Lecture 5
20 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

Ozone hole

The ozone hole refers to a significant thinning of the ozone layer, primarily observed in the Antarctic stratosphere during the spring season (September to November).

Where it primarily formed in the past?

Antarctica: The ozone hole formed over Antarctica, centered near the South Pole. This region is most affected due to the unique meteorological and chemical conditions in the Southern Hemisphere.

Polar Stratospheric Clouds

Catalytic Ozone Destruction

Isolation of Antarctic Air (Polar Vortex)

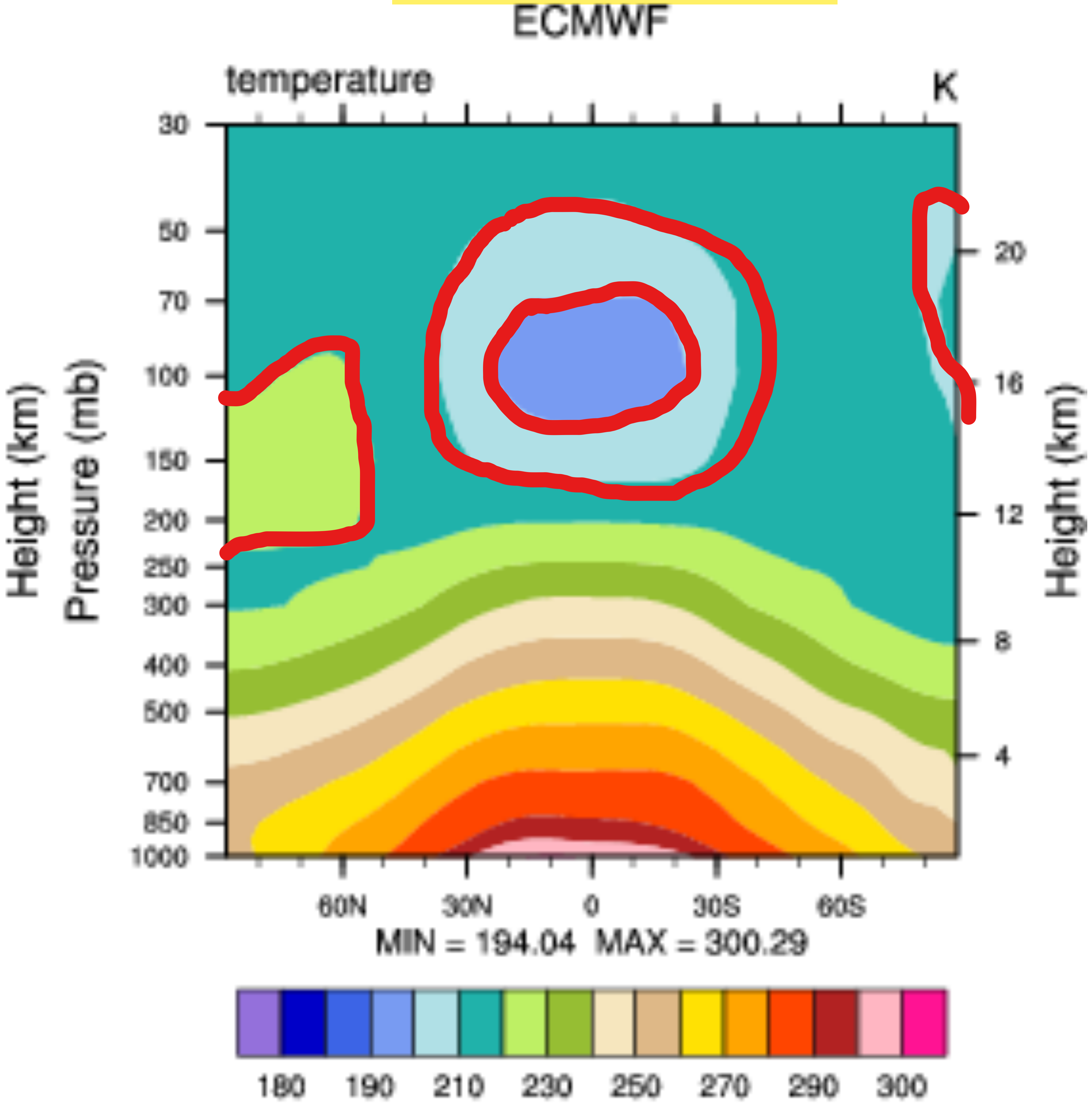
Anthropogenic Emissions

First Observed: The ozone hole was first observed in the 1980s, although it began forming earlier as a result of increased industrial emissions. The worst depletion occurred in the late 1990s and early 2000s, with ozone levels in the Antarctic region dropping by as much as 60-70%

Recovery: Thanks to the Montreal Protocol (1987), which phased out the production of CFCs and other ozone-depleting substances, the ozone hole has been gradually recovering since the early 2000s. Full recovery is expected by the 2060s, depending on global adherence to ozone protection measure

https://www.nasa.gov/earth-and-climate/nasa-data-aids-ozone-holes-journey-to-recovery/

Annual mean vertical structure of temperature



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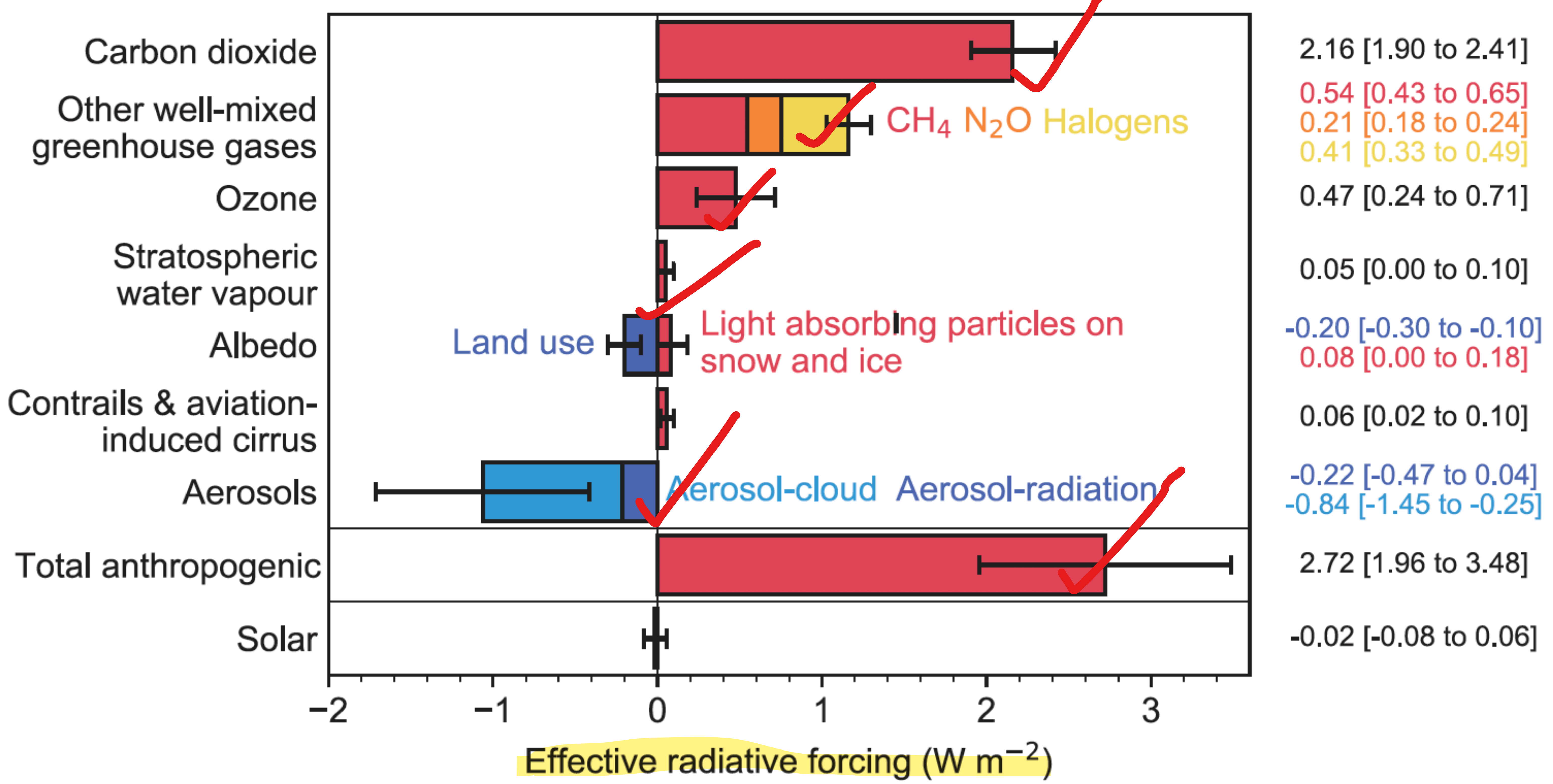
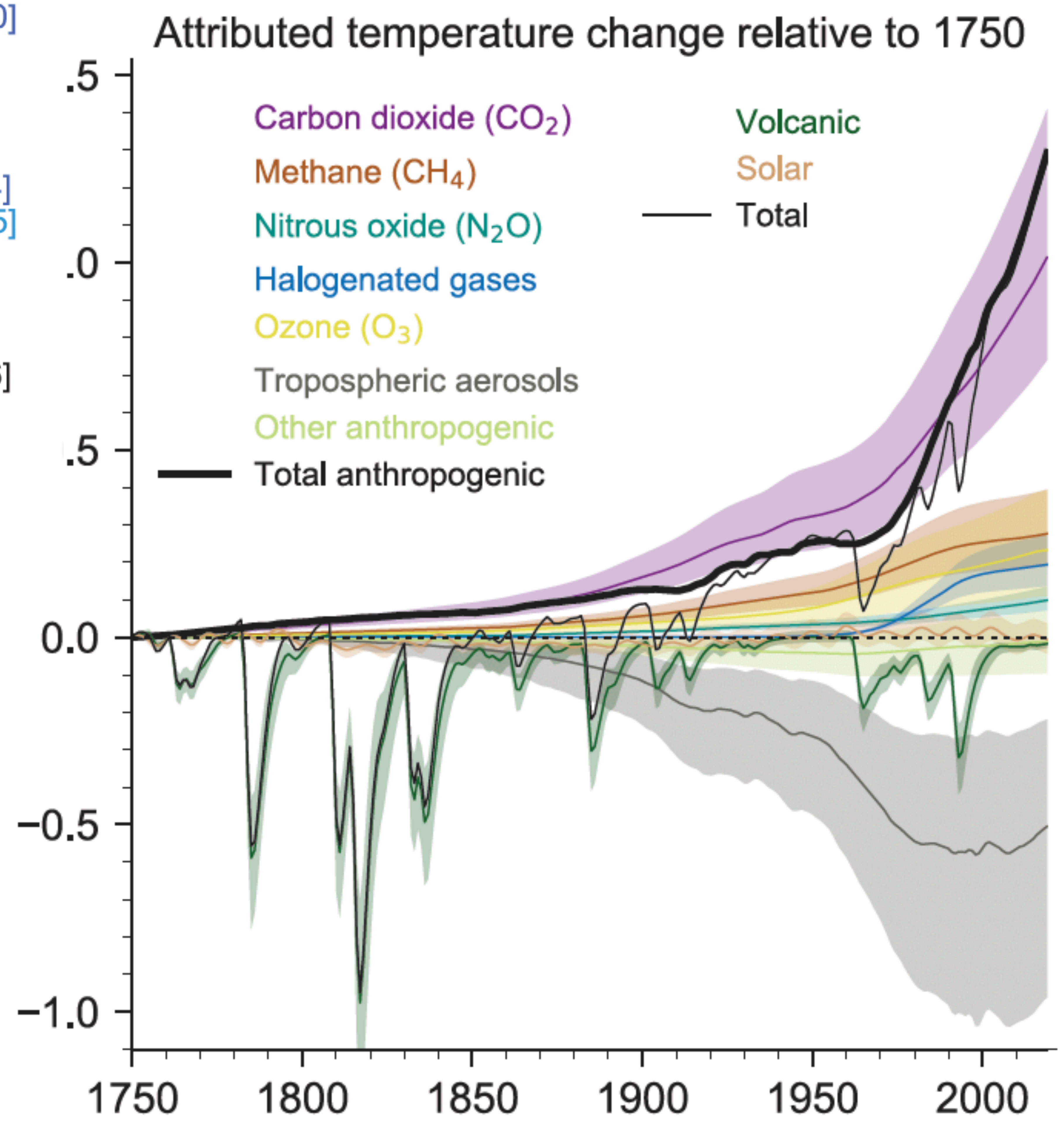

Change in effective radiative forcing from 1750 to 2019
ERF (W m^{-2})
Carbon dioxide
2.16 [1.90 to 2.41]
Other well-mixed greenhouse gases
CH_4 N_2O Halogens
0.54 [0.43 to 0.65]
0.21 [0.18 to 0.24]
0.41 [0.33 to 0.49]
Ozone
0.47 [0.24 to 0.71]
Stratospheric water vapour
0.05 [0.00 to 0.10]
Albedo
Land use
Light absorbing particles on snow and ice
-0.20 [-0.30 to -0.10]
0.08 [0.00 to 0.18]
Contrails & aviation-induced cirrus
0.06 [0.02 to 0.10]
Aerosols
Aerosol-cloud
Aerosol-radiation
-0.22 [-0.47 to 0.04]
-0.84 [-1.45 to -0.25]
Total anthropogenic
2.72 [1.96 to 3.48]
Solar
-0.02 [-0.08 to 0.06]
−2
−1
0
1
2
3
Effective radiative forcing (W m^{-2})


Attributed temperature change relative to 1750
Carbon dioxide (CO_2)
Methane (CH_4)
Nitrous oxide (N_2O)
Halogenated gases
Ozone (O_3)
Tropospheric aerosols
Other anthropogenic
Total anthropogenic
Volcanic
Solar
Total
.5
.0
.5
0.0
−0.5
−1.0
1750
1800
1850
1900
1950
2000

Climate Sensitivity

$$\boxed{\Delta F_{net} = \Delta F_S - \Delta F_L}$$

$$\lambda = \frac{-\Delta T}{\Delta F_{net}} - - units(K/Wm^{-2})$$

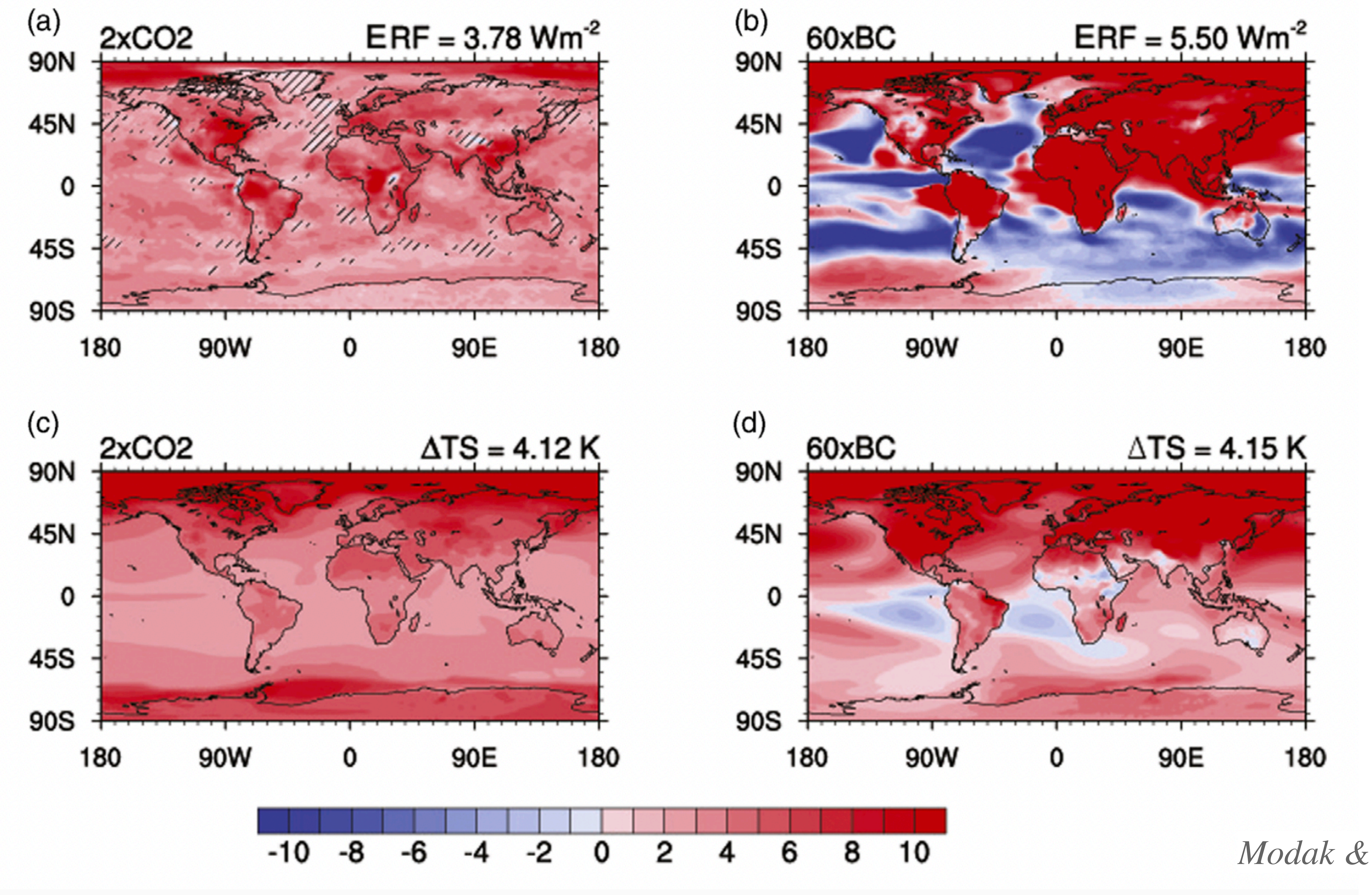
$\lambda \equiv$ climate sensitivity

$\alpha \equiv$ climate feedback factor $(\frac{1}{\lambda})$

Beware of the symbol used in the literature

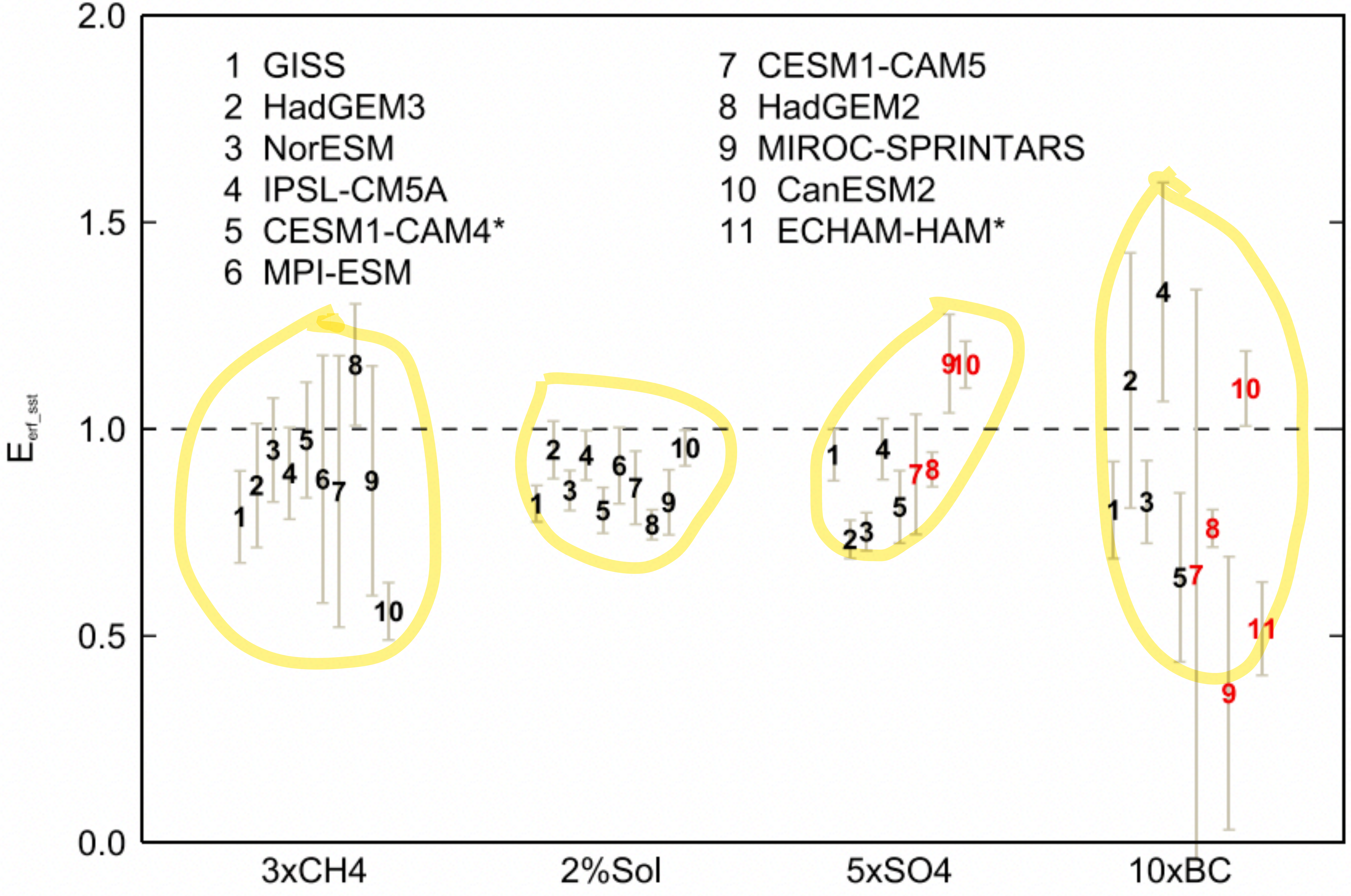
Created by
Angshuman Modak

Dependence of λ on Forcing agents



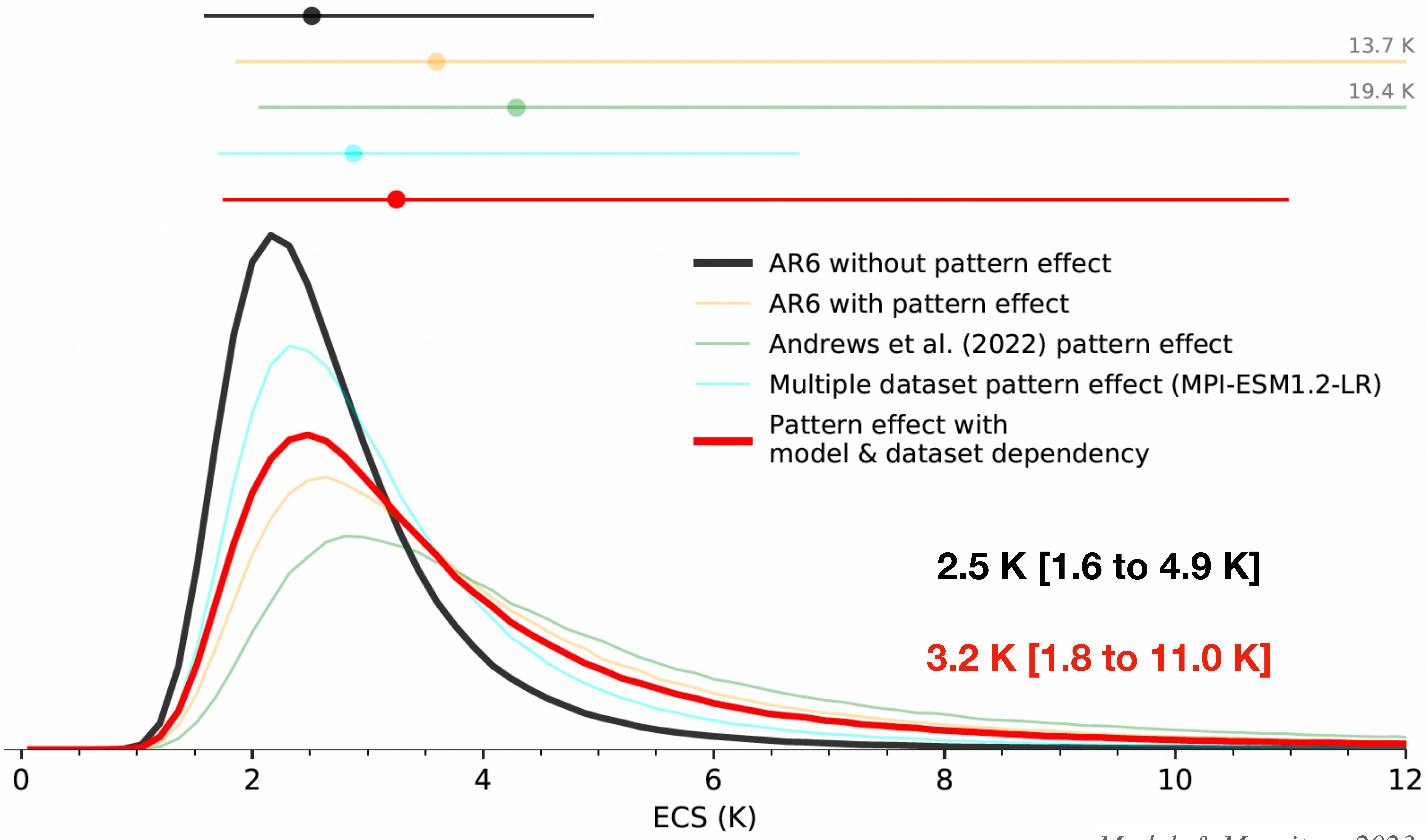
Modak & Bala 2019

Efficacy of Climate Forcings (E_{erf_sst})



Richardson et al, 2019, JGR-A

Dependence of λ on Time



Modak & Mauritsen 2023, ACP, IPCC AR6 WGI

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).

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

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

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

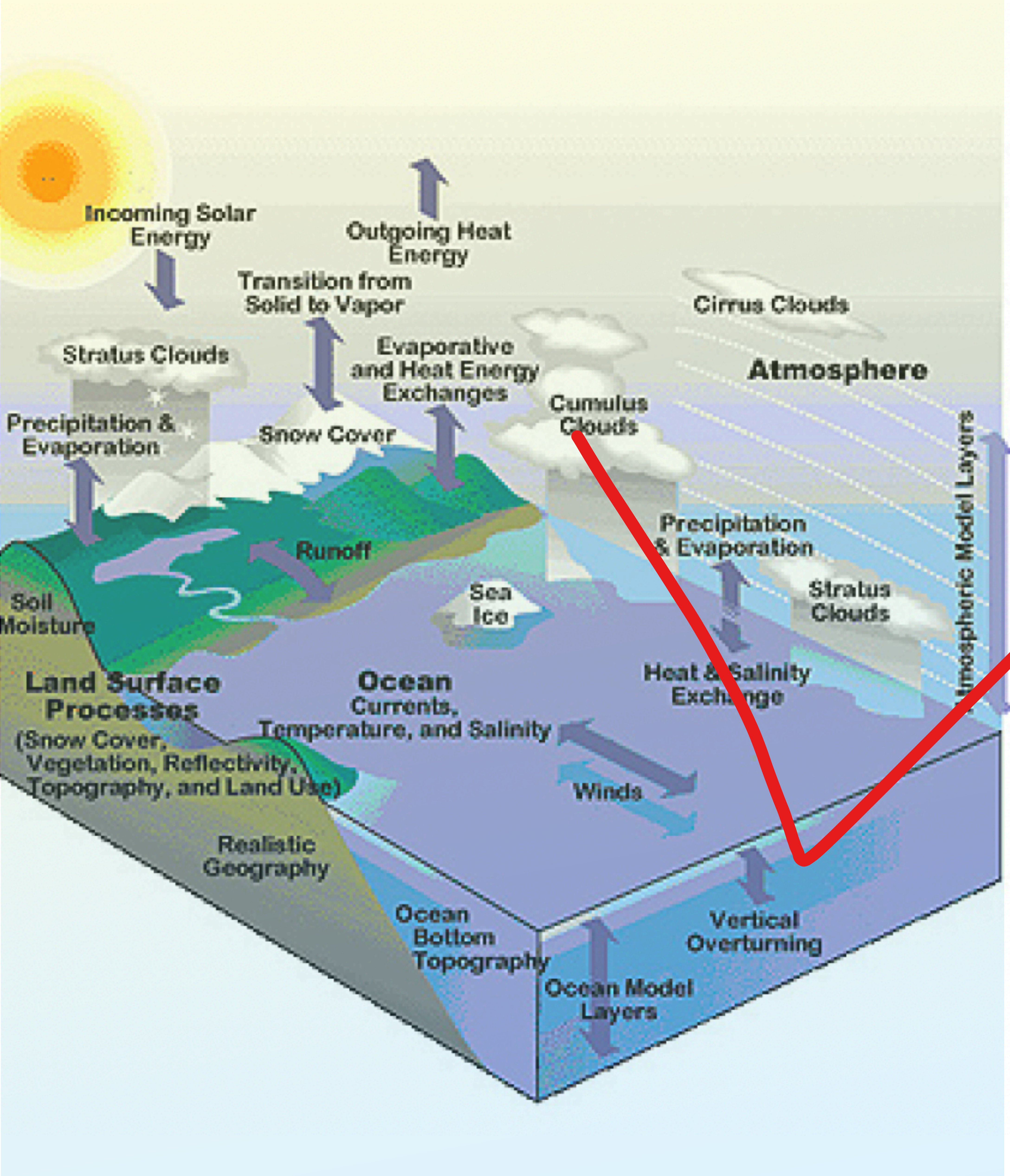
$$\frac{Dw}{Dt} - \frac{u^2+v^2}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega u\cos\phi + F_{rz}$$

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

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

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

Interactions between different components



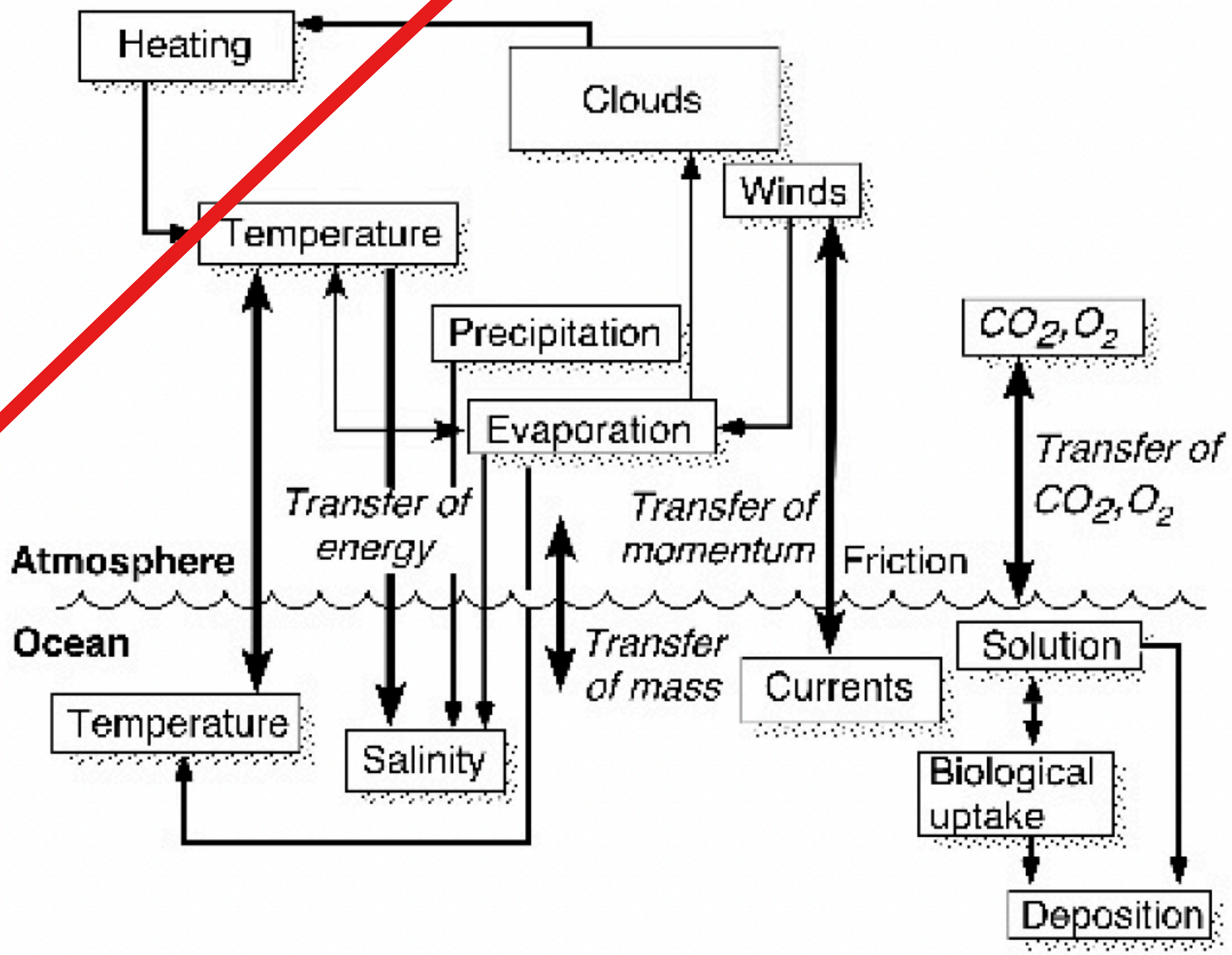


Figure 1.3 A representation of the major coupling mechanisms between the atmosphere and ocean subsystems. The relative importance of these coupling mechanisms varies with latitude. The feedback between atmospheric temperature and oceanic salinity is interesting because it is strong only in the sense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

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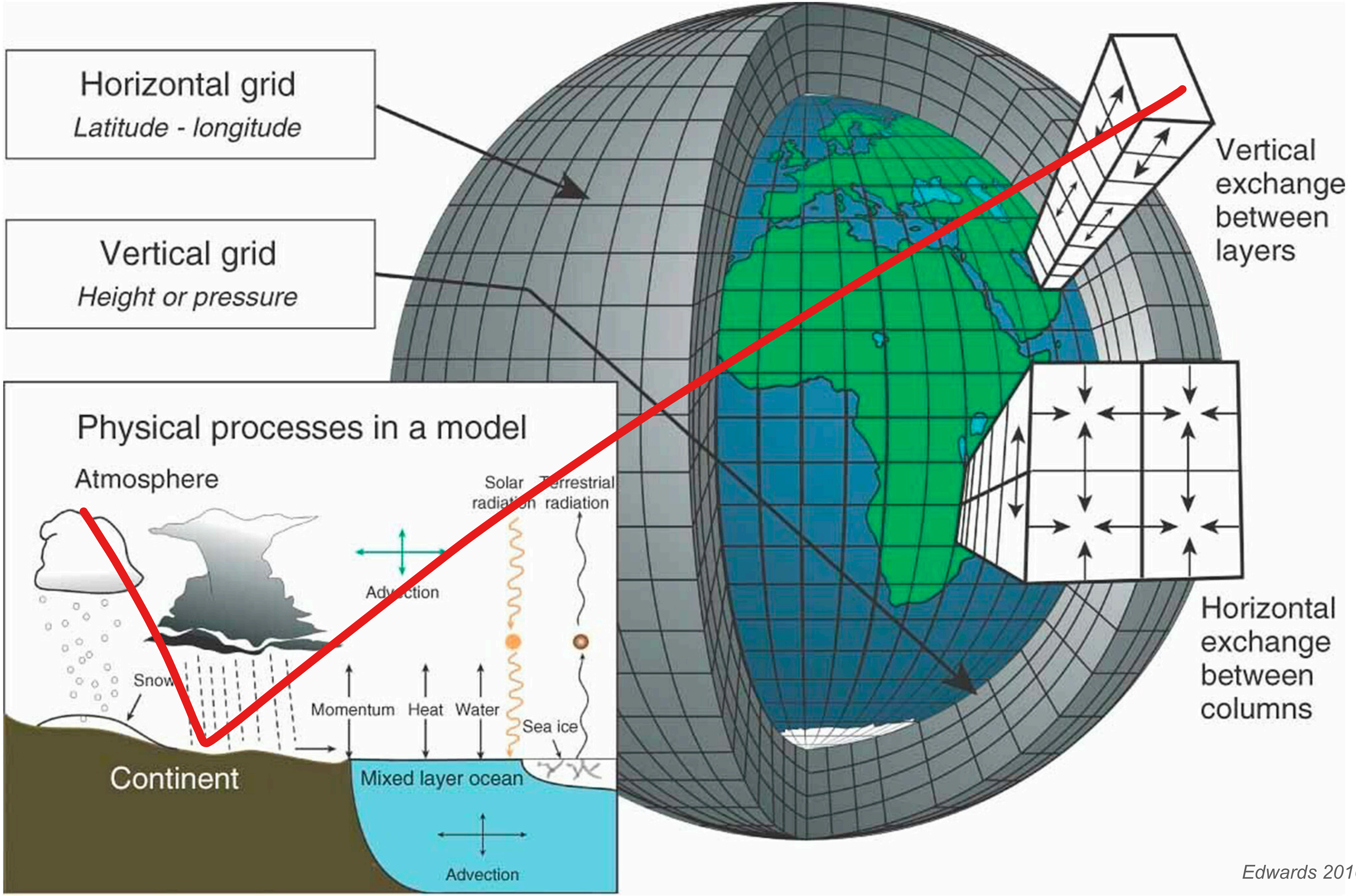

Edwards 2010

The World in Global Climate Models