Climate model basics

ASP Modelling Winter School

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Antarctica New Zealand

Antarctic Science Platform

NIWA
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VICTORIA UNIVERSITY OF WELLINGTON
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI

Antarctic Research Centre
Te Pūtahi Rangahau i te Kōpakatanga ki te Tonga

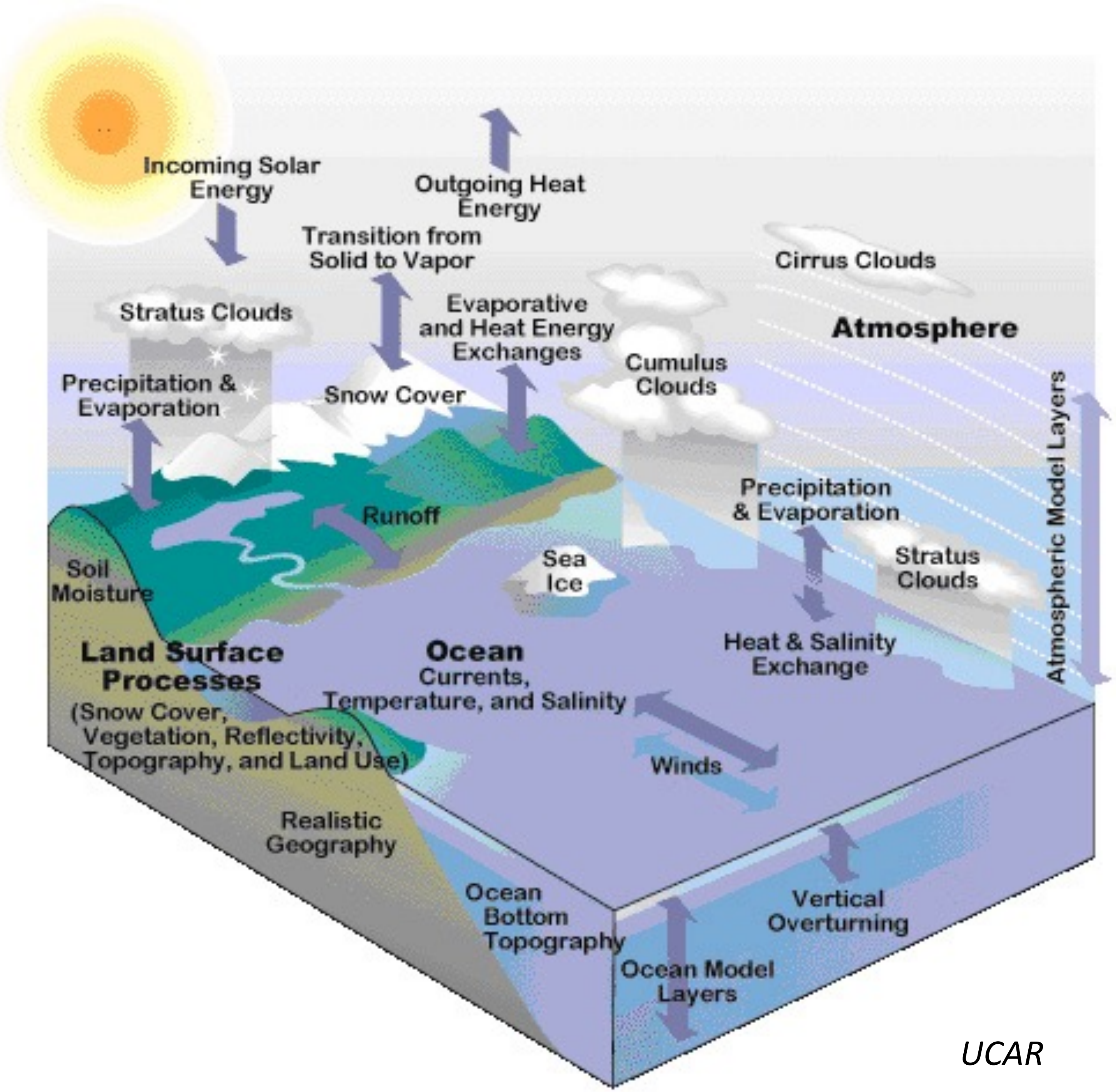
GNS SCIENCE
TE PŪ AO

Topics covered

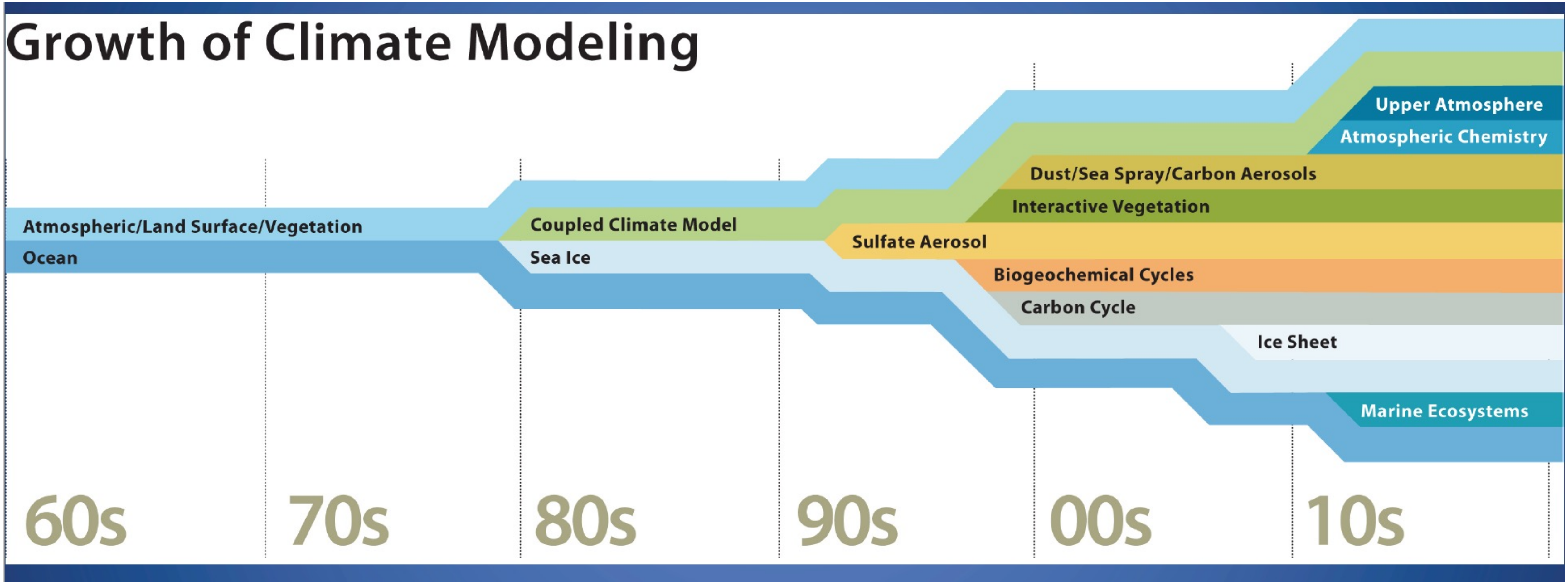
- Climate model components & types
- The carbon cycle & climate sensitivity
- CMIP and other MIPs
- IPCC AR6 interactive atlas

Climate Model Components

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



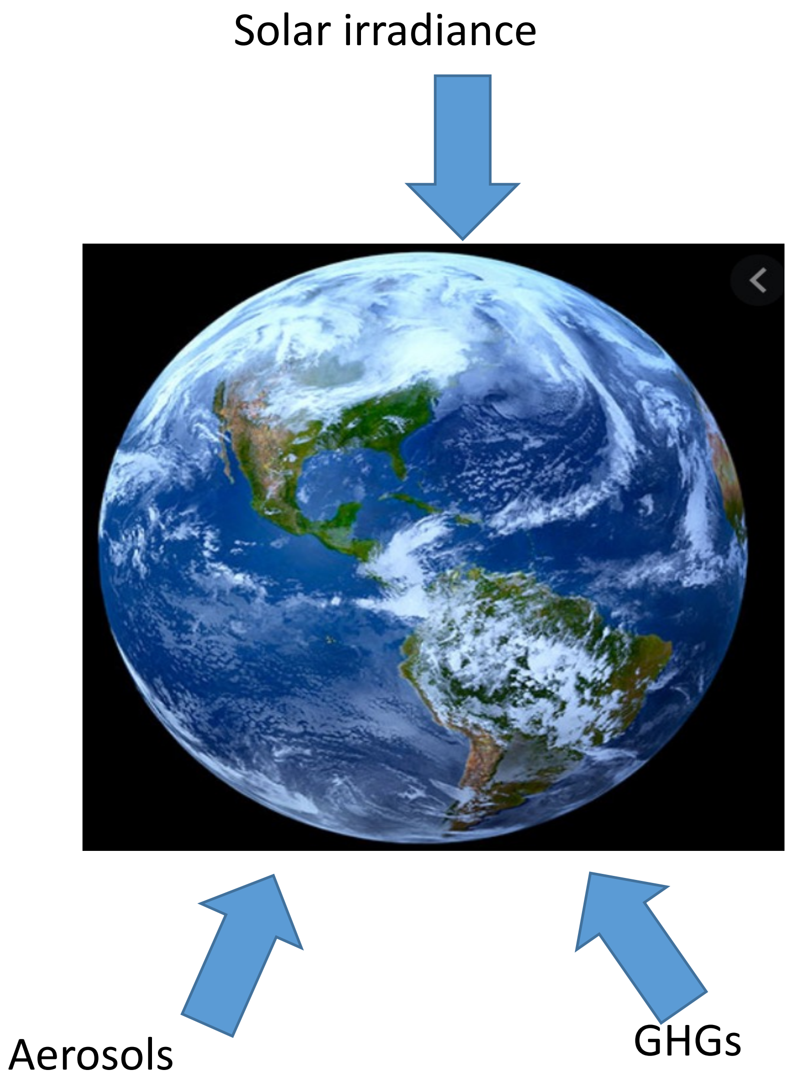
UCAR


Growth of Climate Modeling
Upper Atmosphere
Atmospheric Chemistry
Dust/Sea Spray/Carbon Aerosols
Interactive Vegetation
Atmospheric/Land Surface/Vegetation
Coupled Climate Model
Sulfate Aerosol
Ocean
Sea Ice
Biogeochemical Cycles
Carbon Cycle
Ice Sheet
Marine Ecosystems
60s
70s
80s
90s
00s
10s

Inputs to a climate model

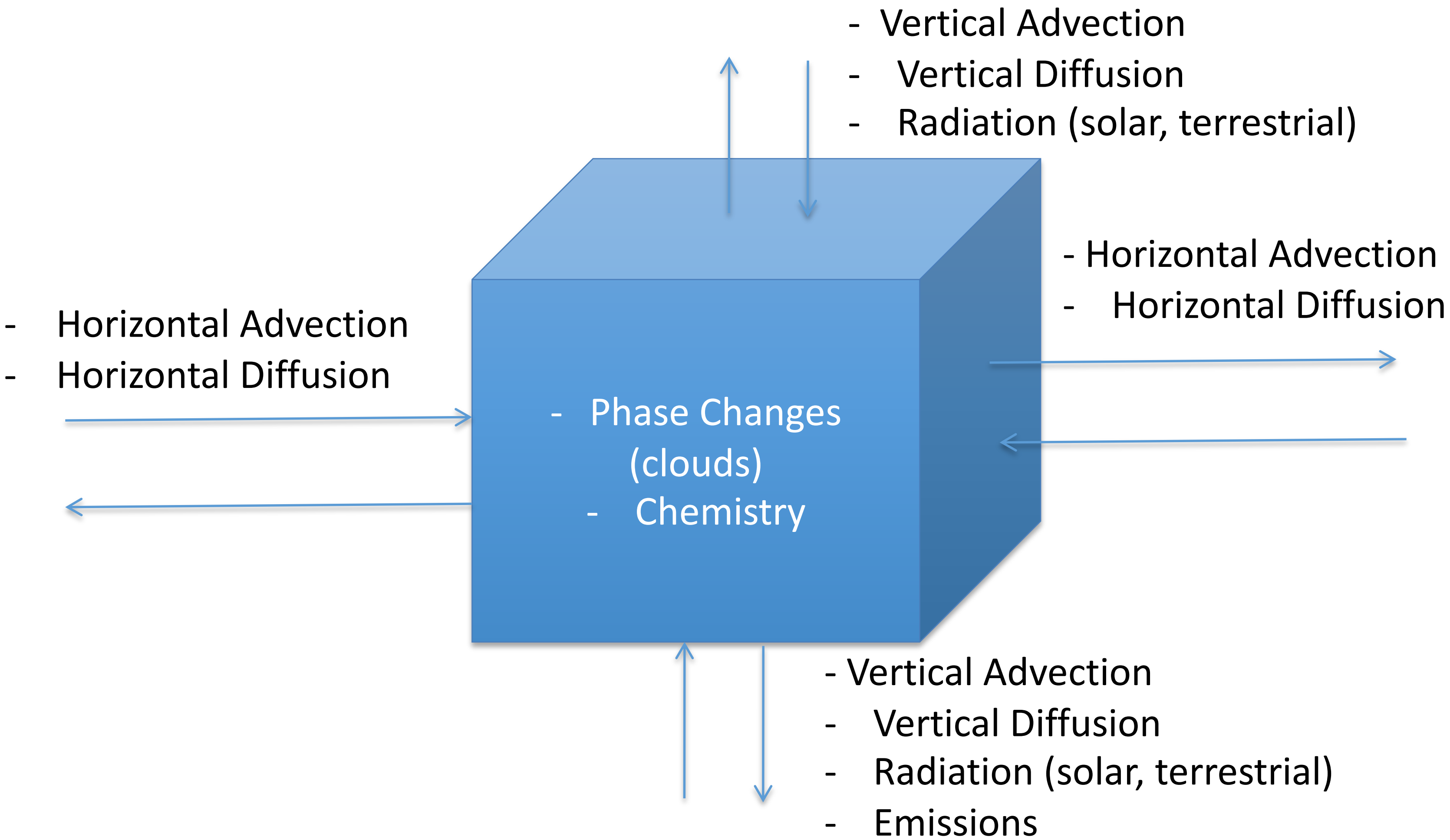
- Boundary conditions: Orography/bathymetry, land/sea mask, land surface properties (vegetation, ice, lake, etc.), orbital configuration

- Forcings: Solar radiation, volcanic aerosols, greenhouse gases, ice sheet meltwater



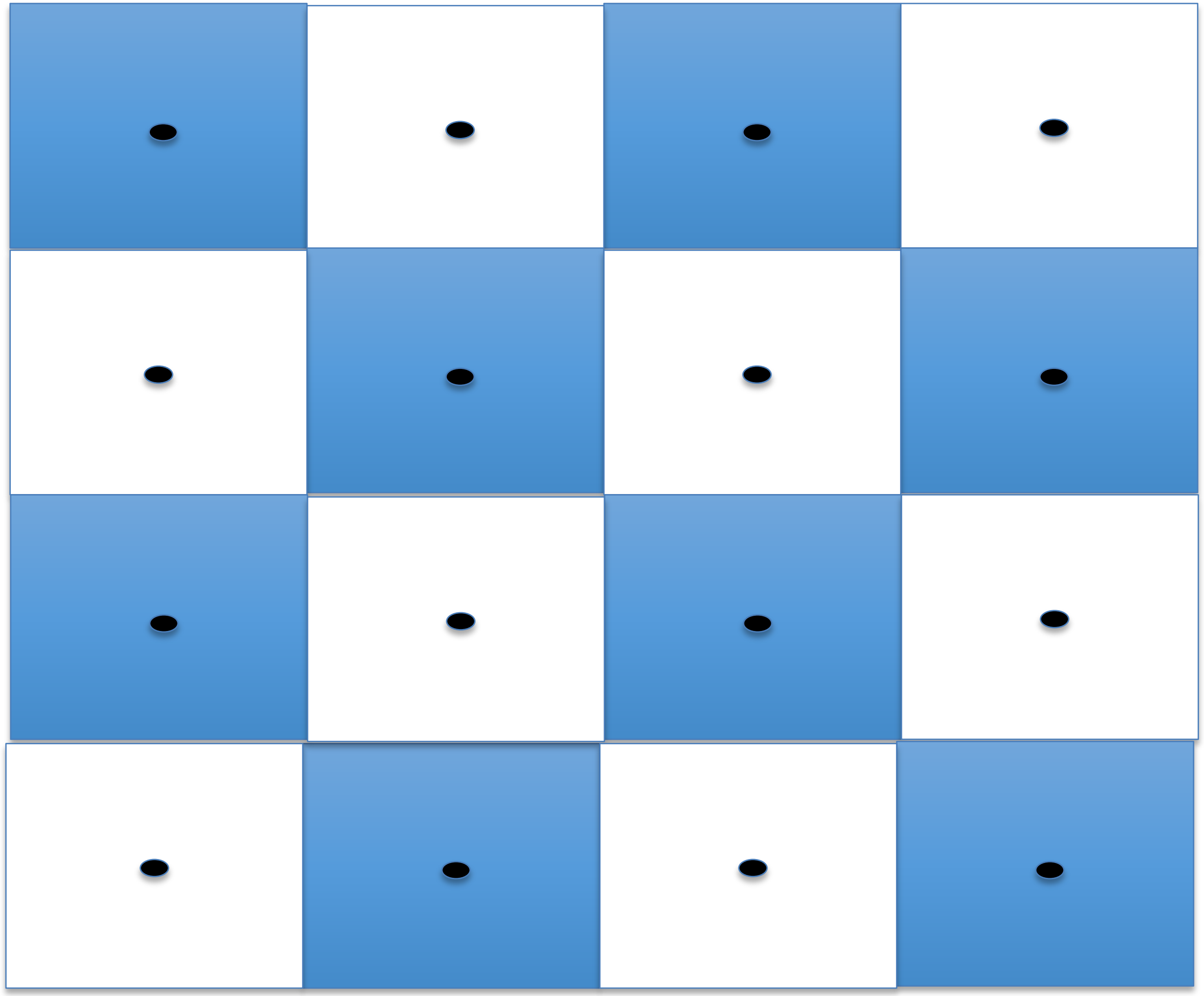
Atmospheric Models

- 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”

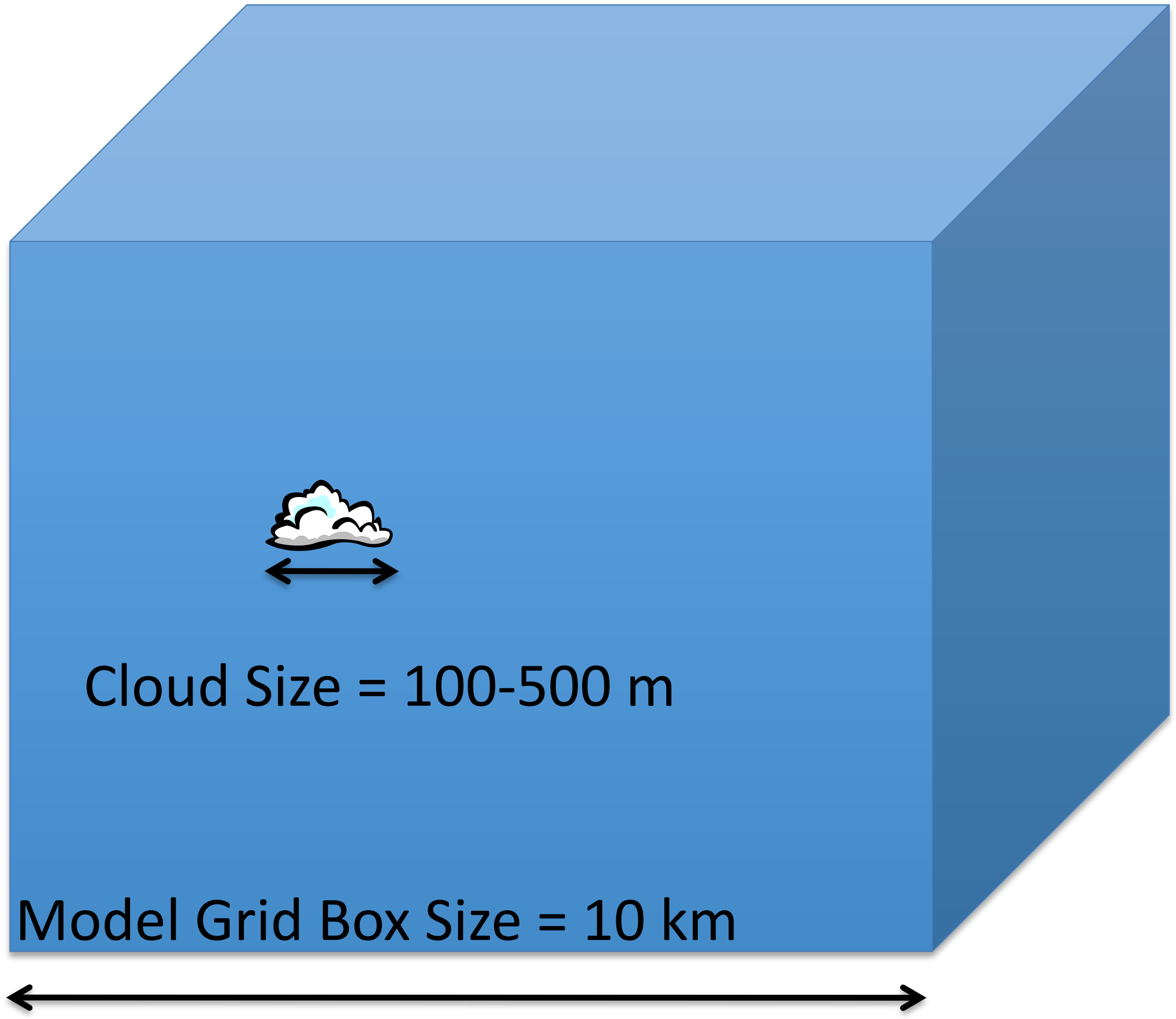


What is a parameterization?

- 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)

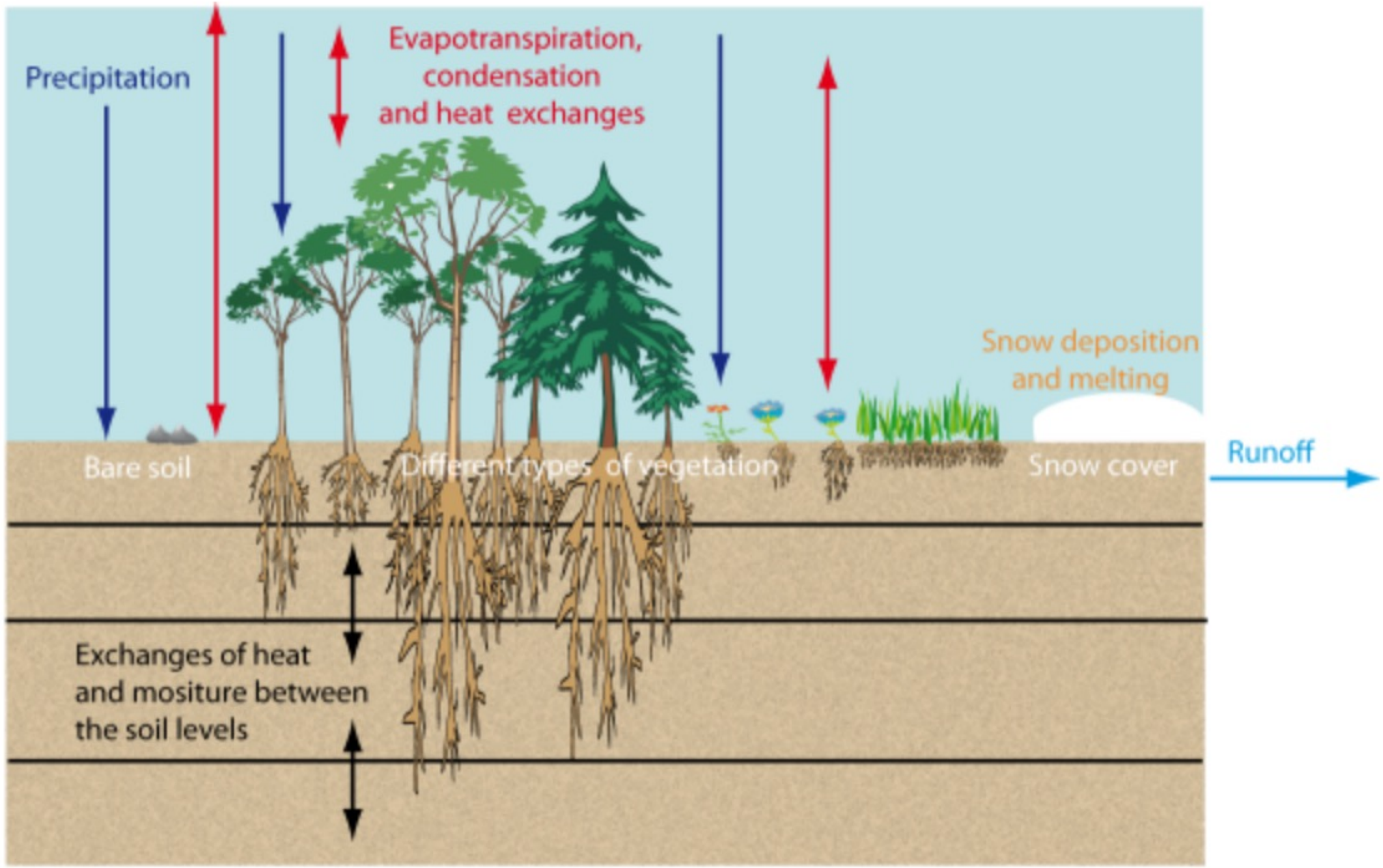
Parameterization example

- 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



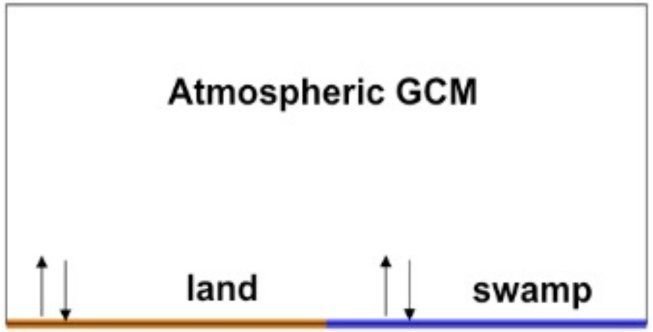
Land-Surface Parameterization

- 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

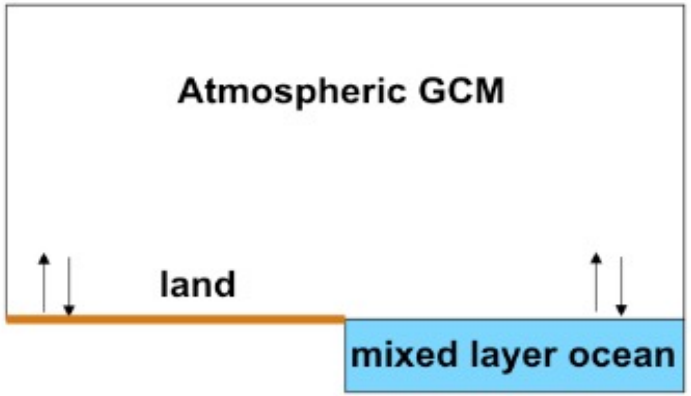


$$S_{\downarrow}(1-\alpha)+F_{\downarrow}-F_{\uparrow}-SH-LH=0$$

https://modelingguru.nasa.gov/docs/DOC-1752

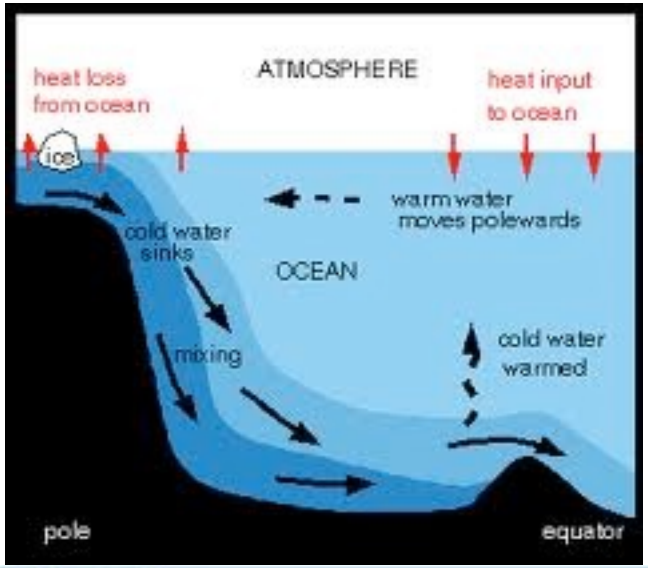
Oceans:
Slab Ocean Model

- 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

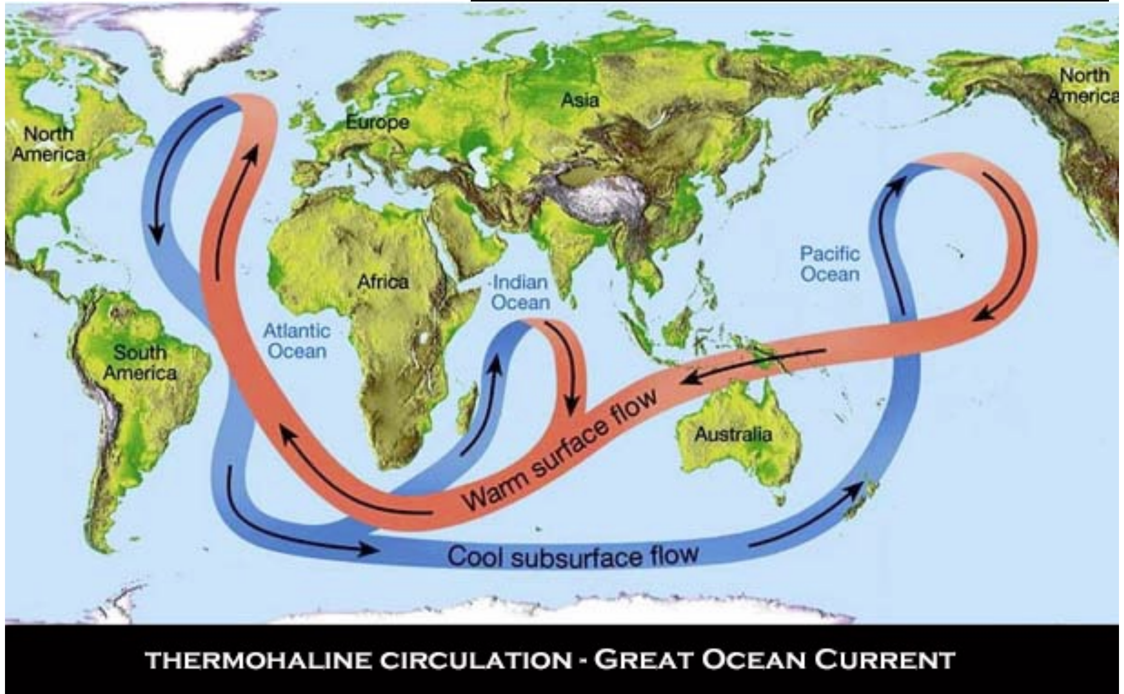


$$\rho c_p h \frac{\partial T}{\partial t} = S_{\downarrow}(1-\alpha) + F_{\downarrow} - F_{\uparrow} - SH - LH$$

Oceans:
Full Ocean Model

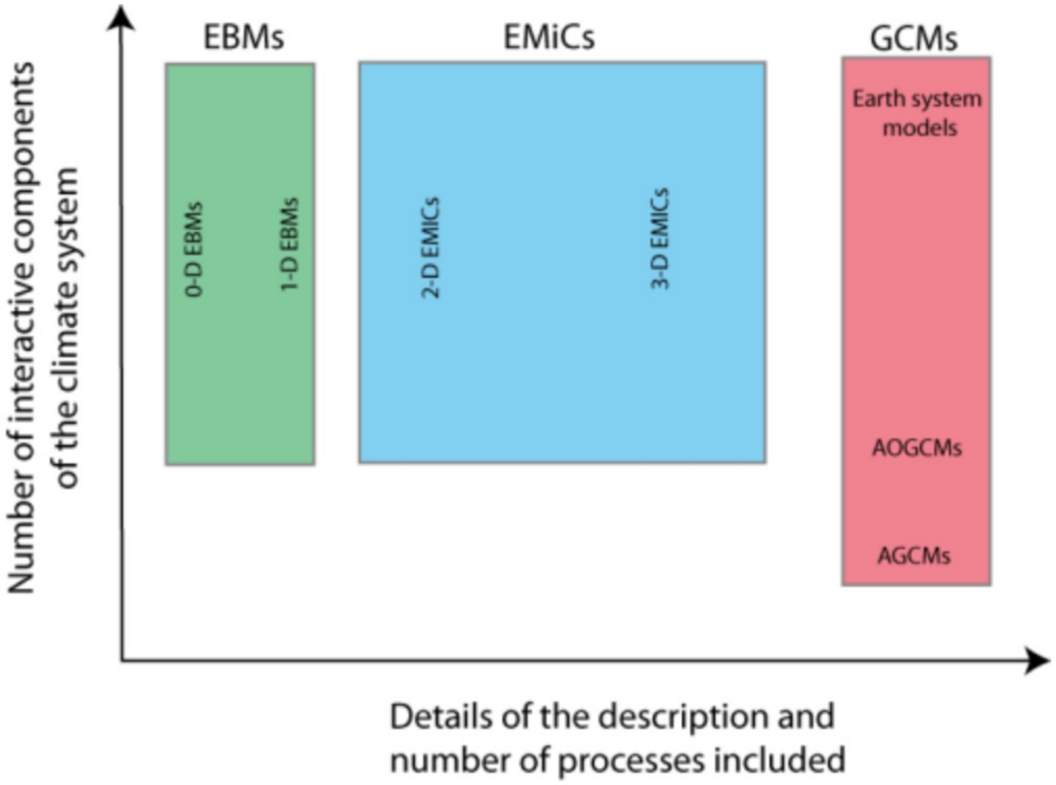


- More computationally expensive
- Includes advection, diffusion & heat storage
- Good representation of ocean-atm feedbacks
- Usually need to run for long time periods to get the ocean to equilibrate (e.g., deep ocean can take 1000+ years to truly equilibrate)



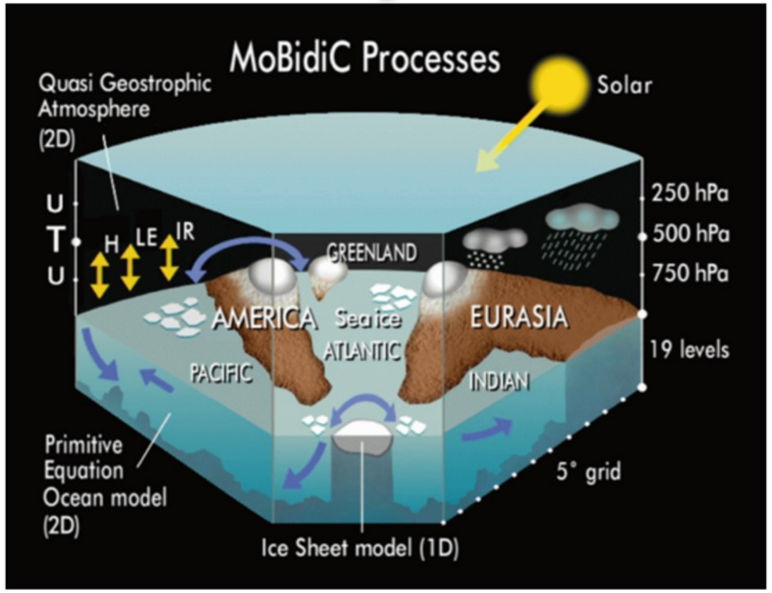
Levels of complexity

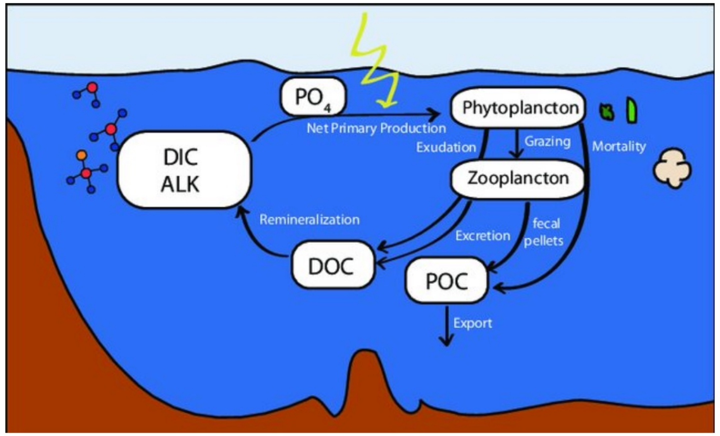
- Different models for different applications
- More processes included mean more computationally expensive to run



Levels of complexity: Intermediate complexity models

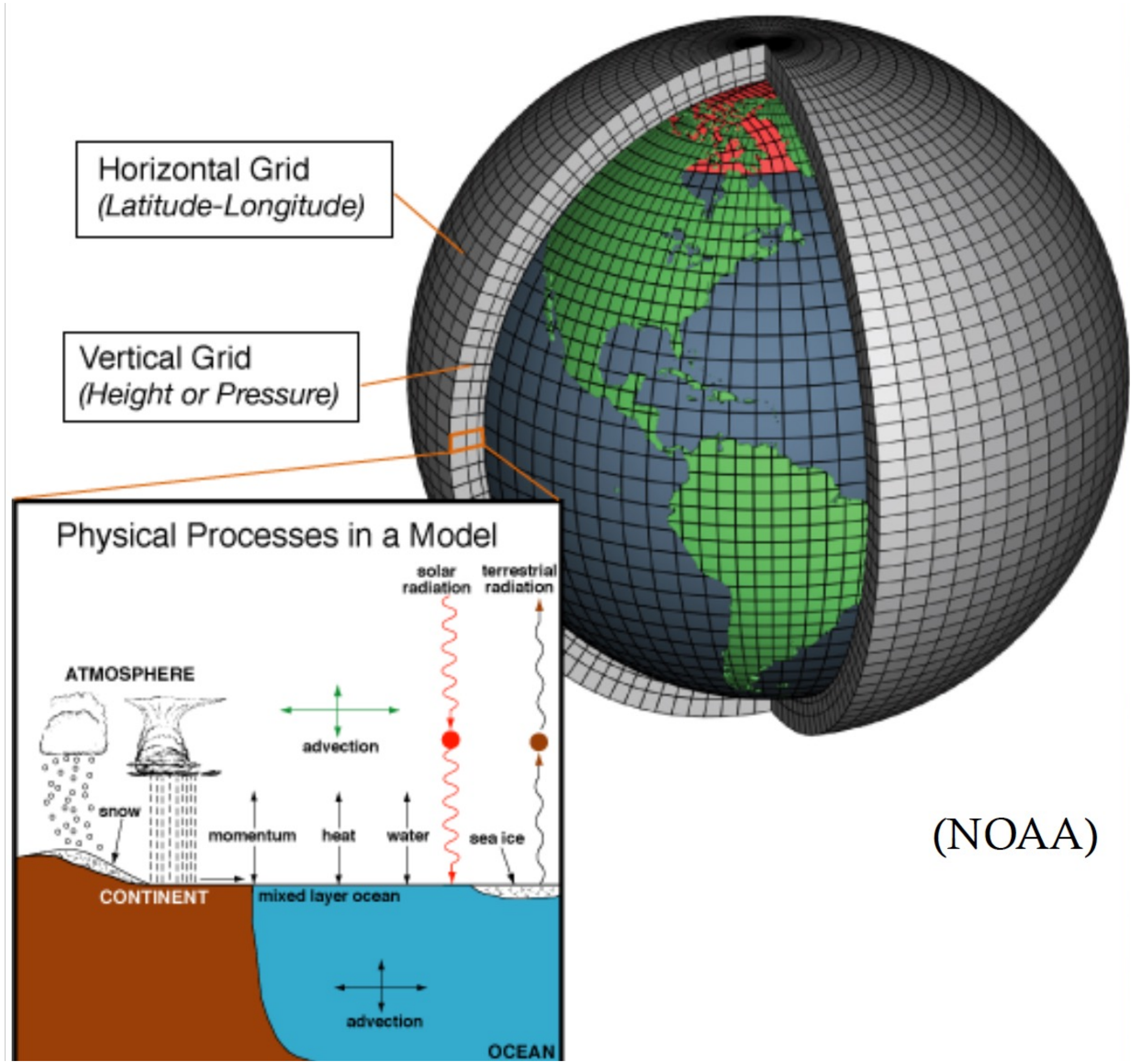
- EMICs include representation of Earth's geography
- Some components simplified/low resolution
- Other components similar to higher-res models
- Efficient to run for very long timescales





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



(NOAA)

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)

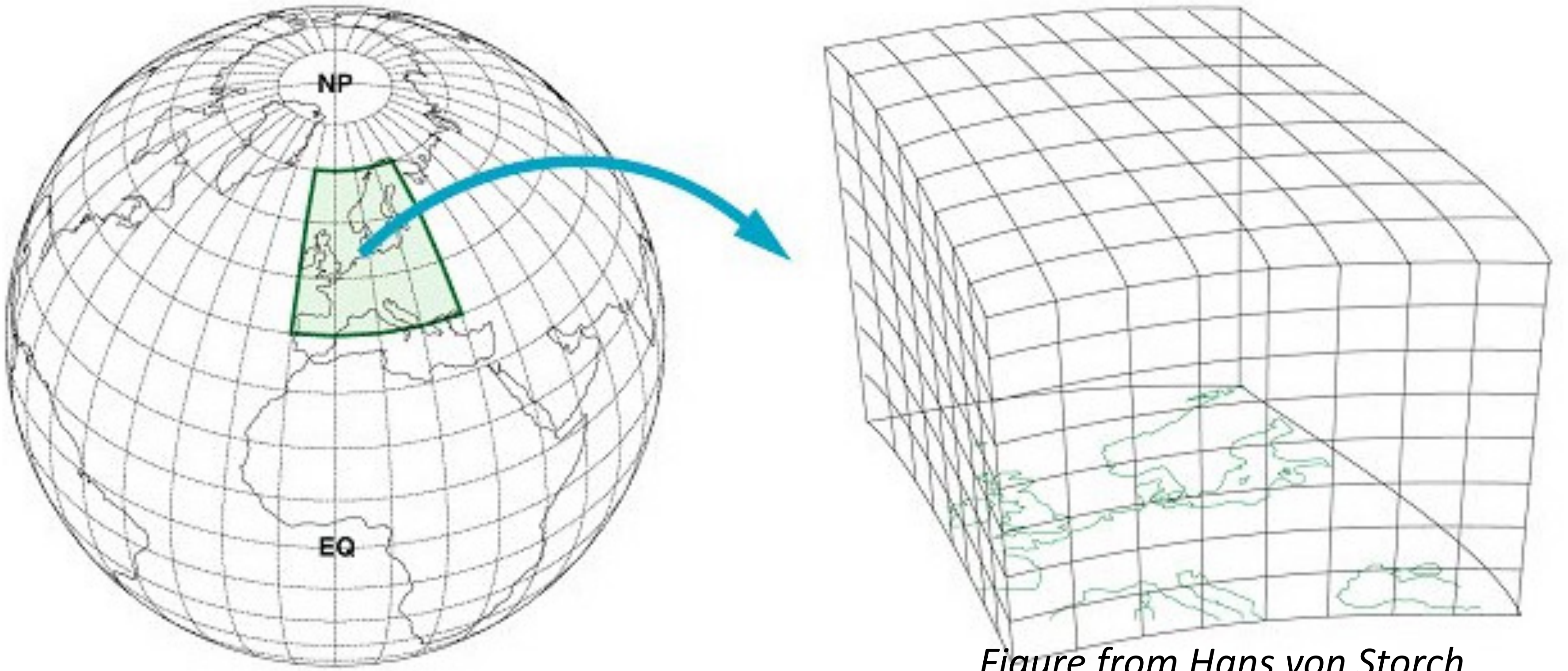
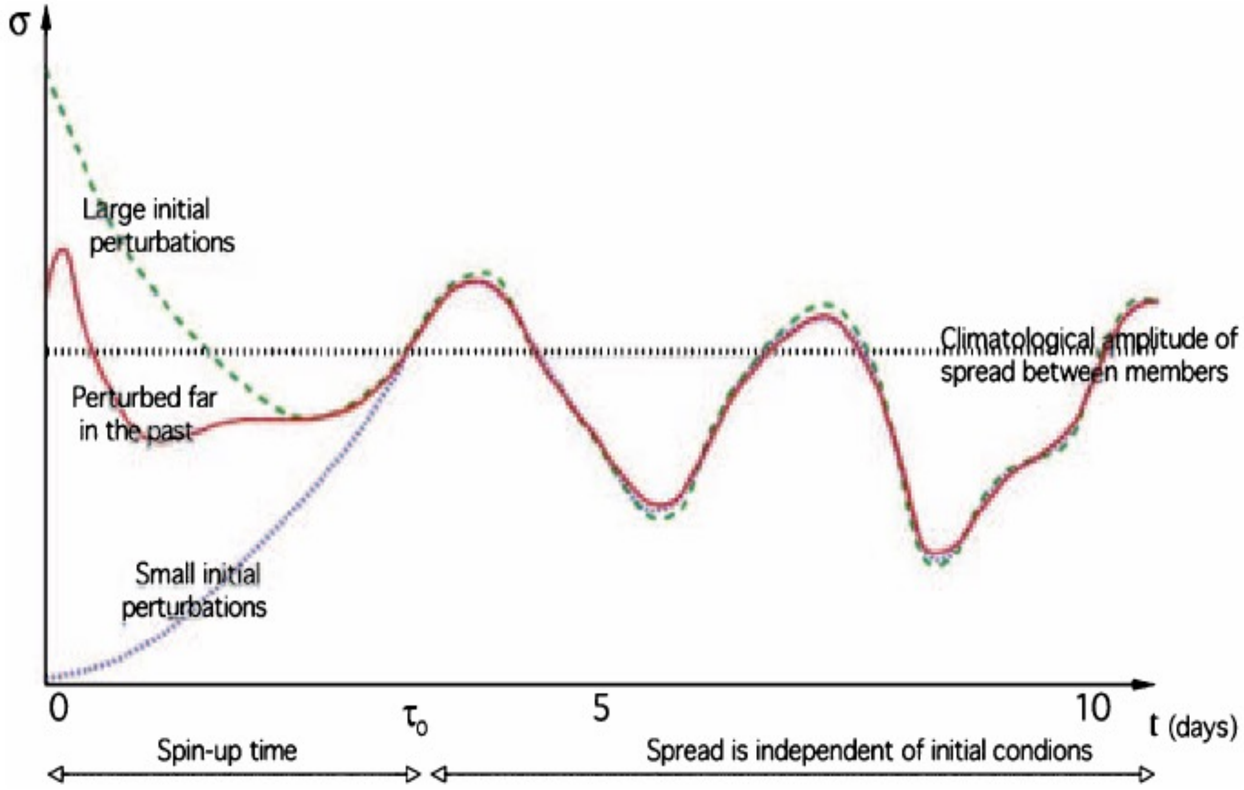


Figure from Hans von Storch

Climate model spinup

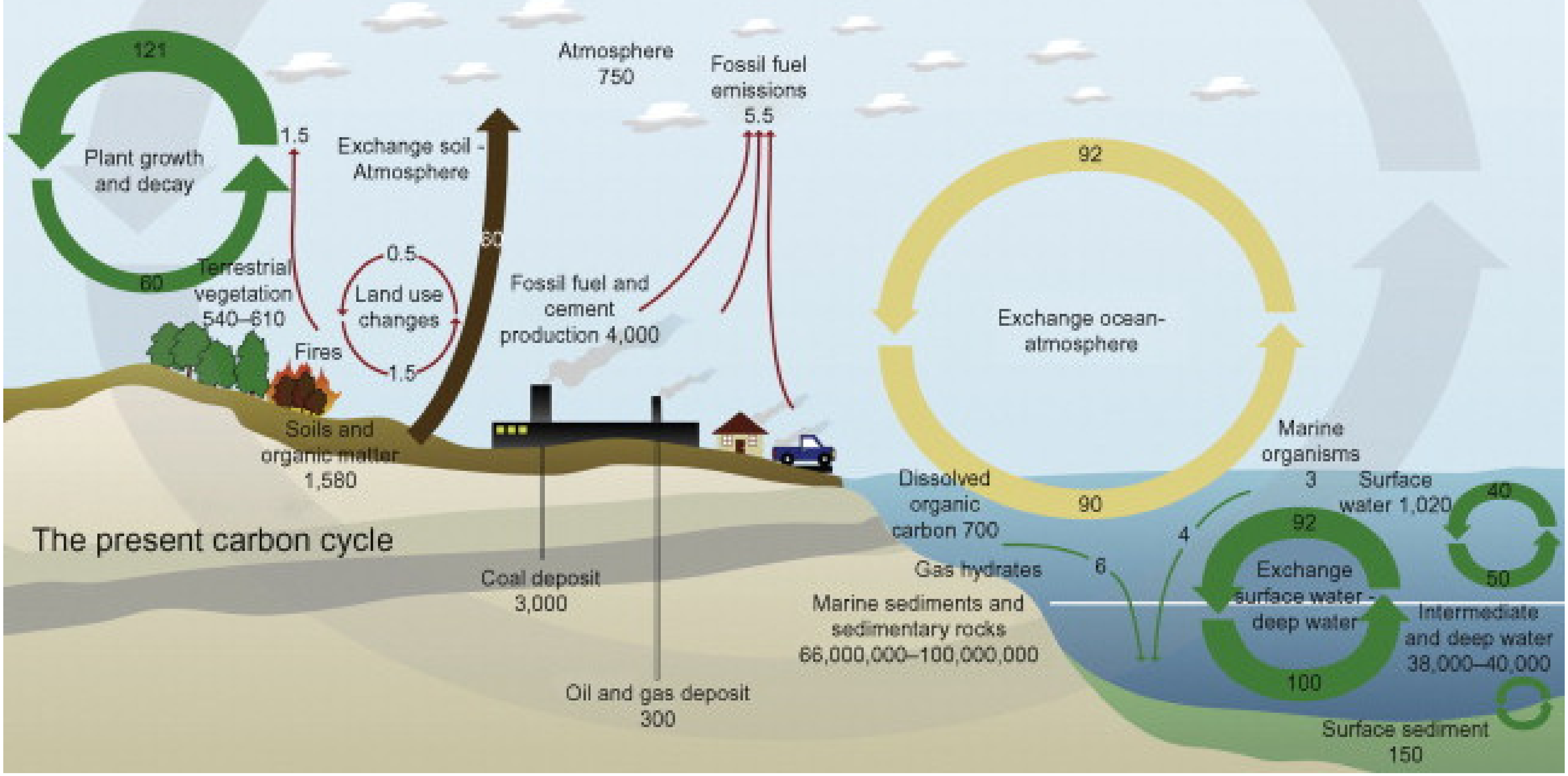


Laprise et al. (2008): Time evolution of spread between members of a conceptual ensemble of simulations

- 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)

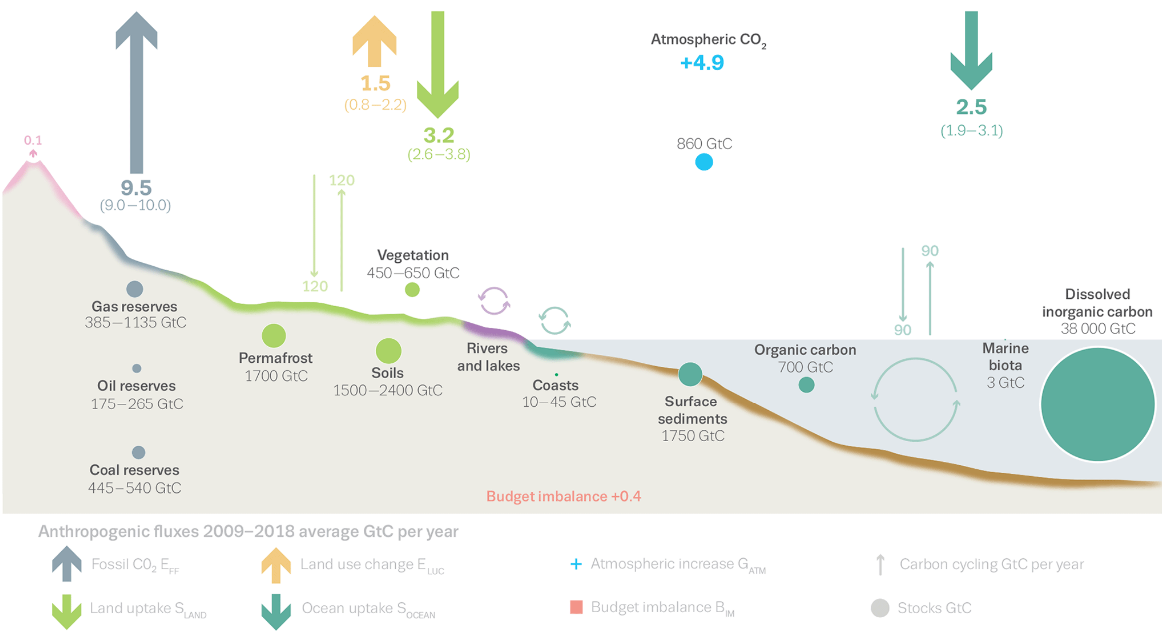
Biogeochemistry & the carbon cycle

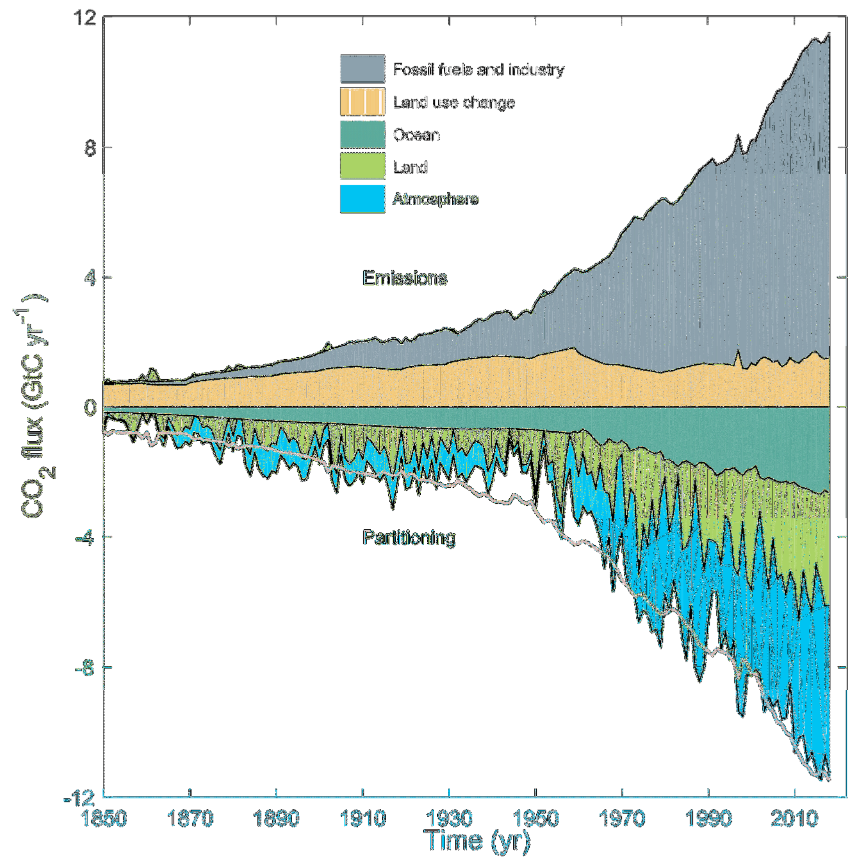
Storage and transfer of carbon between components: ocean, land, atmosphere, sediments



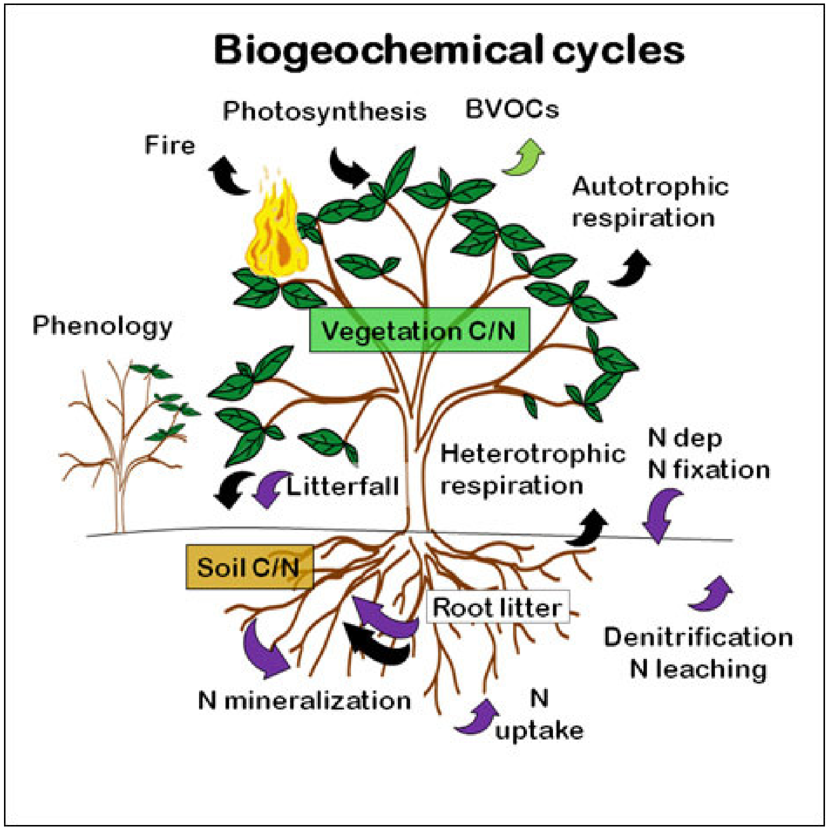
Ref. 1

The global carbon cycle





Land biogeochemical cycles: carbon, nitrogen, and water



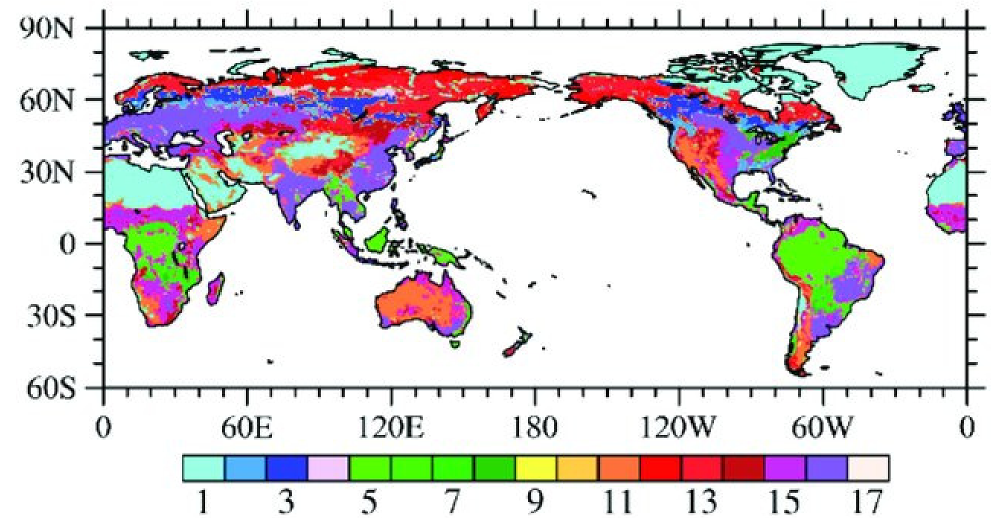
https://www.cesm.ucar.edu/models/clm/biogeochemistry.html

- 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

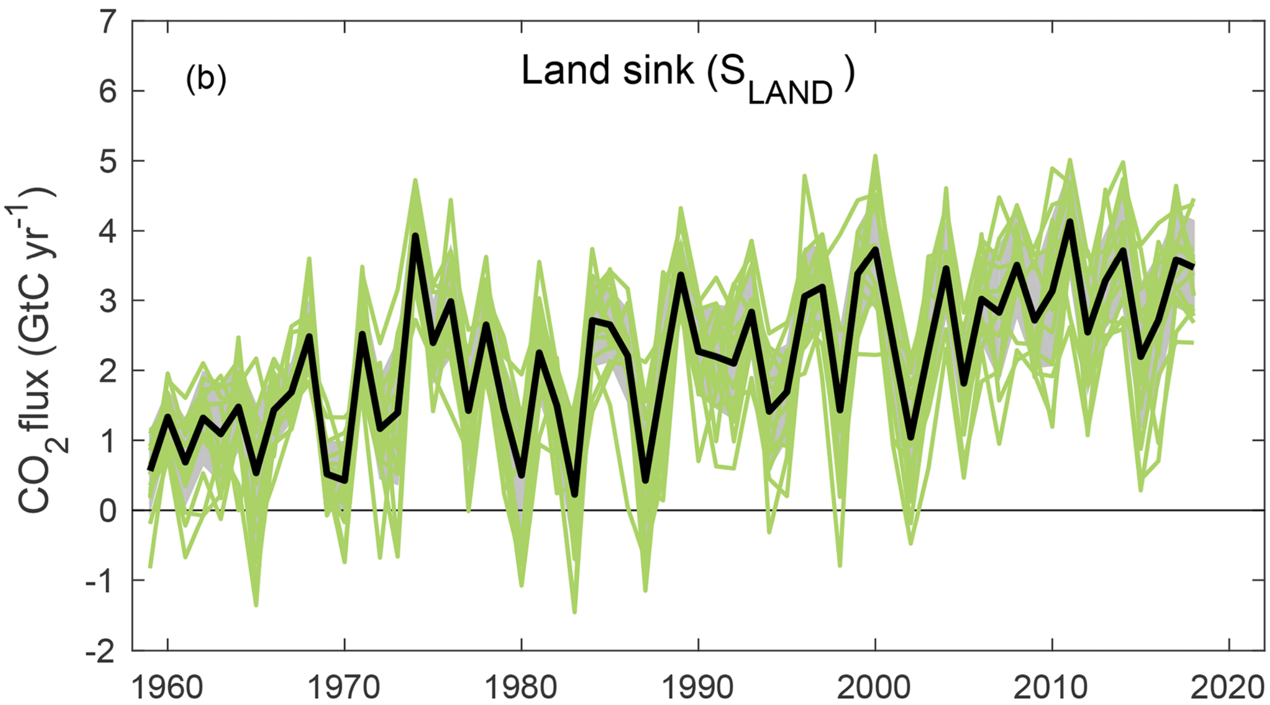
Modern-day distribution of PFTs



Ref. 2

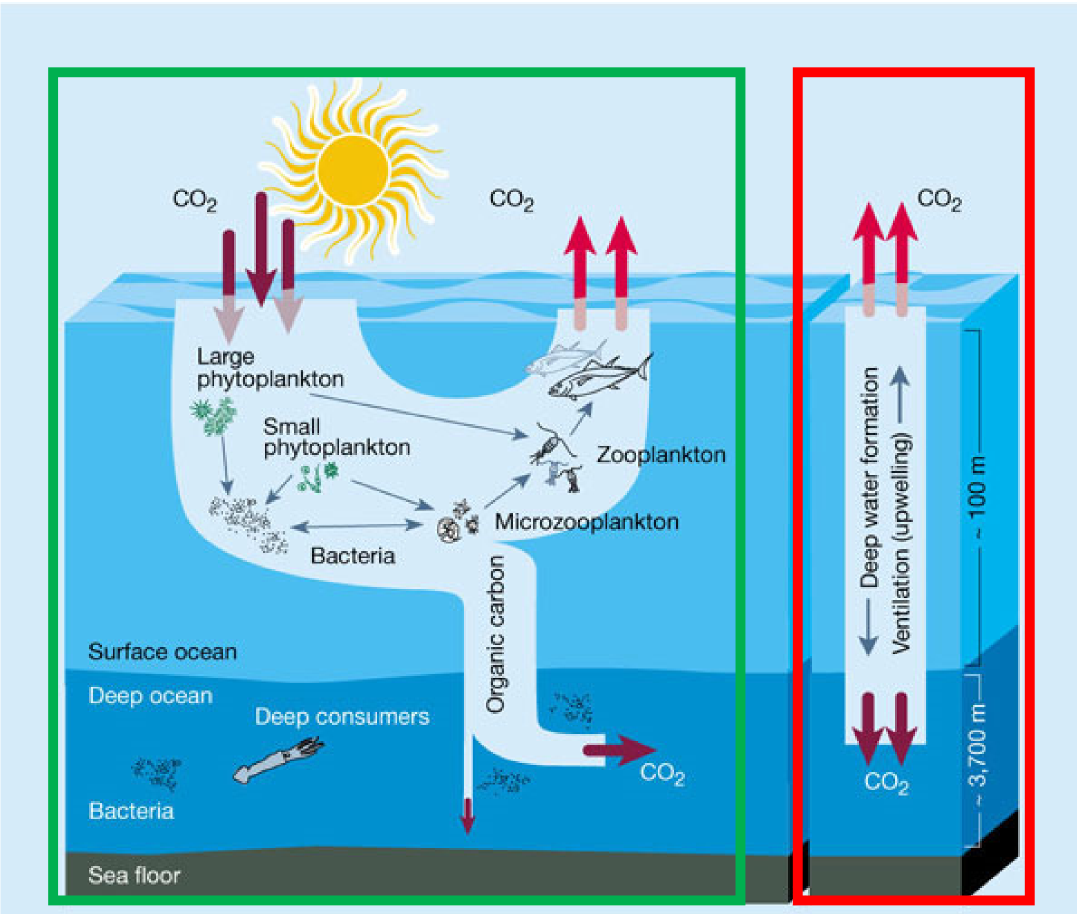
Global terrestrial carbon dynamics

Global estimates of the land carbon sink contain large uncertainties



Ref. 3

Marine carbon cycle



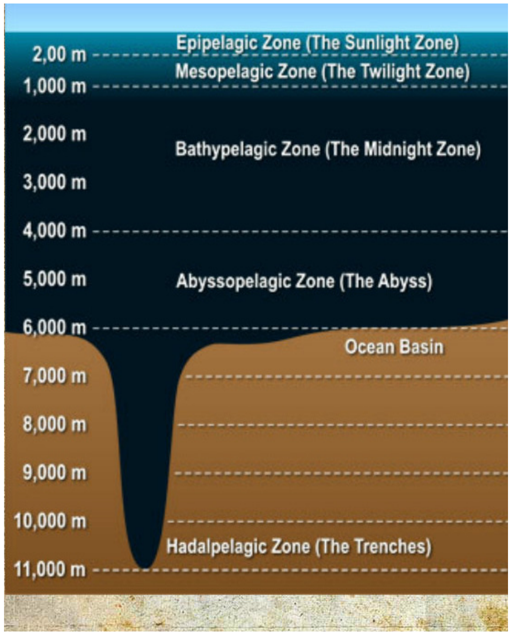
The ocean carbon cycle is regulated by:

- Biological carbon pump
- Ocean circulation and ventilation

Primary processes governing distribution of nutrients, O2, carbon

Biological carbon pump
Ocean circulation and ventilation

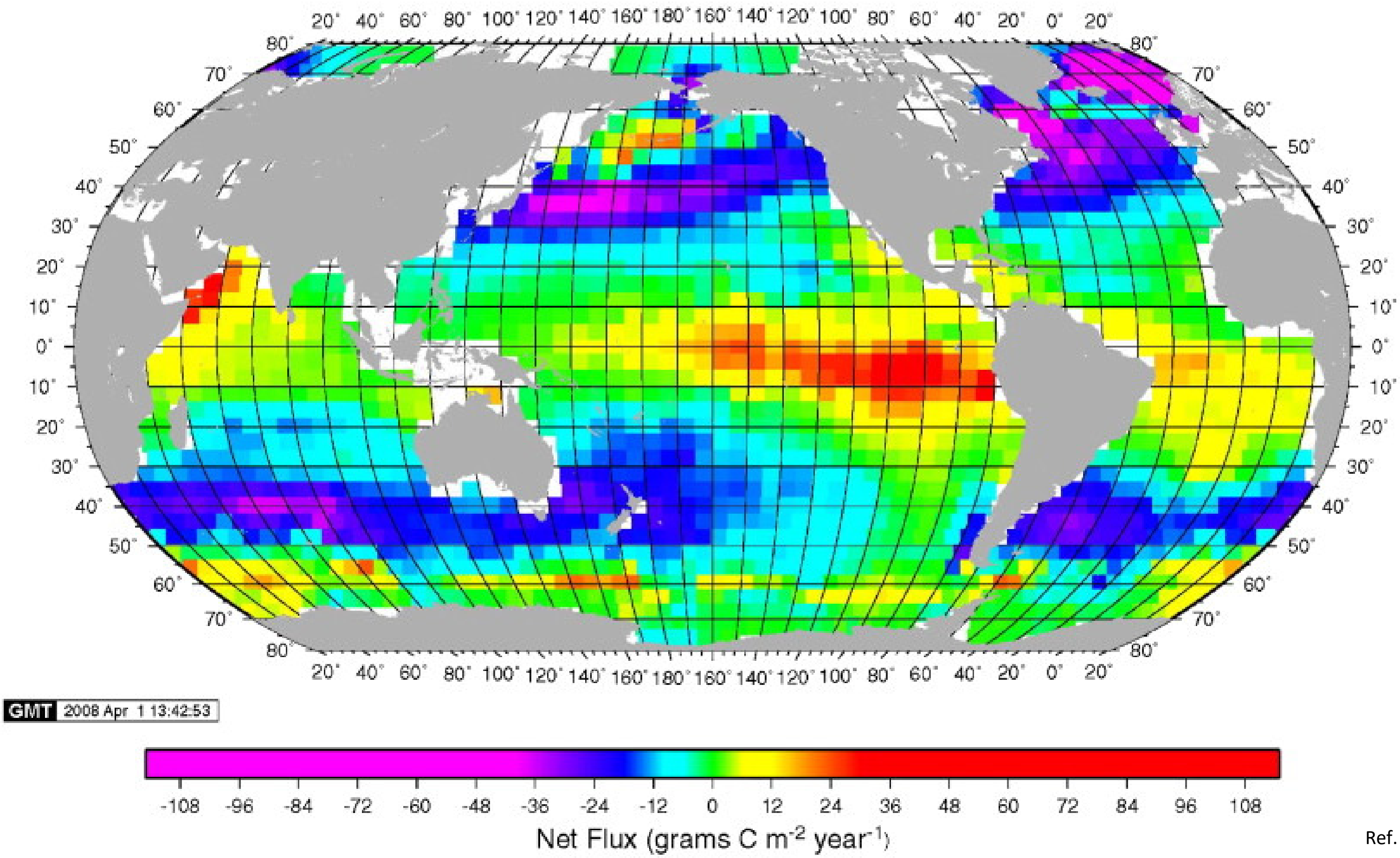
- Biological productivity in euphotic zone
  - Consumes nutrients (nitrate, phosphate, silicate, and calcium) & inorganic carbon (CO_2)
  - Produces organic matter & O_2
- Export of organic matter out of euphotic zone
  - Sinking particles (e.g. detritus, $CaCO_3$ shells, …)
  - Circulation of suspended matter
- Remineralization of organic matter
  - 'reverse' of productivity, consumes O_2
  - releases inorganic material that can be used again
- General circulation
  - Advective transport
  - Lateral & vertical mixing
- Air-sea gas exchange (temperature-dependent)



http://wnct.com/blog/2016/02/26/ocean-zones-and-what-creatures-live-in-them/

Ocean circulation and ventilation

pCO_2 air-sea flux



Ref. 4

Biological carbon pump

What is an NPZD model?

N Nutrient

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

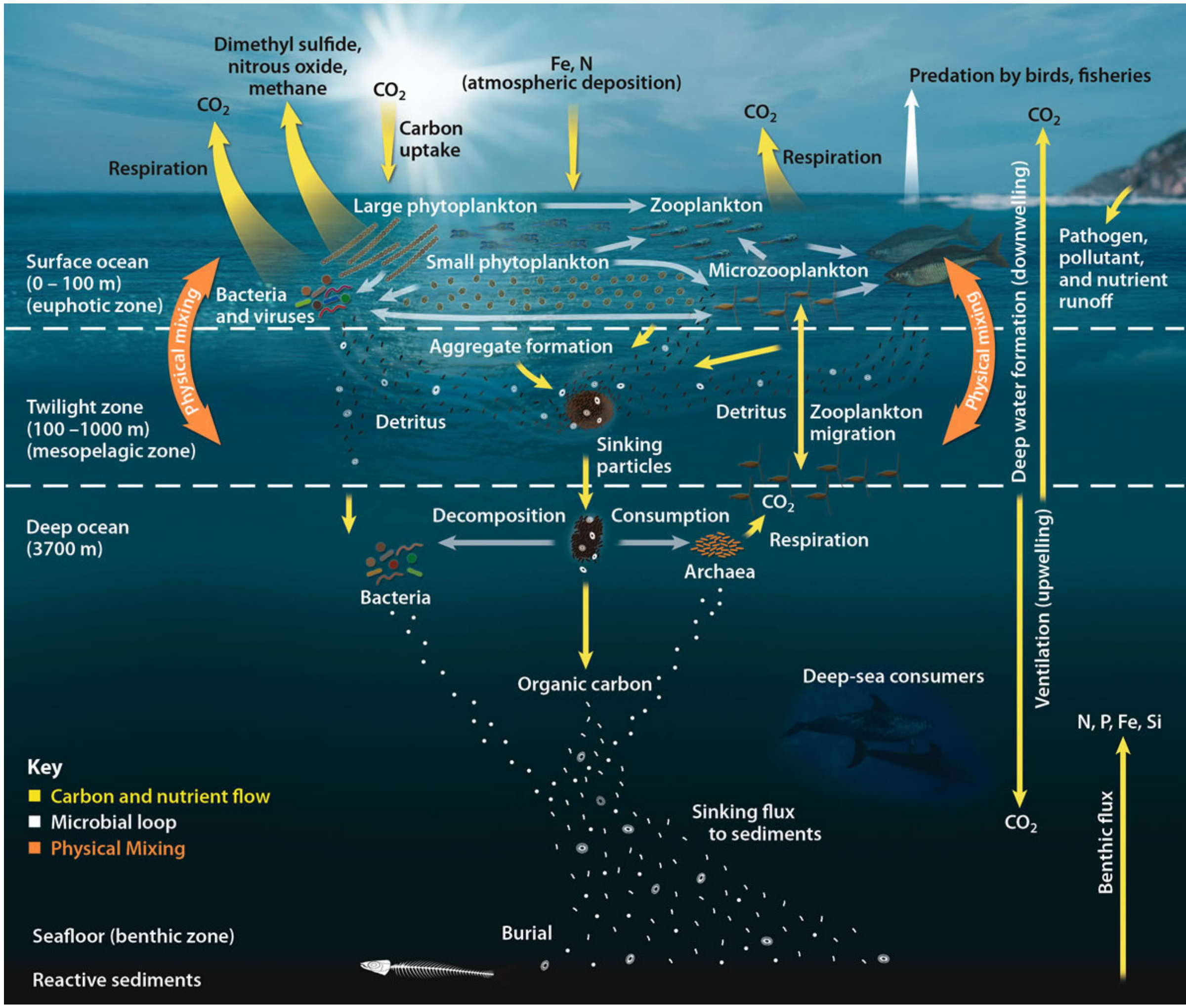
P Phytoplankton

photosynthesizers

Z Zooplankton

grazers

D Detritus



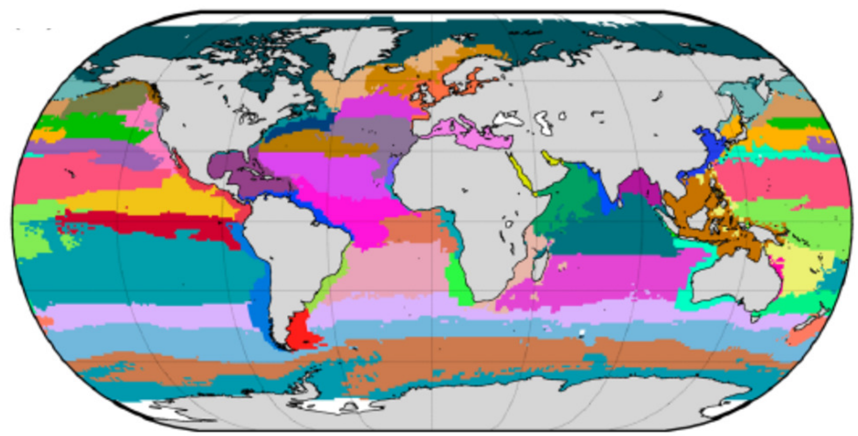
Higher trophic levels usually not represented

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

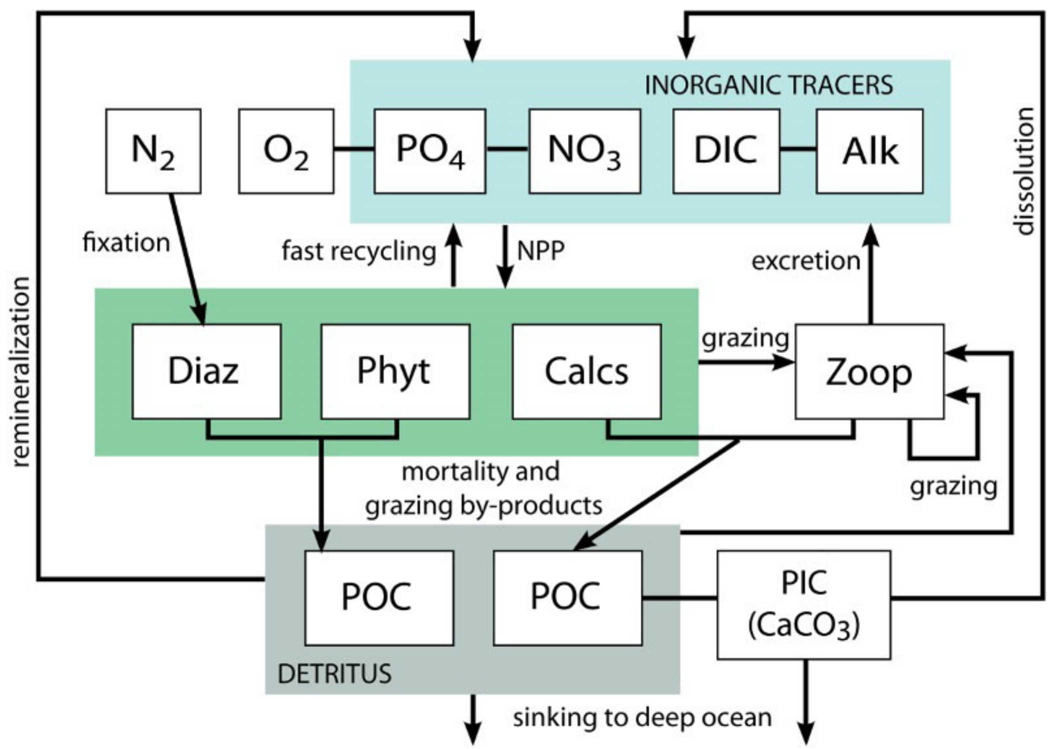
UVic ESCM v2.9 Kiel

N

P

Z

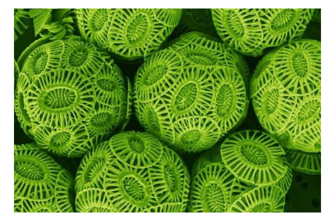
D



Ref 6: Kvale et al. 2015

Mixed phytoplankton

Diazotrophs



Coccolithophores
(*Emiliania huxleyi)*

WCRP
World Climate Research Programme

CMIP6

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

RCP8.5&6: No climate change policy

RCP4.5: Some CC policy (like B1)

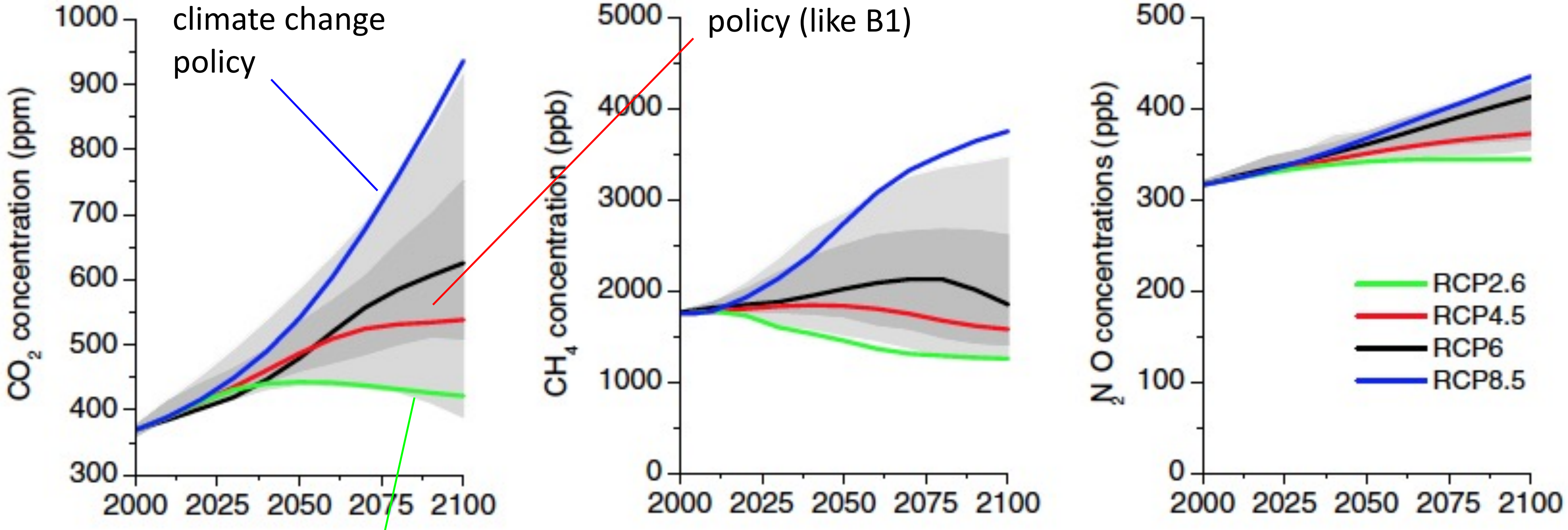
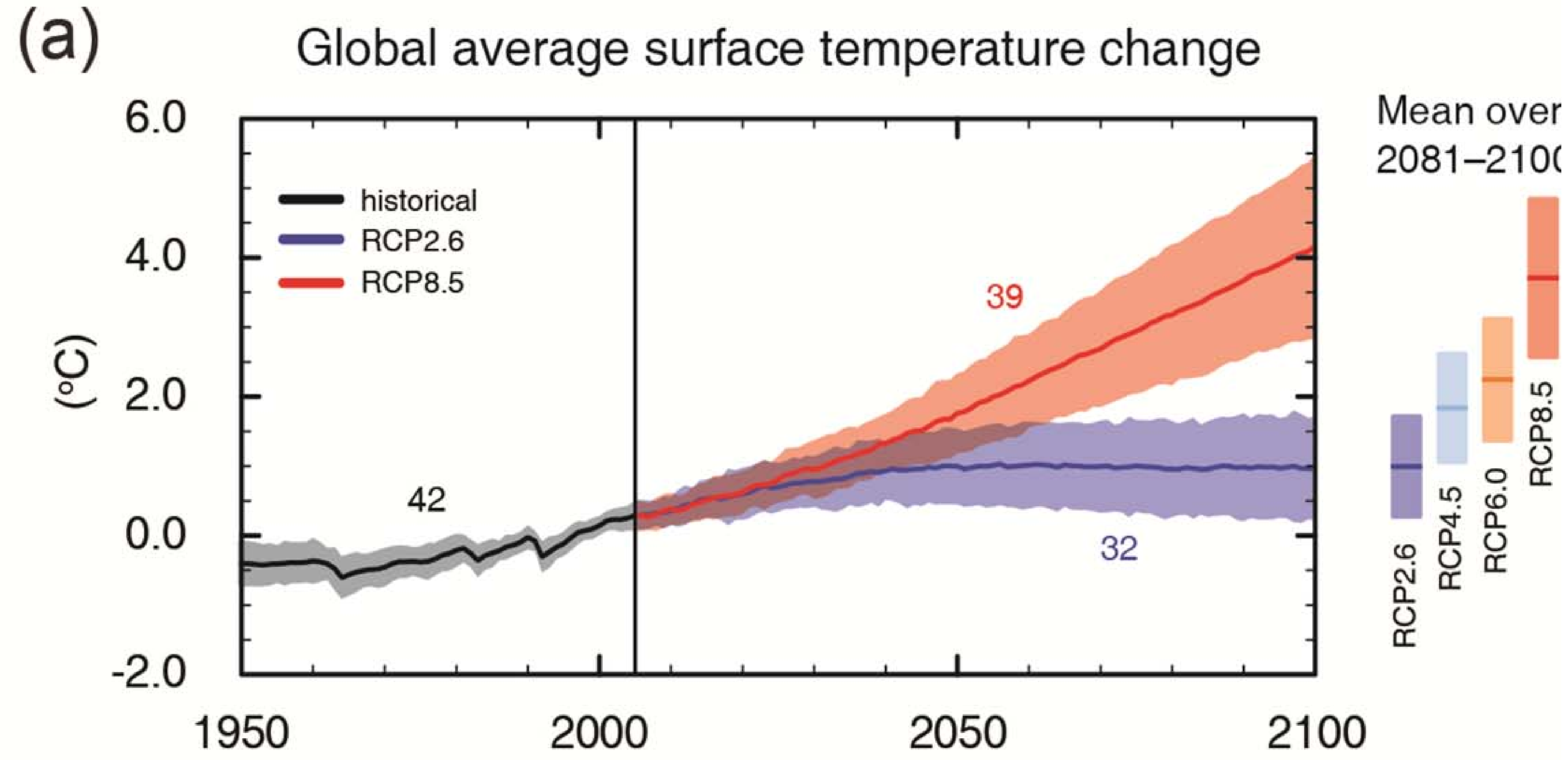


Fig. 9 Trends in concentrations of greenhouse gases. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the recent EMF-22 study (Clarke et al. 2010)

RCP2.6: Stringent CC policy

Van Vurran et al. 2011

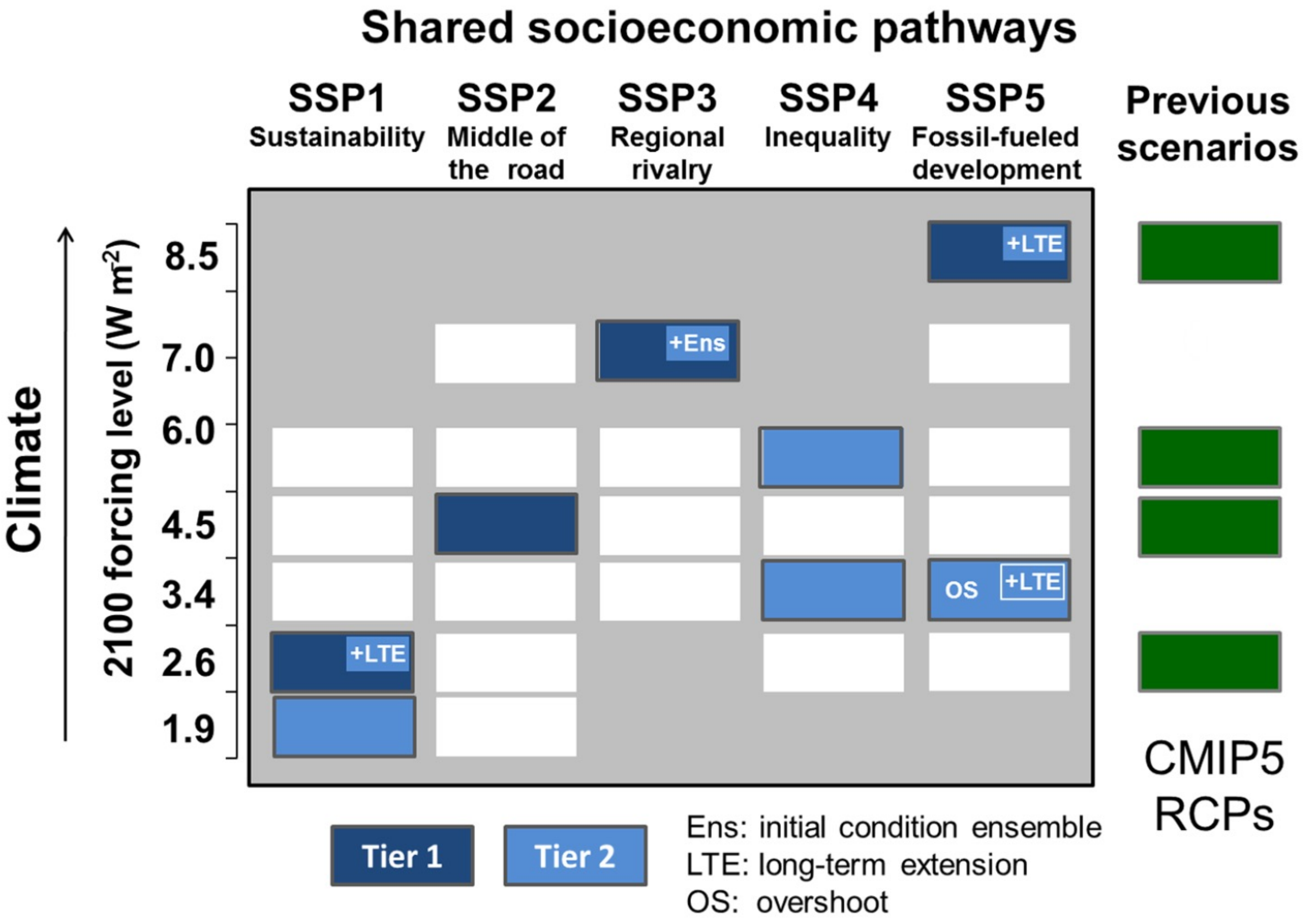
AR5 report: T changes



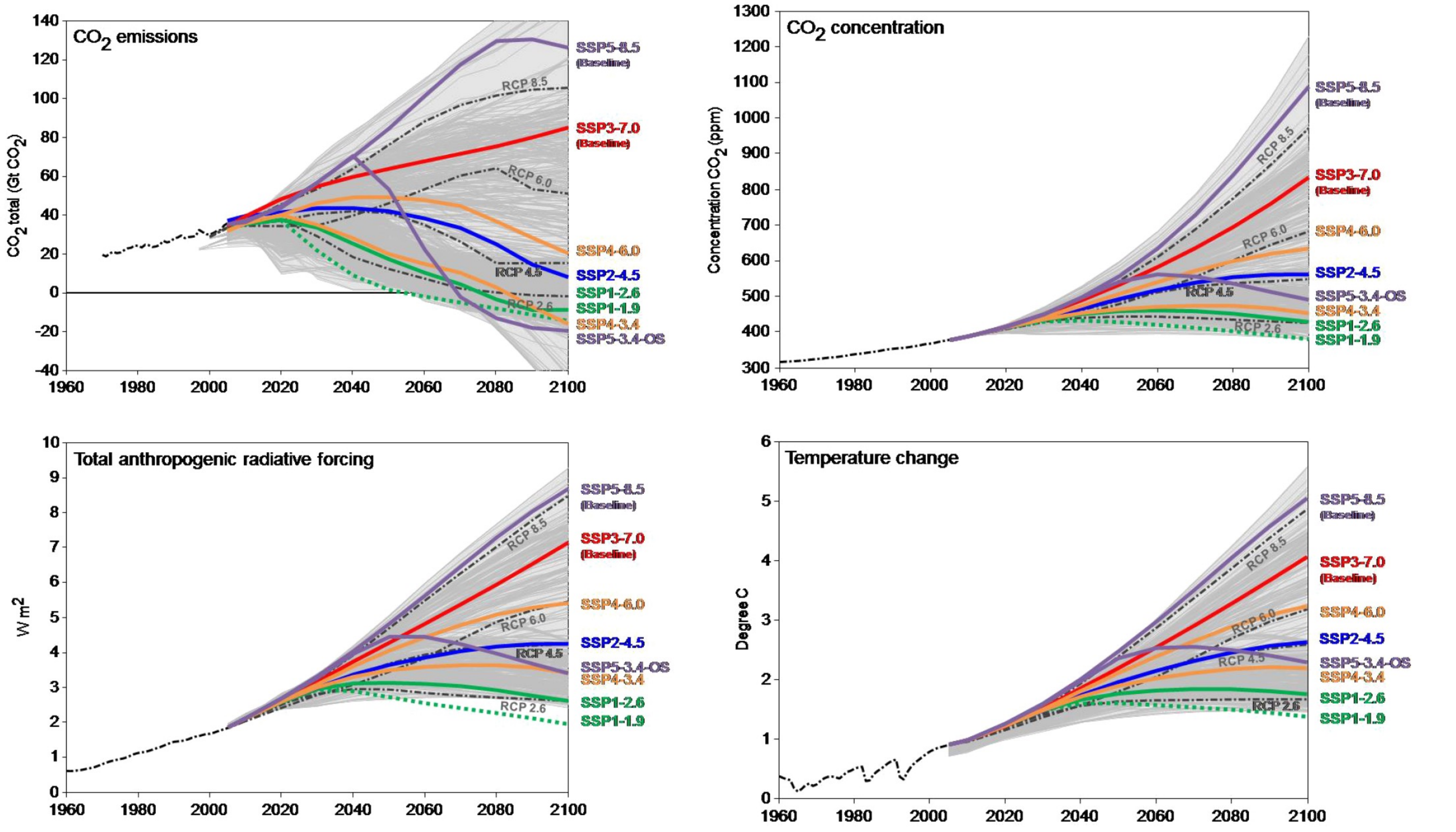
IPCC AR5, 2013

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

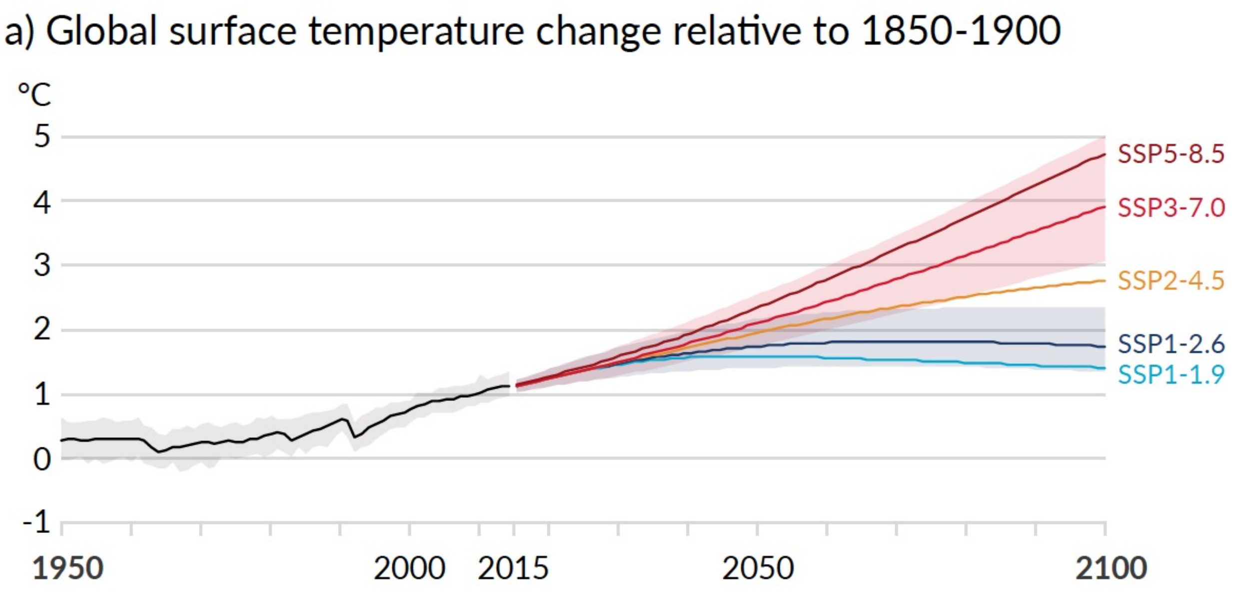


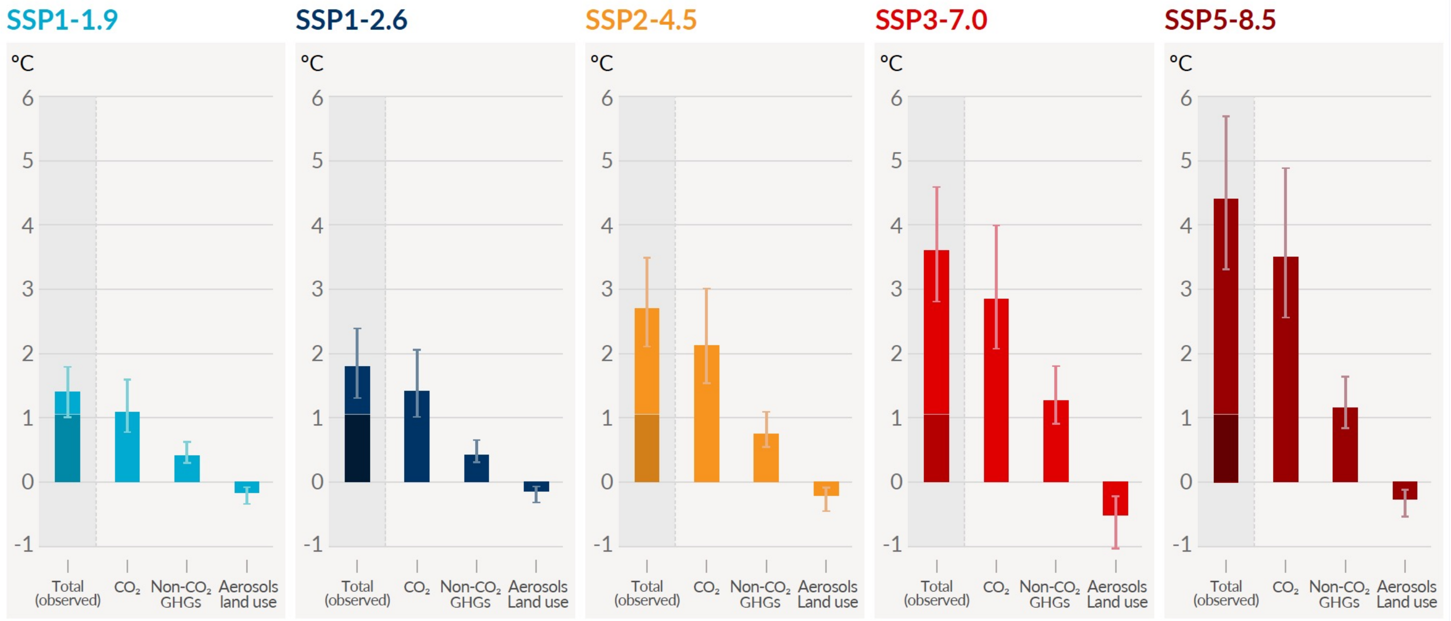
CMIP6: SSP Scenarios



Source: Riahi et al, 2016

AR6: T changes



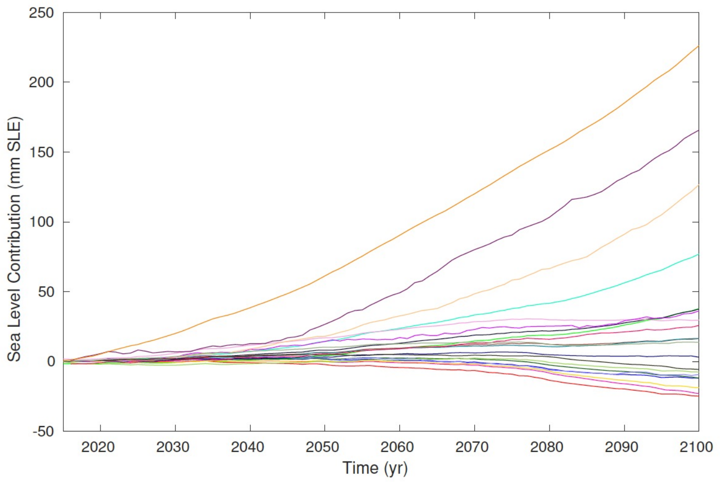


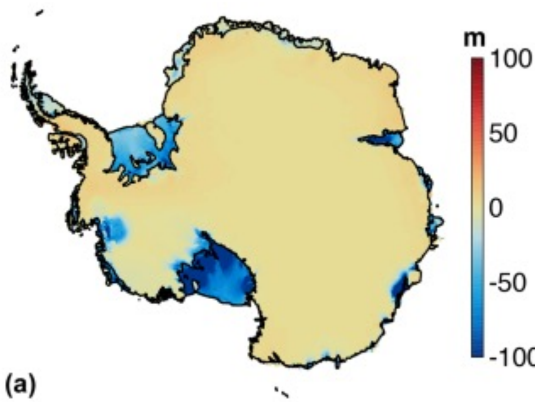
Other “MIPs” affiliated with CMIP6

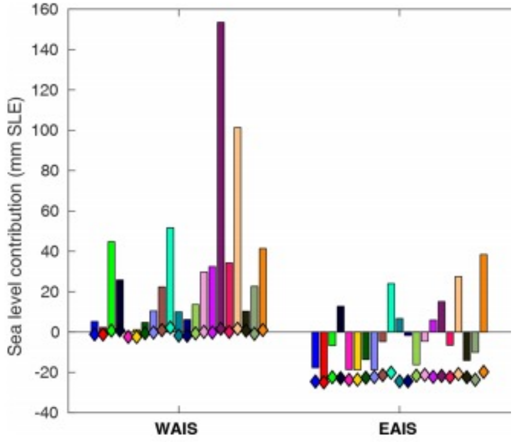
- ISMIP (ice sheets)
- PMIP (paleoclimate)
- CFMIP (cloud feebacks)
- GeoMIP (geoengineering)
- LUMIP (land-use)
- OMIP (ocean-focused)
- VolMIP (volcanic forcing)
- CORDEX (downscaling)

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





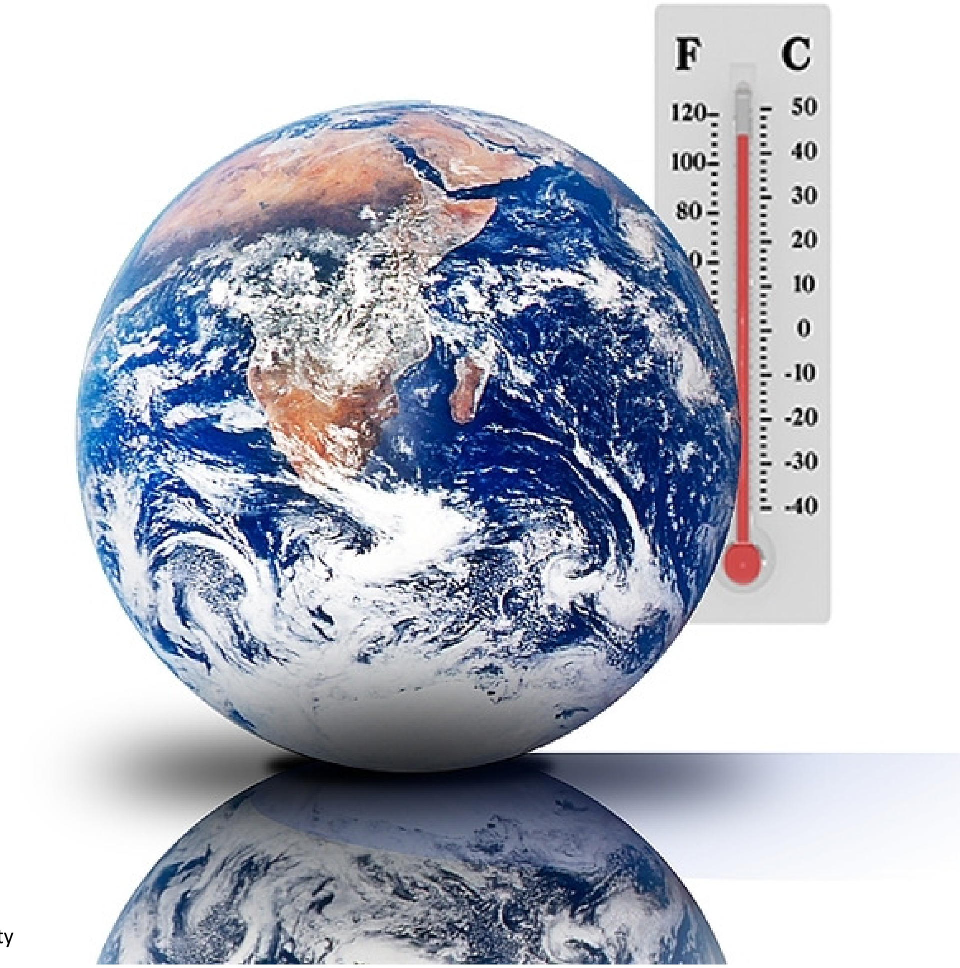


Global Model Data Availability

- 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

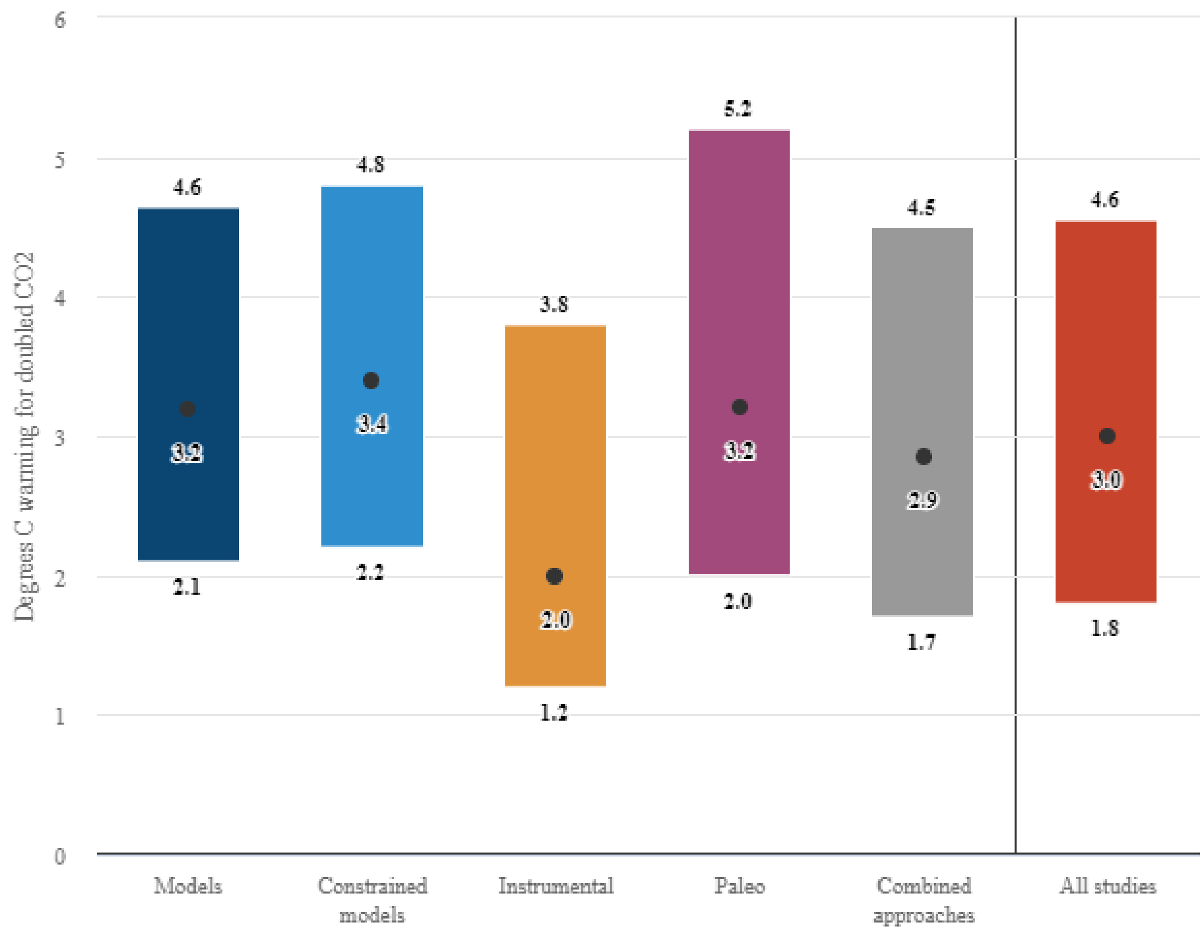
Climate sensitivity

- How much does the surface warm with a doubling of CO_2?
- IPCC AR6 estimate of equilibrium climate sensitivity is **$3^{o}C$,** with a likely range of **$+2.5 - 4^{o}C$** (AR5: $+1.5 – 4.5^{o}C$) for a doubling of pre-industrial CO_2, using models and paleoclimate evidence



https://news.mit.edu/2010/explained-climate-sensitivity

Equilibrium Climate Sensitivity from different sources

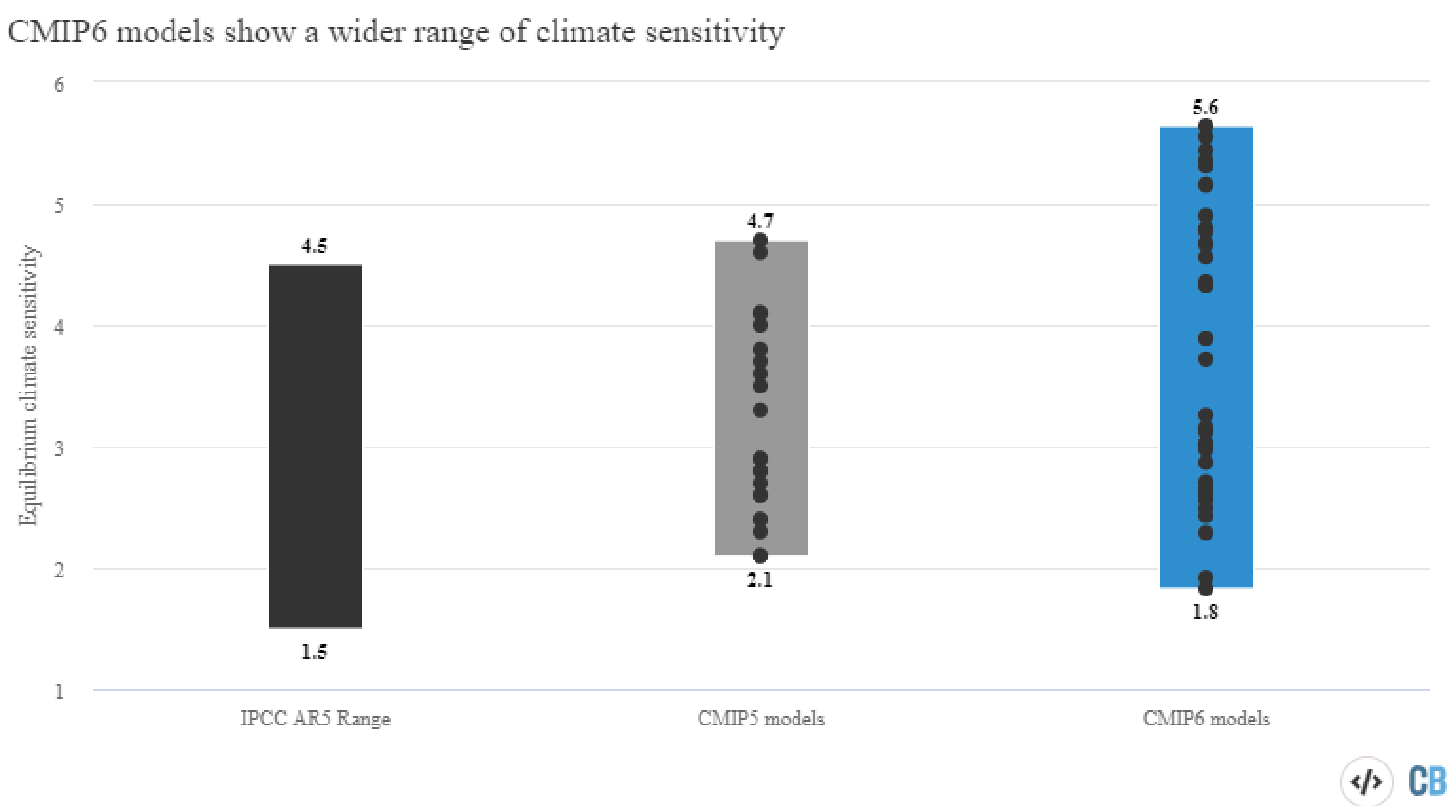


https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity

Equilibrium vs. Transient climate sensitivity

- Model experiments
  - Equilibrium climate sensitivity (ECS) = instantaneous doubling of CO_2, run model to equilibrium (climate has stabilized and only minimal trends remain)
  - Transient climate response (TCR) = the amount of warming that would occur when CO_2 doubles, having increased gradually by 1% each year.
- TCR more closely matches the way the CO_2 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 AR6 gives an ECS of 3^{o}C (likely range 2.5 - 4^{o}C), but a likely TCR of only 1.8^{o}C (likely range 1.4 - 2.2^{o}C)

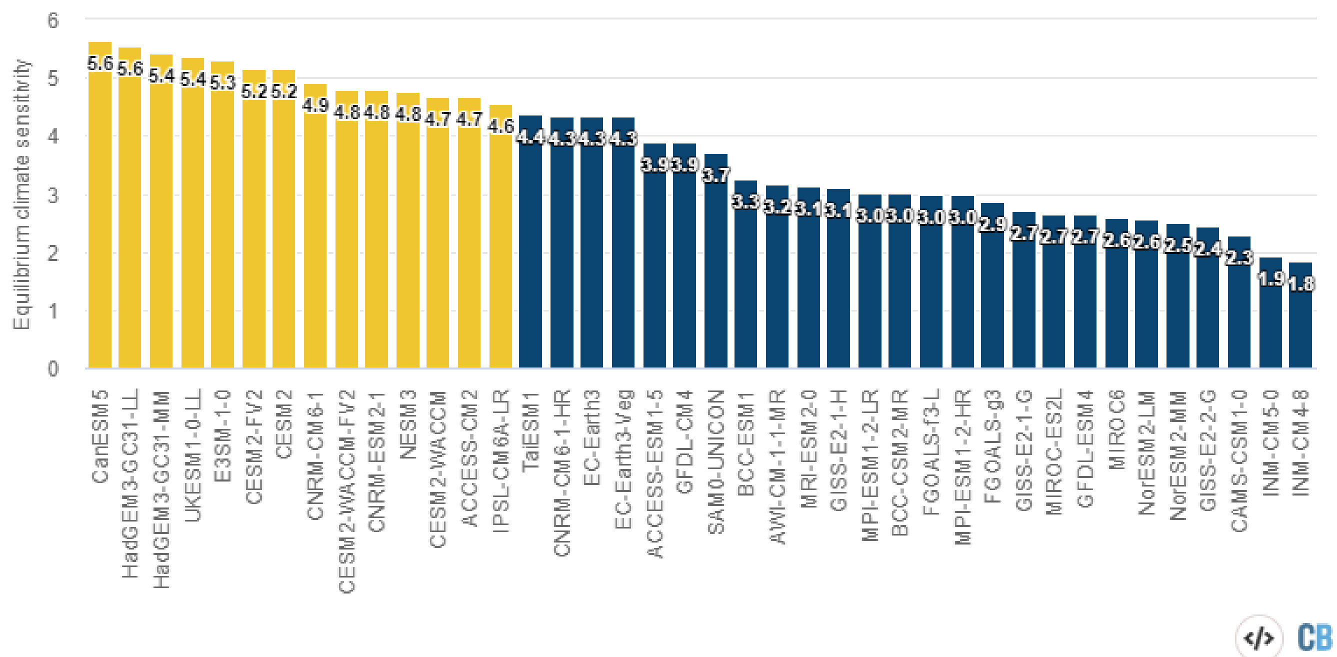
Climate sensitivity in CMIP5/6



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

https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

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.

https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

Why are CMIP6 models more sensitive?

- Many CMIP6 models feature an improved representation of clouds, which has increased climate sensitivity in these models (compared to CMIP5, there is an amplifying cloud feedback that is larger in CMIP6 by about 20%.)
- Biogeochemical feedbacks between components (ice sheets, terrestrial biosphere, ocean circulation) also represent a large source of uncertainty

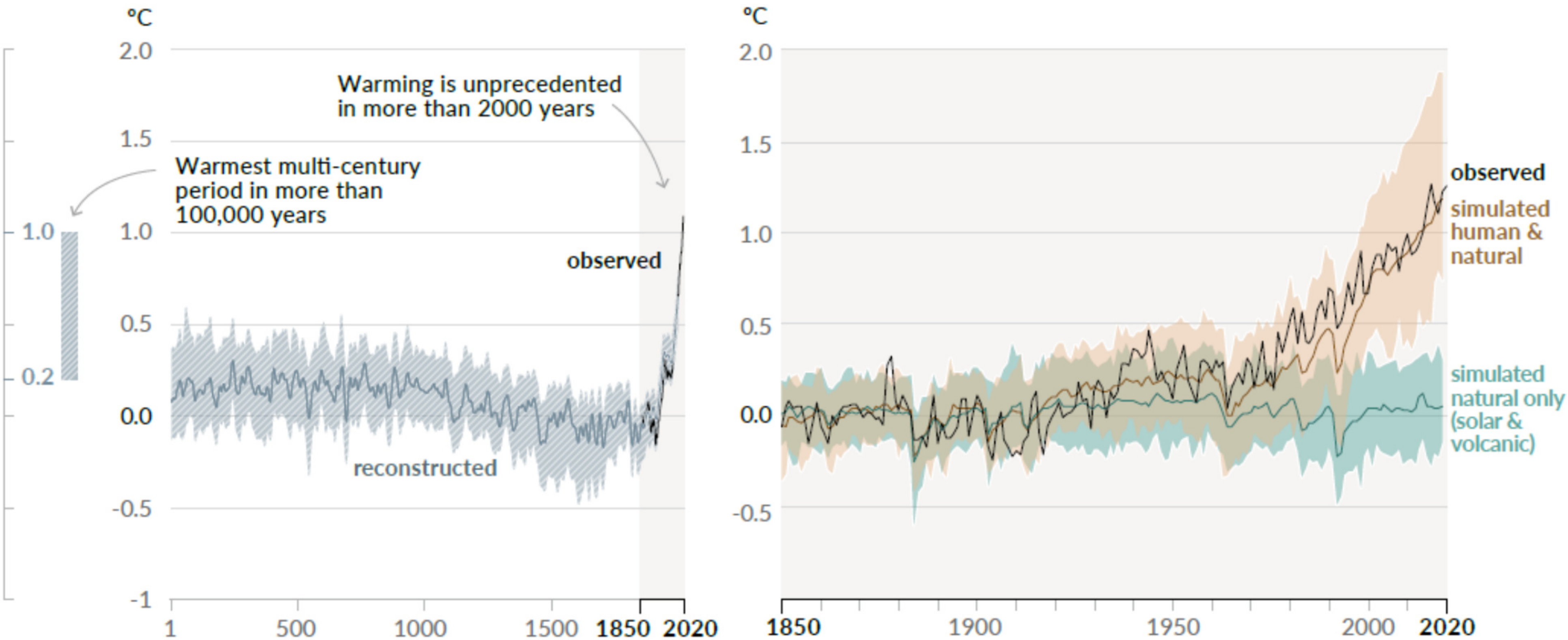
IPCC AR6 WG1 report: highlights

- "**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.
- 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)

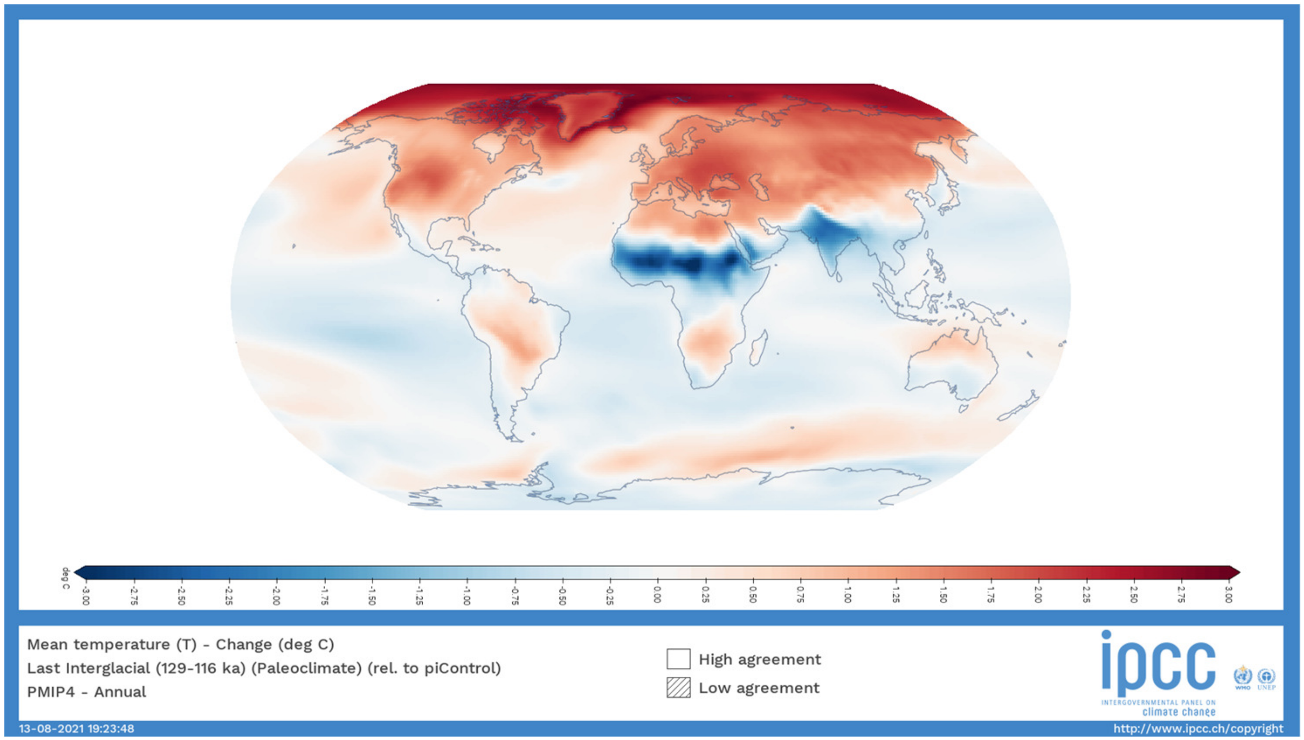


CMIP6 portal

- https://esgf-node.llnl.gov/search/cmip6/

AR6 WG1 interactive atlas

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



Thank you for your attention!

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