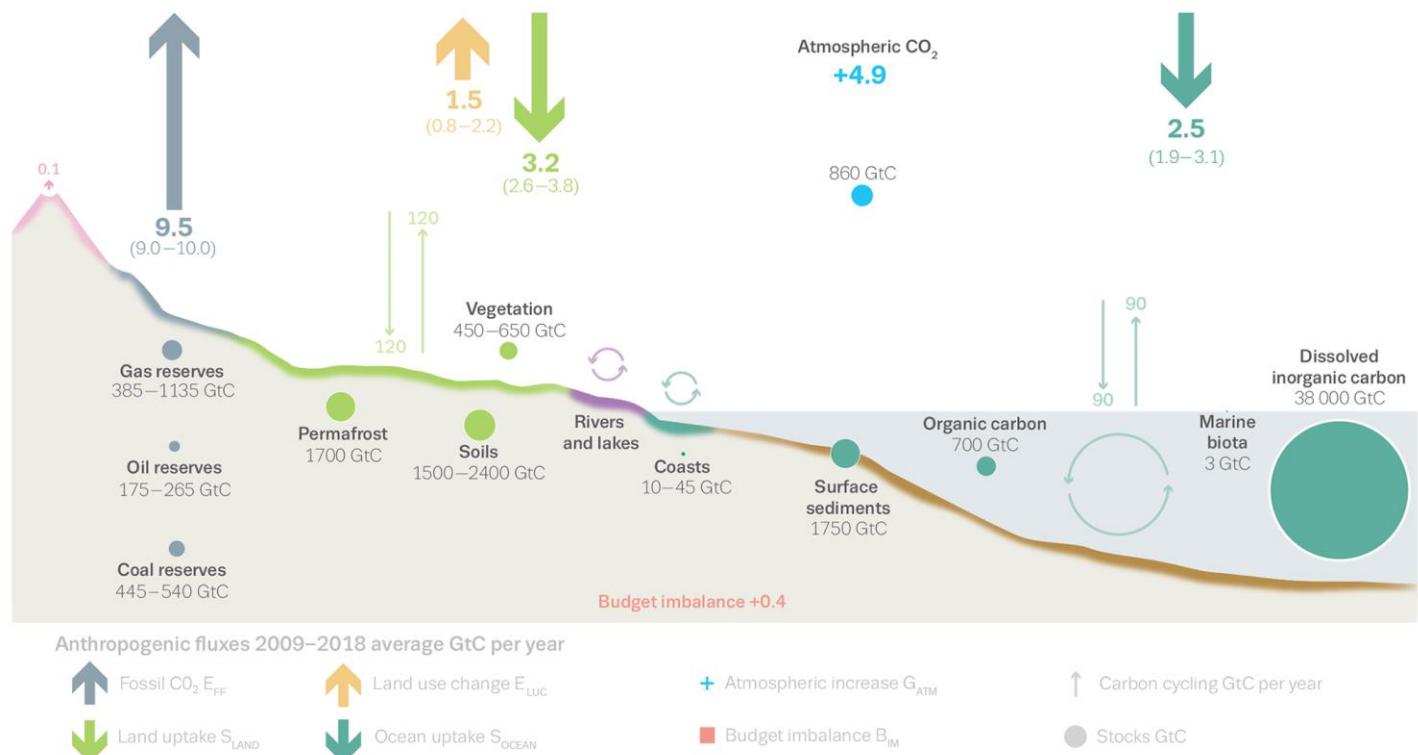
Laprise et al. (2008): Time evolution of spread between members of a conceptual ensemble of simulations

Biogeochemistry & the carbon cycle

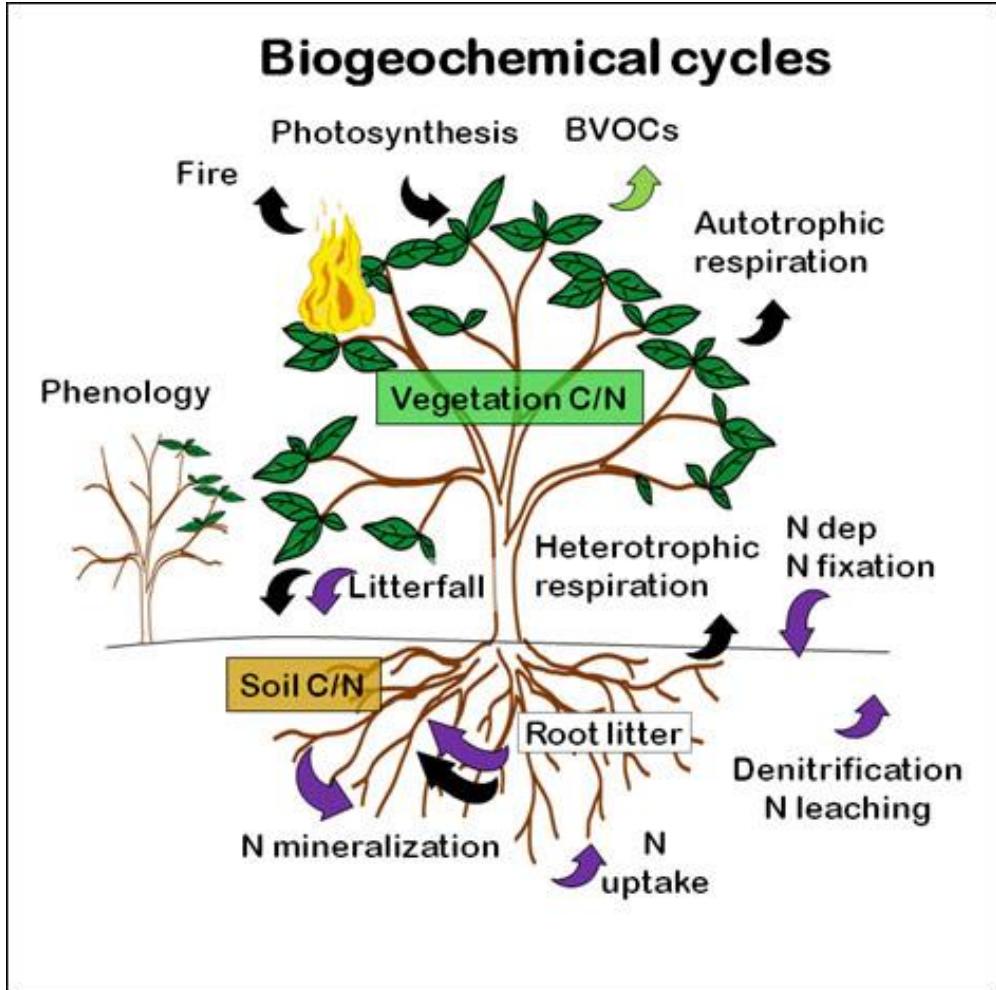
Storage and transfer of carbon between components:
ocean, land, atmosphere, sediments



The global carbon cycle



Land biogeochemical cycles: carbon, nitrogen, and water

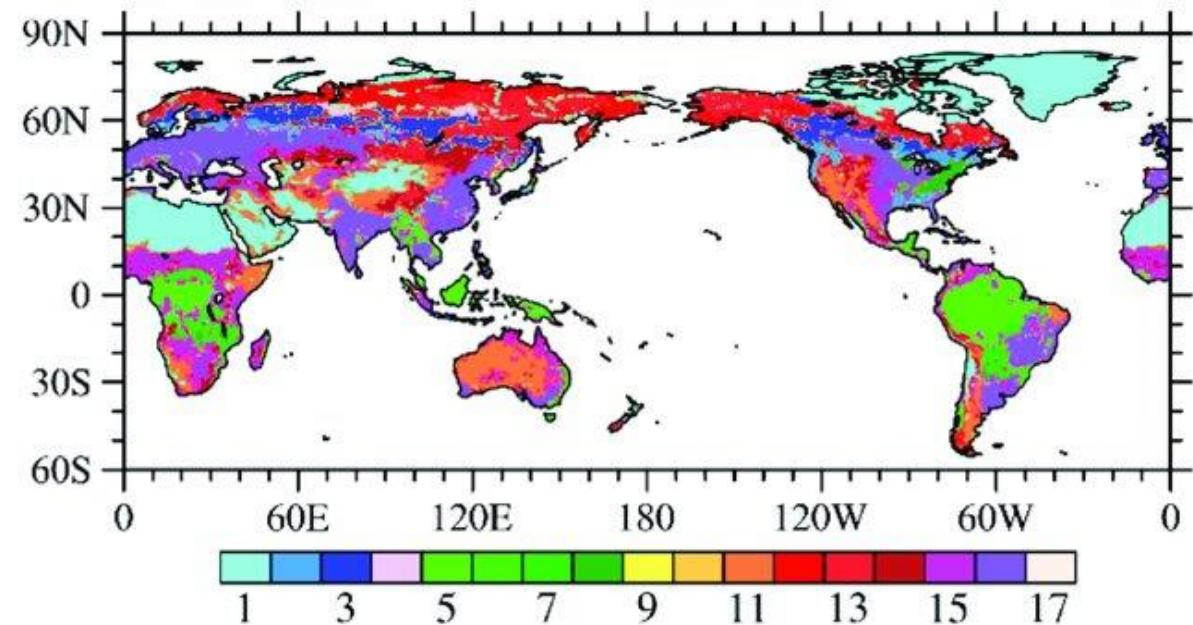


- Plant/soil dynamics are mostly empirical & parameterized in models
- Model parameters dependent on plant functional type
- Growth is most commonly limited by light, water or nutrient availability
- Water, Carbon and Nitrogen cycles commonly included, sometimes Phosphorus

Global terrestrial carbon dynamics: Plant Functional Types (PFT)

- PFT = classification according to physical, phylogenetic and phenological characteristics
- Typical PFTs:
 - Evergreen needleleaf forest
 - Deciduous broadleaf forest
 - C3/C4 grassland
 - Shrubs
 - Cropland
 - Bare ground / desert / ice (no veg)
- Vegetation type / ecosystem in models can be fixed or dynamic (Dynamic vegetation models DVGM)
- Wetlands and permafrost/peatland are often missing
- Land management often missing or greatly simplified

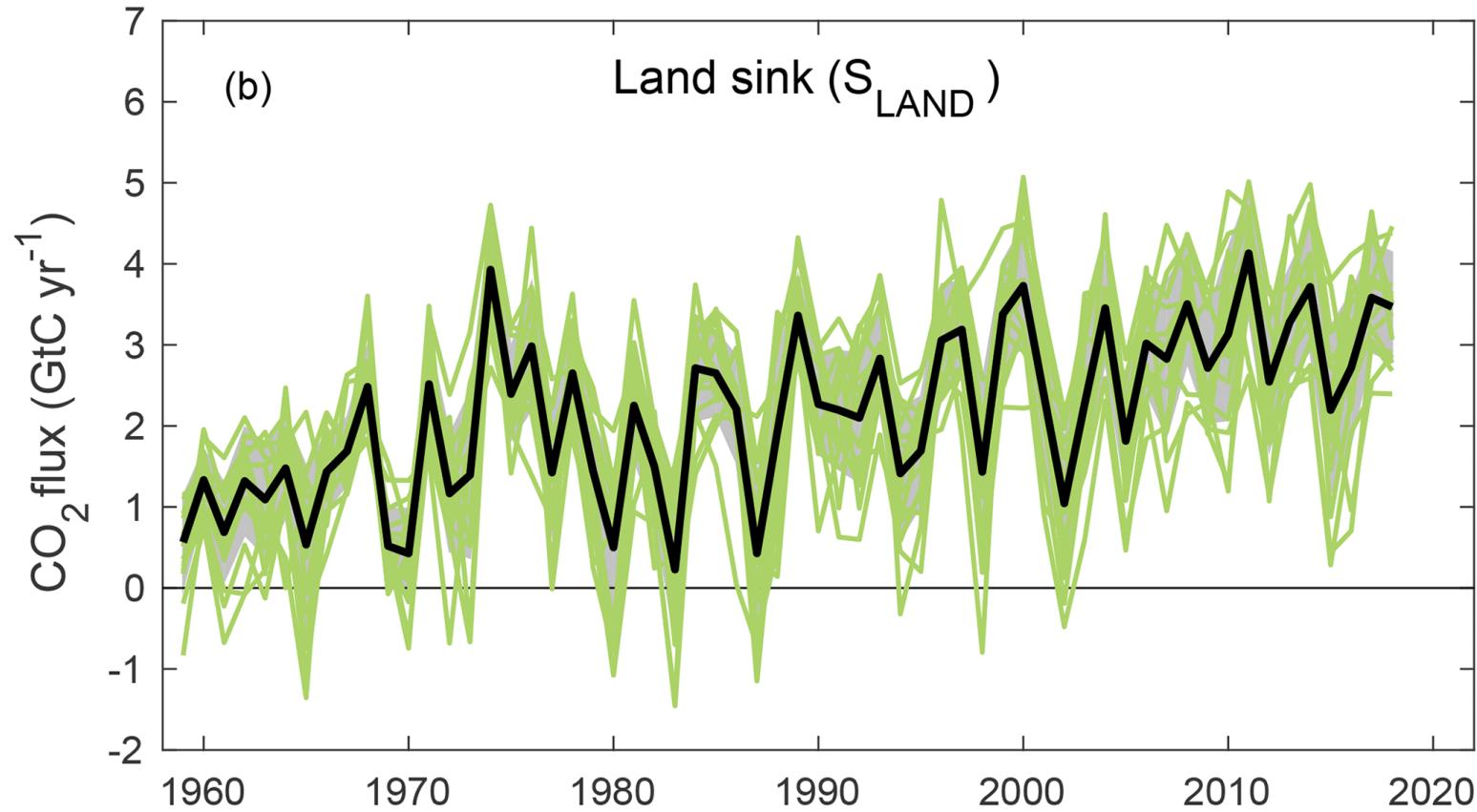
Modern-day distribution of PFTs



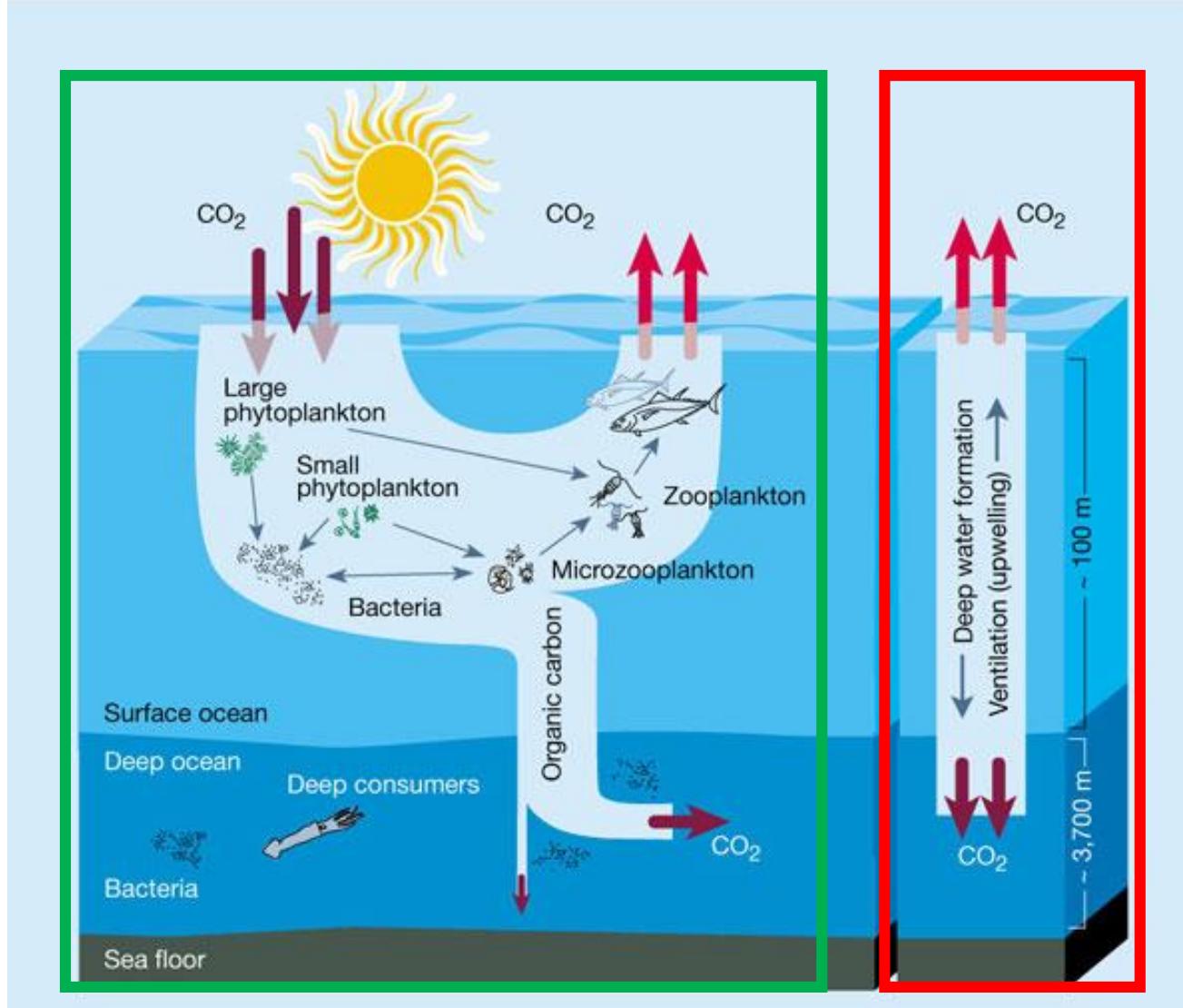
Ref. 2

Global terrestrial carbon dynamics

Global estimates of the land carbon sink contain large uncertainties



Marine carbon cycle



The ocean carbon cycle is regulated by:

- Biological carbon pump
- Ocean circulation and ventilation

Primary processes governing distribution of nutrients, O₂, carbon

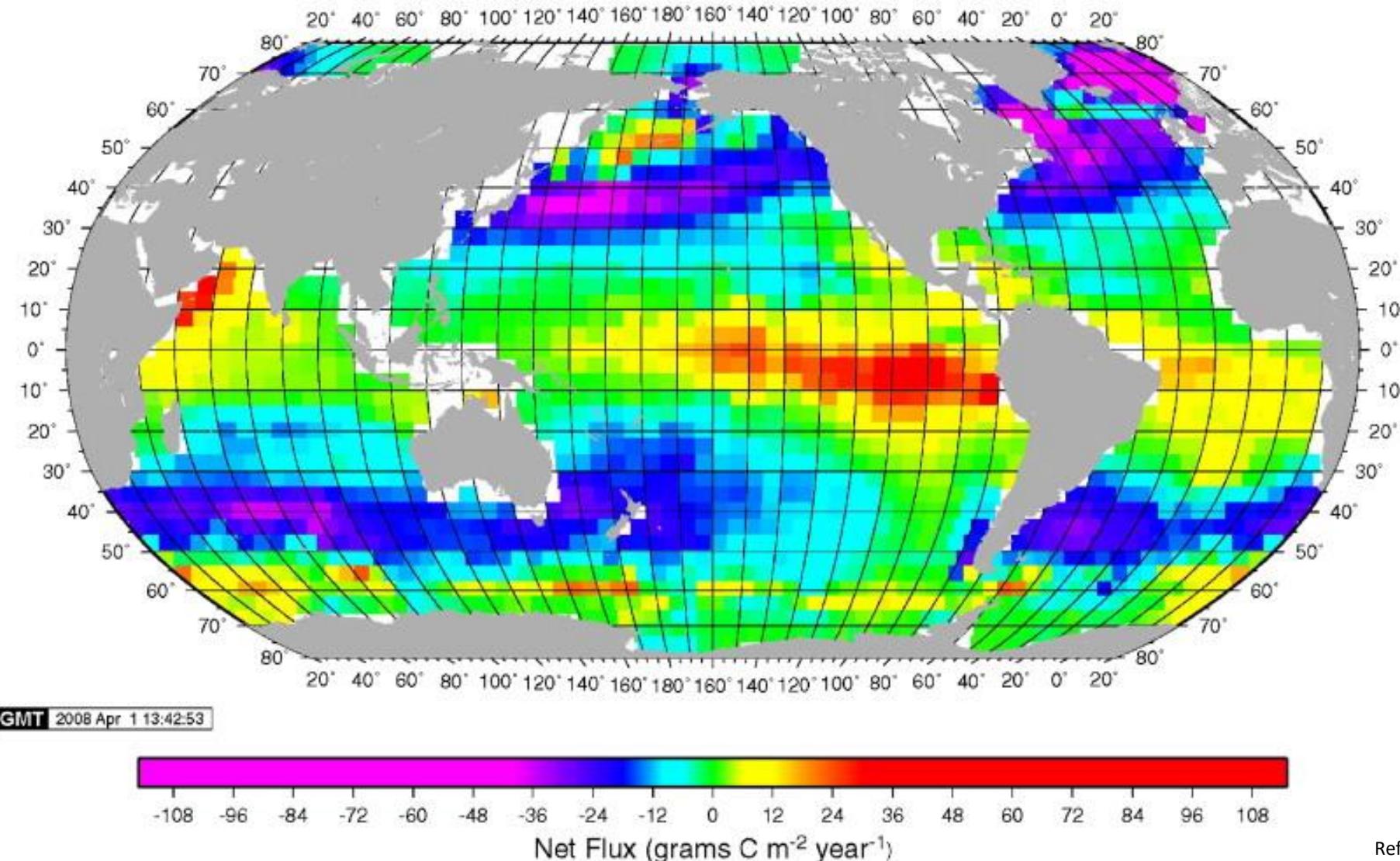
Biological carbon pump
Ocean circulation and ventilation

- Biological productivity in euphotic zone
 - Consumes nutrients (nitrate, phosphate, silicate, and calcium) & inorganic carbon (CO₂)
 - Produces organic matter & O₂
- Export of organic matter out of euphotic zone
 - Sinking particles (e.g. detritus, CaCO₃ shells, ...)
 - Circulation of suspended matter
- Remineralization of organic matter
 - ‘reverse’ of productivity, consumes O₂
 - releases inorganic material that can be used again
- General circulation
 - Advective transport
 - Lateral & vertical mixing
- Air-sea gas exchange (temperature-dependent)



Ocean circulation and ventilation

pCO₂ air-sea flux



Biological carbon pump

What is an NPZD model?

N Nutrient

nitrate, ammonium, phosphate, silicate, iron, etc.

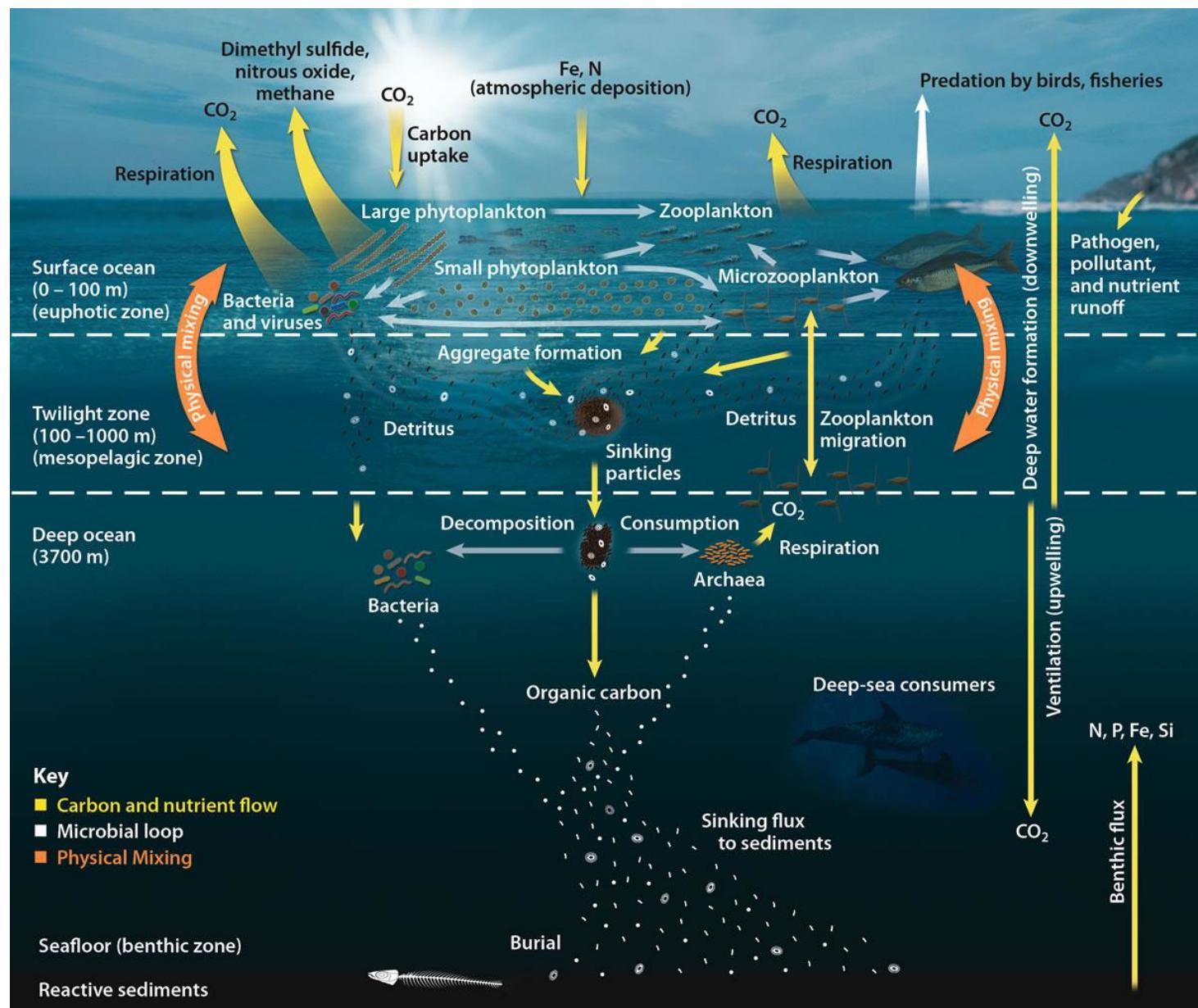
P Phytoplankton

photosynthesizers

Z Zooplankton

grazers

D Detritus



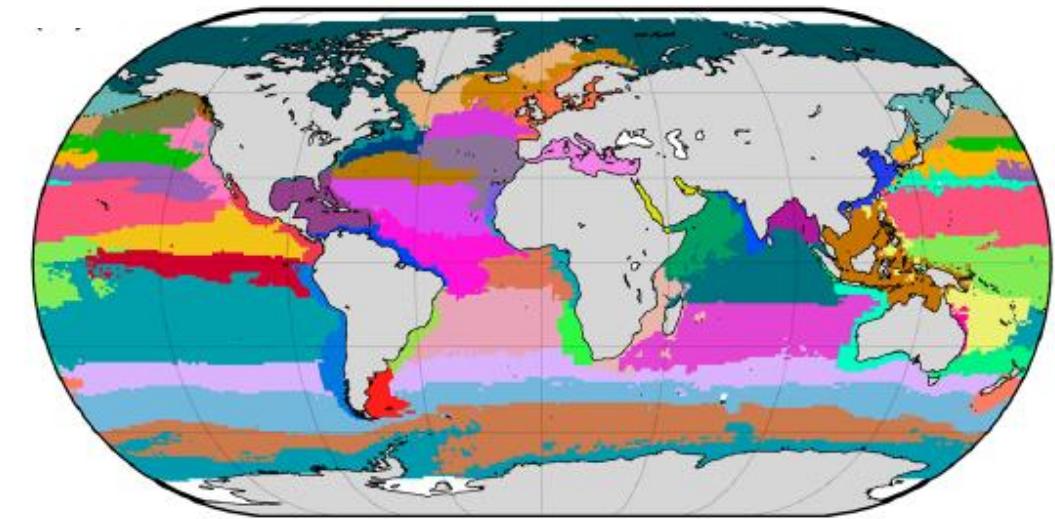
Higher trophic levels usually not represented

https://en.wikipedia.org/wiki/Remineralisation#/media/File:Oceanic_Food_Web.jpg

Plankton Functional Types (PFT)

- Analogous to plant functional types on land
- Considerations in defining PFTs (Le Quere et al. 2005):
 1. has an explicit biogeochemical role
 2. Has a distinct set of physiological, environmental, or nutrient requirements controlling its biomass and productivity
 3. Has distinct effects on the performance of other PFTs, for instance, through selective depletion of nutrients or grazing
 4. Is of quantitative importance in at least some region of the ocean

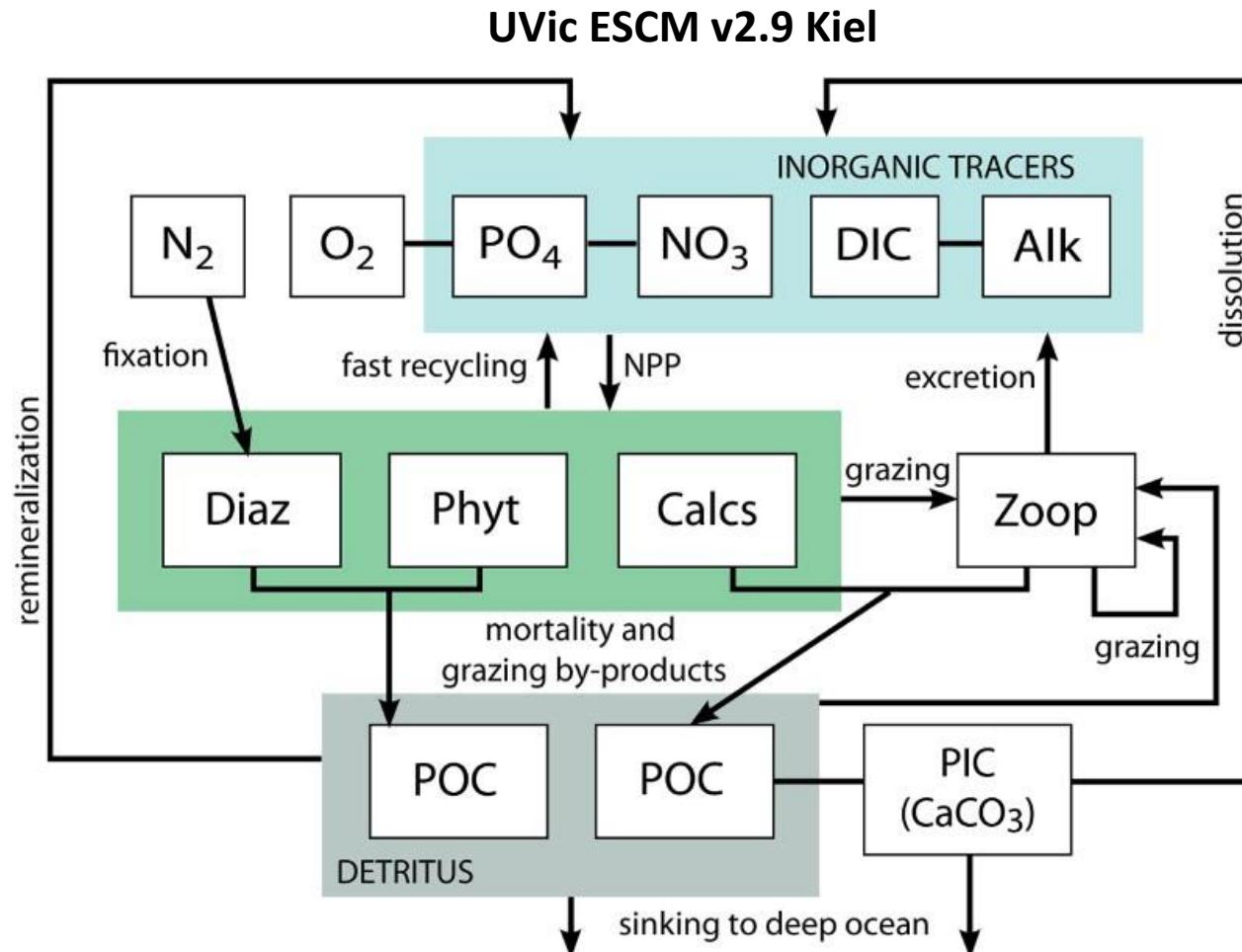
Biogeochemical provinces
in the ocean



Ref. 5

Example of model representation: UVic ESCM

N
P
Z
D



Coccolithophores
(*Emiliania huxleyi*)



World Climate Research Programme

Coupled Model Intercomparison Project

- Standardized set of climate model experiments
- How does the Earth climate system respond to forcing?
- Identify origins/consequences of model biases
- Determine internal variability and uncertainty

Modelling groups around the world

- CMIP5: 31 participating institutions
- CMIP6: 42 participating institutions



AR5 report: RCPs

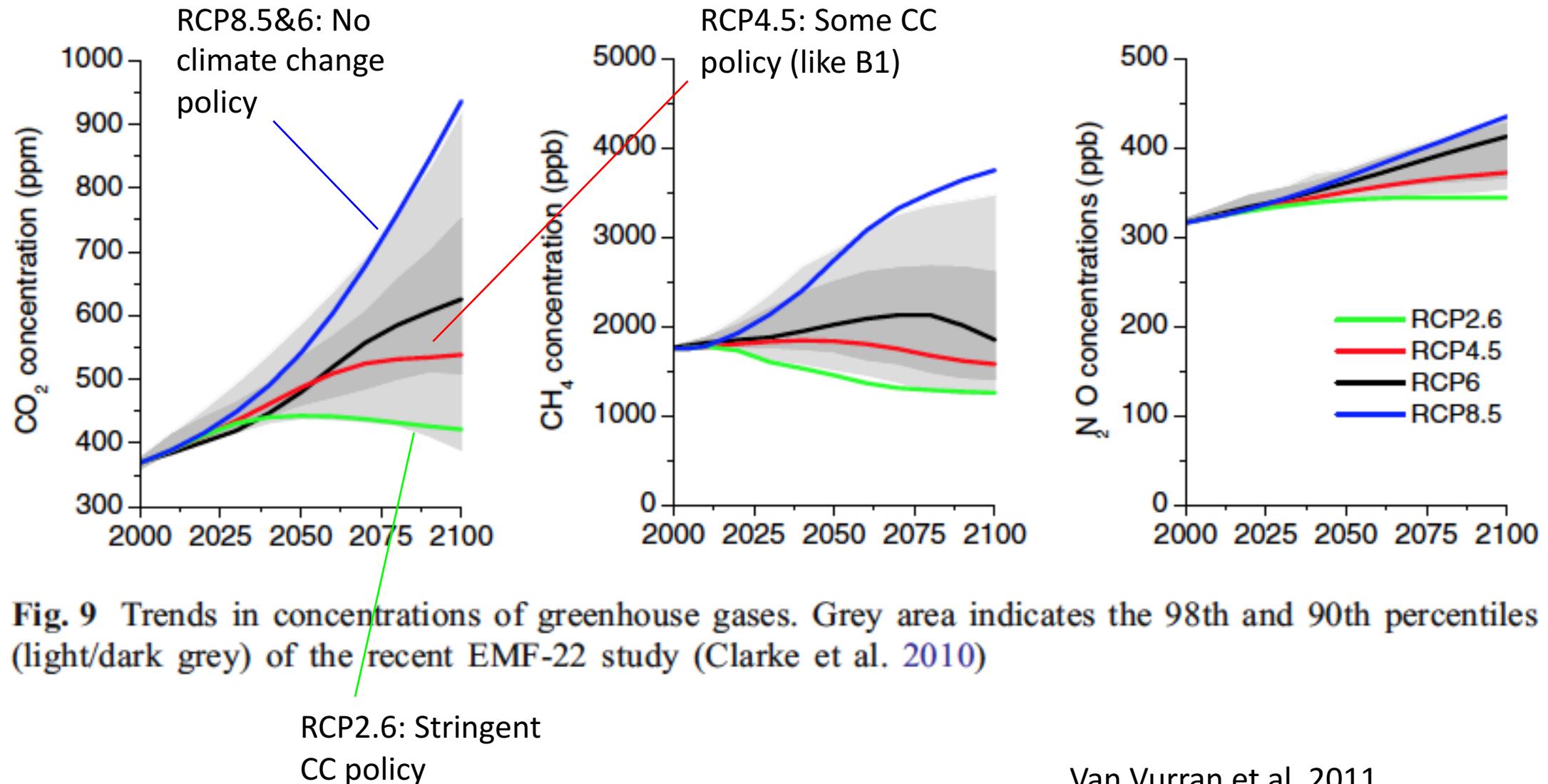


Fig. 9 Trends in concentrations of greenhouse gases. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the recent EMF-22 study (Clarke et al. 2010)

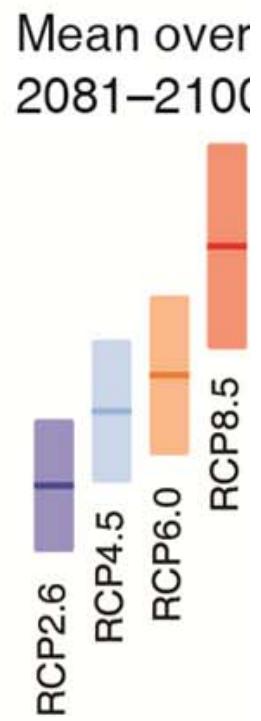
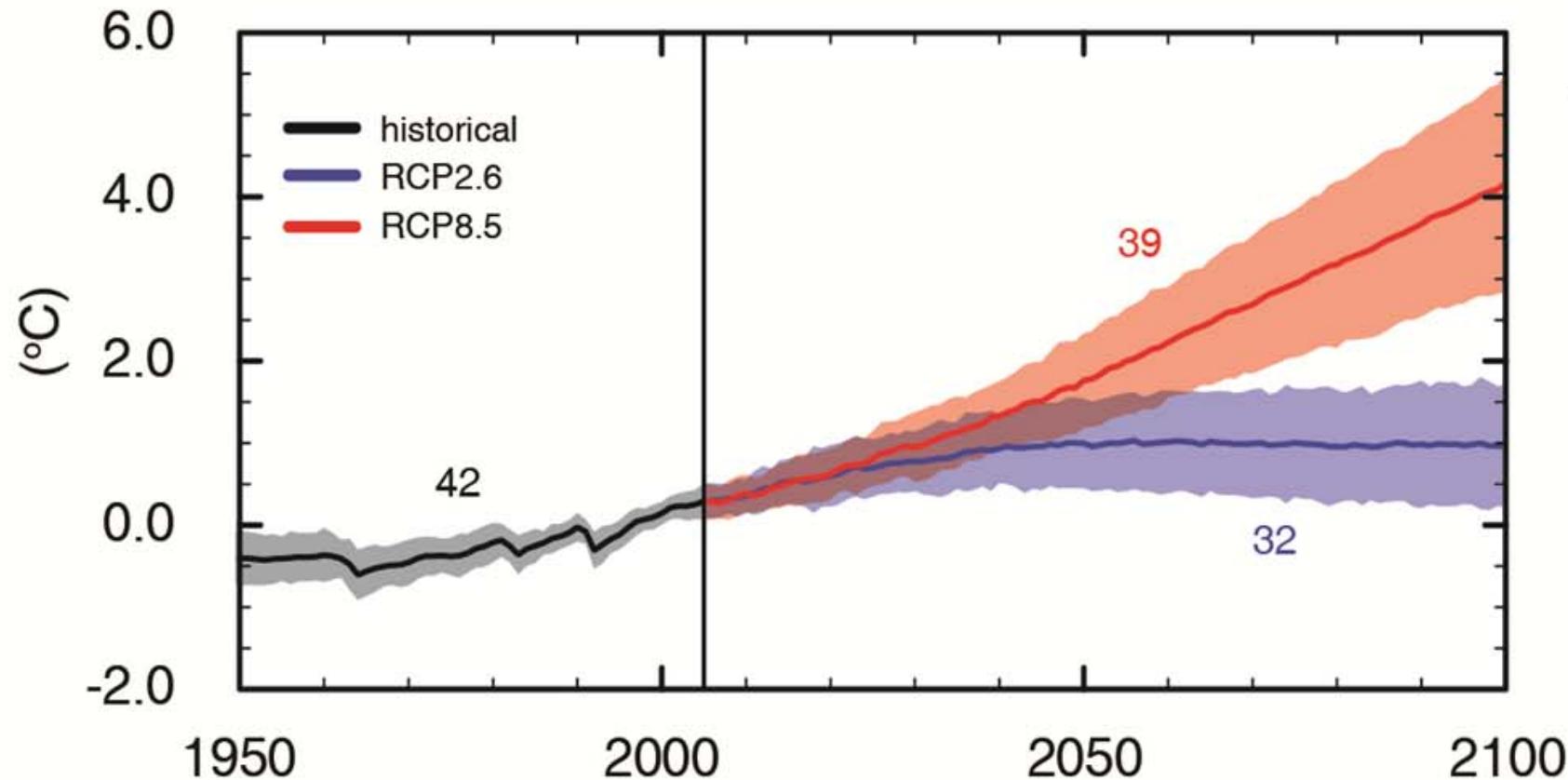
RCP2.6: Stringent
CC policy

Van Vurran et al. 2011

AR5 report: T changes

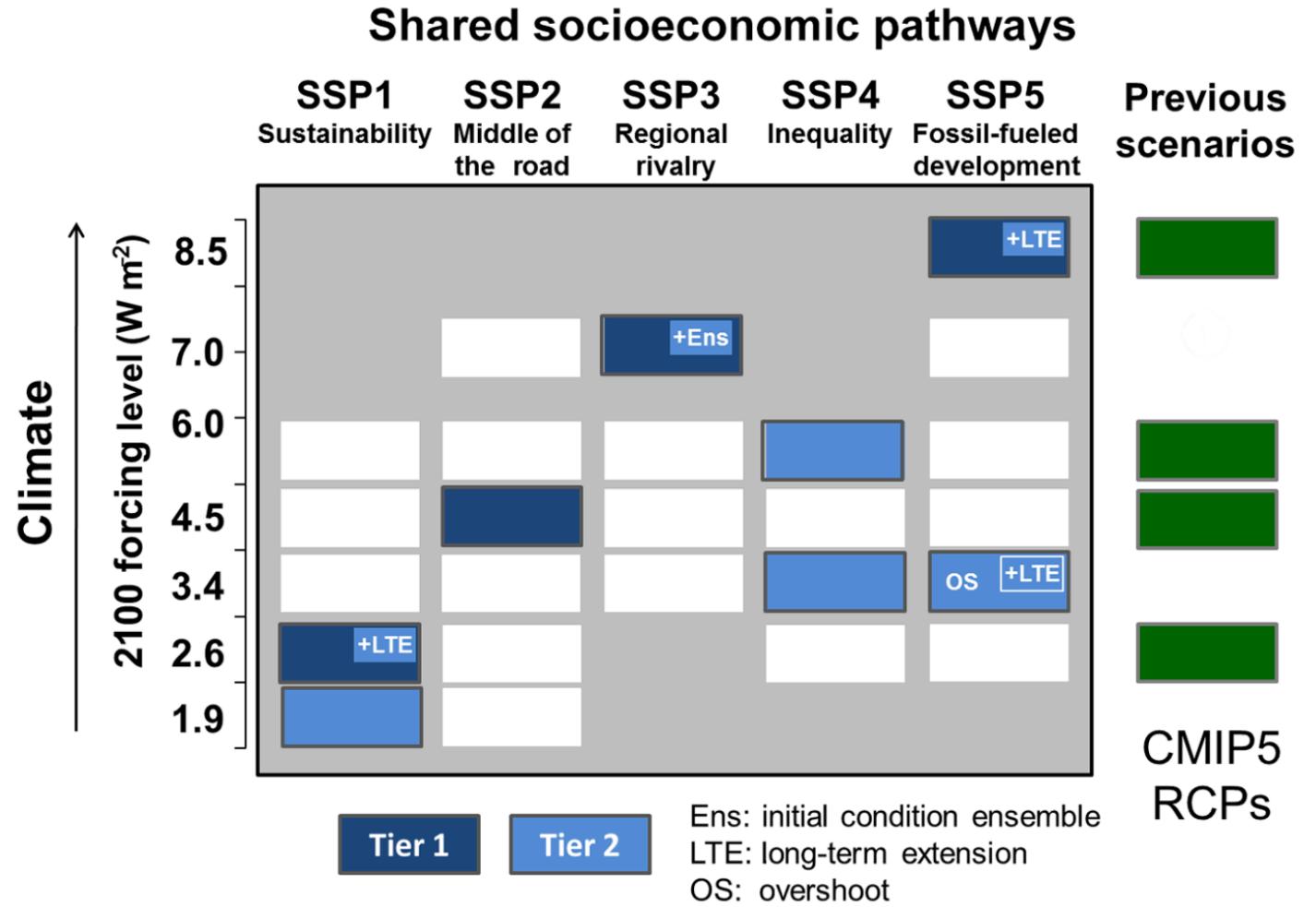
(a)

Global average surface temperature change

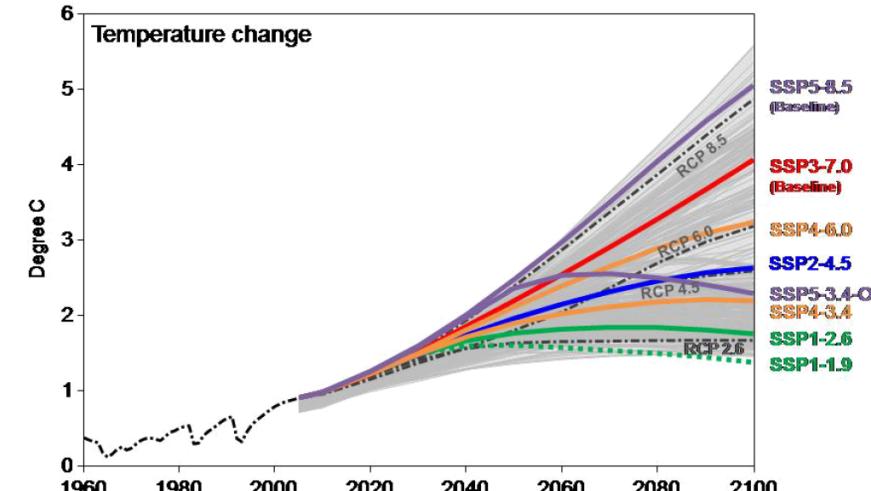
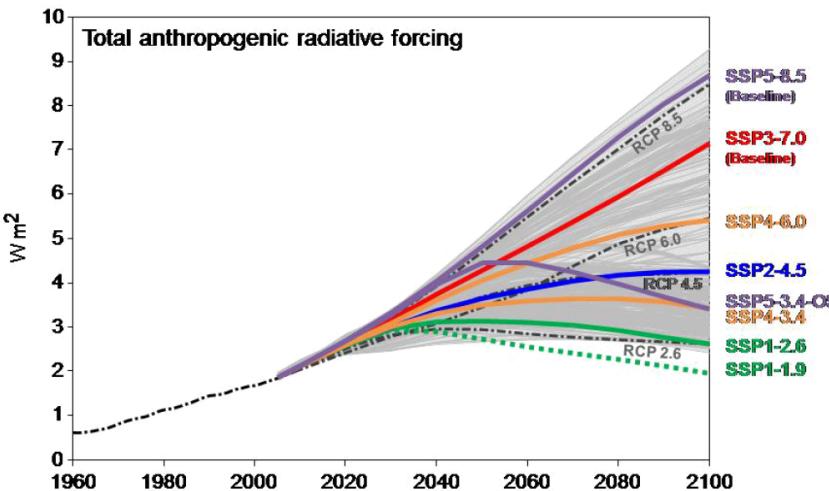
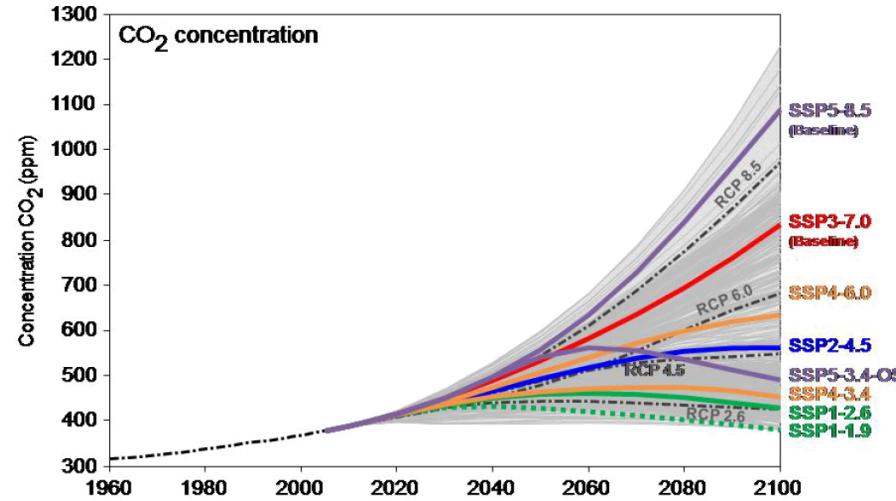
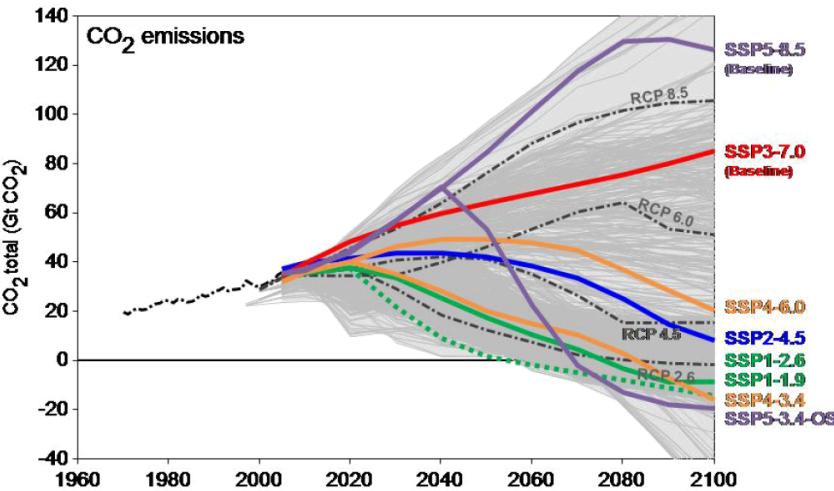


AR6 report: New scenarios

- Consider both radiative forcing and shared socioeconomic pathways
- Tier 1 and Tier 2 experiments for modelling groups to participate in CMIP6



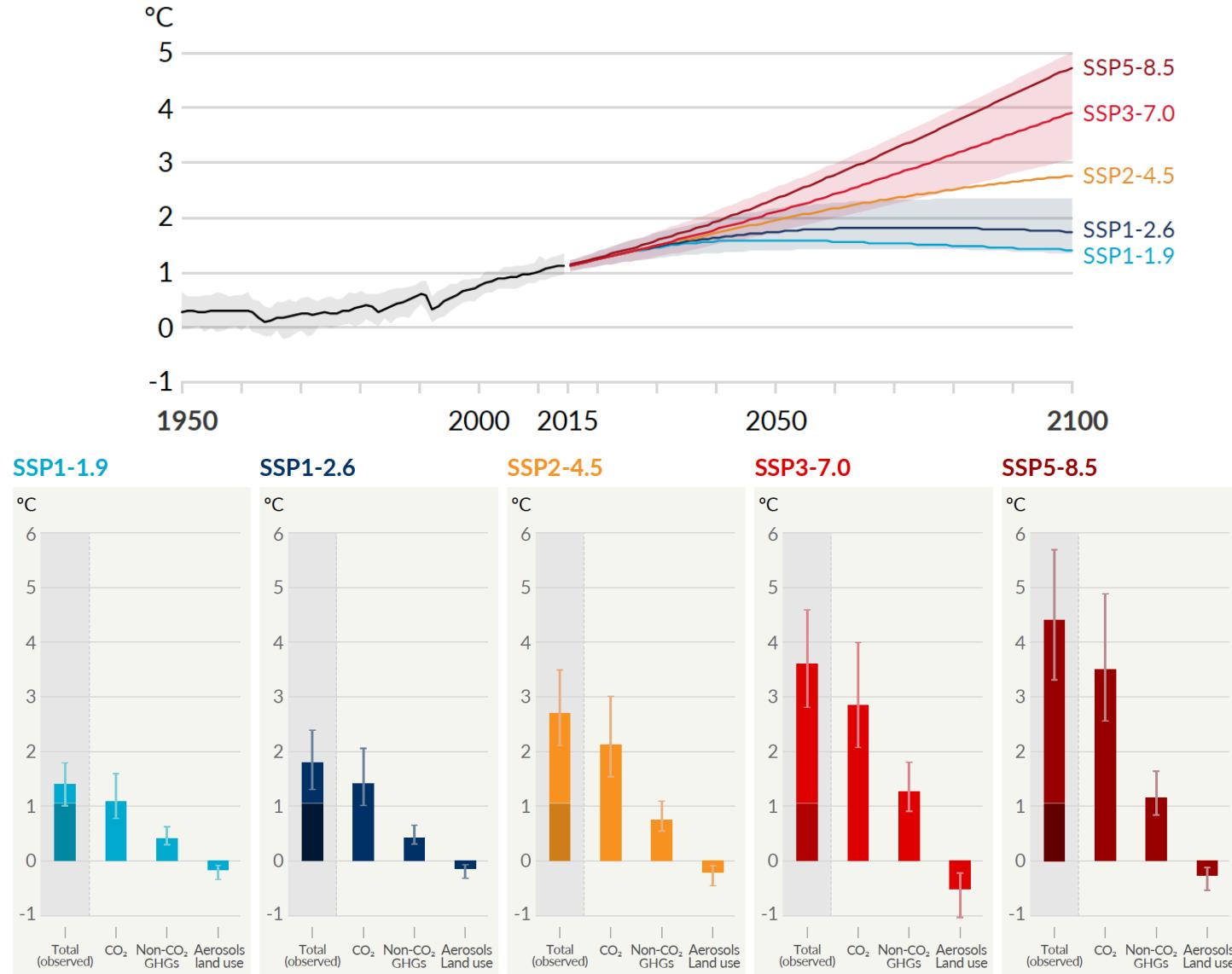
CMIP6: SSP Scenarios



Source: Riahi et al, 2016

AR6: T changes

a) Global surface temperature change relative to 1850-1900



CMIP5 vs CMIP6

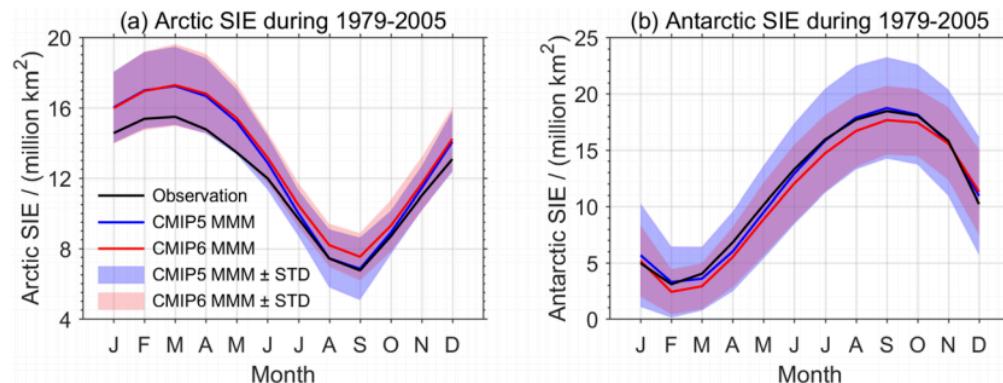
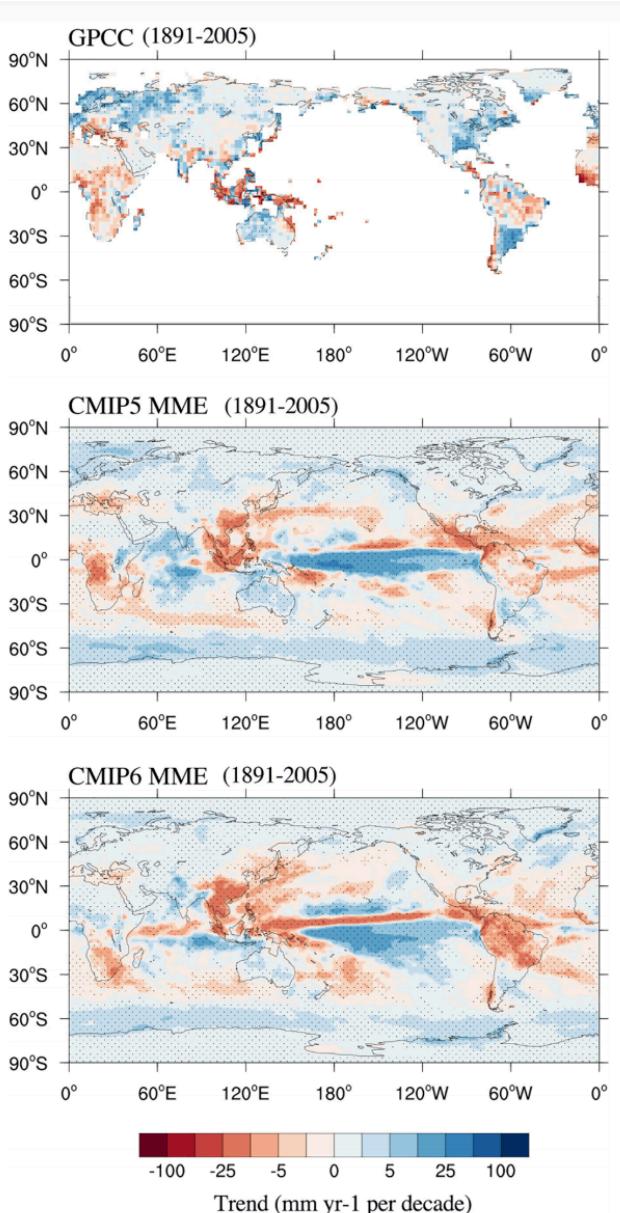
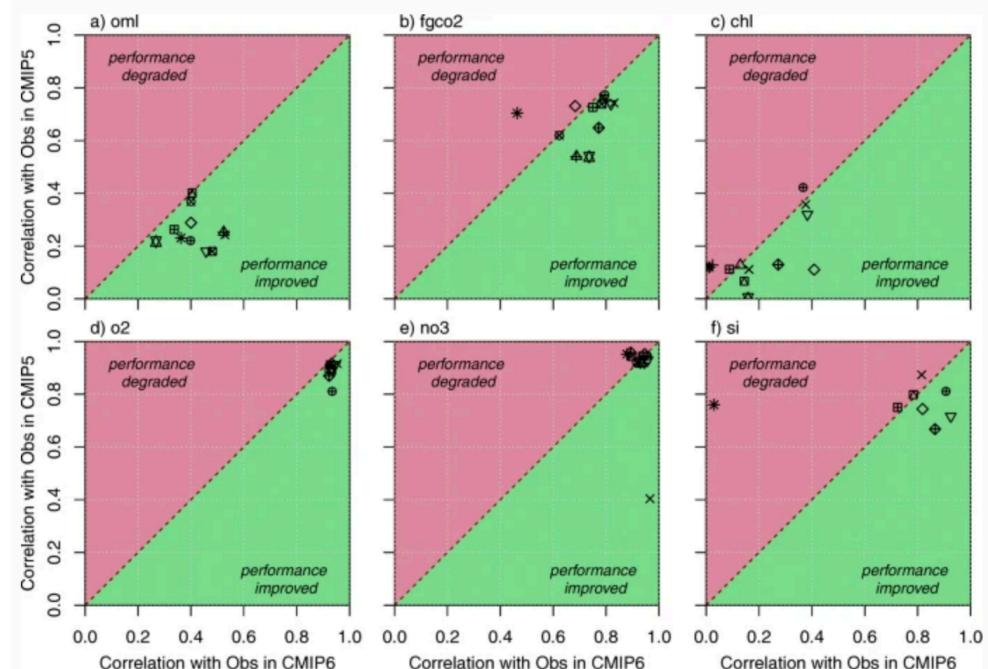


Fig. 6

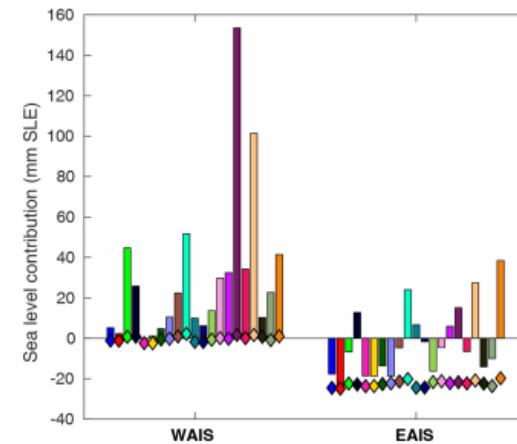
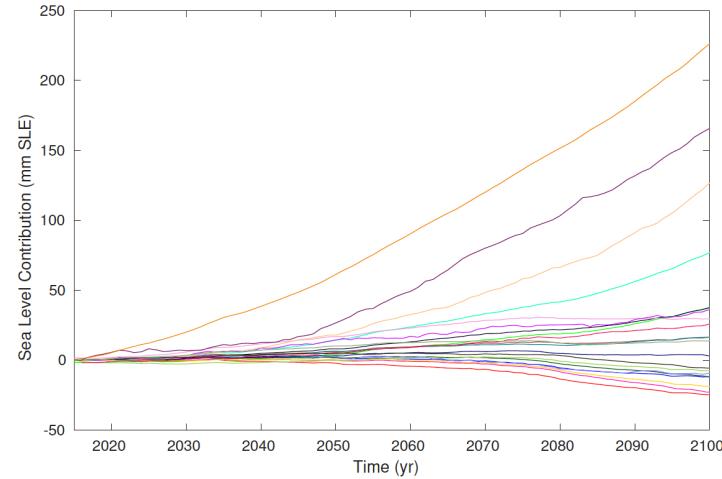
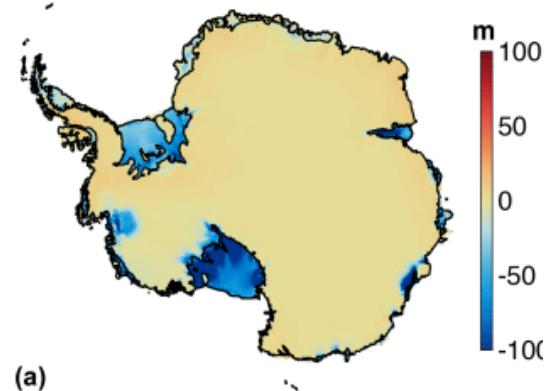


Other “MIPs” affiliated with CMIP6

- ISMIP (ice sheets)
- PMIP (paleoclimate)
- CFMIP (cloud feedbacks)
- GeoMIP (geoengineering)
- LUMIP (land-use)
- OMIP (ocean-focused)
- VolMIP (volcanic forcing)
- CORDEX (downscaling)

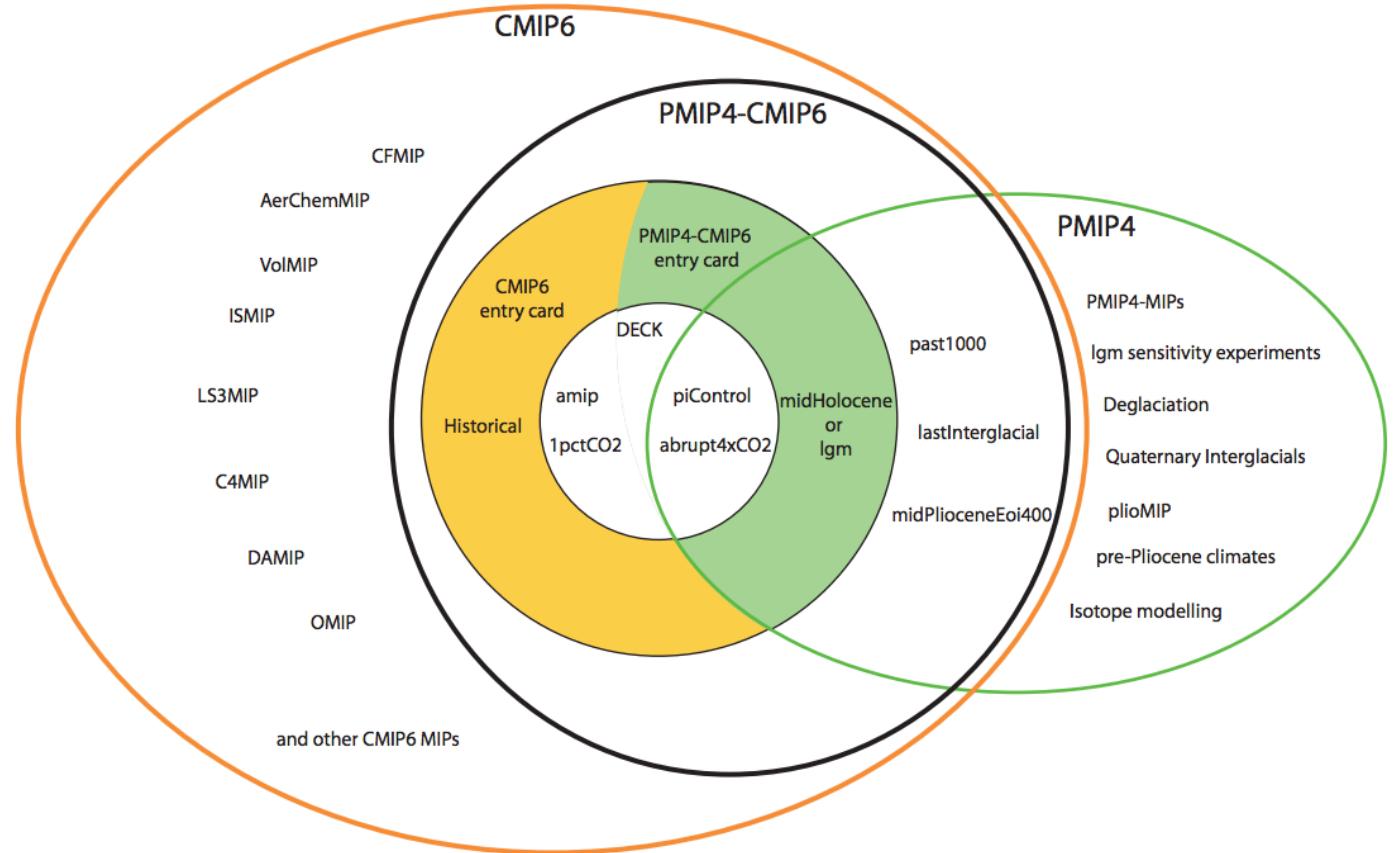
ISMIP6-Antarctica

- Used range of CMIP5 forcing, some CMIP6
- Large model spread
- High emission scenario: range of -8 to +30 cm
- Positive contributions from WAIS, but large range of how much
- Models split on EAIS direction of change

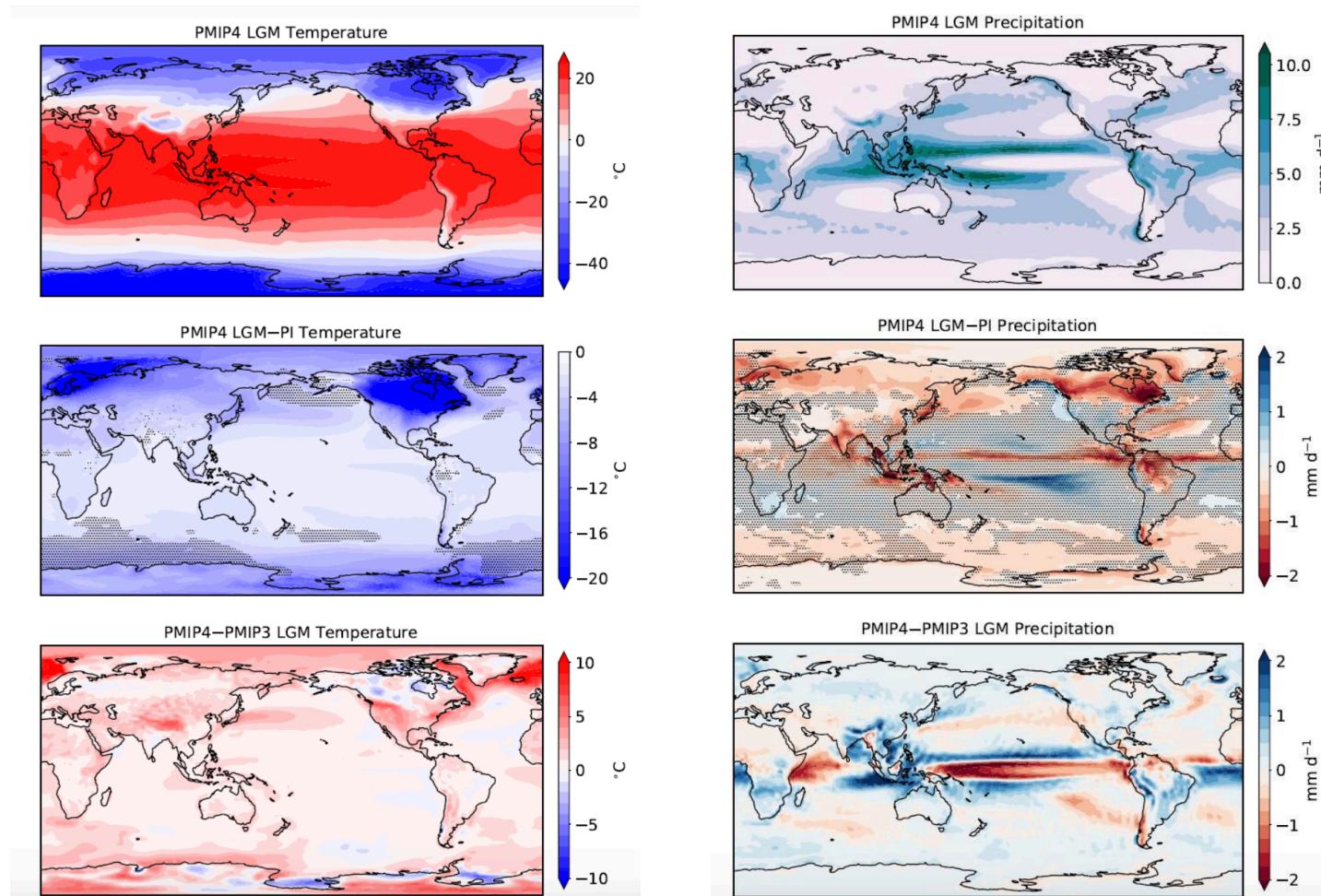


PMIP4

- Understand the response to climate to different climate forcings for documented states
- Last Millennium, Mid-Holocene (6 ka), LGM (21 ka), LIG (127 ka), mid-Pliocene WP (3.2 Ma)
- Need to account for different forcings + boundary conditions

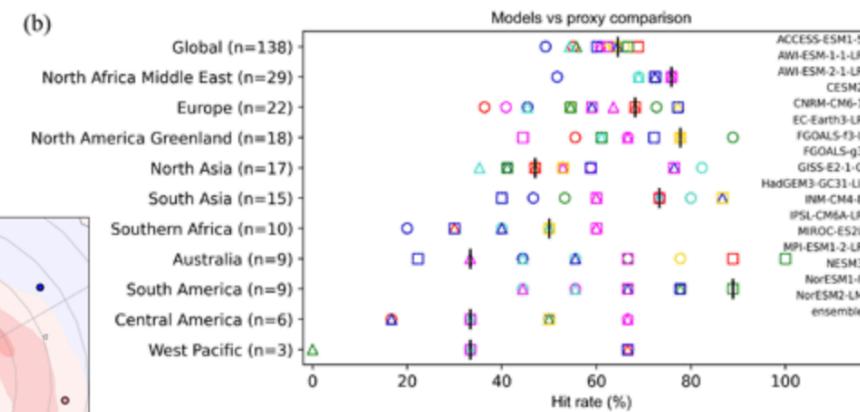
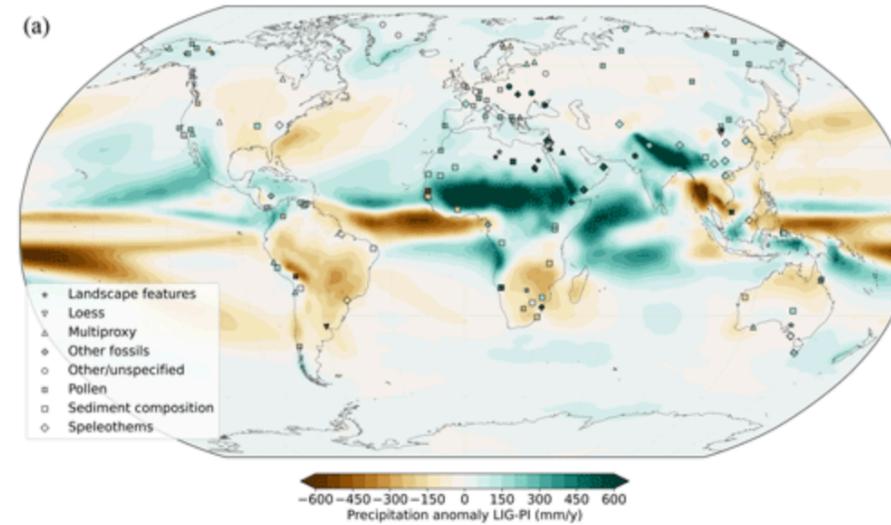
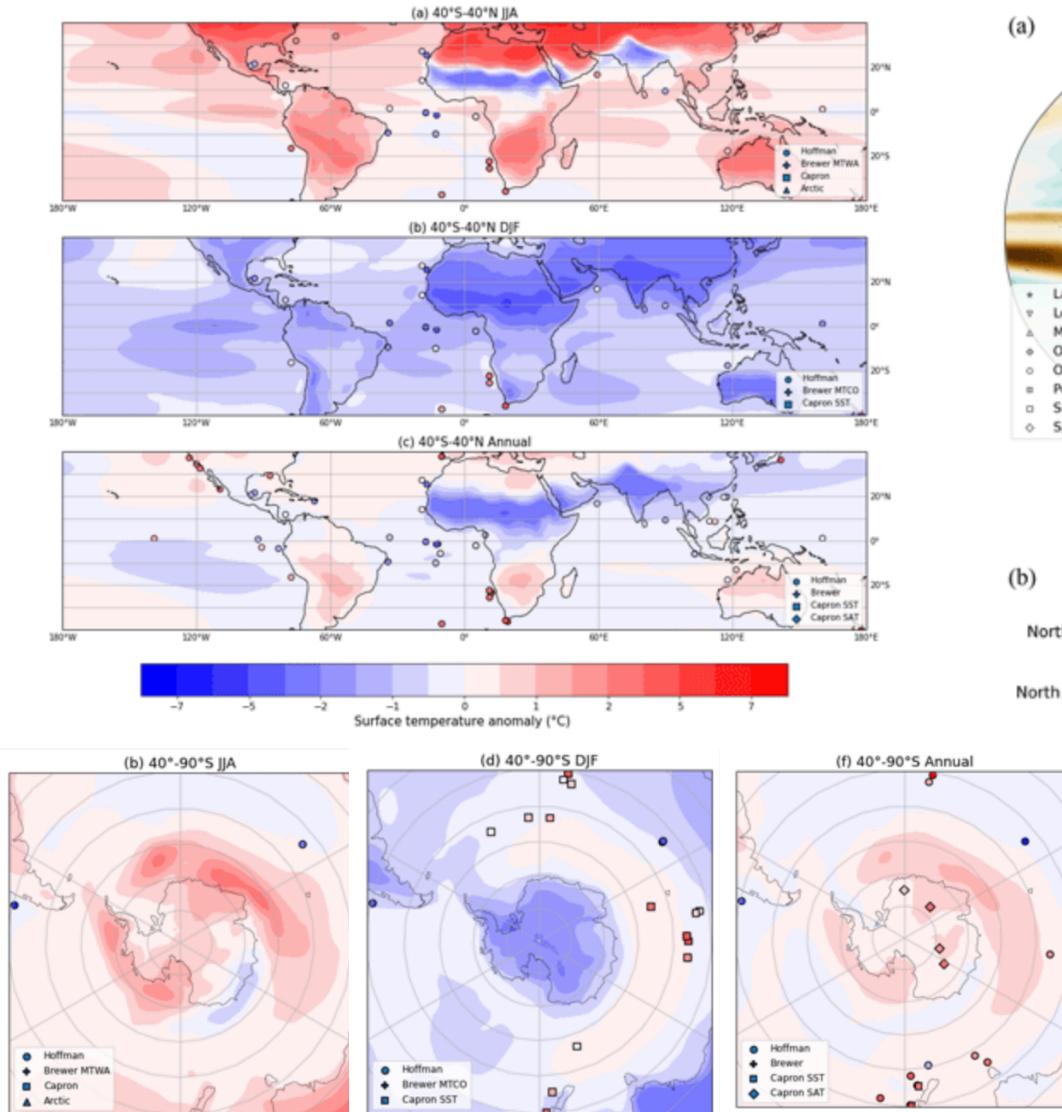


PMIP4 results: LGM



- PMIP4 LGM warmer/wetter than PMIP3
- Uses more realistic NH ice sheets

PMIP4 results: LIG



- Disagreement with proxies of DJF temp anomalies
- Precip anomalies show wide range of “success”

Summary of CMIP

- Includes many MIPs, not just climate projections
- Climate projections do not include meltwater from ice sheets
- AIS modelling very uncertain
- Deglaciation simulations expected for CMIP6 (lower Tier experiments)
- Paleoclimate simulations are the best way to assess models – though model-proxy comparisons are difficult (more from Liz)

Global Model Data Availability

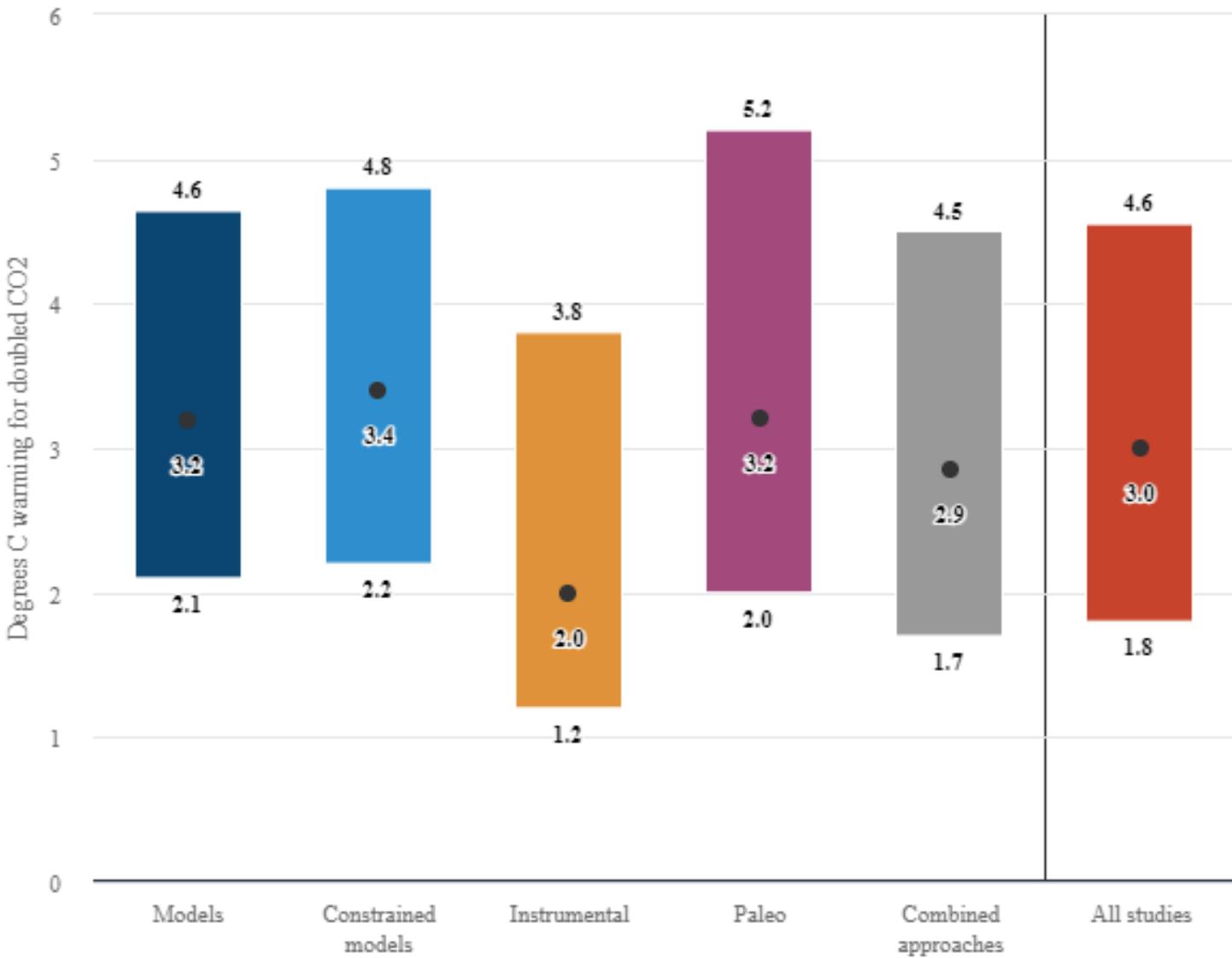
- Outputs are archived for analysis by anyone!
- Sponsored by the World Climate Research Program (WCRP)
- CMIP outputs (includes PMIP)
 - CMIP3 for the Fourth Assessment (AR4)
 - CMIP5/PMIP3 for the Fifth Assessment (AR5)
 - CMIP6/PMIP4 for the Sixth Assessment (AR6)
- In tutorial, we will download output from CMIP6 portal

Climate sensitivity

- How much does the surface warm with a doubling of CO₂?
- IPCC AR5 estimates of equilibrium climate sensitivity are between **+1.5 - 4.5°C** for a doubling of pre-industrial CO₂, using models and paleoclimate evidence



Equilibrium Climate Sensitivity from different sources

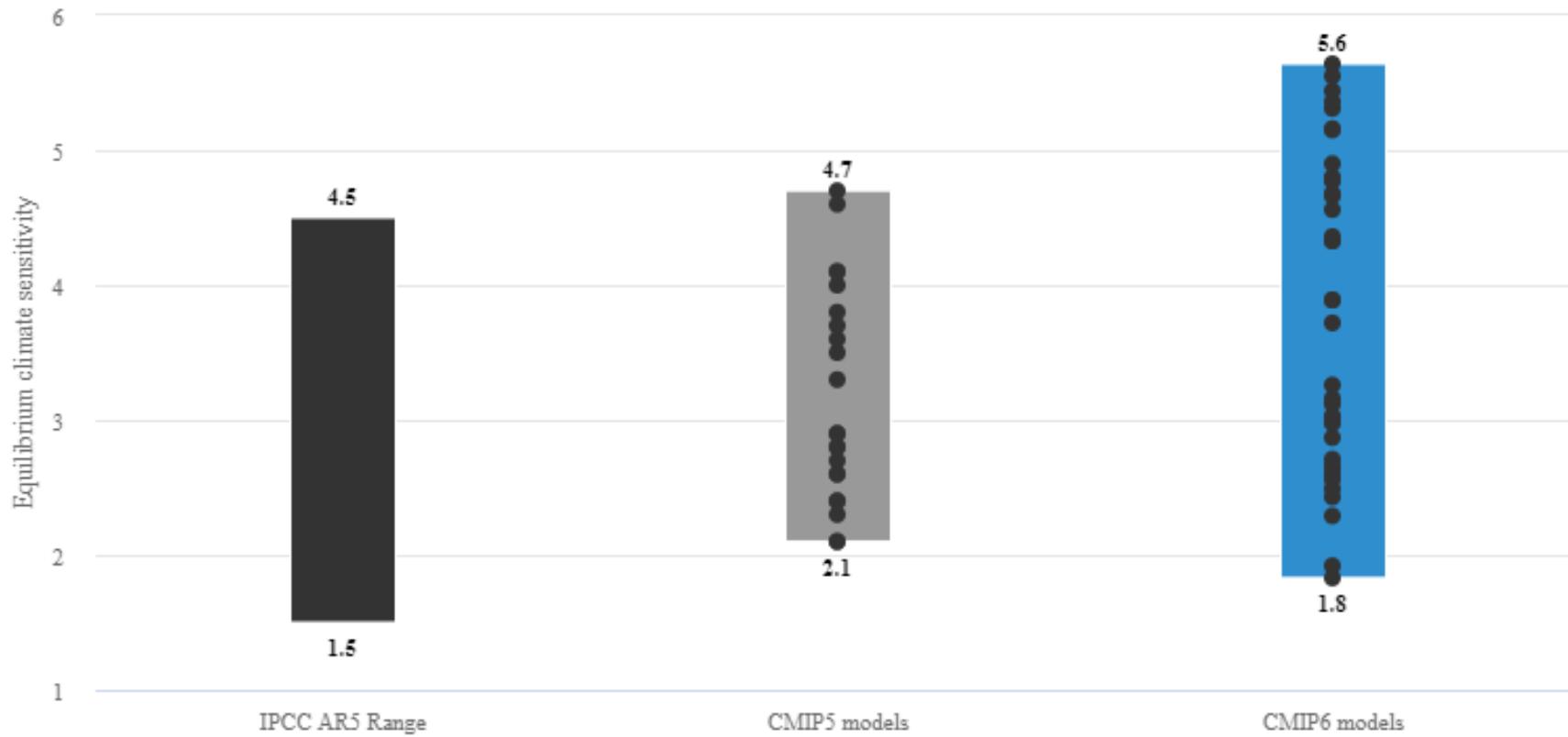


Equilibrium vs. Transient climate sensitivity

- Model experiments
 - Equilibrium climate sensitivity (ECS) = instantaneous doubling of CO₂, run model to equilibrium (climate has stabilized and only minimal trends remain)
 - Transient climate response (TCR) = the amount of warming that would occur when CO₂ doubles, having increased gradually by 1% each year.
- TCR more closely matches the way the CO₂ concentration has changed in the past; the distribution of heat between the atmosphere and oceans has not yet reached equilibrium
- TCR tends to be lower than ECS. The IPCC AR5 gives an ECS of 1.5 - 4.5°C, but a likely TCR of only 1.0 - 2.5°C

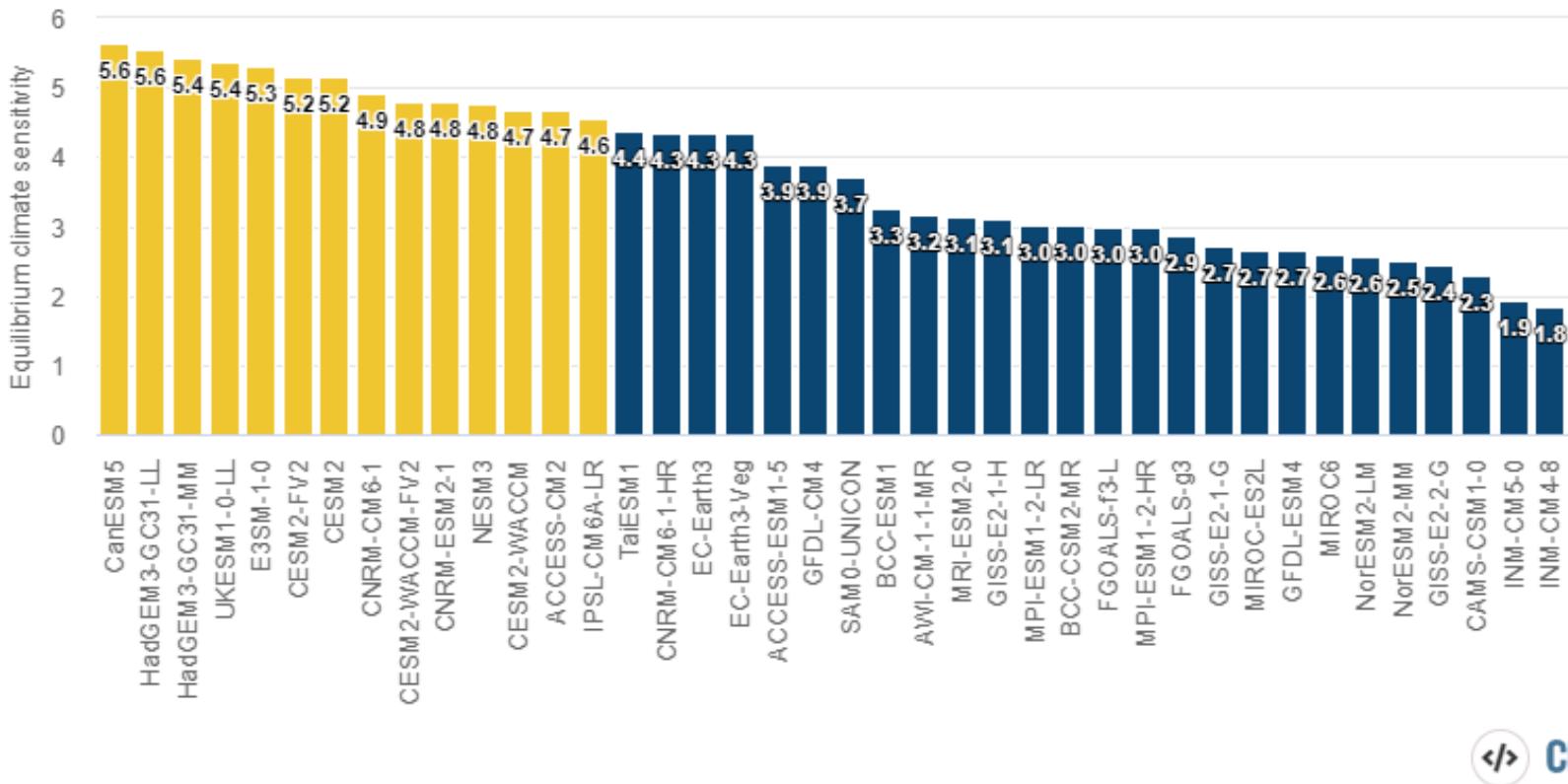
Climate sensitivity in CMIP5/6

CMIP6 models show a wider range of climate sensitivity



Likely ECS range (e.g. with an estimated 66% chance of occurring) from the IPCC AR5 (black bar), CMIP5 model ECS values (grey), and CMIP6 model ECS values (blue). Chart by Carbon Brief using [Highcharts](#).

Climate sensitivity in CMIP6 models



ECS values from the 40 CMIP6 models available as of May 2020 where necessary experiments to calculate ECS (using the Gregory method) are currently available. Models with an ECS above the IPCC AR5 likely range are shown in yellow. Note that not all models shown are independent, as some modeling groups – such as CESM2 – have multiple versions. Chart by Carbon Brief using Highcharts.



Why are CMIP6 models more sensitive?

- Many CMIP6 models feature improved representation of clouds, which has increased climate sensitivity in these models
- Feedbacks between components represent a large source of uncertainty

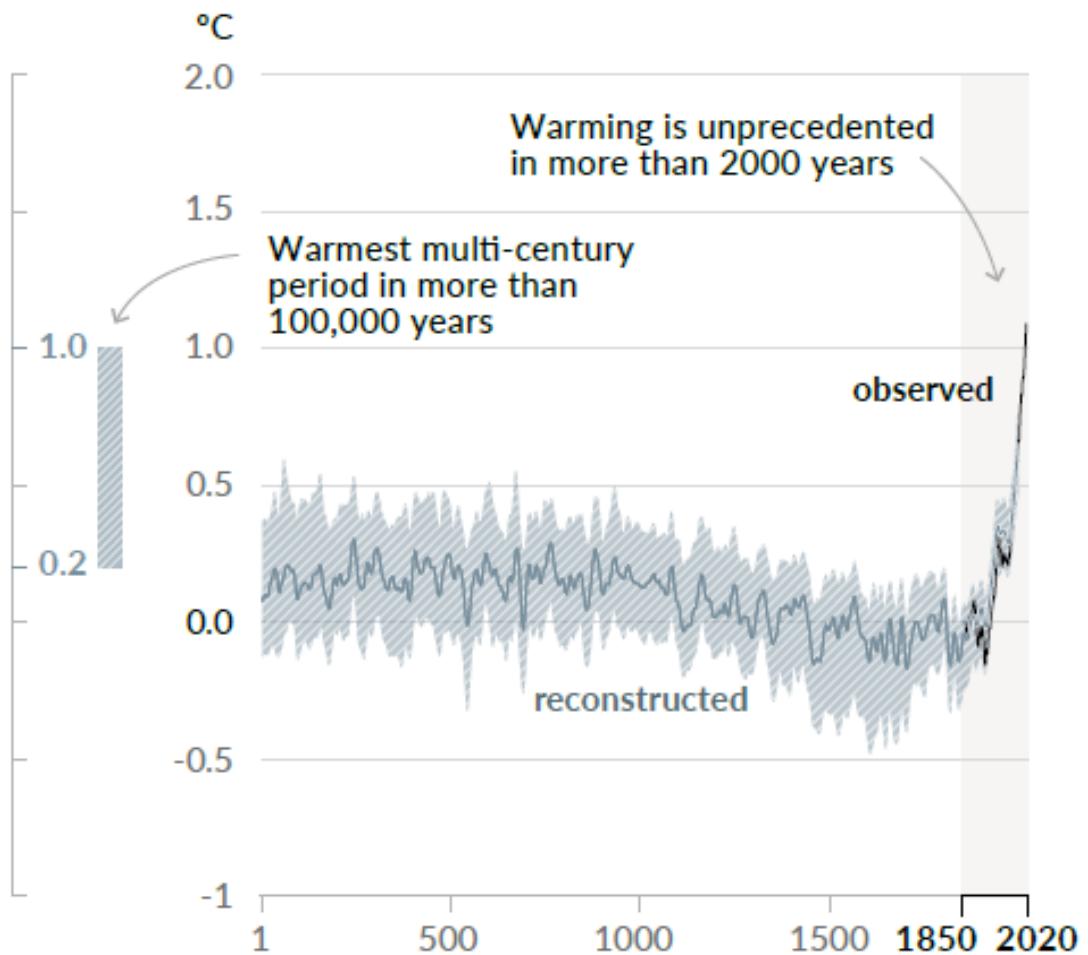
To be continued....

IPCC AR6 WG1 report: highlights

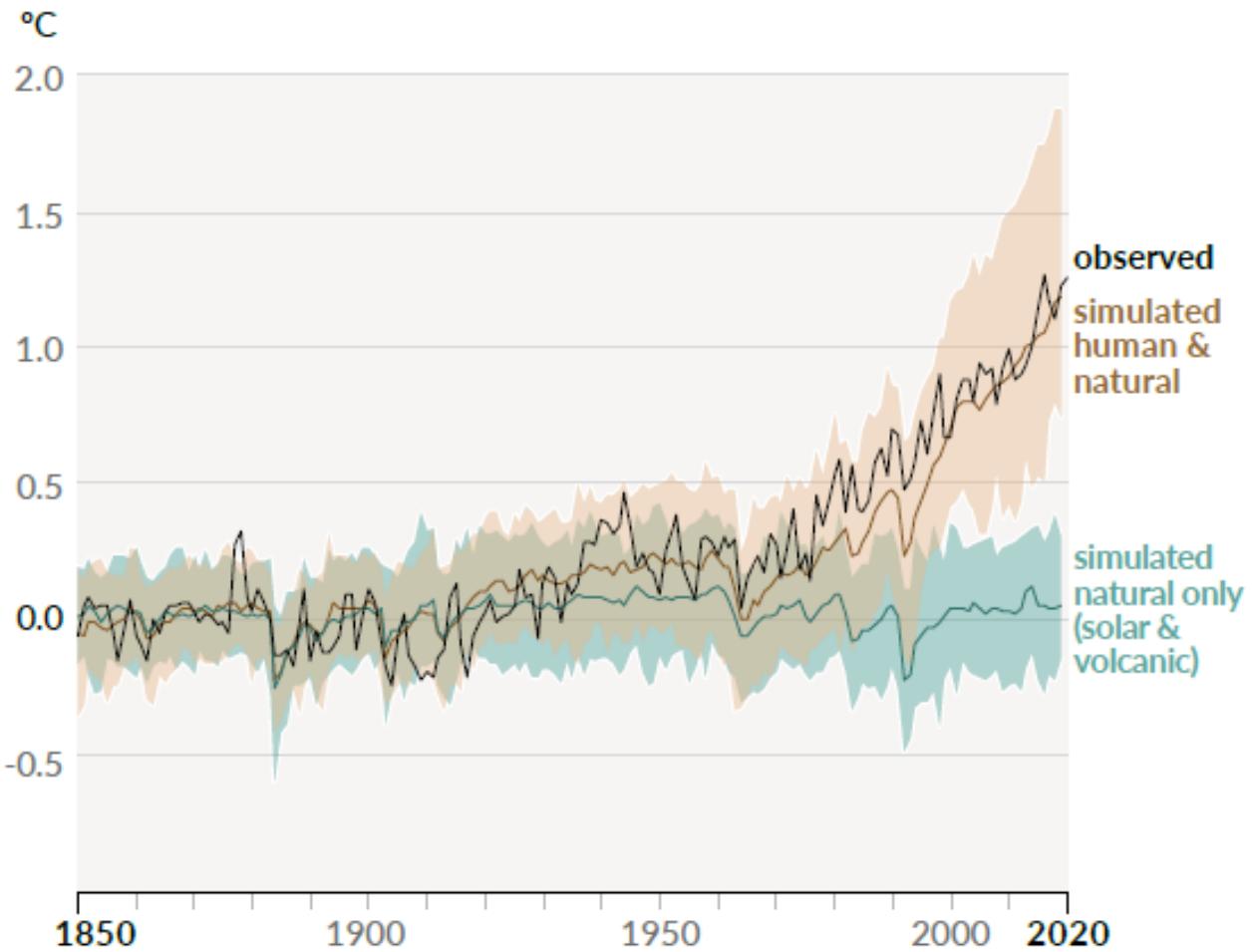
- “**It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.**”
- Each of the last four decades has been successively warmer than any decade that preceded it since 1850.
- The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019¹¹ is 0.8°C to 1.3°C, with a best estimate of 1.07°C.
- There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability. ... It is *very likely* that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only *limited evidence*, with *medium agreement*, of human influence on the Antarctic Ice Sheet mass loss.
- Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. ... Human influence was *very likely* the main driver of these increases since at least 1971.
- **The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.**

Changes in global surface temperature relative to 1850-1900

a) Change in global surface temperature (decadal average) as reconstructed (1-2000) and observed (1850-2020)



b) Change in global surface temperature (annual average) as observed and simulated using **human & natural** and **only natural factors** (both 1850-2020)



AR6 WG1 interactive atlas

<https://interactive-atlas.ipcc.ch/>

Thank you for your
attention!



References

1. Hannah, L. Climate Change Biology, 2010. <https://doi.org/10.1016/C2009-0-01619-5>
2. Yang, M.; Zuo, R.; Wang, L.; Chen, X. A Simulation Study of Global Evapotranspiration Components Using the Community Land Model. *Atmosphere* **2018**, 9, 178. <https://doi.org/10.3390/atmos9050178>
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