Last Lecture 6: Hands-on
23 January 2025

Lecture 7
27 January 2025

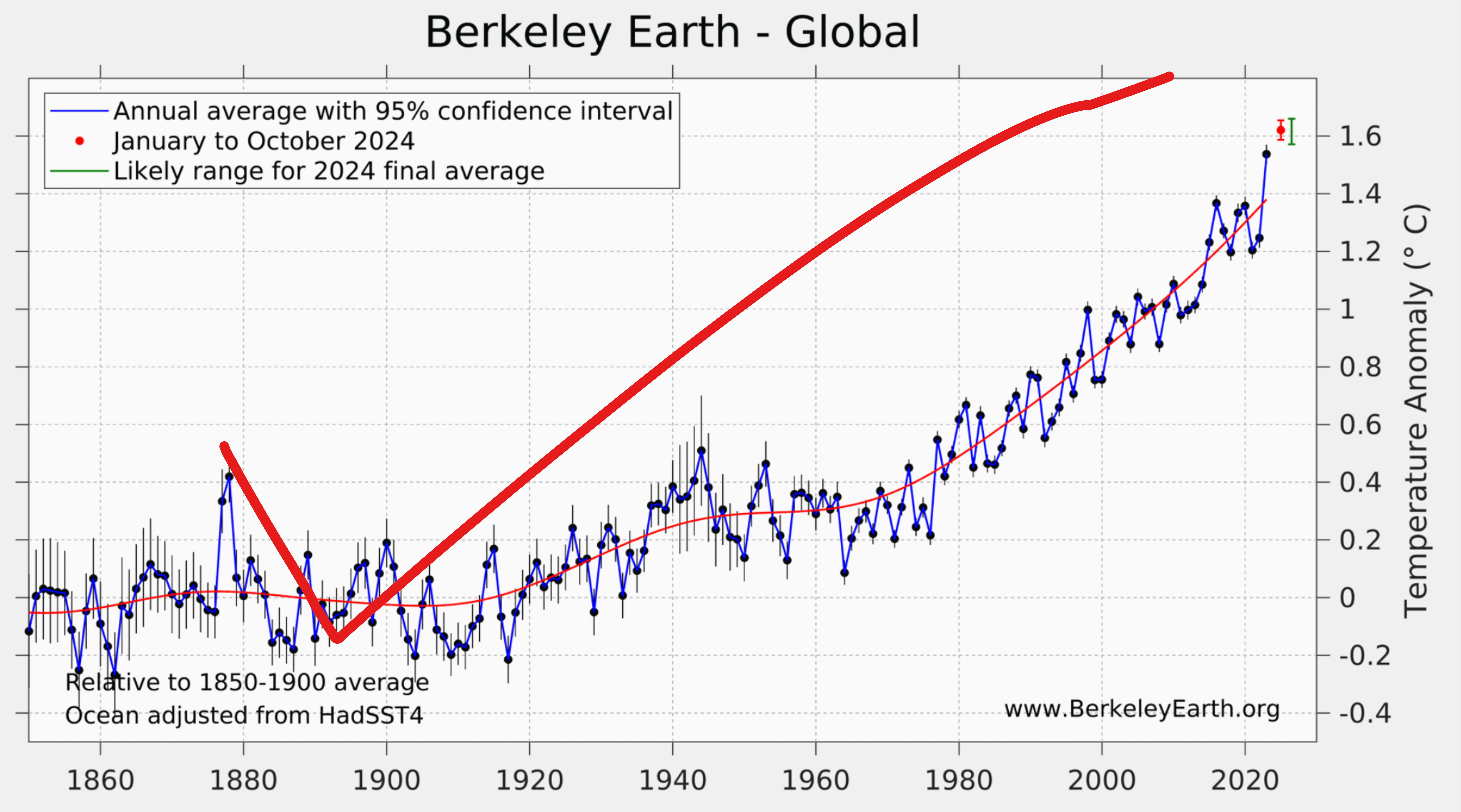
CM 615

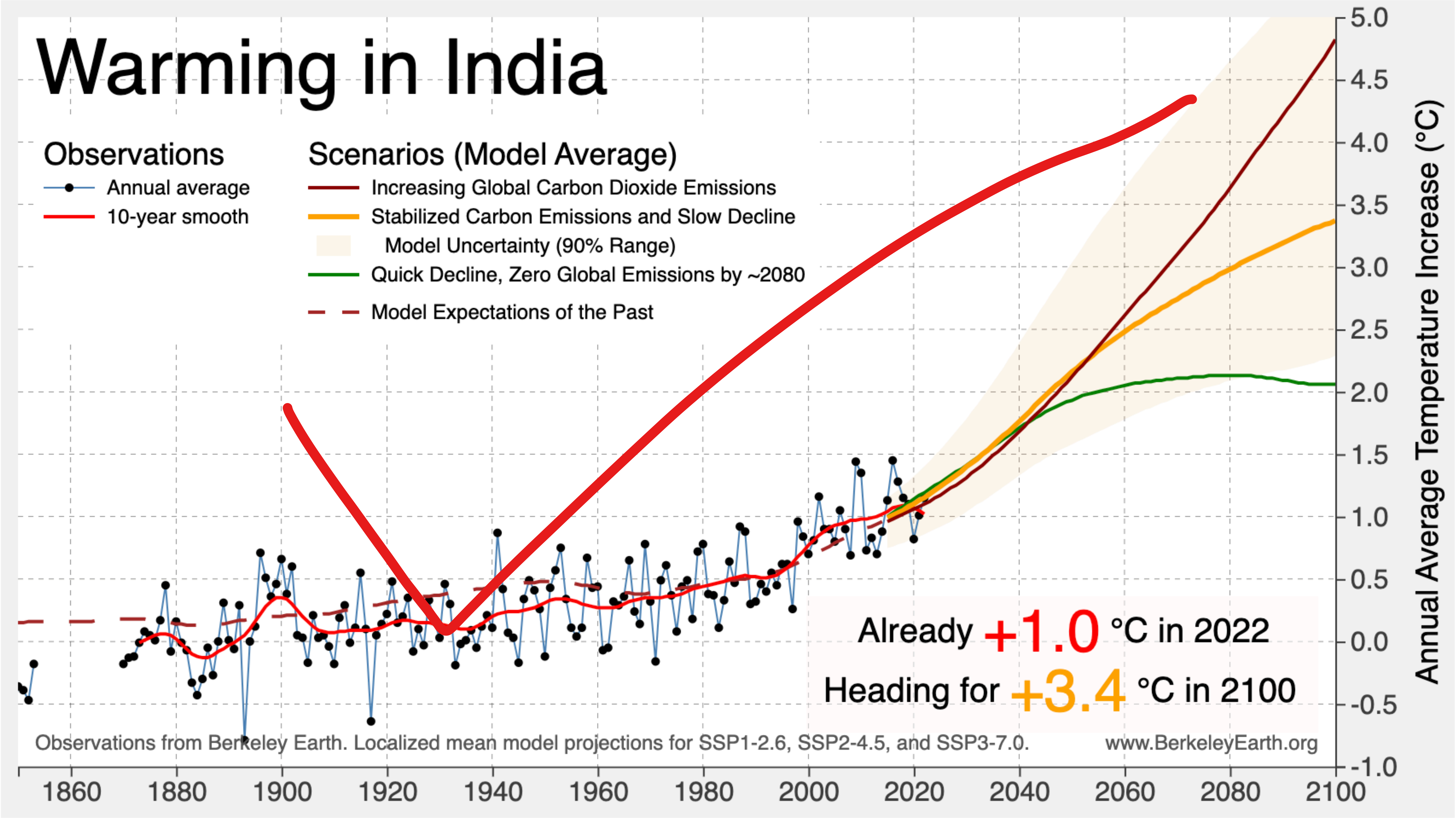
Climate change Impacts & Adaptation

Mean state of the atmosphere, Hydrostatic balance, General circulation-3-cell, Hydrological cycle, Radiative forcing & climate response

Angshuman Modak
Climate Studies, IIT Bombay

Historical warming…

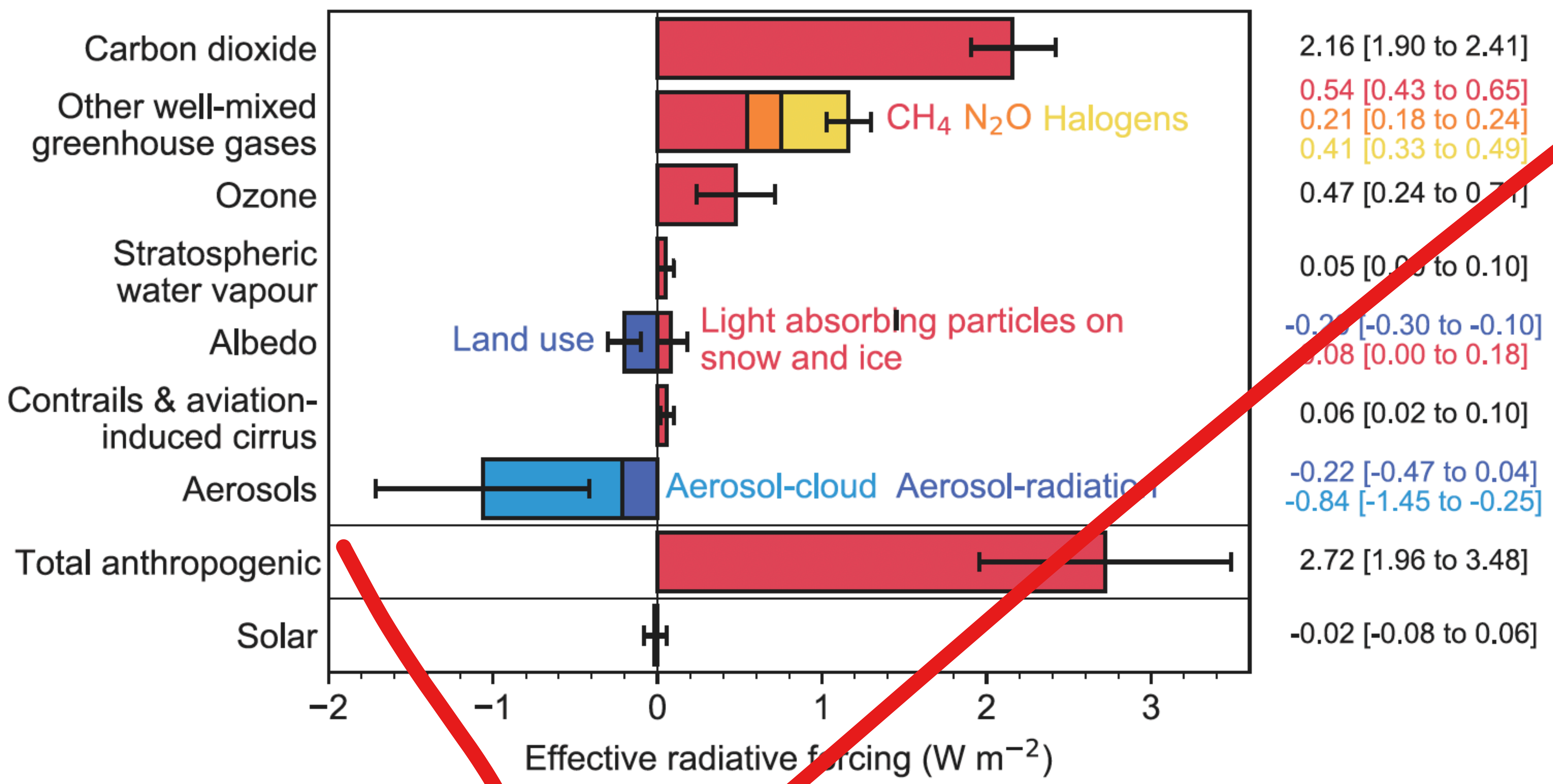




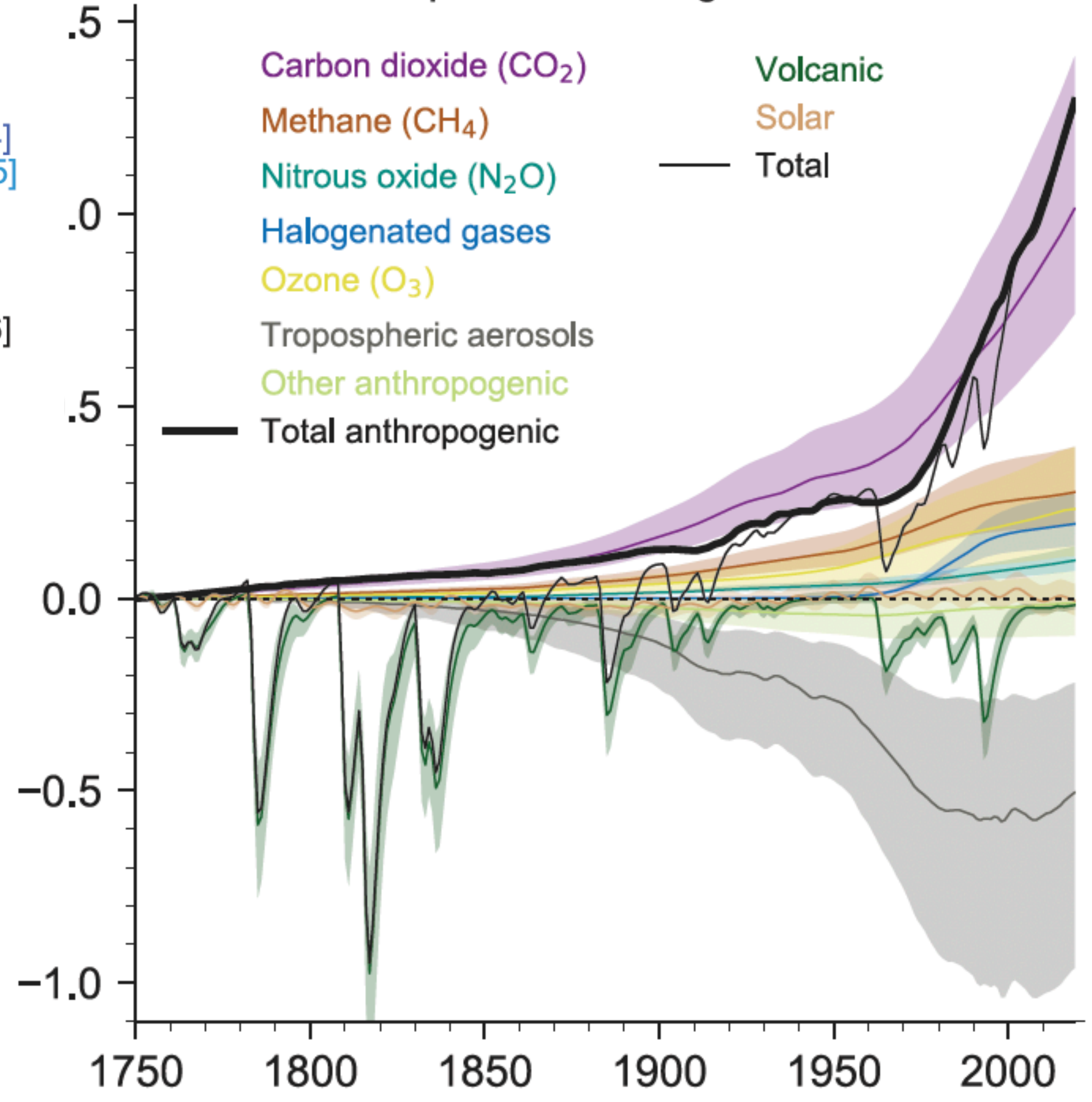
Warming in India
Observations
Annual average
10-year smooth
Scenarios (Model Average)
Increasing Global Carbon Dioxide Emissions
Stabilized Carbon Emissions and Slow Decline
Model Uncertainty (90% Range)
Quick Decline, Zero Global Emissions by ~2080
Model Expectations of the Past
Already +1.0 °C in 2022
Heading for +3.4 °C in 2100
Observations from Berkeley Earth. Localized mean model projections for SSP1-2.6, SSP2-4.5, and SSP3-7.0.
www.BerkeleyEarth.org
Annual Average Temperature Increase (°C)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1860
1880
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100

IPCC AR6

Change in effective radiative forcing from 1750 to 2019



Attributed temperature change relative to 1750



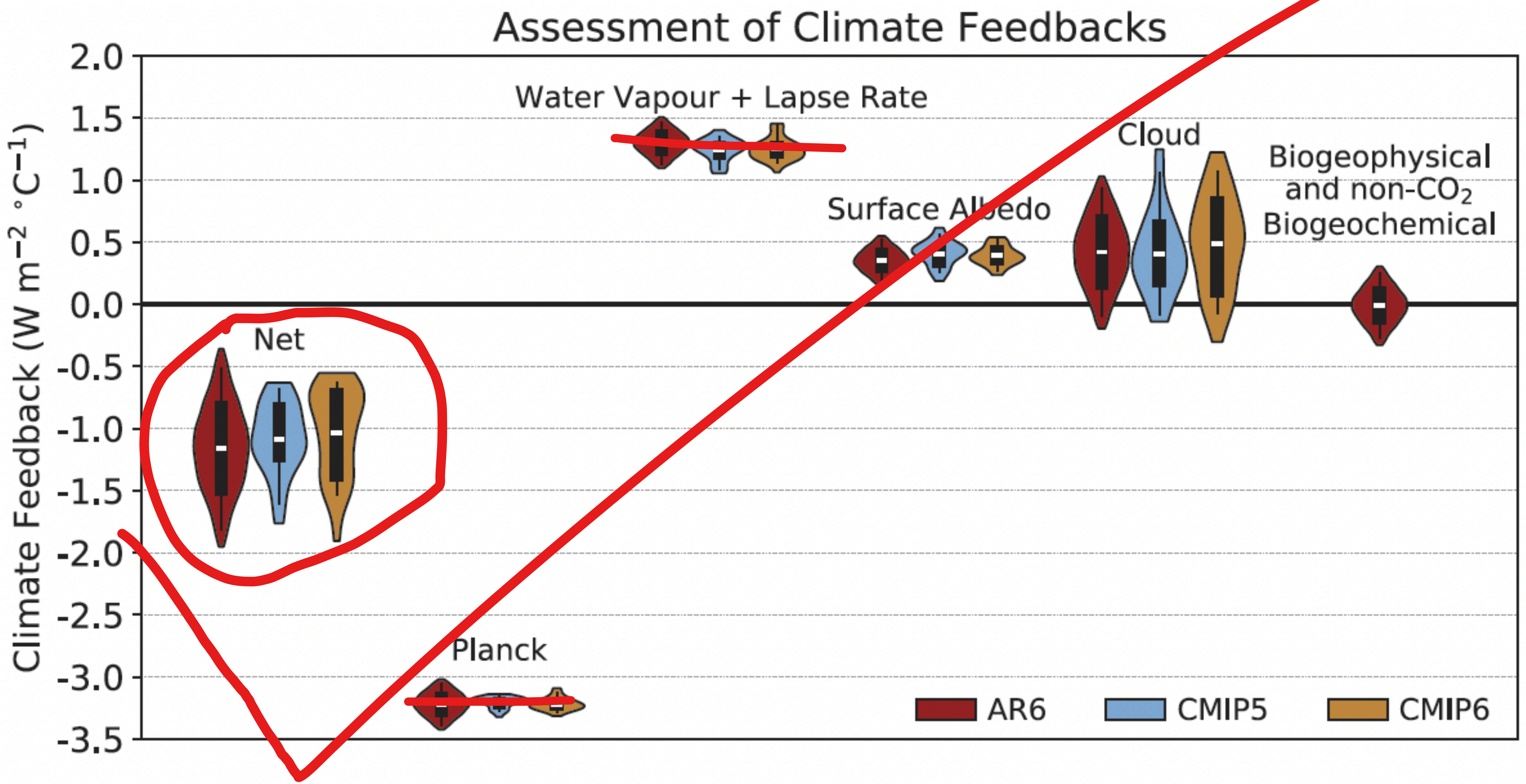


Figure 7.10 | Global mean climate feedbacks estimated in *abrupt4xCO2* simulations of 29 CMIP5 models (light blue) and 49 CMIP6 models (orange), compared with those assessed in this Report (red). Individual feedbacks for CMIP models are averaged across six radiative kernels as computed in Zelinka et al. (2020).

IPCC AR6

Climate models & how we model them?

- Numerical models (General Circulation Models or GCMs), representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations

- These are tools for investigating the response of the climate system to various forcing.

- Can be used for making climate predictions on varying scales and projecting future climate.

- Understand past climate and be informed & anticipate the future

- All this is accomplished by breaking the oceans and atmosphere into many small grid boxes, and using the underlying physical, chemical, and biological relationships to calculate values for the properties of each box and the interactions between different boxes.

Fundamental equations solved in GCMs

1. *Conservation of energy* (the first law of thermodynamics)
   i.e. Input energy = increase in internal energy plus work done
2. *Conservation of momentum* (Newton's second law of motion)
   i.e. Force = mass × acceleration
3. *Conservation of mass* (the continuity equation)
   i.e. The sum of the gradients of the product of density and flow-speed in the three orthogonal directions is zero. This must be applied to air and moisture for the atmosphere and to water and salt for the oceans, but can also be applied to other atmospheric and oceanic 'tracers' such as cloud liquid water.
4. *Ideal gas law* (an approximation to the equation of state – atmosphere only)
   i.e. Pressure × volume is proportional to absolute temperature × density

A Climate Modelling Primer, Third Edition. K. McGuffie and A. Henderson-Sellers.

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$$\frac{D\mathbf{U}}{Dt} = -2\boldsymbol{\Omega} \times \mathbf{U} - \frac{1}{\rho}\nabla p + \mathbf{g} + \mathbf{F}_r$$

$$\frac{Du}{Dt} - \frac{uv\tan\phi}{a} + \frac{uw}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\Omega v\sin\phi - 2\Omega w\cos\phi + F_{rx}$$

$$\frac{Dv}{Dt} + \frac{u^2\tan\phi}{a} + \frac{vw}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega u\sin\phi + F_{ry}$$

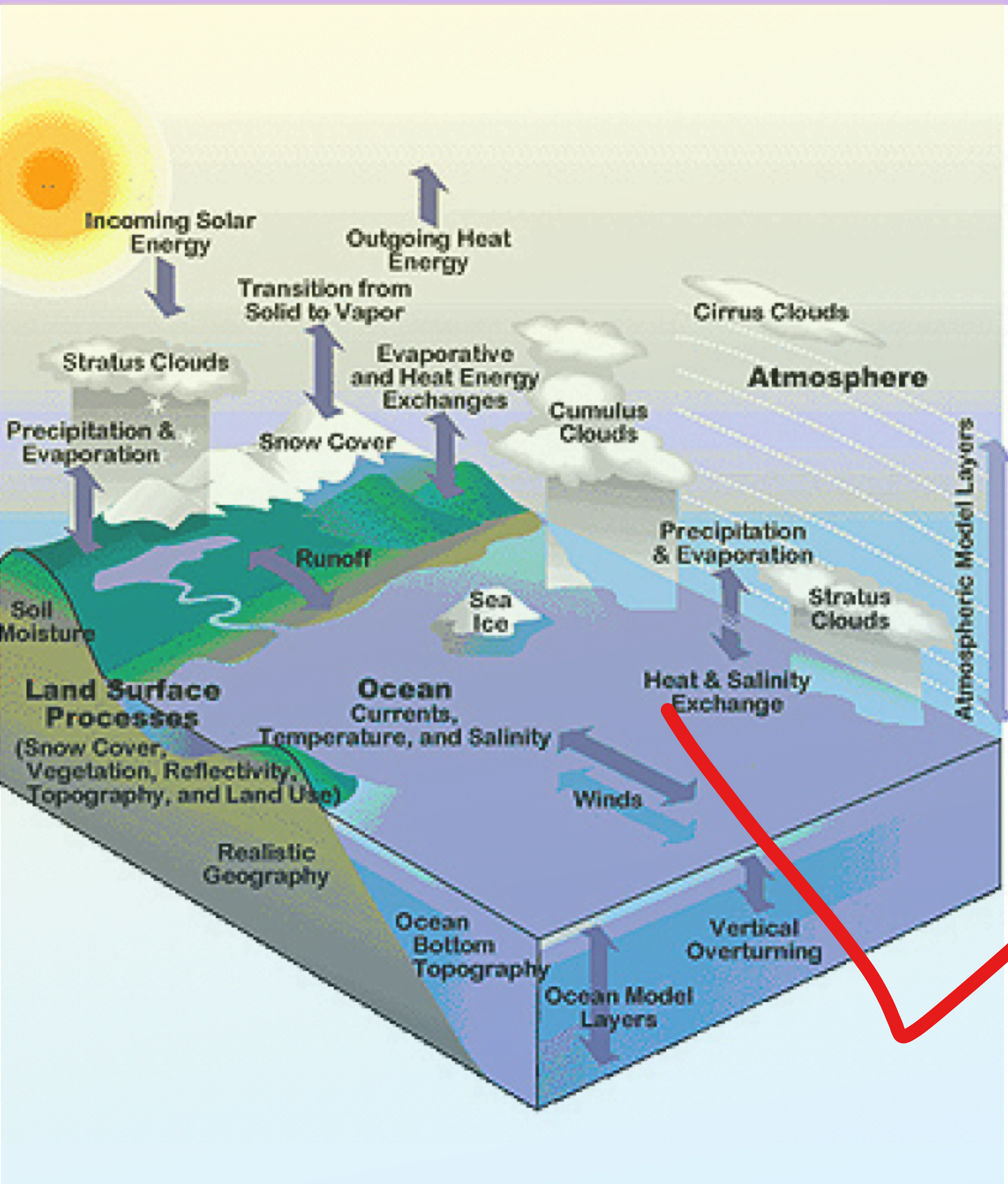
$$\frac{Dw}{Dt} - \frac{u^2+v^2}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega u\cos\phi + F_{rz}$$

$$\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) - S_p\omega = \frac{J}{c_p}$$

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \bullet \mathbf{U} = 0$$

$$S_p = (\Gamma_d - \Gamma)/\rho g$$

Interactions between different components



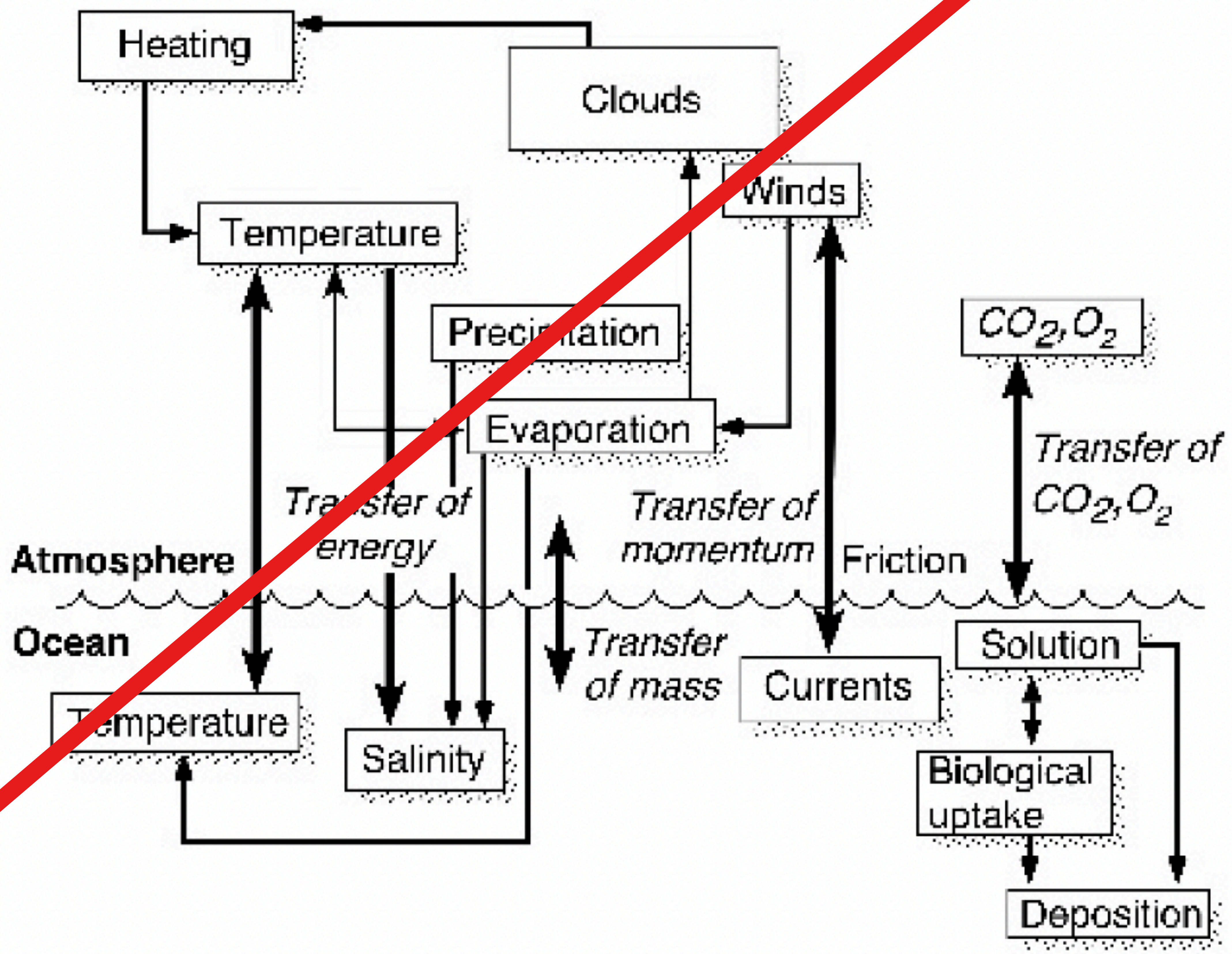


Figure 1.3 A representation of the major coupling mechanisms between the atmosphere and ocean subsystems. The relative importance of these coupling mechanisms varies with latitude. The feedback between atmospheric temperature and oceanic salinity is interesting because it is strong only in the sense of the atmosphere forcing the ocean

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Components of MPI-ESM

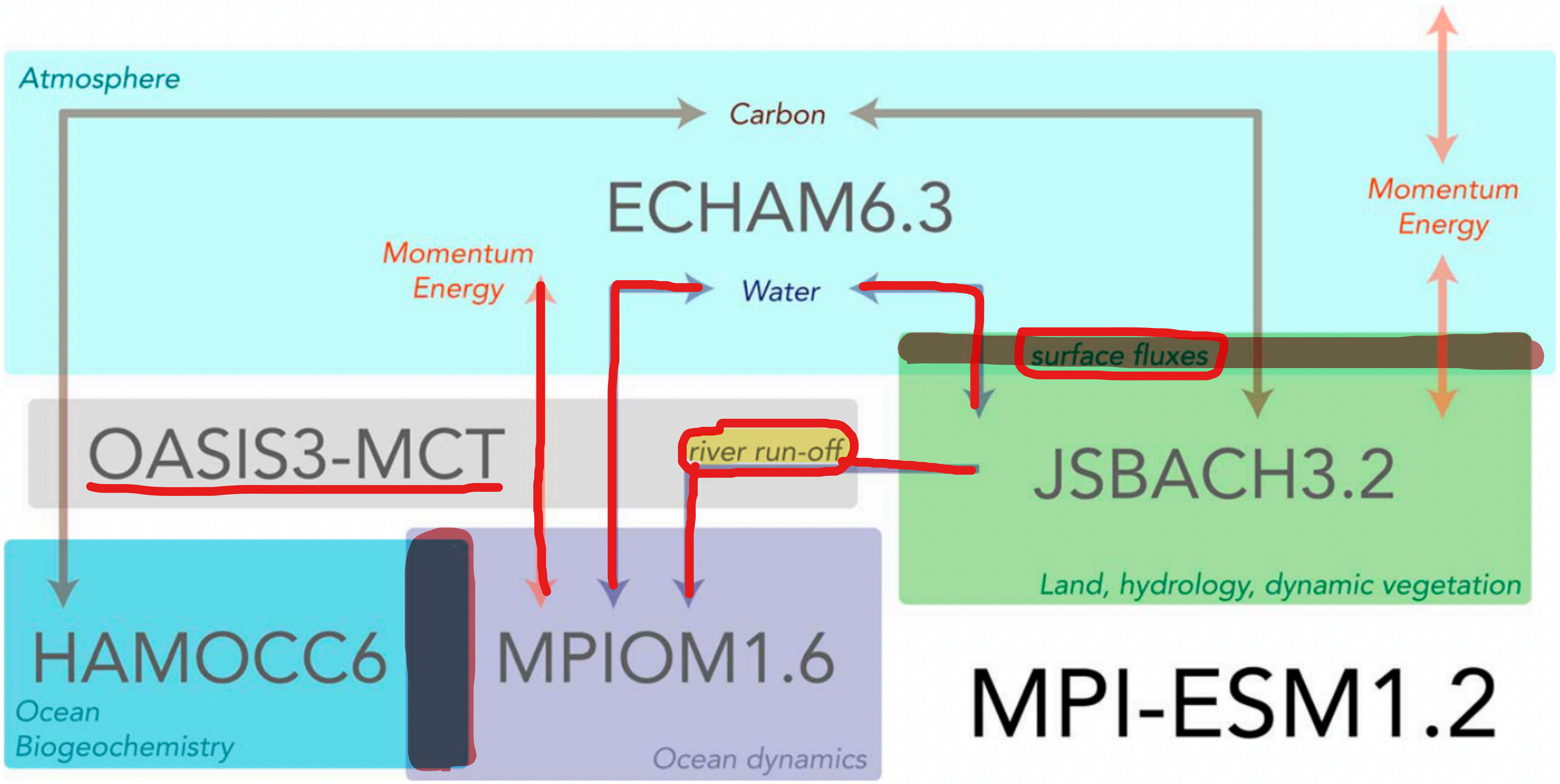
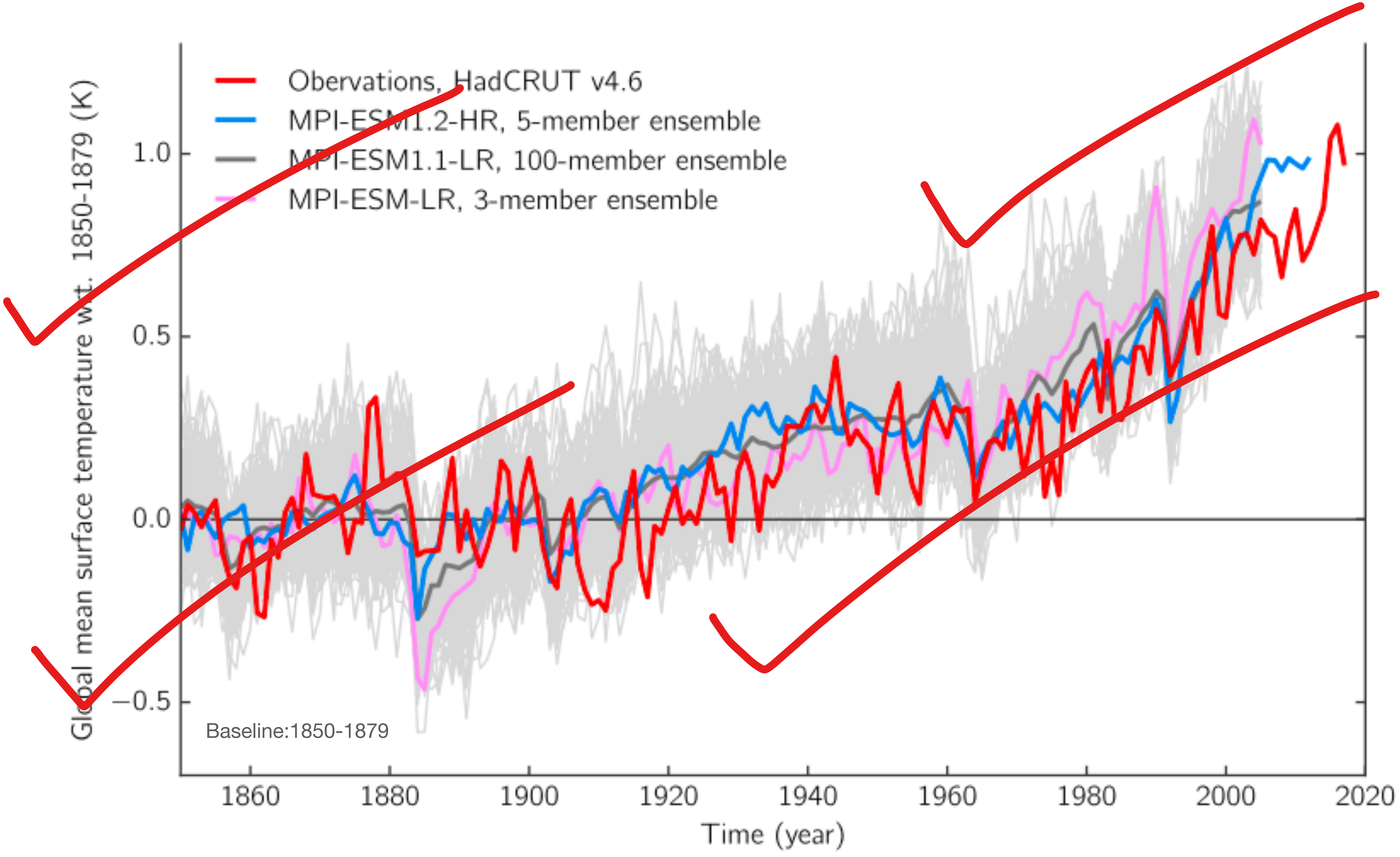


Figure 1. Schematic overview of the components of MPI-ESM1.2 and how these are coupled. The atmosphere ECHAM6.3 is directly coupled with the land surface model JSBACH3.2, whereas the ocean biogeochemistry model HAMOCC6 is directly coupled to the ocean dynamic model MPIOM1.6. These two major model component blocks are in turn coupled through the OASIS3-MCT coupler software.

Mauritsen et al. 2019

Components of CESM2

Danabasoglu et al. 2020



Obervations, HadCRUT v4.6
MPI-ESM1.2-HR, 5-member ensemble
MPI-ESM1.1-LR, 100-member ensemble
MPI-ESM-LR, 3-member ensemble
Global mean surface temperature w.r.t. 1850-1879 (K)
1.0
0.5
0.0
−0.5
Baseline:1850-1879
1860
1880
1900
1920
1940
1960
1980
2000
2020
Time (year)

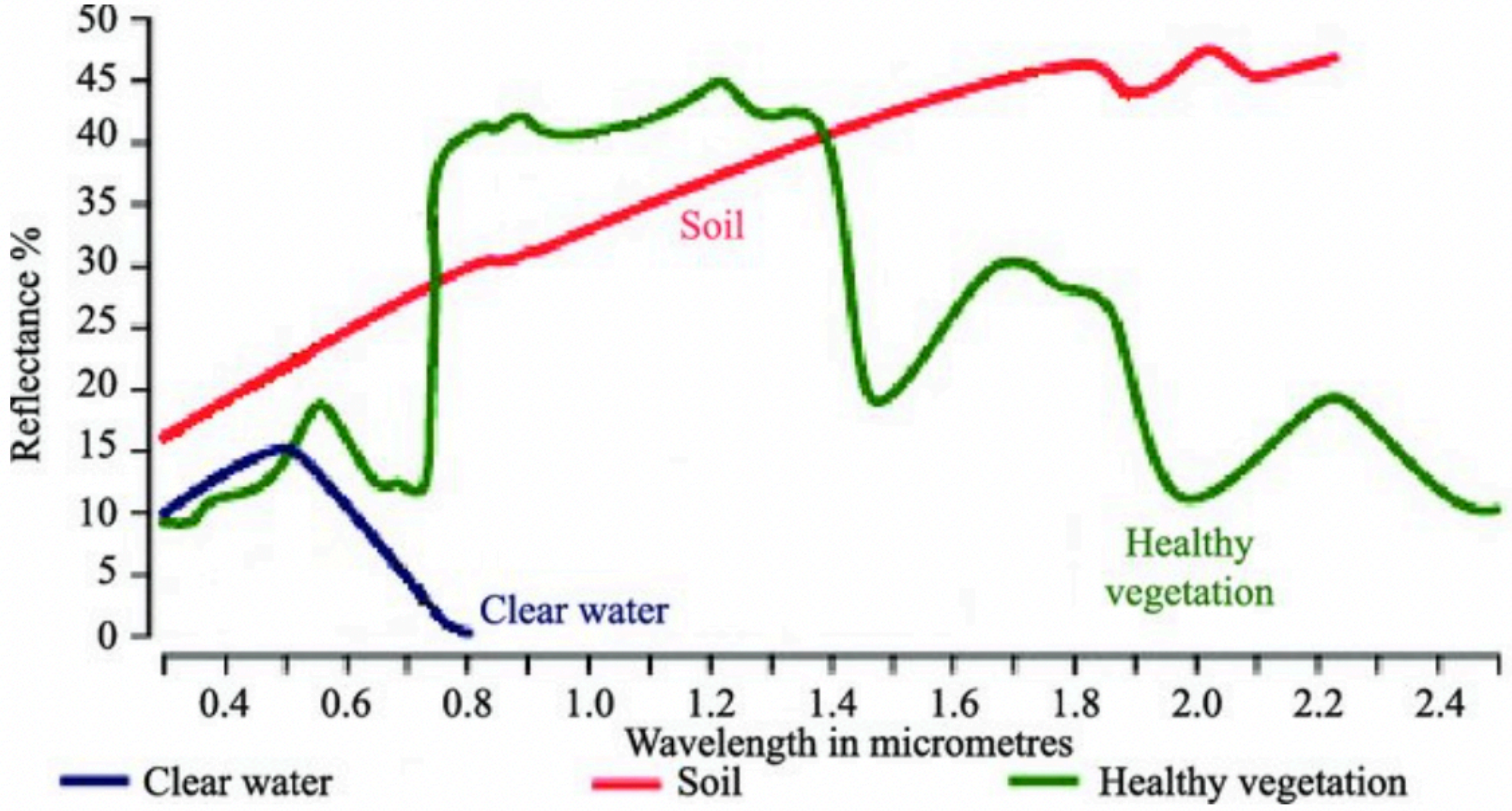

CESM2(CAM6)
CESM1(LENS)
EXP(A)
CESM2(WACCM6)
HADCRU45
GISTEMP
NOAA
Temperature Anomaly °C
1.5
1.0
0.5
0.0
-0.5
Baseline: 1850-1870
1850
1900
1950
2000

ERSSTv5
mean=18.29
CESM2(CAM6)
mean=18.69
CESM2(CAM6) - ERSSTv5
mean=0.39
rms=0.77
CESM2(WACCM6)
mean=18.63
CESM2(WACCM6) - ERSSTv5
mean=0.33
rms=0.75
CESM1(LENS)
mean=18.02
CESM1(LENS) - ERSSTv5
mean=-0.27
rms=0.67
0 4 8 12 16 20 24 28 32 36
-5 -4 -3 -2 -1 0 1 2 3 4 5

Land atmosphere interactions

- Land has lower thermal inertia than ocean – can heat up rapidly than ocean.
- Friction from land would be higher
- The type of interaction can depend on the type of land – forest covered or bare land or concrete or Roads or …
- Heats atmosphere through sensible heat and long wave emission.
- Albedo of the land (dependent on land cover) can significantly affect climate

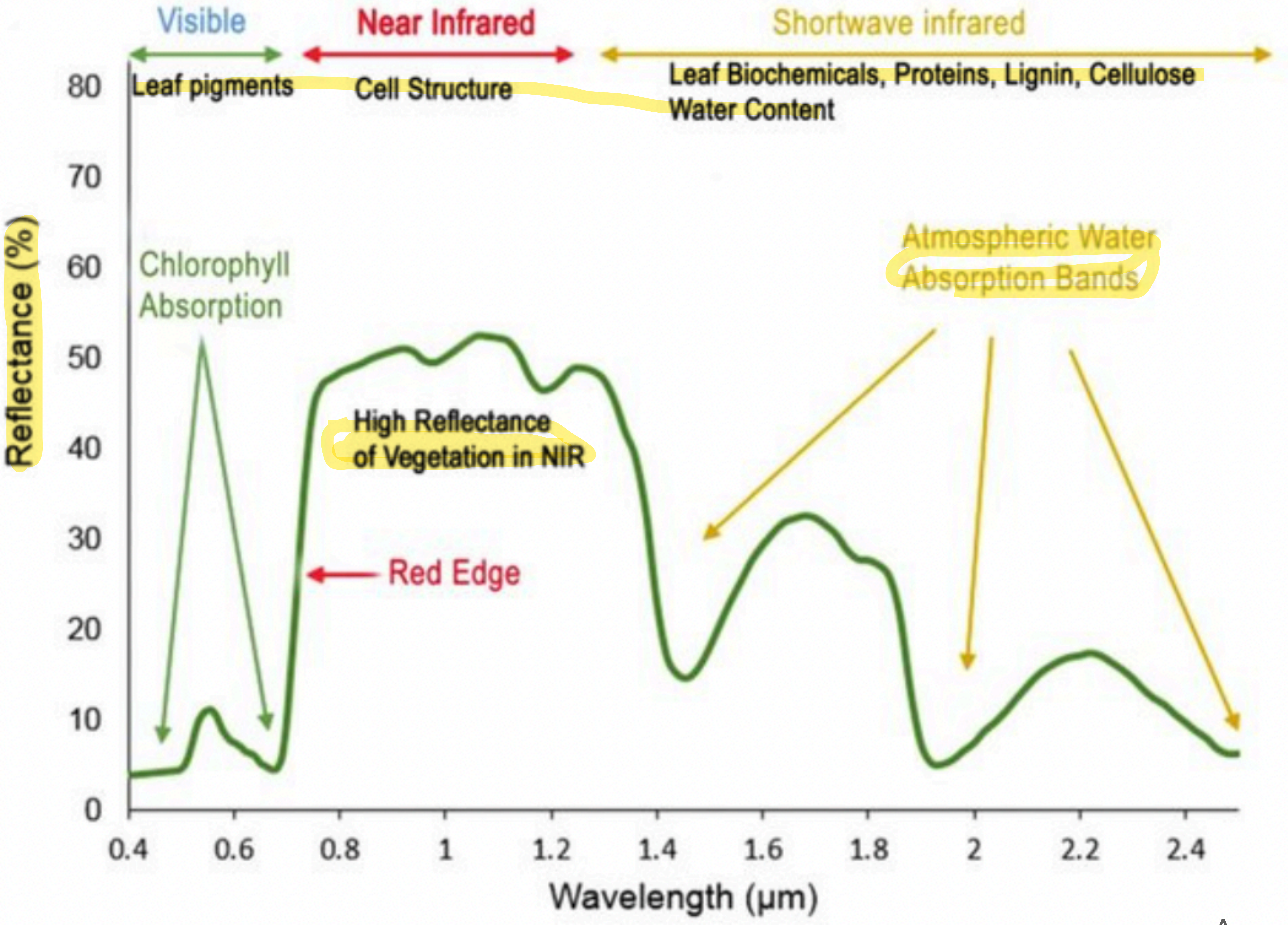
Spectral reflectance curves of different land cover types



Kumar & Reshmidevi 2013

Land atmosphere interactions

Spectral reflectance curves of vegetation



Anamaria Roman & Tudor-Mihai Ursu 2016

Land atmosphere interactions

- Land cover can also affect the moisture exchange between land and ocean
- The precipitation (rainfall or snowfall) can **runoff** forming streams which join together to form larger streams/ rivers
- The precipitation can **infiltrate into deeper ground** - infiltrated water can either stay or flow as underwater streams which may join with surface streams (it is estimated that significant part of Kaveri in the delta region flows as sub-surface streams).
- Precipitation falling over high mountains could form permanent ice-cover and significantly modify the albedo
- Some of the ice may start moving down as glaciers – these in turn could feed into perennial rivers – Ganga, Yamuna, Bhramaputra and Indus get significant part of the flow especially in the lean season from melting of glaciers.
- River flow discharges into oceans can change the salinity– this salinity change can have significant impact on the upper layers of the ocean and hence on ocean-atmosphere interaction (processes over Northern Bay of Bengal are an example of this).

Community Land Model, NCAR (CESM)

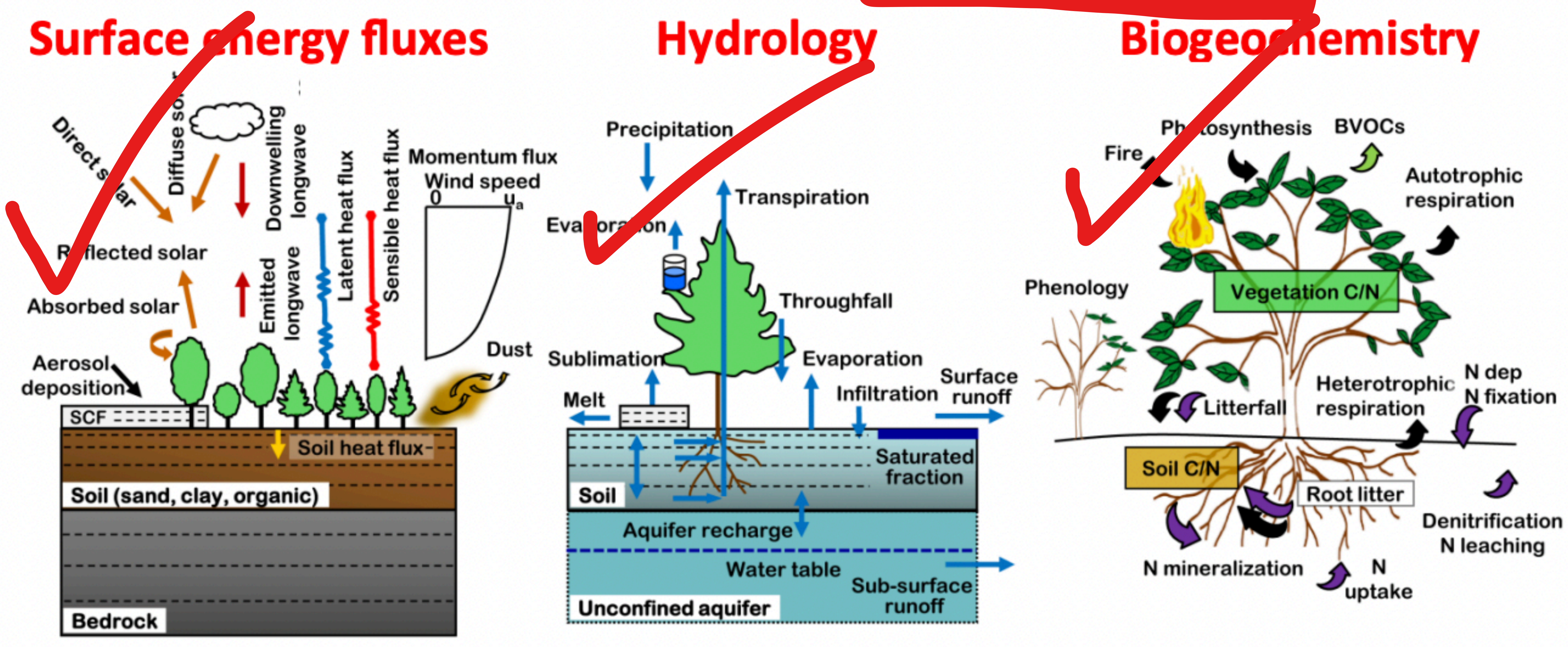
CLM5.0

Fluxes of energy, water, CO_2, CH_4, BVOCs, and Nr and the processes that control these fluxes in a changing environment

Oleson et al. (2013) NCAR/TN-503+STR (420 pp)

Lawrence et al. (2011) J. Adv. Mod. Earth Syst., 3, doi: 10.1029/2011MS000045

Lawrence et al. (2012) J Climate 25:2240-2260

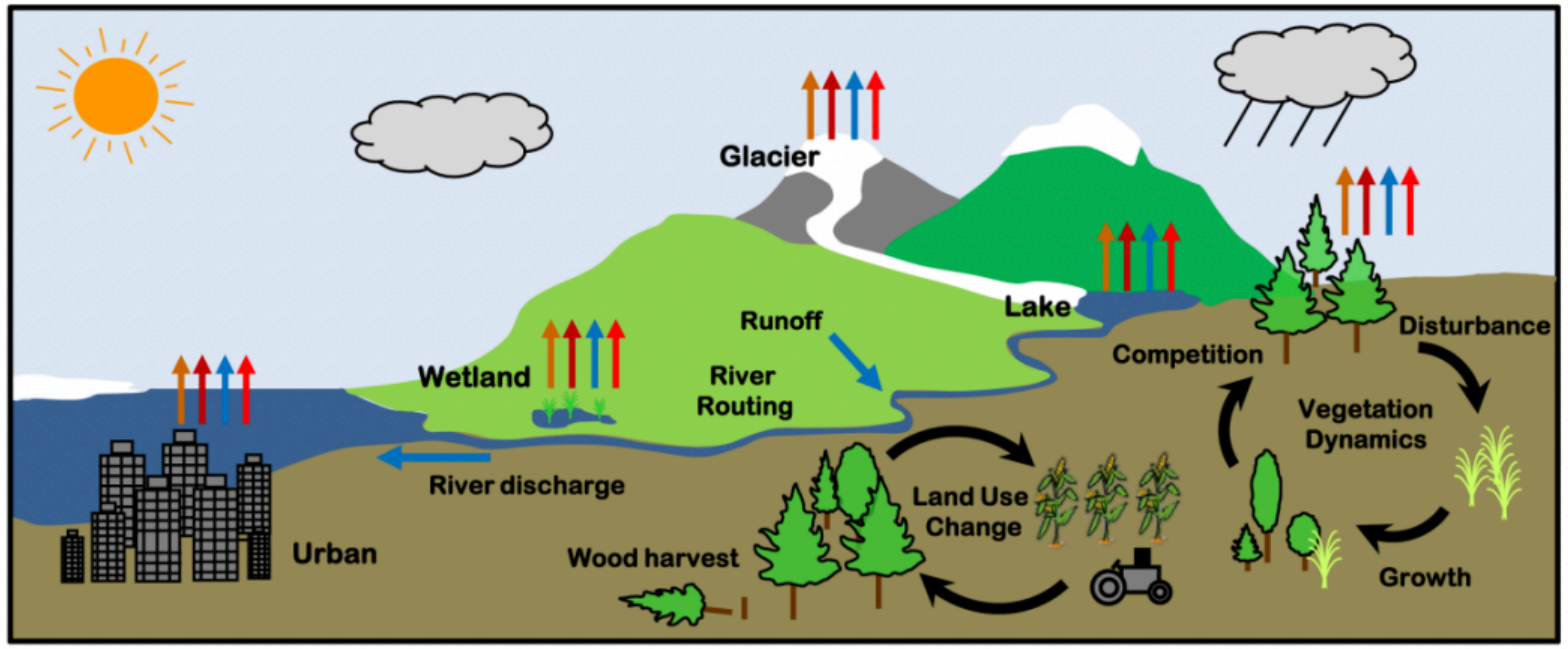


Spatial scale

~100 km

Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century (disturbance, land use, succession)
- Paleoclimate (biogeography)



Landscape dynamics

Lawrence et al. 2019