Lecture 4
16 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

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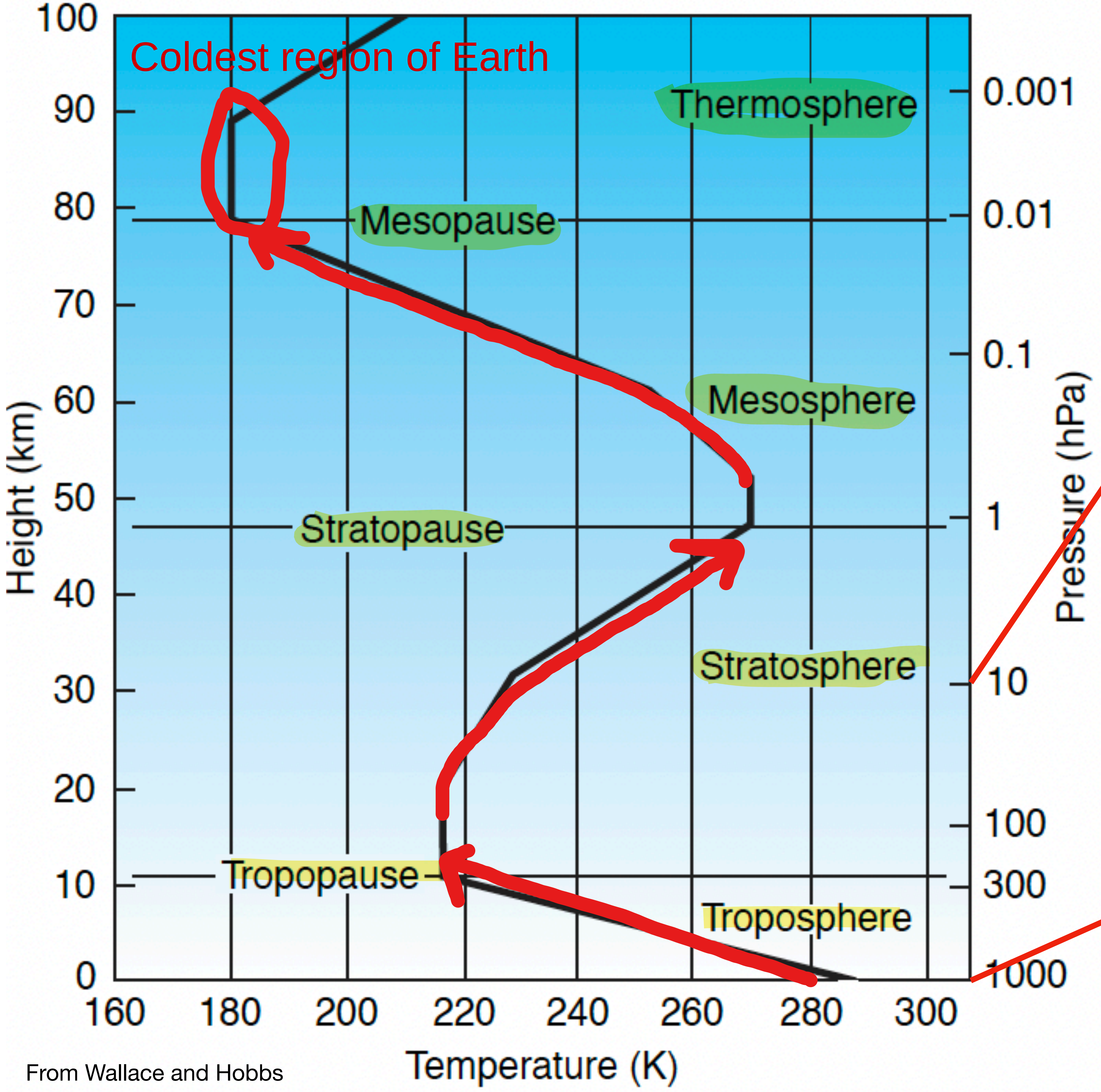
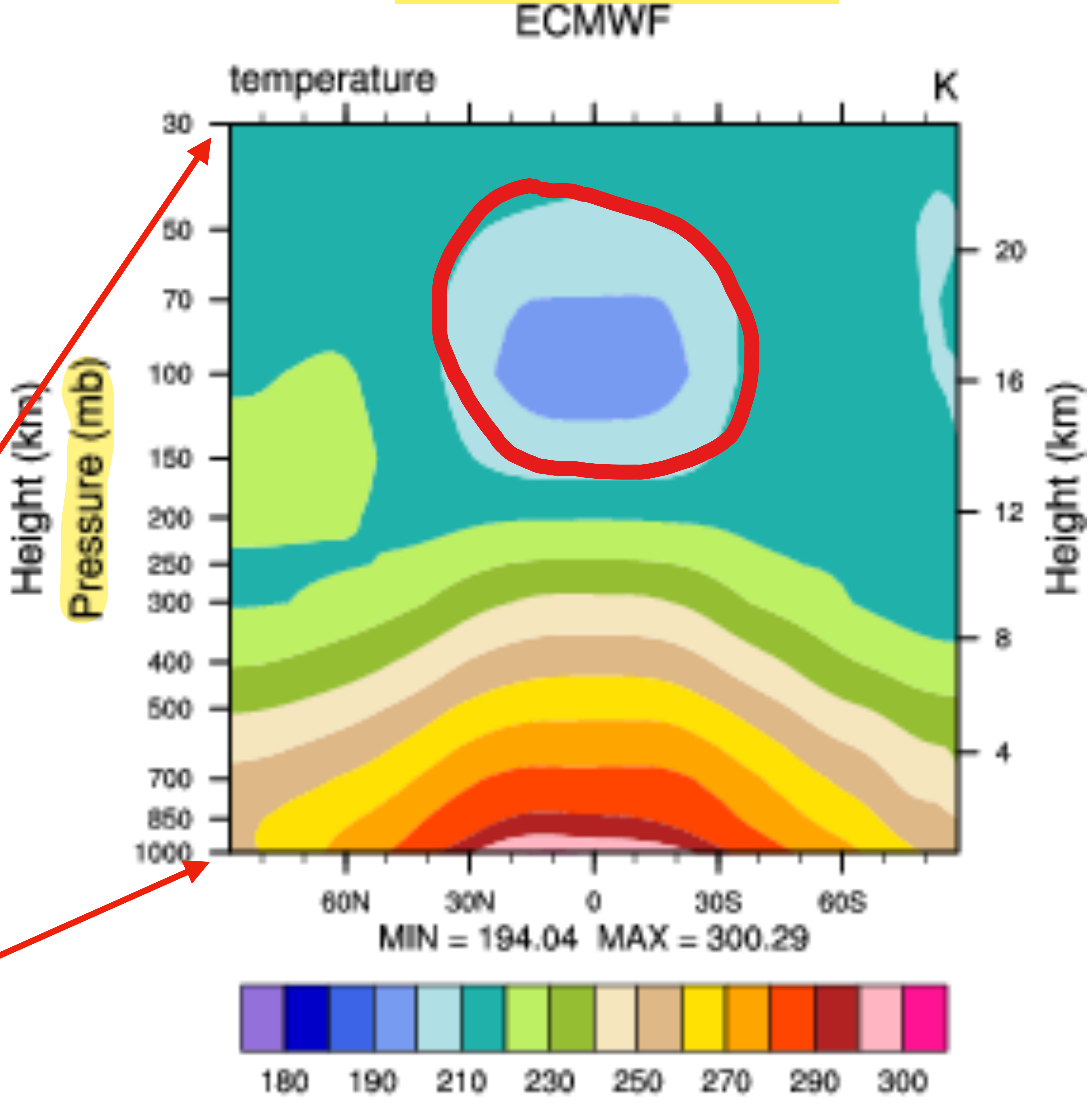
Temperature profile



From Wallace and Hobbs

Annual mean vertical structure of temperature



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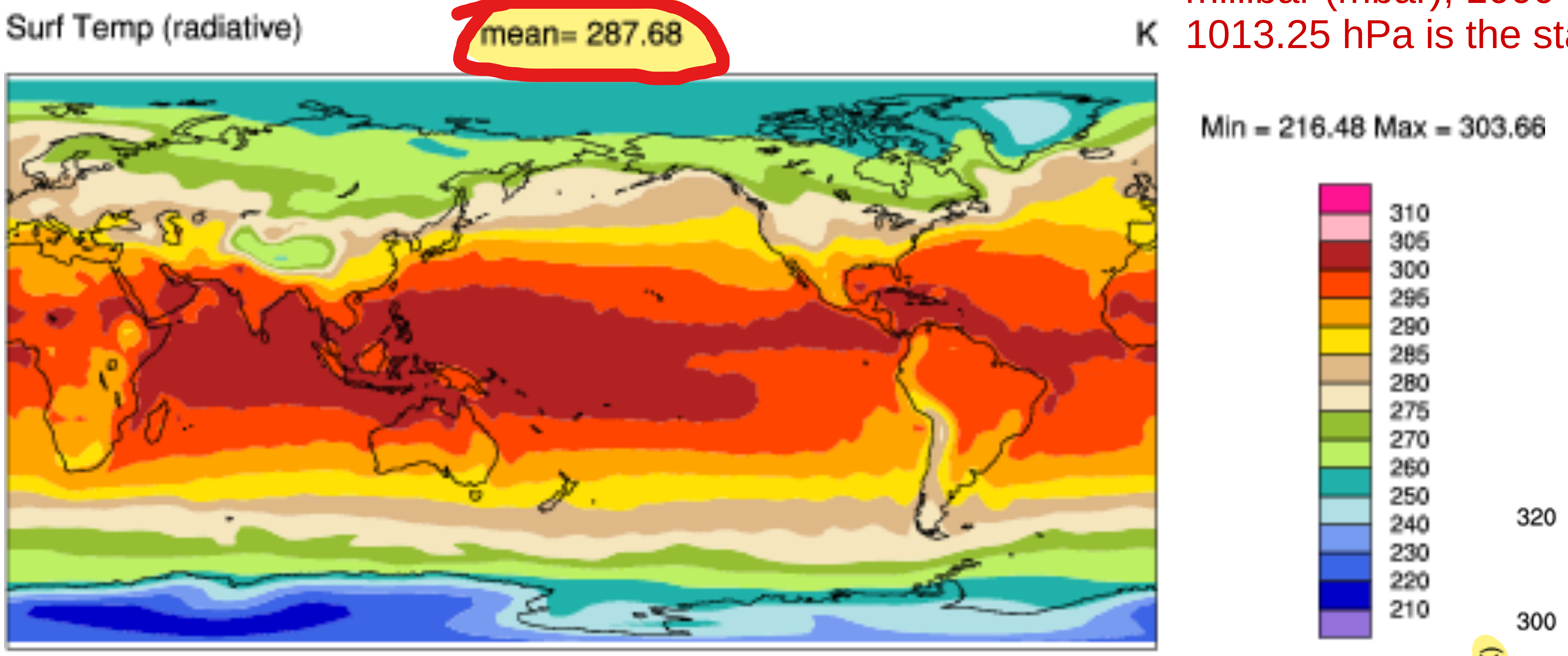
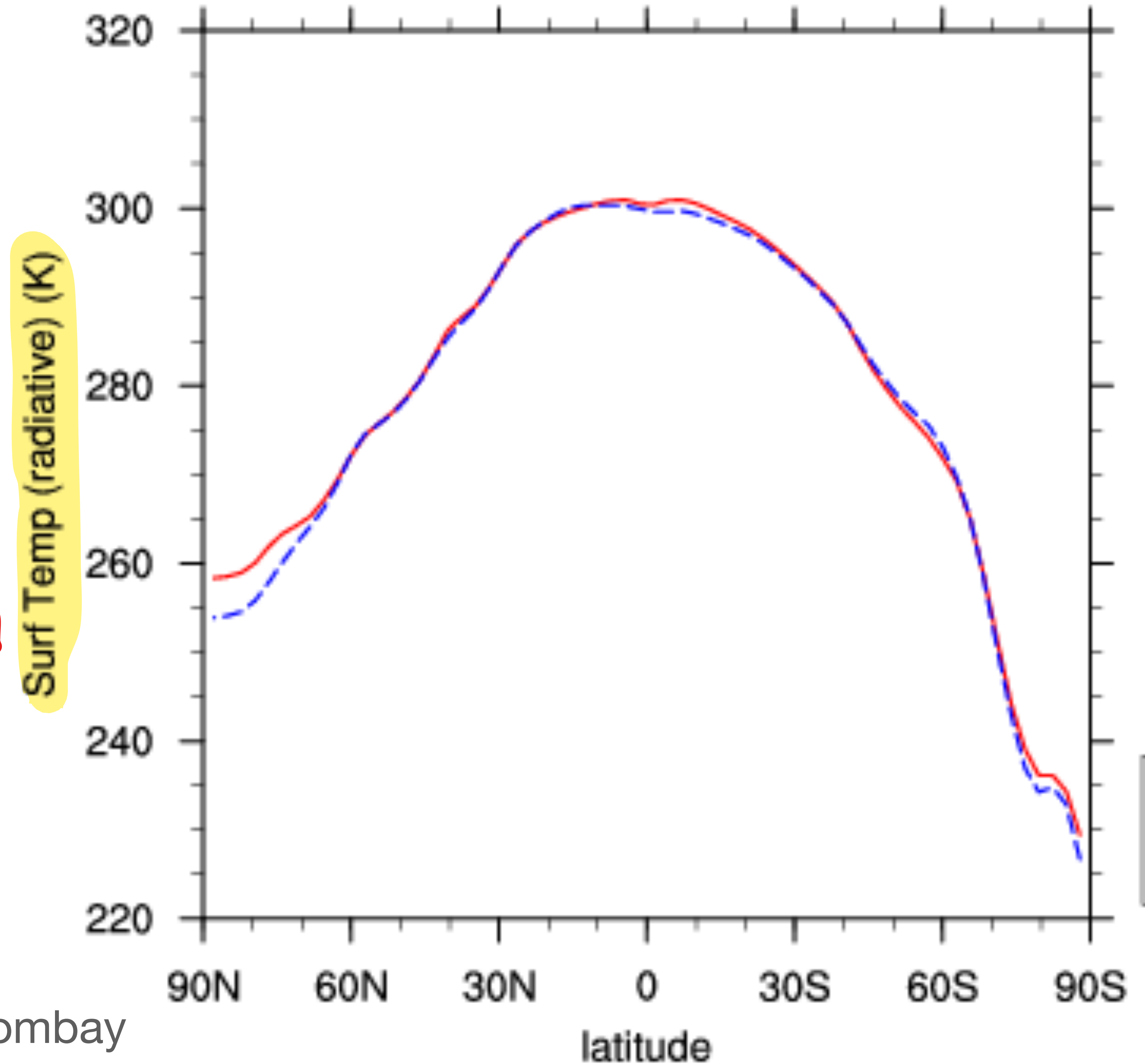
Annual mean surface temperature

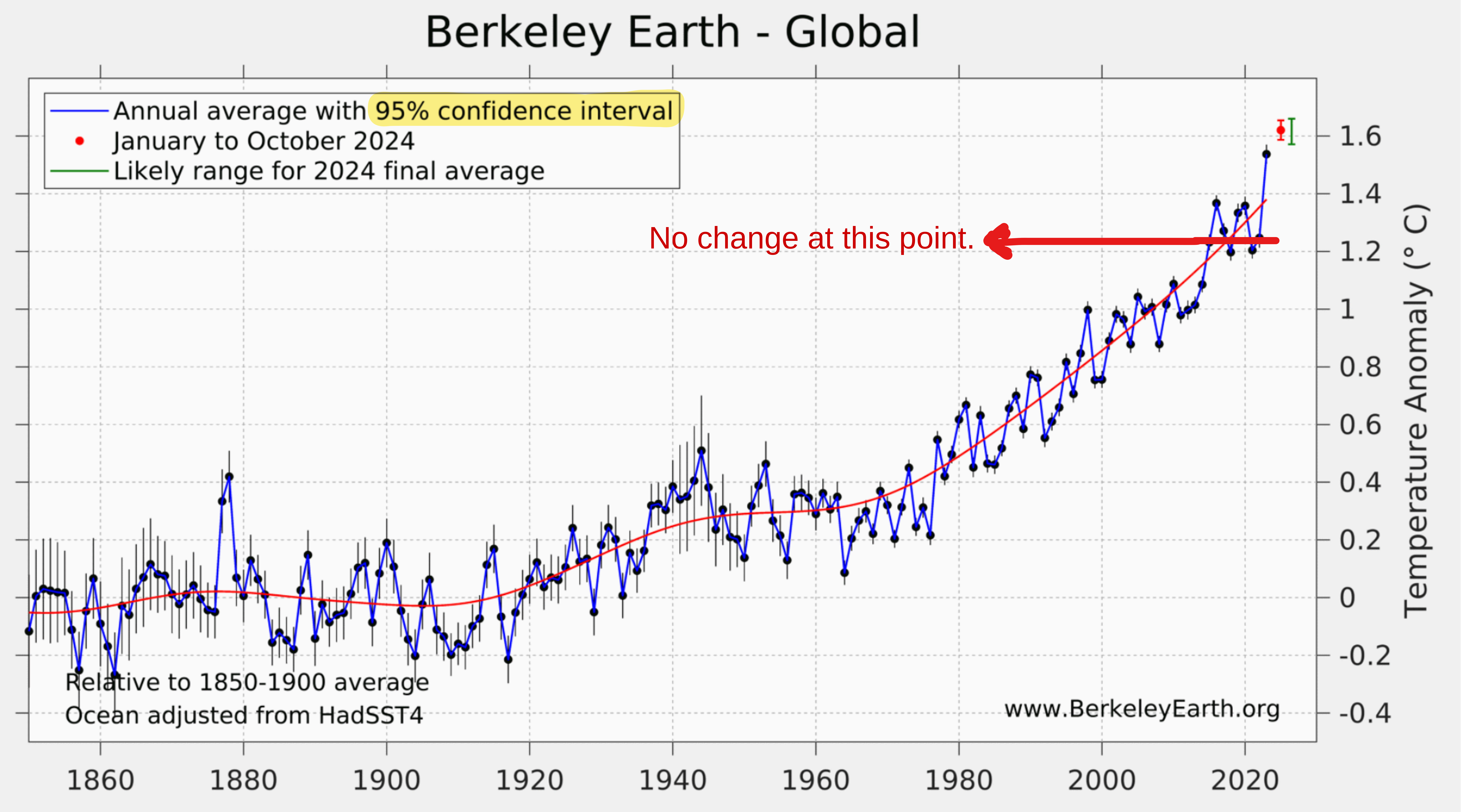
1 hPa (hecto Pascal) = 100 pascal (Pa), 1 hPa = 1 millibar (mbar), 1000 hPa = 1000 millibars, and 1013.25 hPa is the standard pressure at sea level.

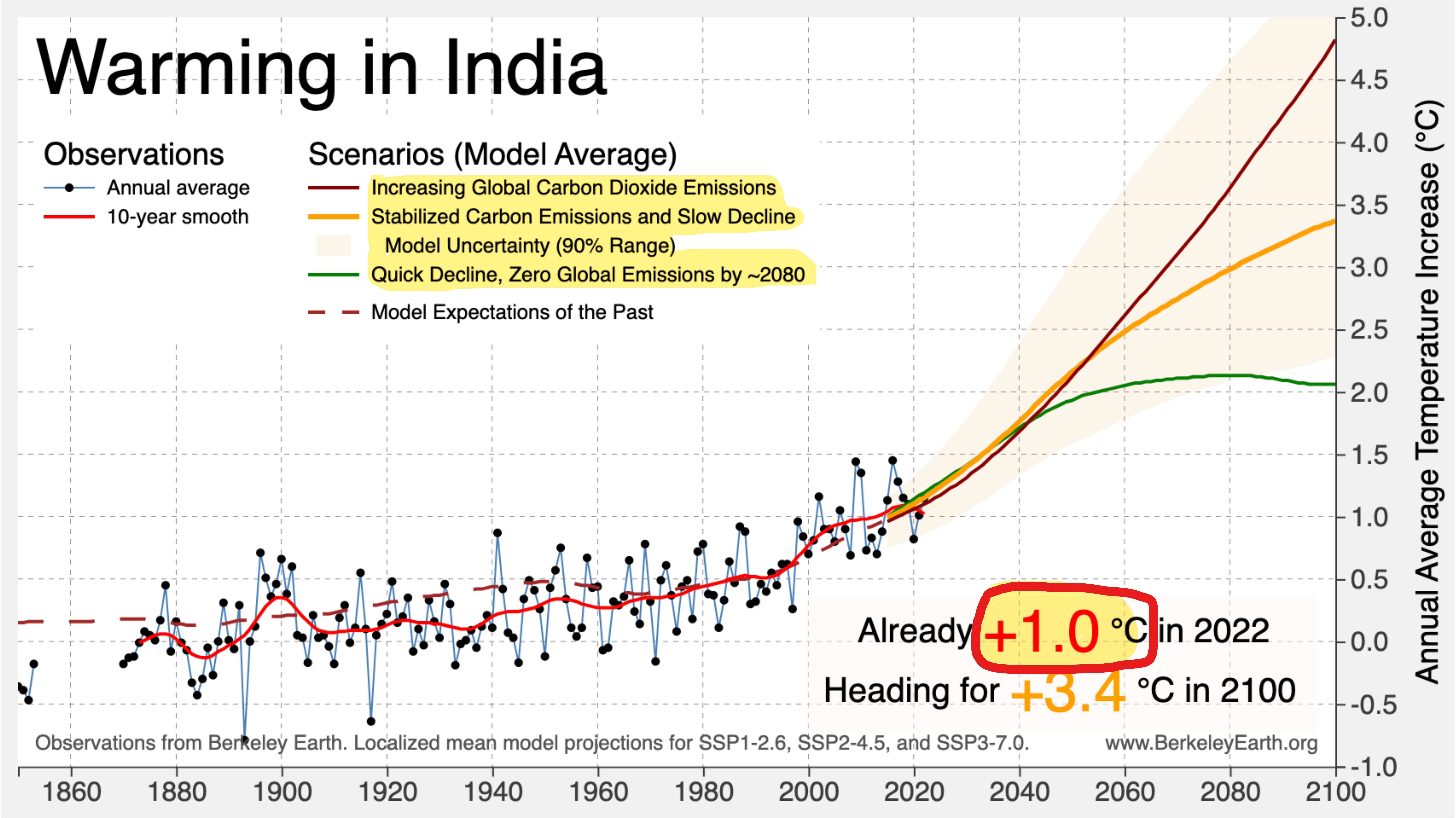


Ts



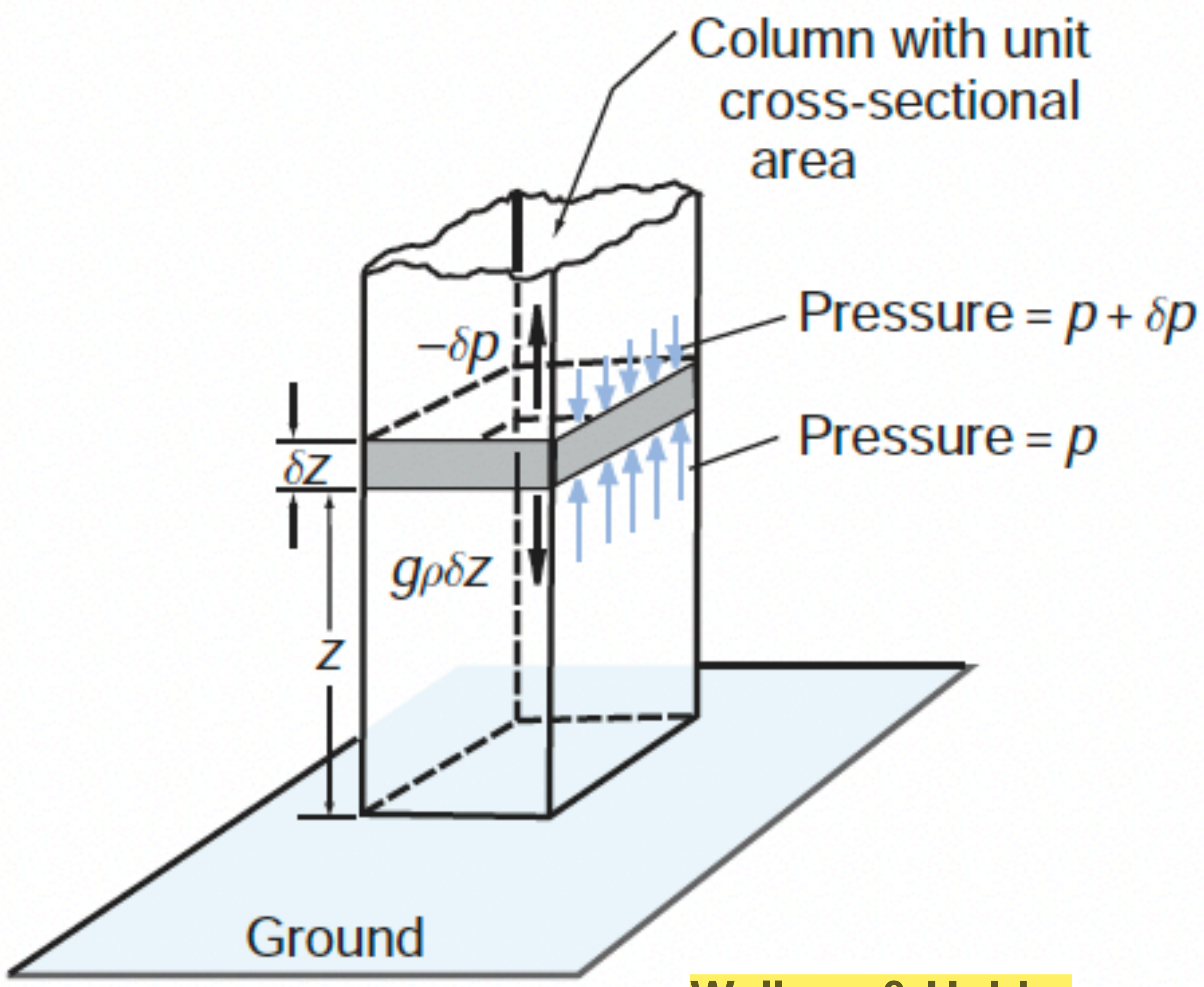
Historical warming…




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

Hydrostatic Equilibrium

- PGF = Gravitational attraction
- $$-\frac{1}{\rho}\frac{\partial p}{\partial z} = g$$
- $$\int_{sfc}^{top} dp = -\int_{sfc}^{top} \rho g dz$$



Wallace & Hobbs

- Generally, g is assumed to be constant, but we know it varies because of
  - Distance from Earth's centre
  - Latitude due to non-sphericity of Earth

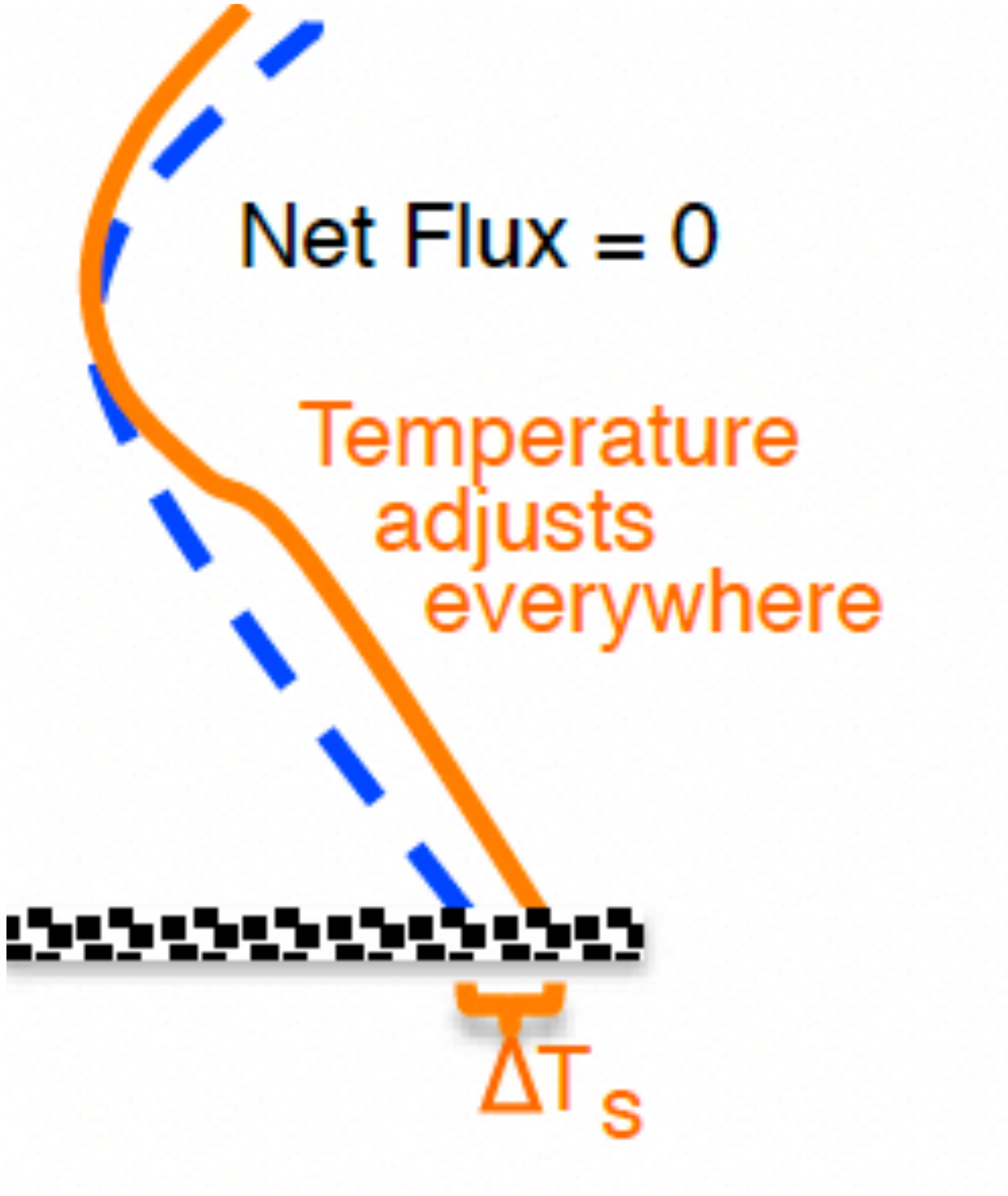
Equation of State of Air

- $pV = nR^*T$
- For dry air,
  - $pv = R_d T$, Specific Density $p = \rho_d R_d T$
- For water vapor,
  - $pv = R_v T$, $p = \rho_v R_v T$
- Dalton's law of partial pressures
  - $p = p_d + p_v$
- For moist air,
  - $pv = R_d T_v$ where $T_v = T(1 + 0.608 q_v)$
  - T_v is virtual temperature

- Universal gas constant in SI, R* = 8.314 J/K/mol
- $R_d = 287 J/K/kg$
- $R_v = 461 J/K/kg$
- Molecular weight
  - $M_d = 28.96 g/mol$
  - $M_v = 18.0 g/mol$
  - $q_v = \dfrac{m_v}{m_d + m_v}$, specific humidity
- Find the significance of virtual temperature ?

$\Delta U = Q + W$

Deriving Lapse rate $\Gamma = -\dfrac{dT}{dz}$ from 1st law of thermodynamics



$$\boxed{dh = dq + v\,dp}$$

Adiabatic Process

$$1)\quad C_p\,dT = \cancel{dq}^{\,0} + v\,dp$$

$$2)\quad \frac{dT}{dz} = \frac{1}{c_p}\, v\, \frac{dp}{dz}$$

$$3)\quad \frac{\partial T}{\partial z} = \frac{1}{c_p} \cdot v(-\rho g)$$

Lapse rate

$$4)\quad \frac{\partial T}{\partial z} = \boxed{-\frac{g}{c_p} = 9.8\ \text{K/km}}$$

- How does the temperature decrease, given hydrostatic balance ?

Class participation

- For a homogenous atmosphere, derive an expression for pressure?
- For the same atmosphere, what would be the lapse rate?

Constant Lapse rate Atmosphere
How does pressure varies with altitude?

$$-\frac{\partial T}{\partial z} = \text{constant} = \Gamma$$

$$T = T_0 - \Gamma z$$

$$\partial p = -\rho g \partial z$$

$$\Rightarrow \partial p = -\frac{p}{R_d T} g \partial z$$

$$\Rightarrow \frac{\partial p}{p} = -\frac{g}{R_d} \frac{\partial z}{T_0 - \Gamma z}$$

$$\Rightarrow \ln \frac{p}{p_0} = -\frac{g}{R_d} \int_0^z \frac{\partial z}{T_0 - \Gamma z} \quad (1)$$

$$= \frac{g}{R_d \Gamma} \ln \frac{T_0 - \Gamma z}{T_0}$$

$$\Rightarrow \ln \frac{p}{p_0} = \frac{g}{R_d \Gamma} \ln \frac{T}{T_0} \quad (2)$$

$$\Rightarrow p = p_0 \left(\frac{T}{T_0}\right)^{g/R_d \Gamma} \quad (3)$$

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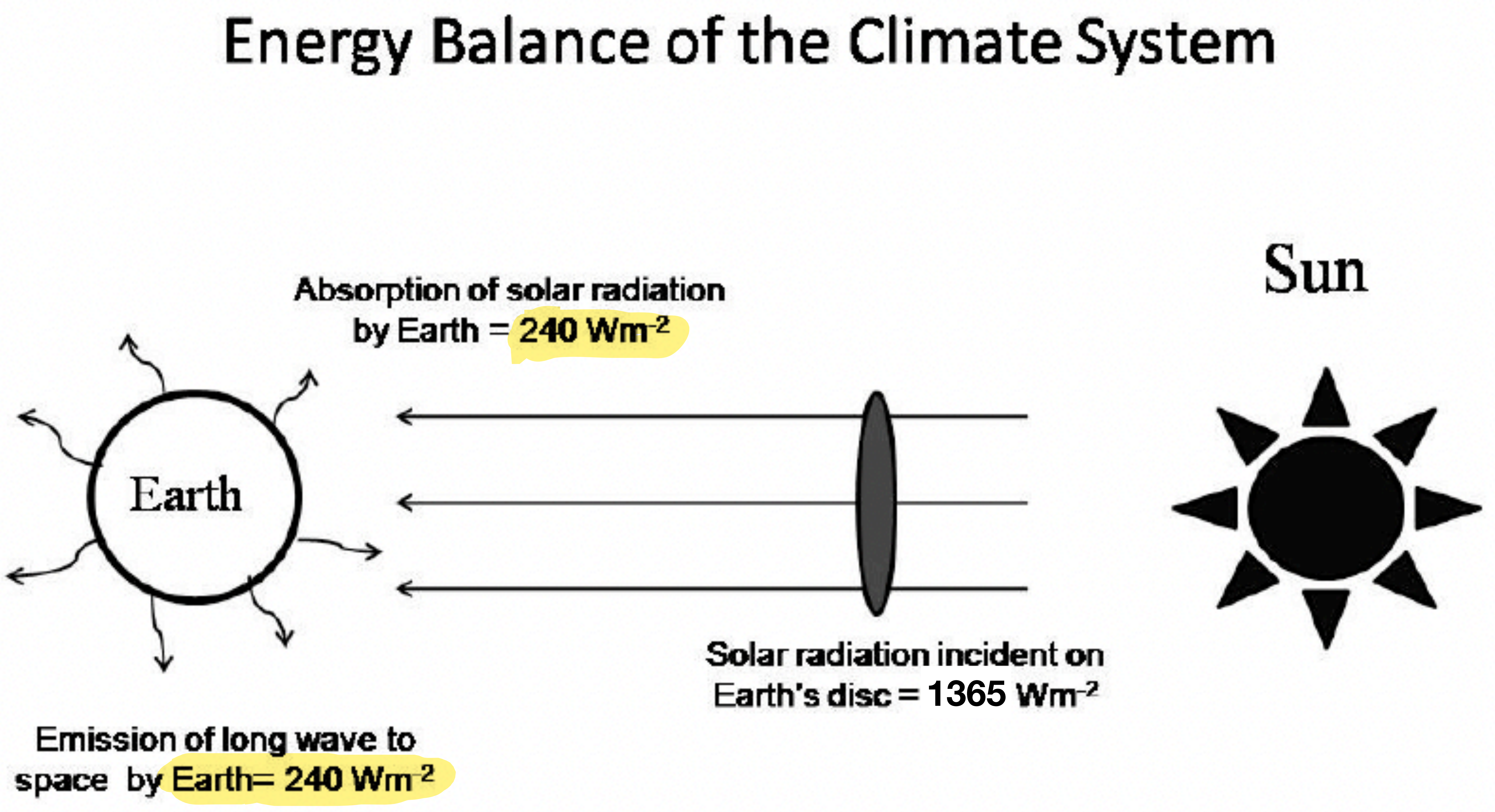
Radiative equilibrium



$$\frac{S}{4}(1-\alpha) - \sigma T_e^4 = N = 0$$

$\alpha = 0.3$

$S = 1365 Wm^{-2}$

$T_e = 255K$

$T_s = 288K$

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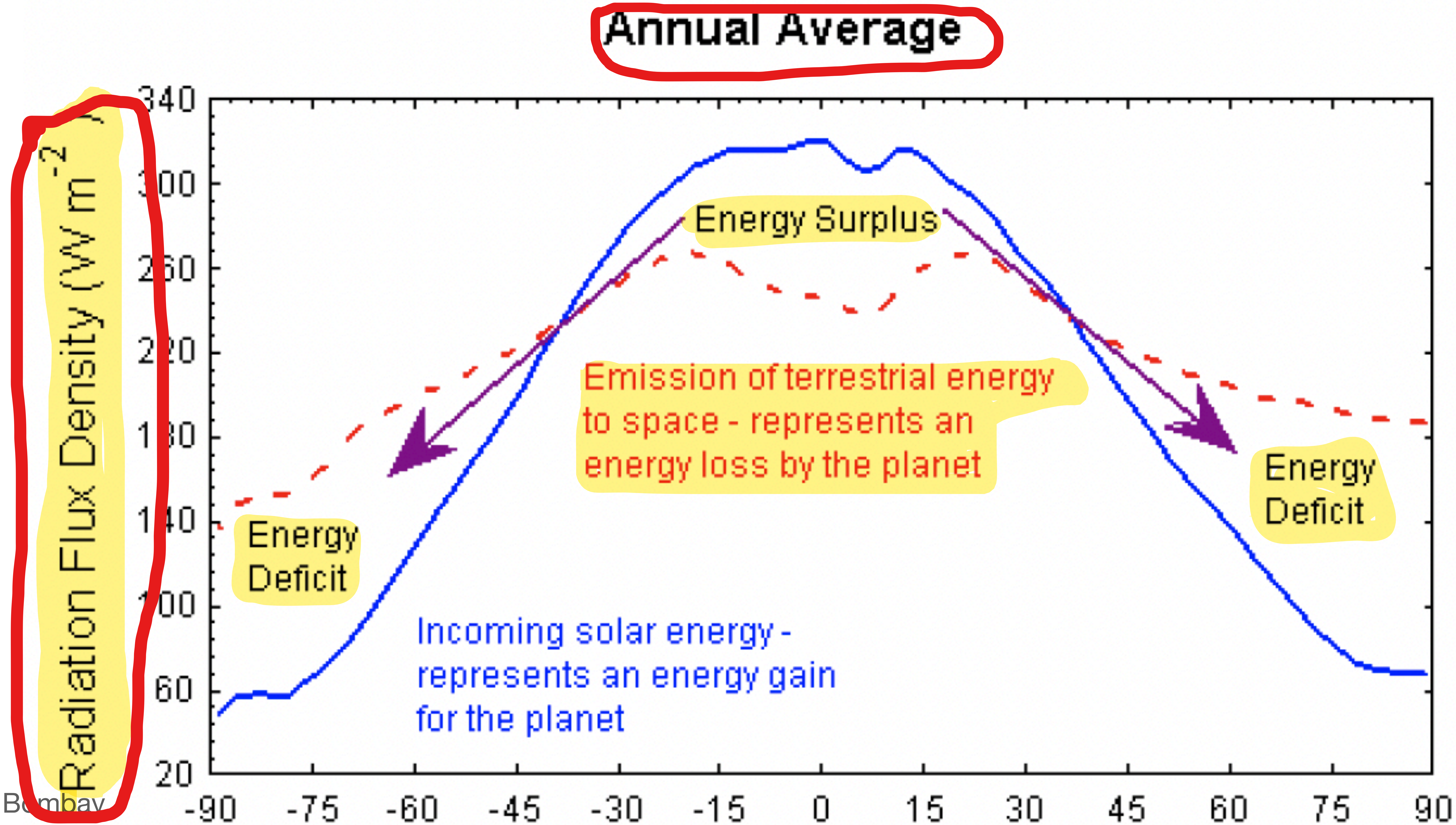
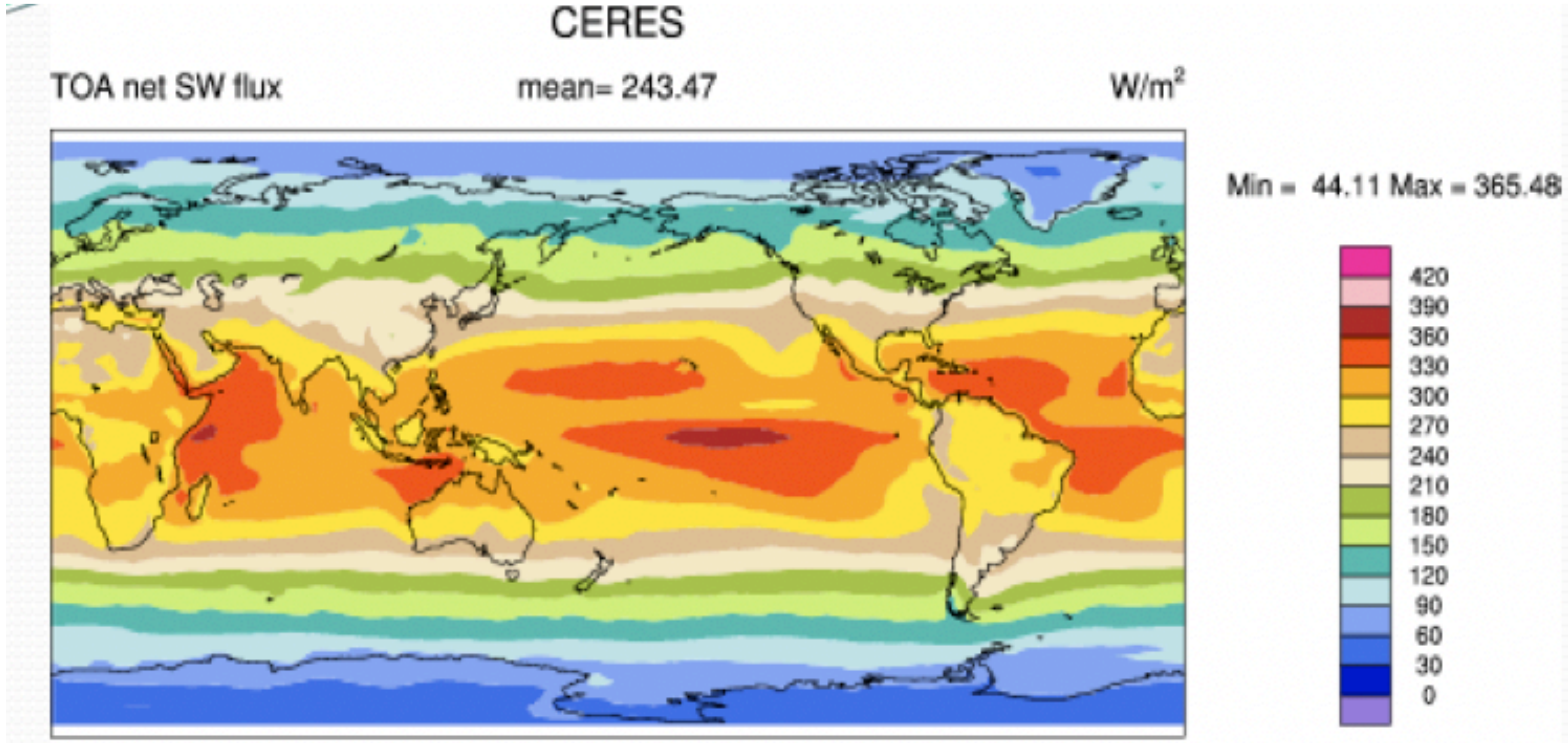
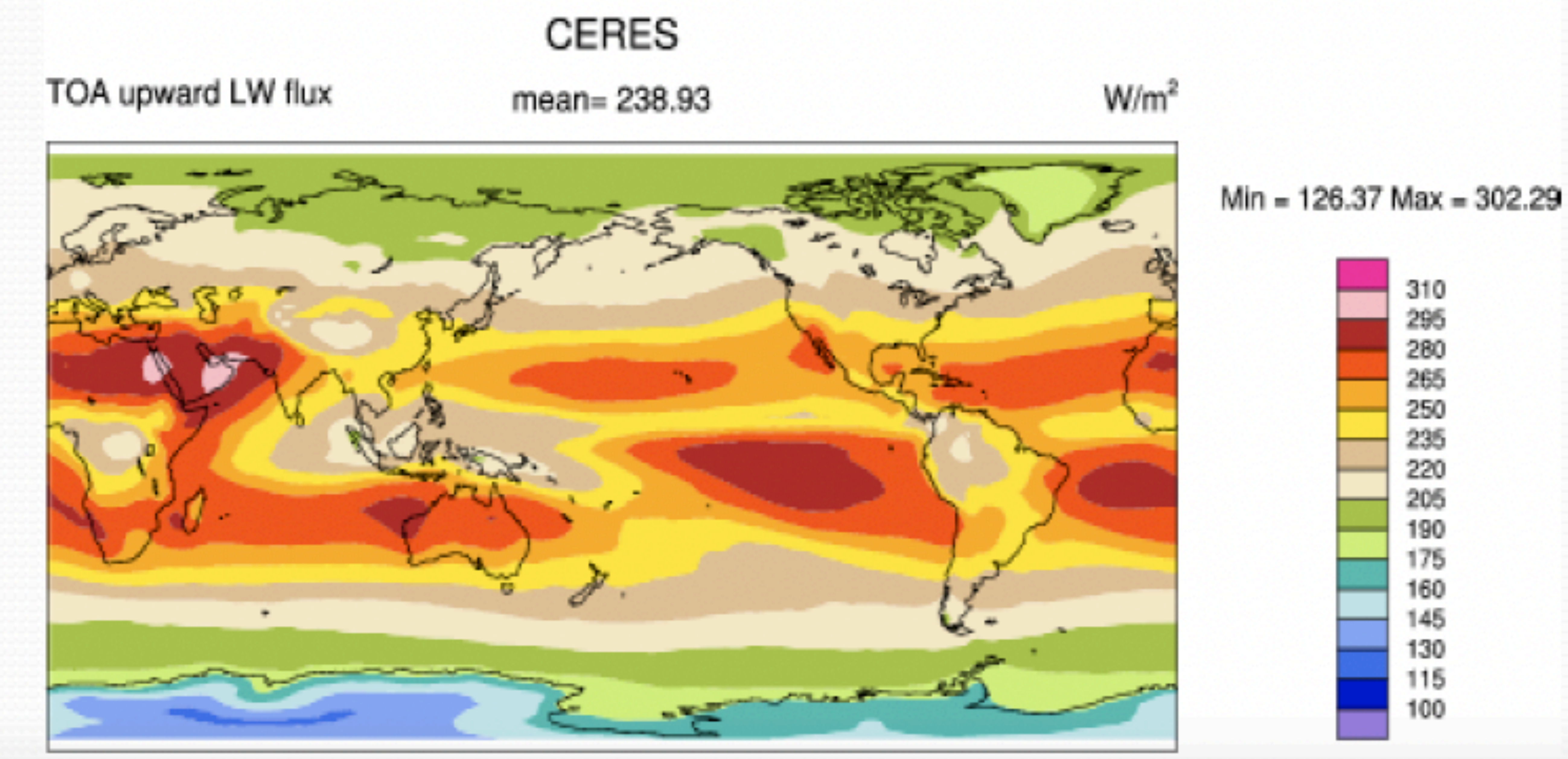
Causes of large-scale circulation

- Uneven heating of Earth surface. Equator receives more heat than radiates, reverse in poles.
- Circulation of atmosphere redistributes ~60% and of ocean ~40% of energy.



Annual mean TOA Radiative budget





Tropics are gaining heat and poles are loosing.

How to remove this imbalance?

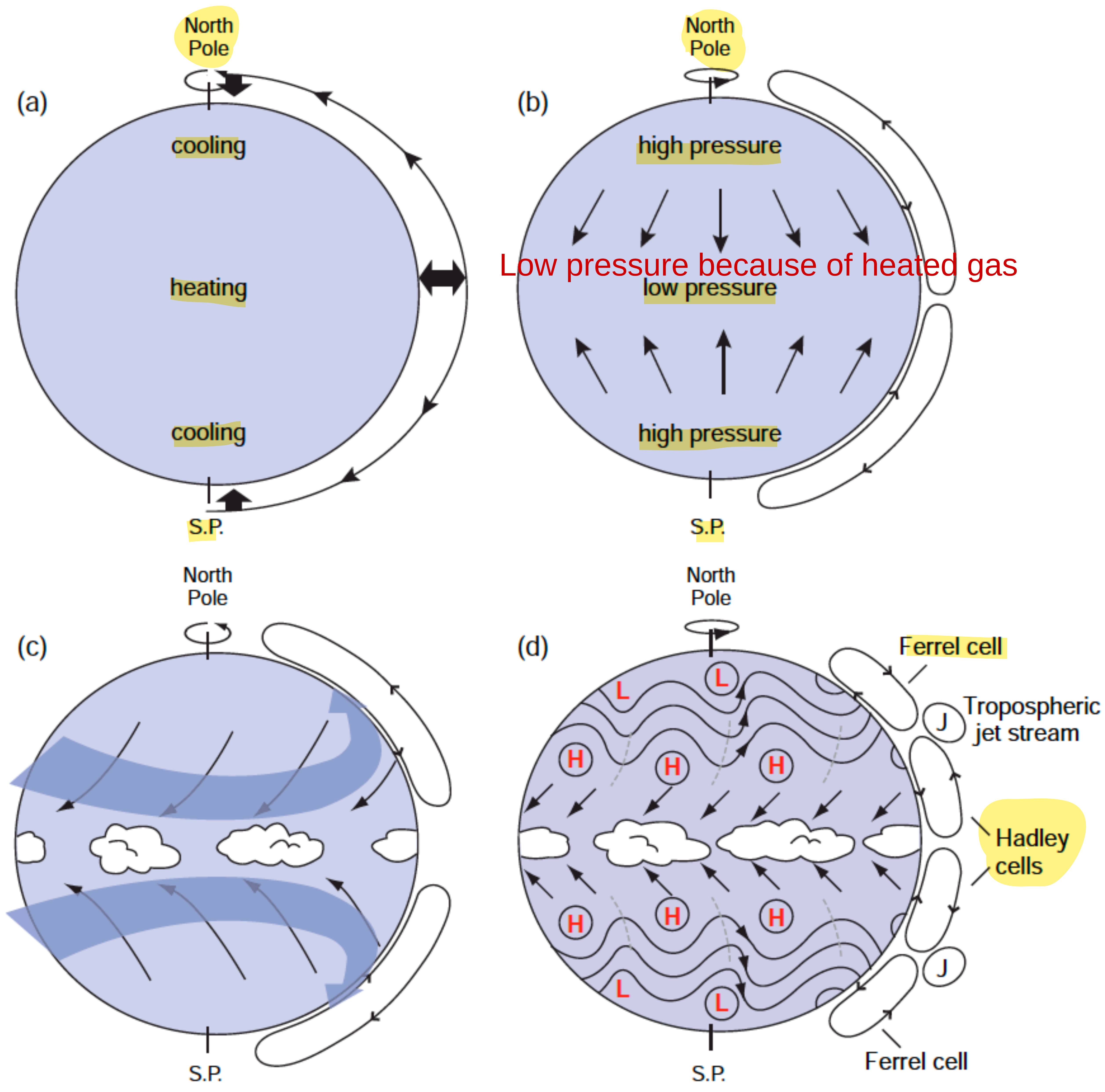
The circulation in the atmosphere and oceans transport heat from the tropics to the polar regions

General circulation

- State of rest in a GCM
- No continents
- Equinox

- Atmospheric dynamics
- Clouds types
- Hadley cells
- Easterlies & Westerlies
- Baroclinic instability
- Extratropical cyclones
- Ferrel cells

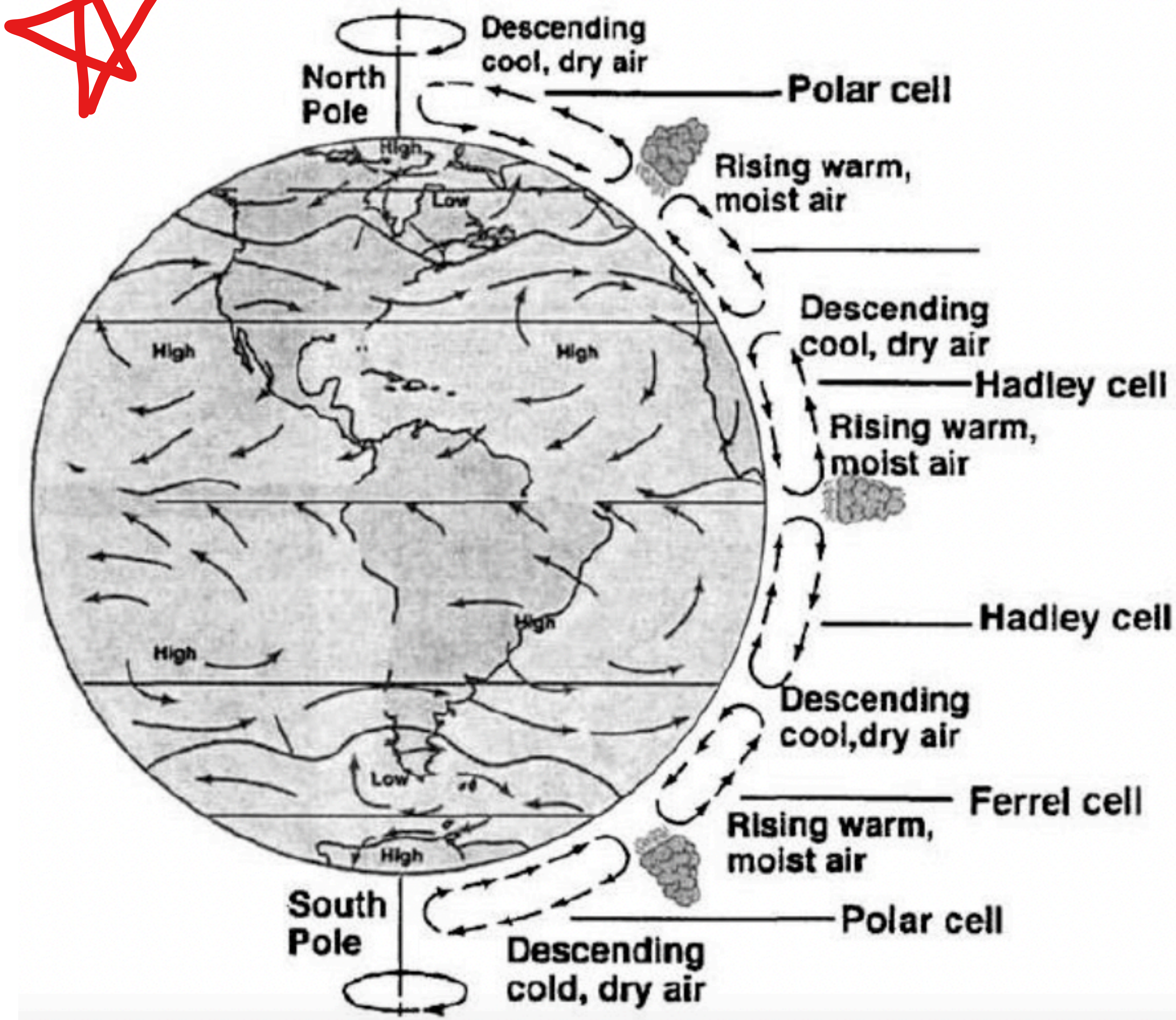
?



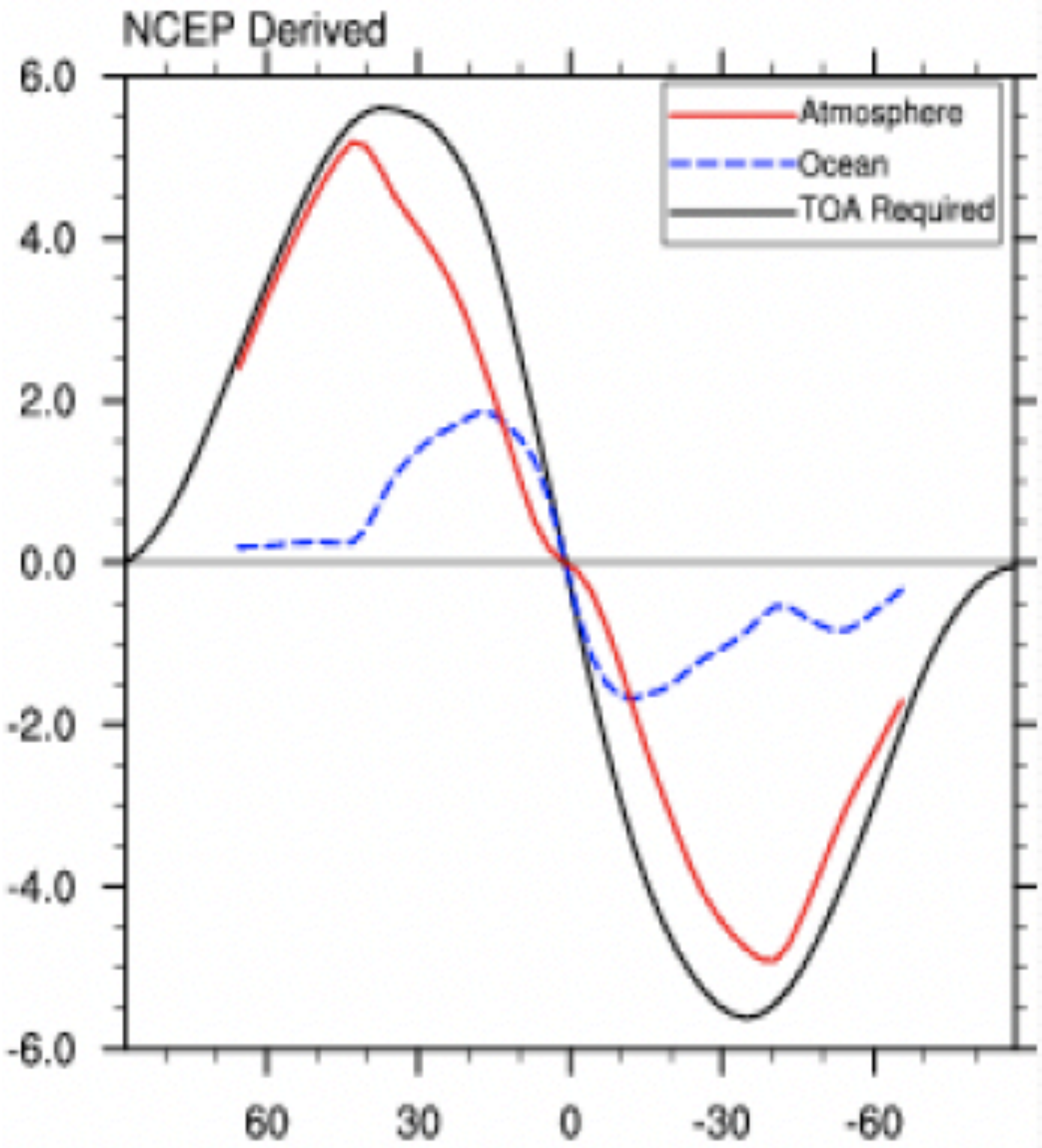
Wallace & Hobbs Schematic depiction of the general circulation as it develops from a state of rest in a climate model for equinox

General Circulation

Three cell model



- Air rises at equator and descends ~30N/30S. Deflected at tropopause to N or S. Cold air reverse flow to the equator at the surface.
- Low pressure gradients, weak winds at equator, doldrums.
- Excessive radiative heating at equator balanced a little by evapo-transpiration, still air is much warmer.
- Warm moist air over tropics, highly unstable, lifts and cools to form tall cumulus clouds. Large latent heat release further increases buoyancy.
- Net transport of sensible heat to higher latitudes is larger than latent heat (water vapour) to the equator.
- Cooling and convergence form a heavy layer of air atop, leading to a semi-permanent "high pressure" system at ~30N/30S called "sub-tropical high."
- Descending air warms by compression, warm, dry leading to deserts.
- Surface winds are steady, from the east, towards the equator. Called trade winds, used for early maritime transport.
- Near equator, NE from 30N and SE from 30 S converge at the Inter Tropical Convergence Zone (ITCZ).
- Uplifting of air causes cloud formation and rainfall. At the surface it confines pollutants in a vertical column and allows study of atmospheric chemistry.
- Shifts in location of the ITCZ influences the monsoon.



Annual Northward Heat Transport

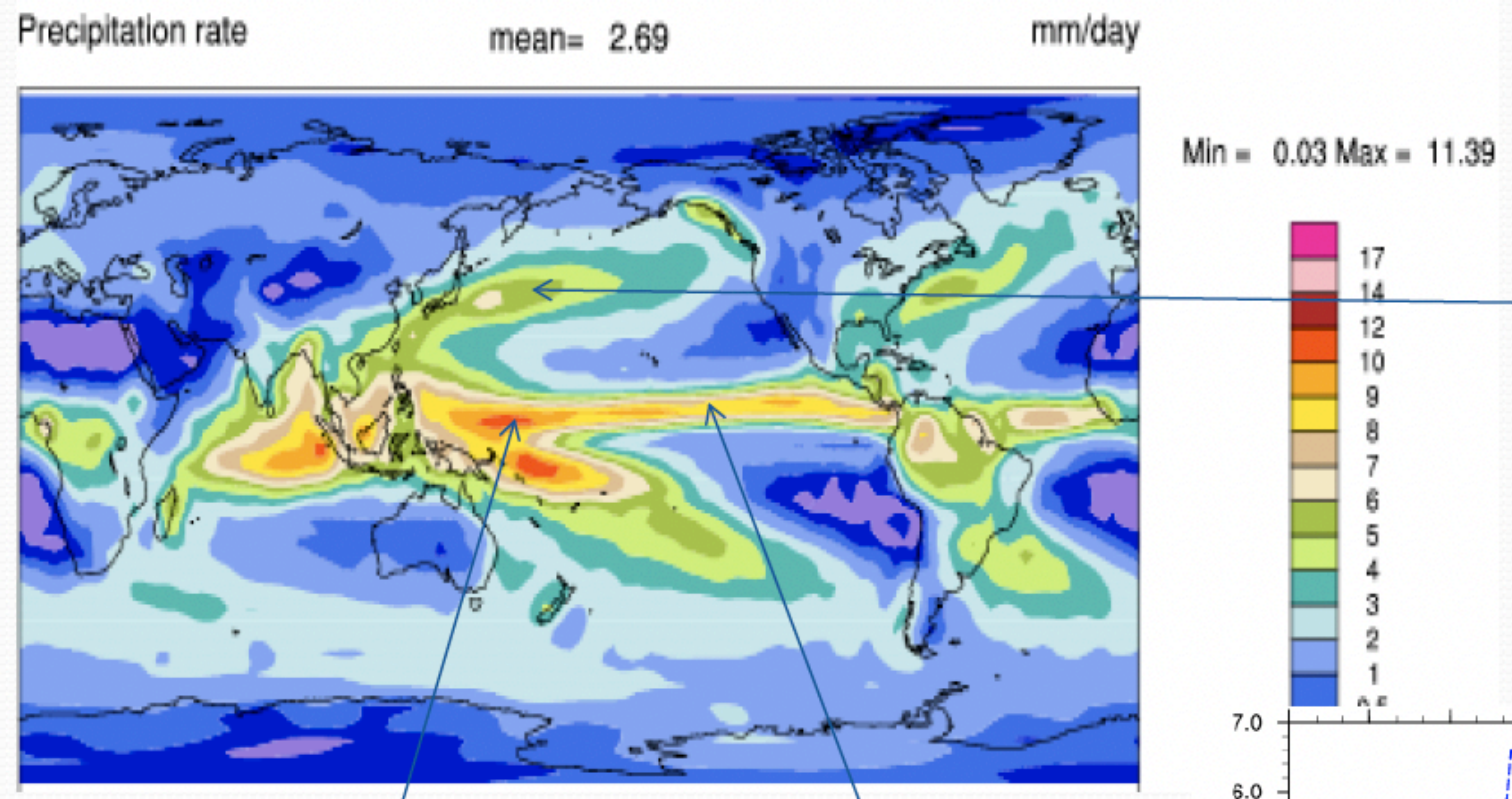
Heat transport vanishes near equator => hemispheres are separately in Radiative equilibrium.

Transport (Wm-2) at any latitude is proportional to radiative budget between that latitude and equator, and inversely proportional to the area of a ring around that latitude

Is the planet in Radiative equilibrium at each latitude?

- No!
- But there should be energy balance at each latitude and altitude?
- Atmospheric and Oceanic circulations transport heat from the equator to the poles
- Atmospheric circulation transports heat from the surface to atmosphere

Annual mean precipitation

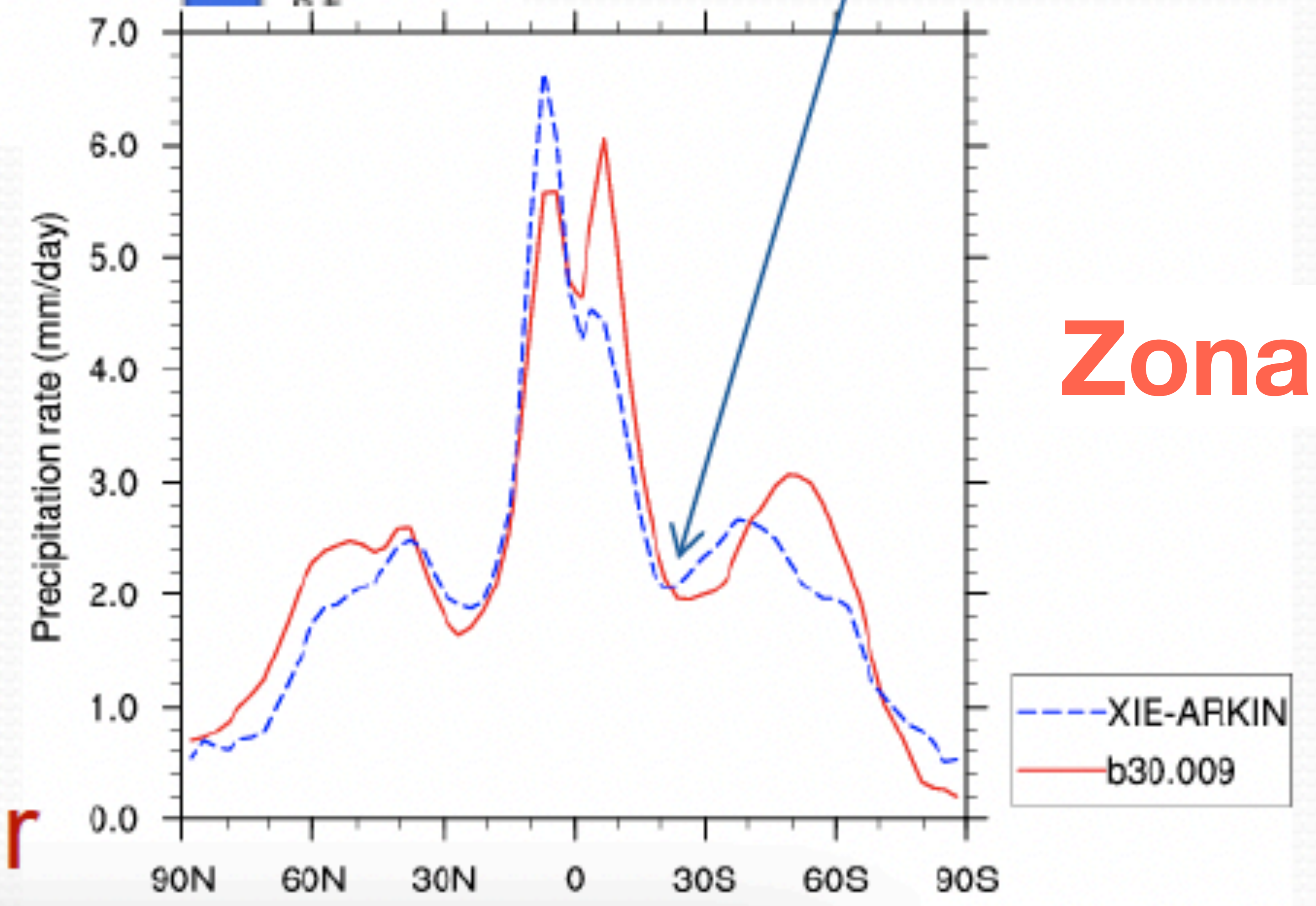


Storm tracks

Subtropics - deserts

Tropical Pacific Warm Pool

ITCZ



Zonal mean

Global mean is about 100 cm per year

Annual mean vertical structure of specific humidity