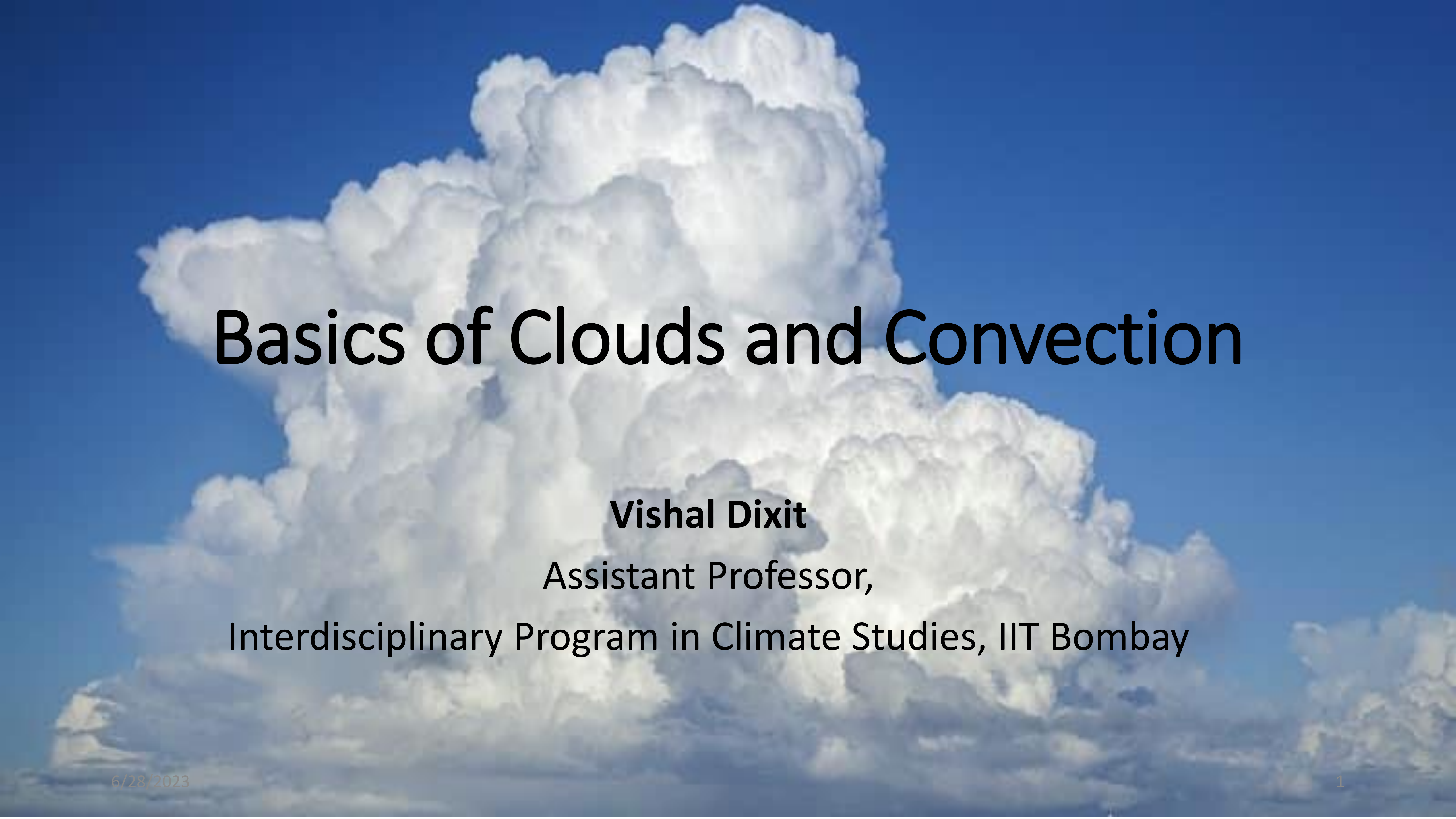


Basics of Clouds and Convection

Vishal Dixit

Assistant Professor,

Interdisciplinary Program in Climate Studies, IIT Bombay

Civilization is possible because earth's temperature is stable and habitable! Was that always so?

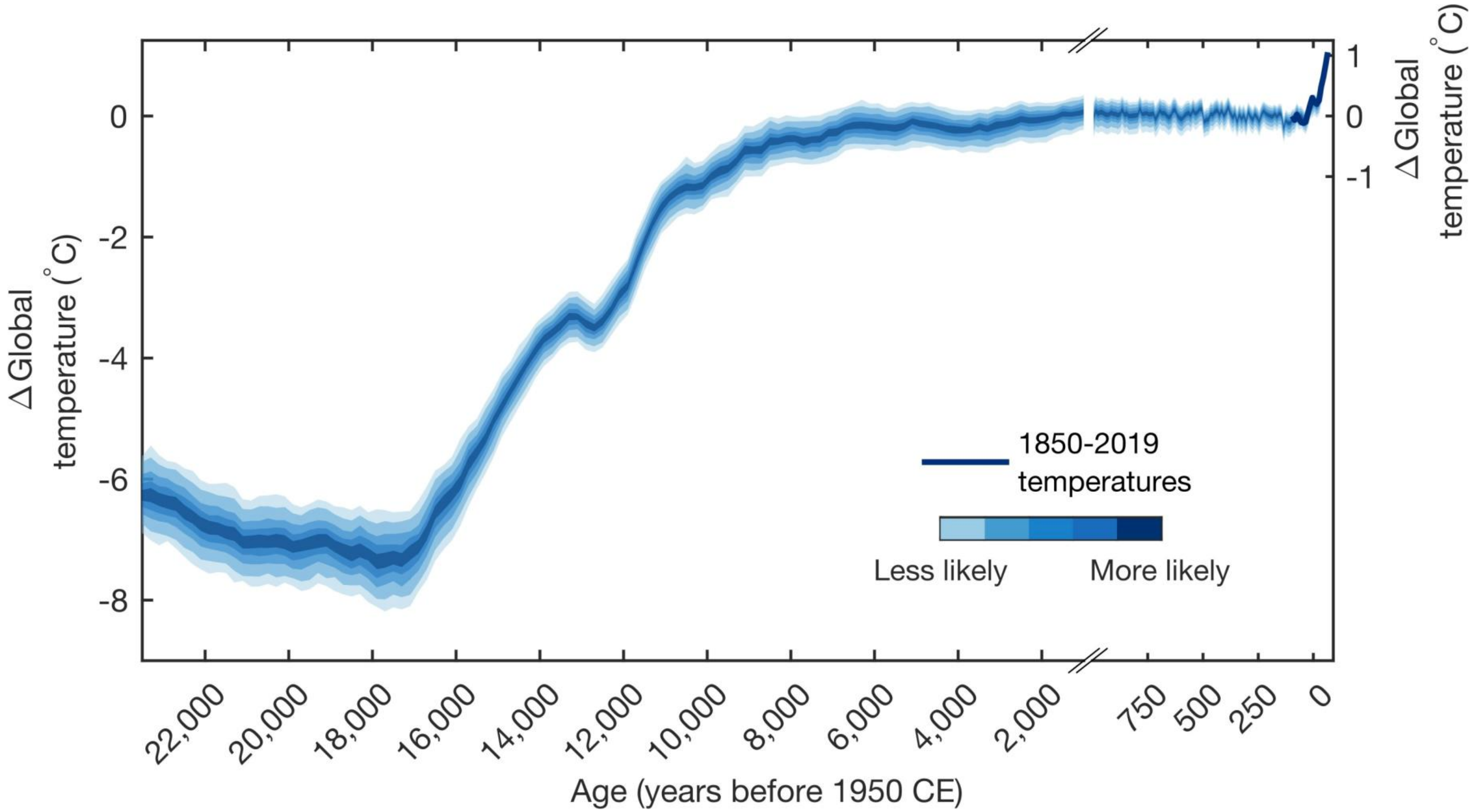
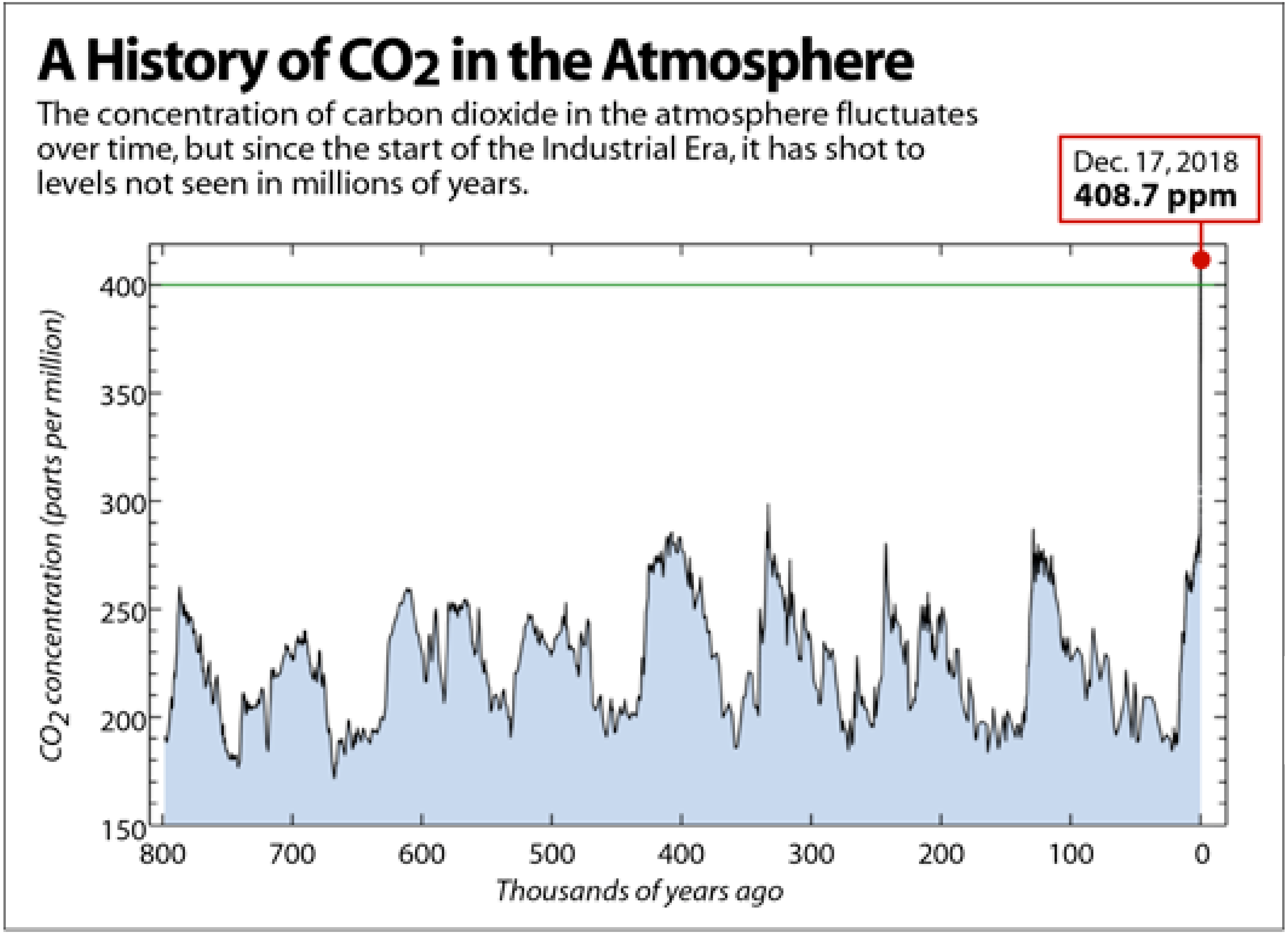


Image: phys.org

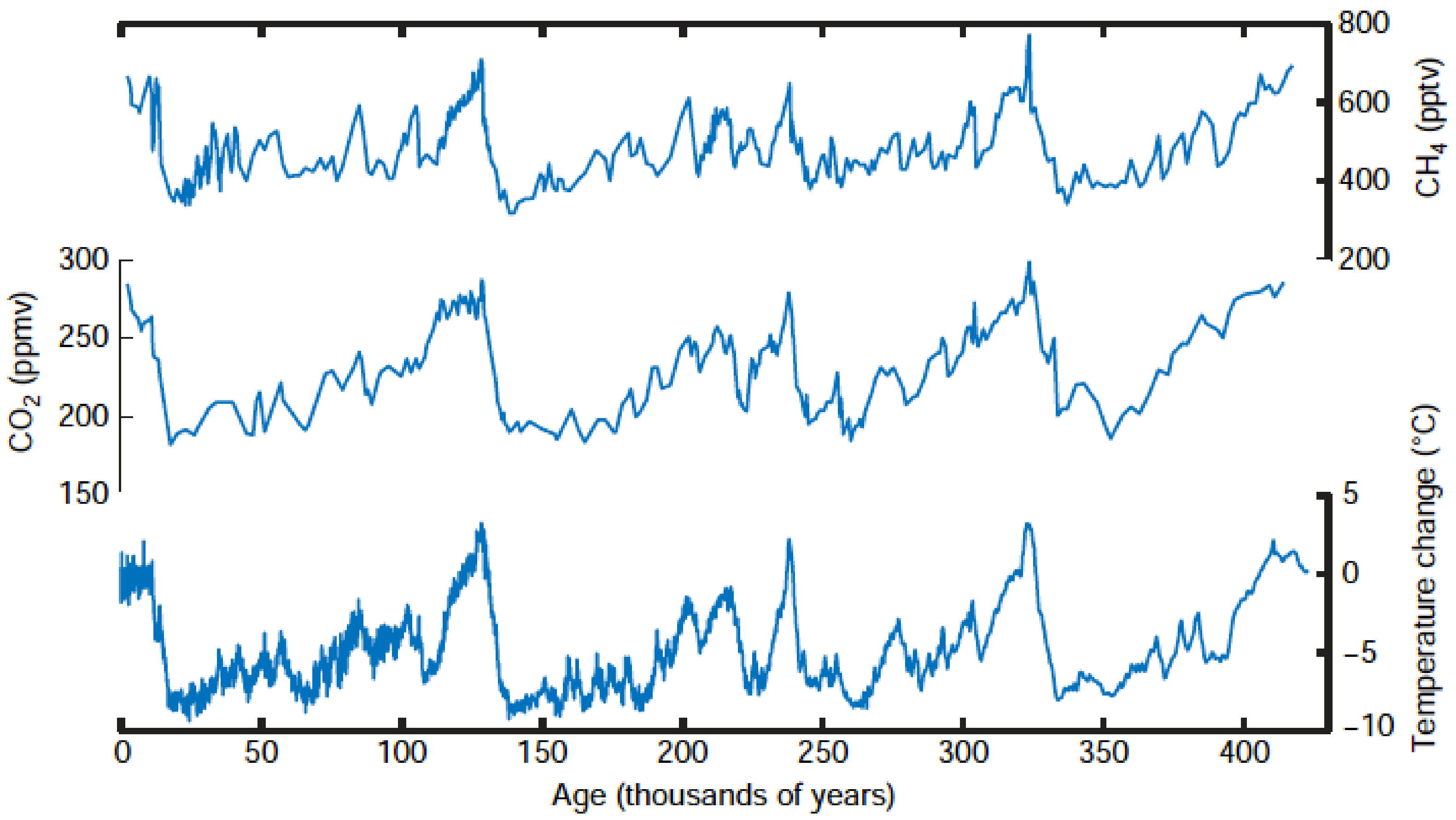


SOURCES: Scripps Institution of Oceanography InsideClimate News

26 June 2023
~ 420 ppm

What is the value today?

Changes in CO_2 levels drive changes in earth's temperature



Food for thought:

Which word(s) better describes the variation in CO_2?

- Linear change
- Cyclical change
- Non-linear change
- Random change

Adapted from a research paper by J R Petit (1999)

Earth's puzzling past :
Snowball – Ice-age – Present day

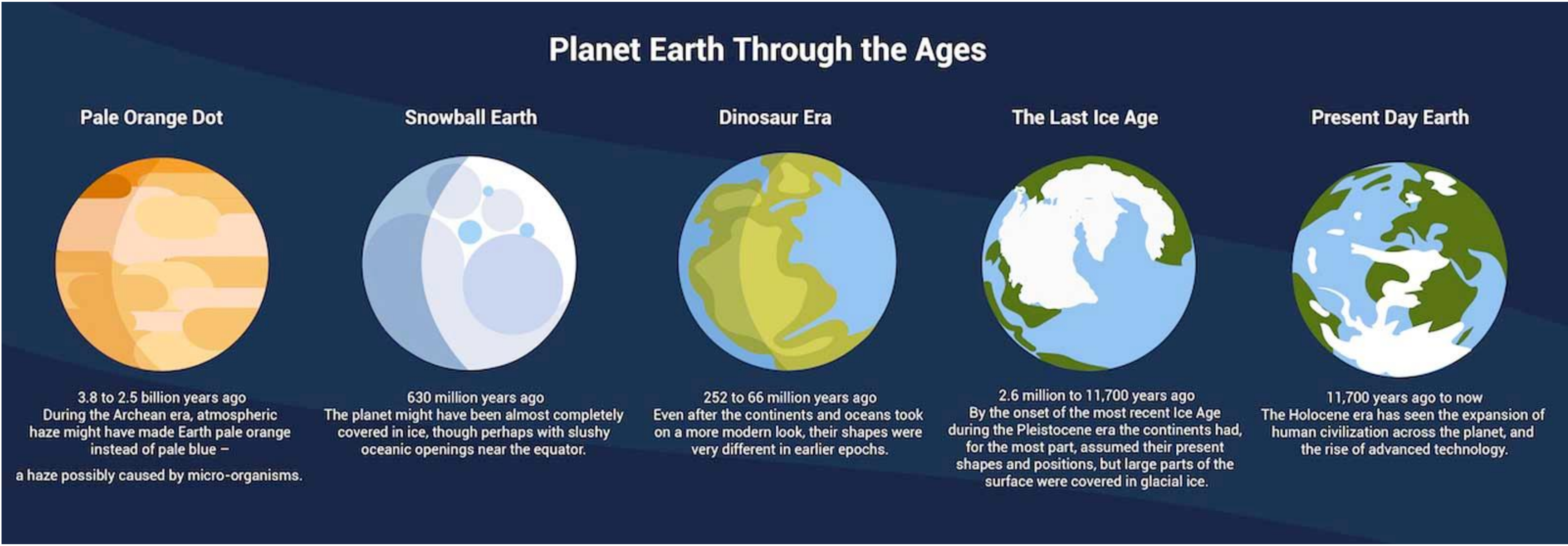
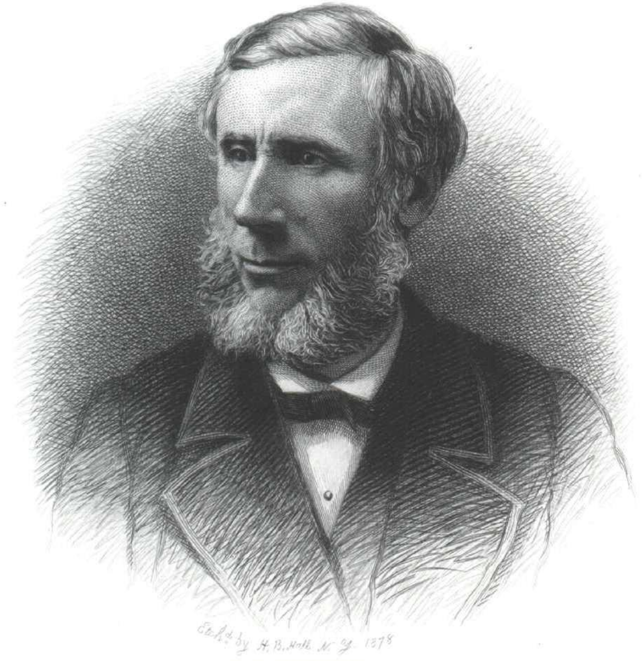


Image credit: NASA/JPL-Caltech/Lizbeth B. De La Torre

What makes earth's temperature habitable?

Fourier (1824)

Greenhouse effect

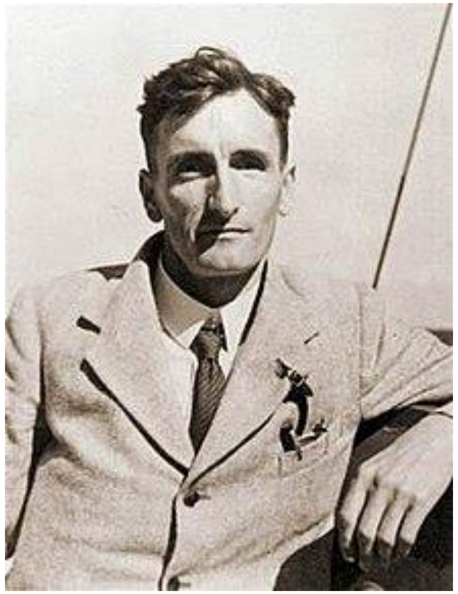


Tyndall (1862)

Water vapor major greenhouse gas

Arrhenius (1896)

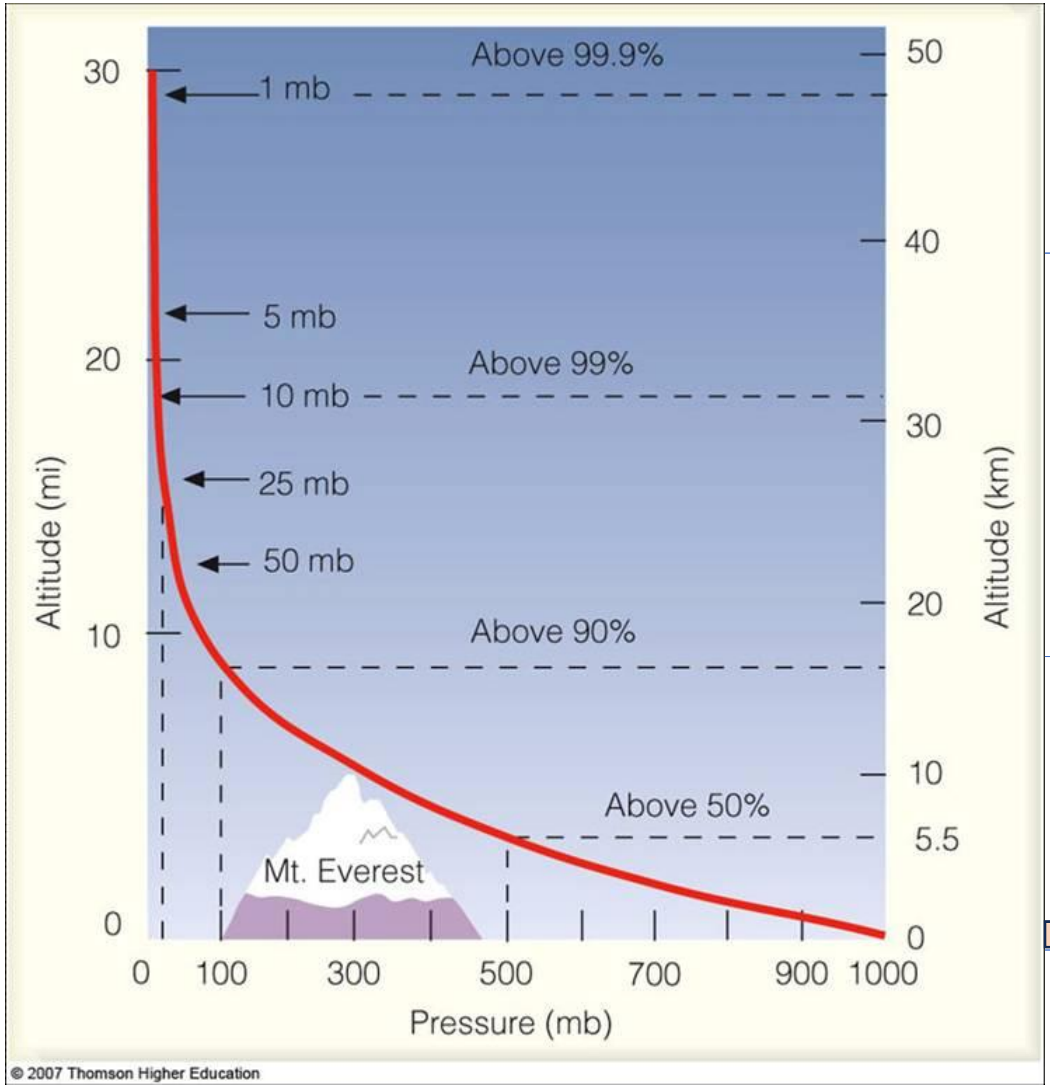
First calculation of global warming

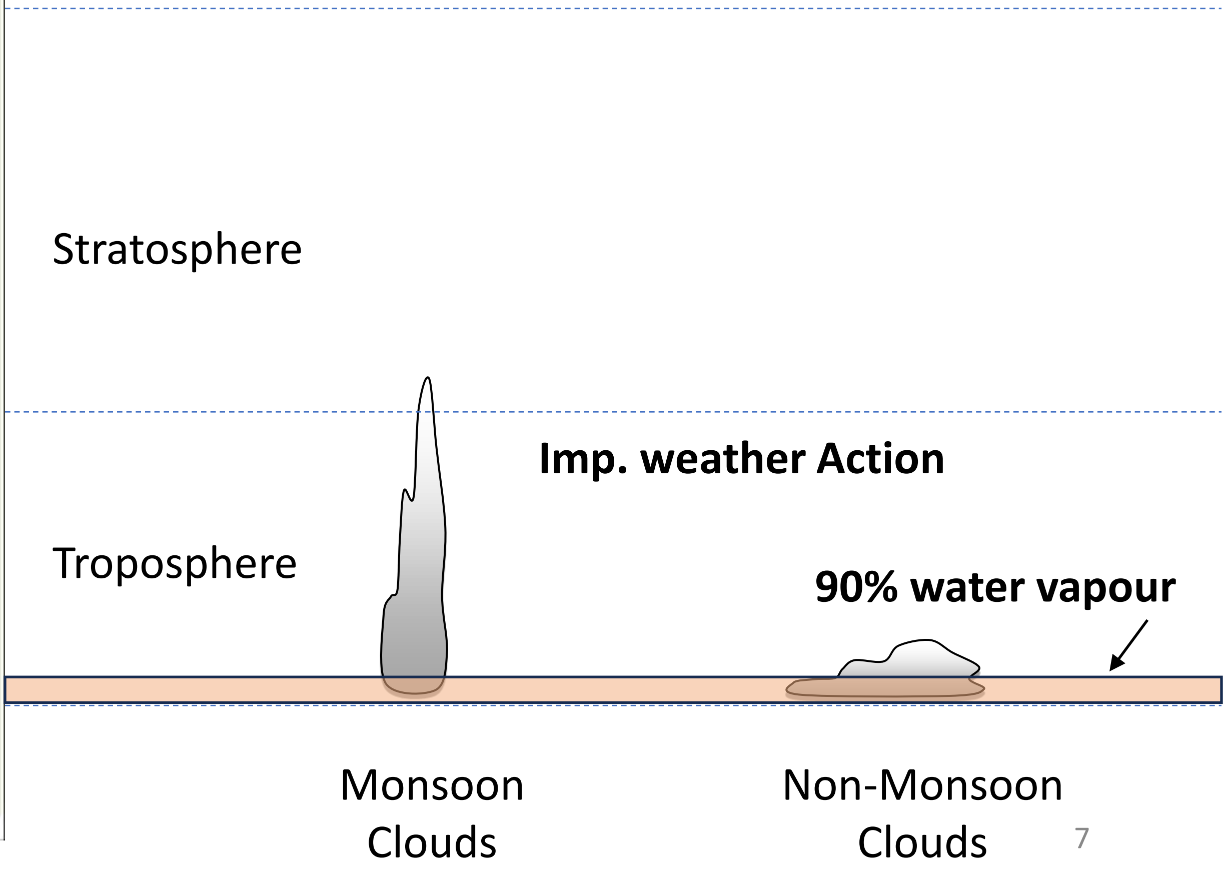


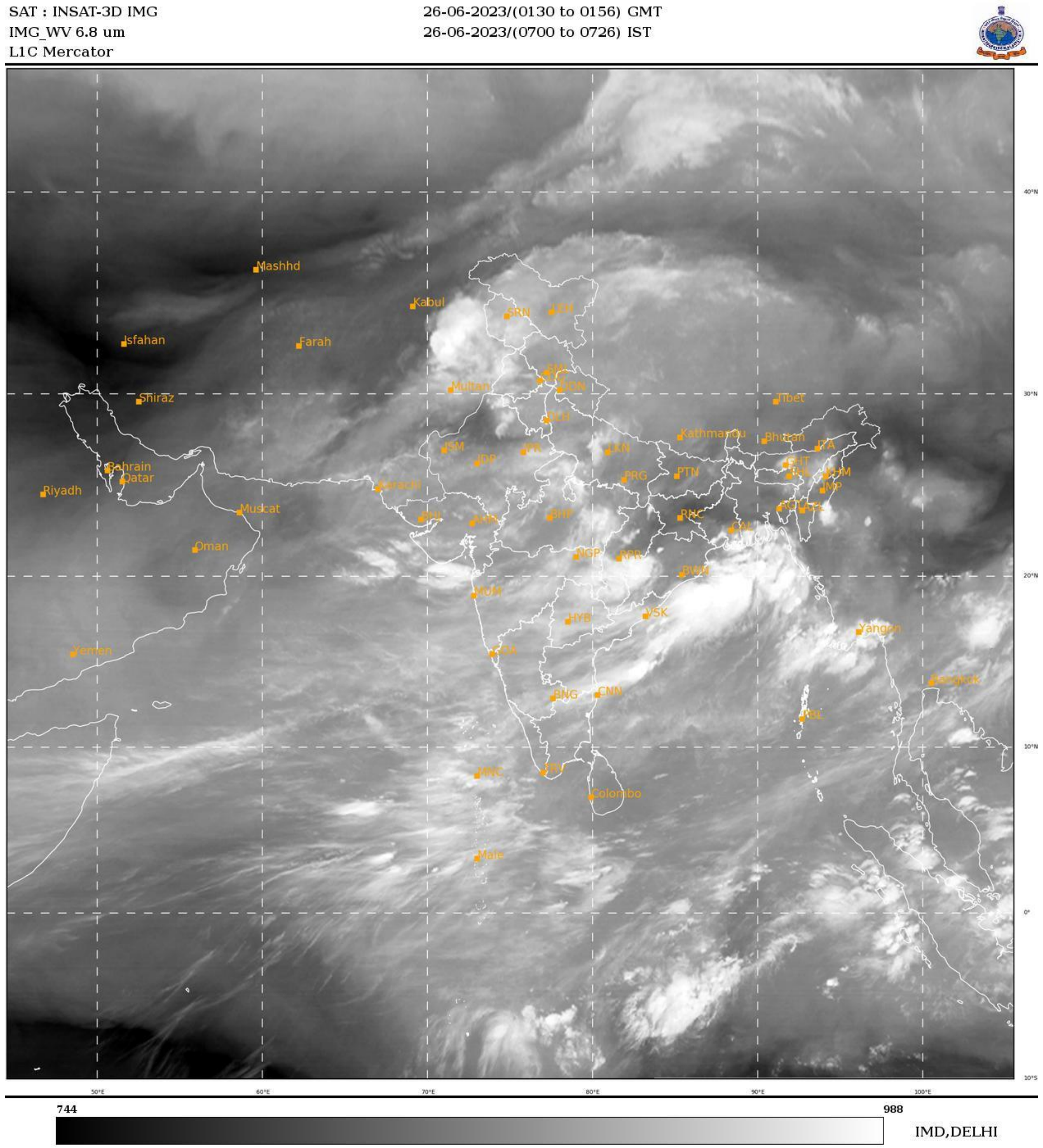
Callander (1938)

CO_2 warming can be beneficial!

90% of atmospheric air mass in Troposphere (first 15km)







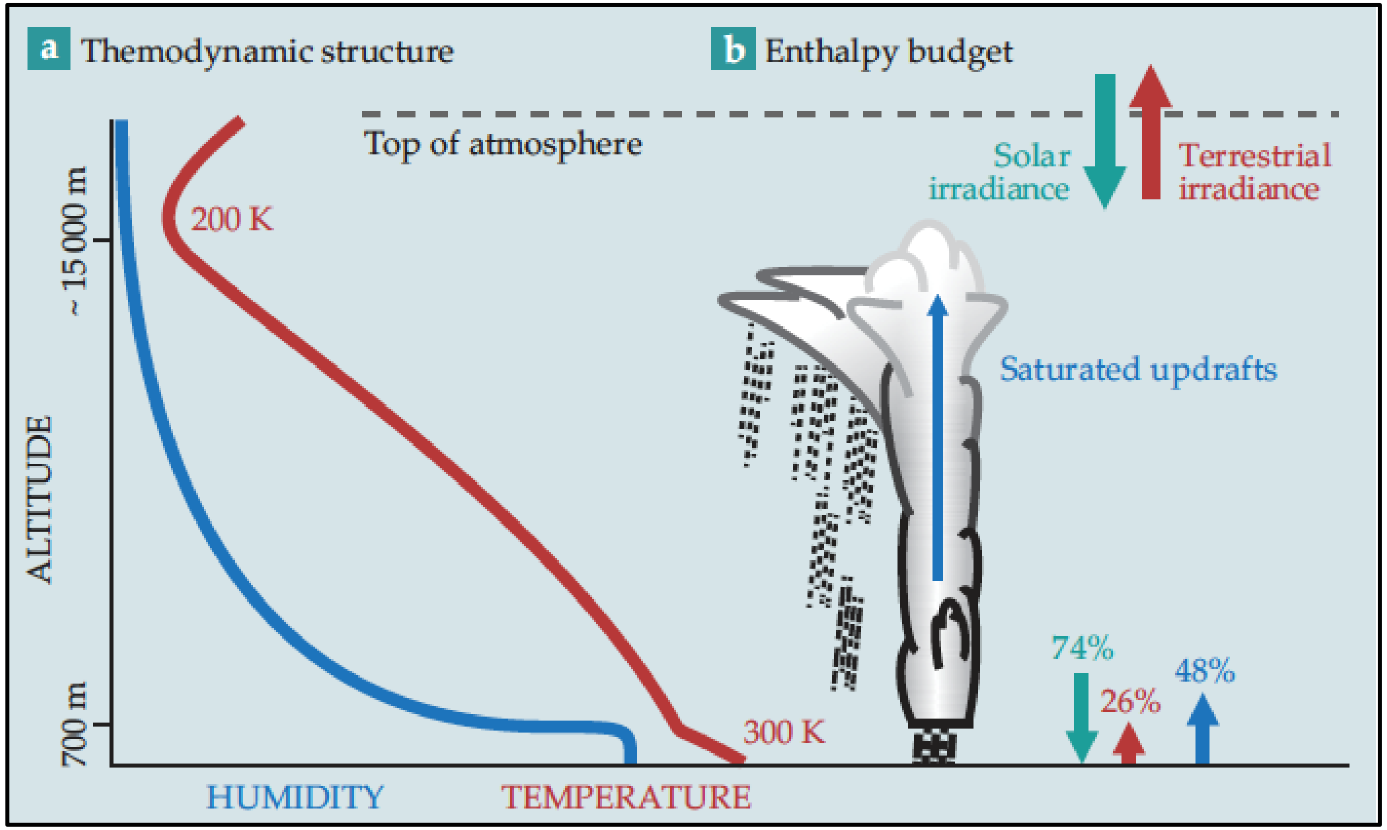
INSAT Upper level water vapour
(White : Abundance of water vapour)

Rainfall : Clouds : Circulations are tightly coupled

Unique properties of water

1. Anomalous latent-heat of phase change
2. Ability to interact with a wide range of radiation spectrum: gate-keeper of energy
3. Lighter molecular weight than air

Water molecule modulates hydrological cycle



- Saturation:

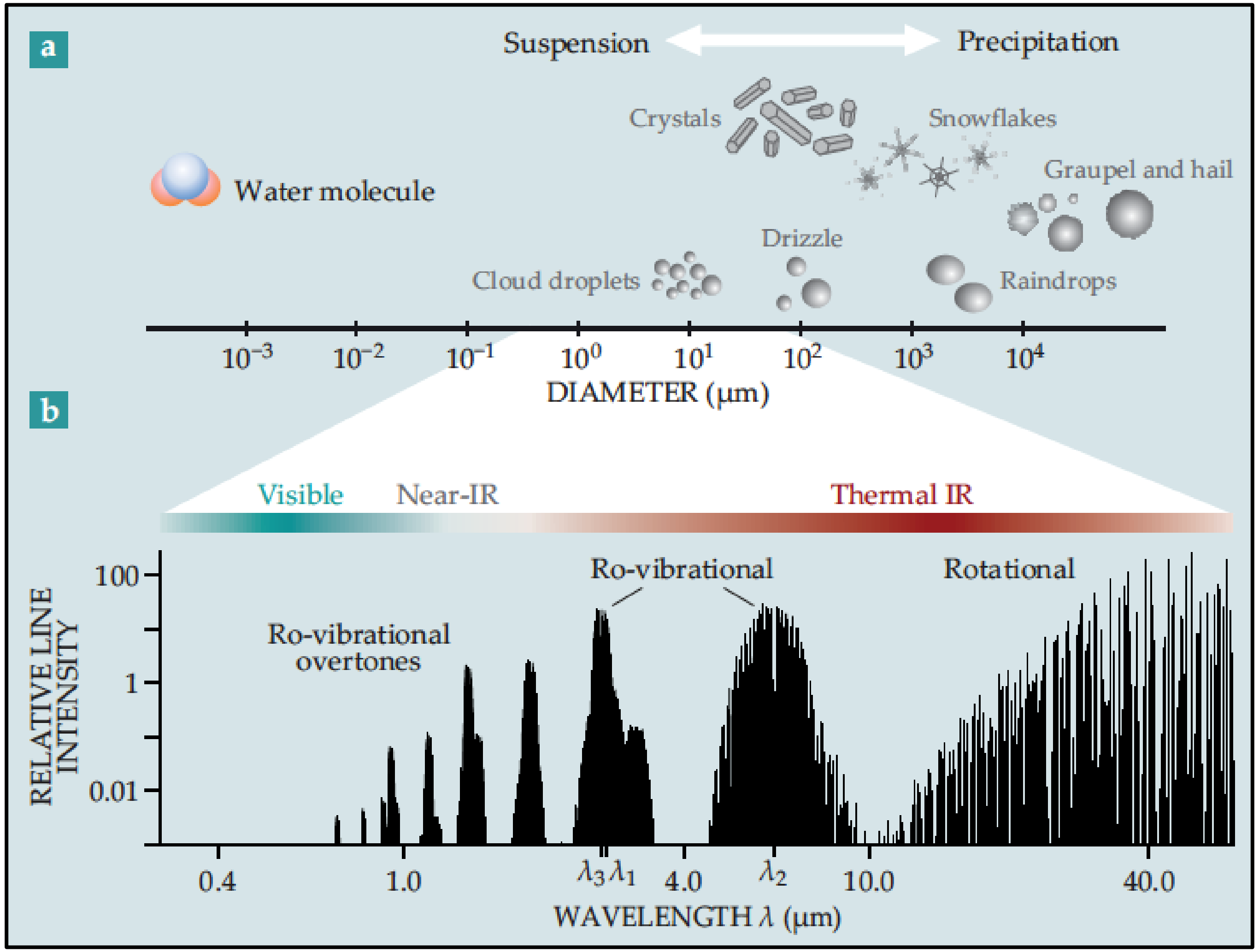
Clausius-Clapeyron equation

$$\ln e_s = \frac{\beta}{T} \ln T$$

- β for water vapor is 3 to 4 times that of other condensable substances like Methane, Ammonia

Stevens and Bony, 2008

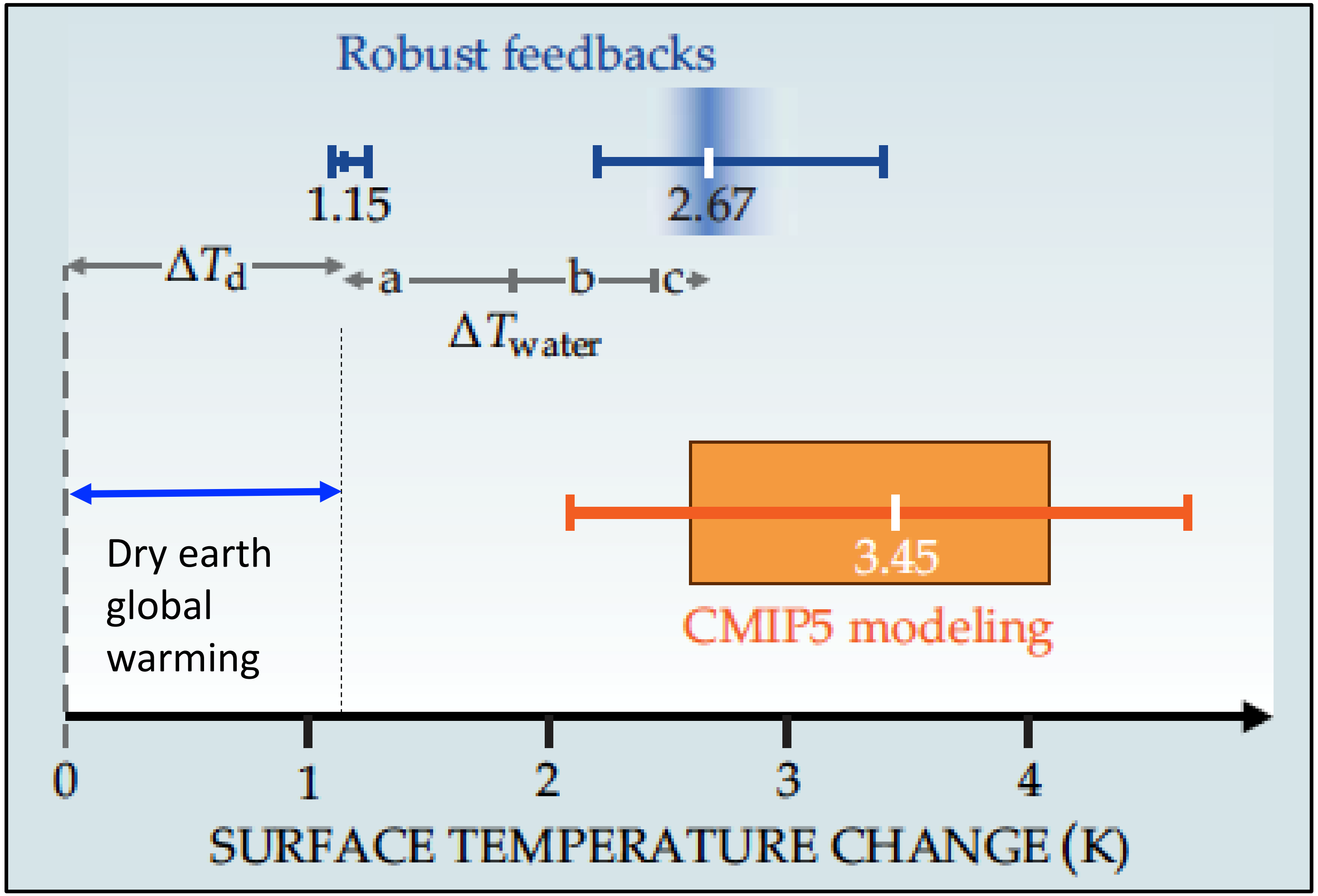
Water molecule: A gatekeeper of radiative energy



- Myriad of effects as "Cloud hydrometeors"
- Absorbs earth's radiation over wide spectrum

Stevens and Bony, 2013

Incomplete understanding of Rain : Cloud : Circulation hampers accurate estimations of Global warming

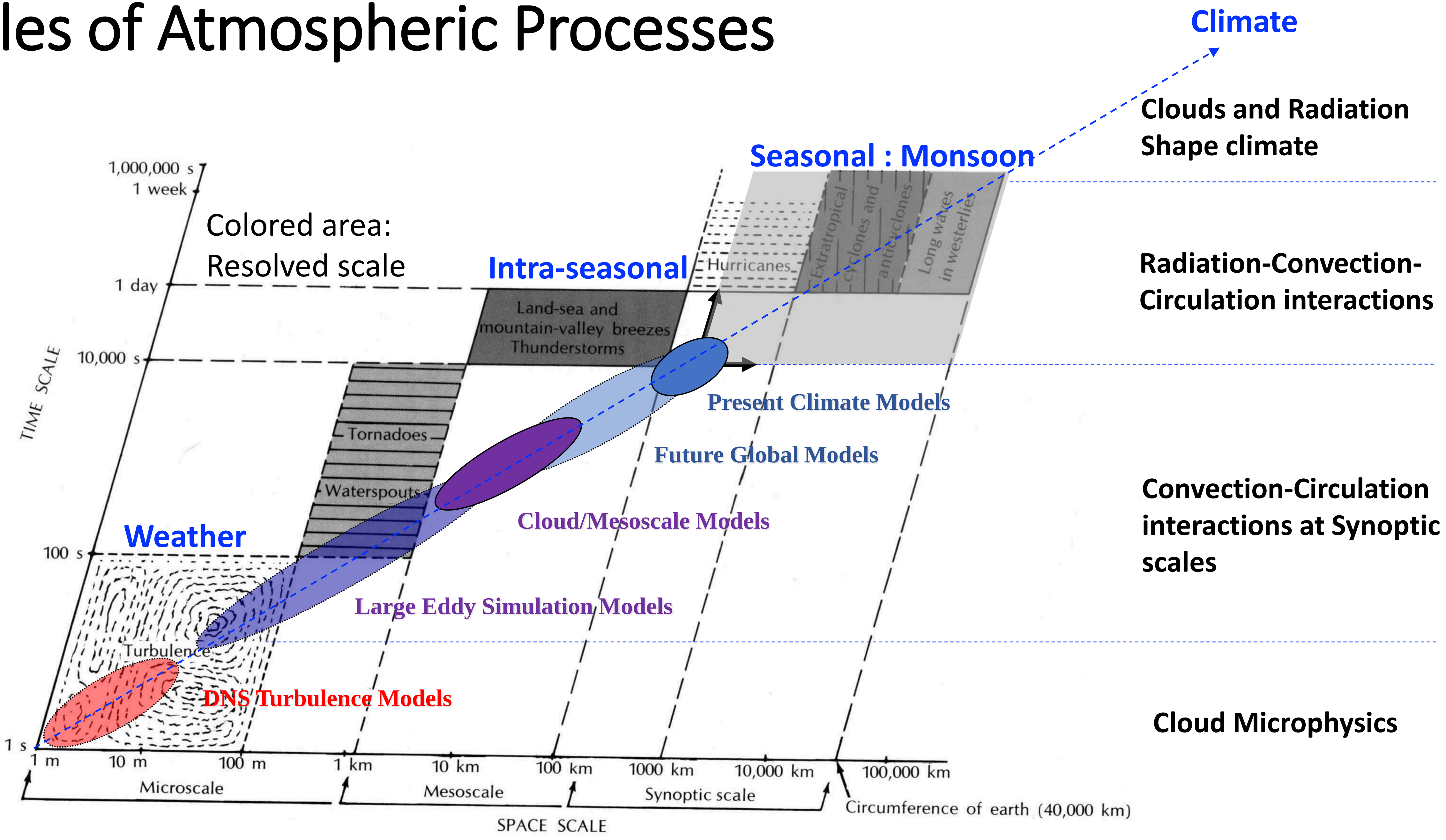


Response to doubling of CO_2 in IPCC Climate models

- uncertainty due to clouds
- Warming only due to CO_2 doubling without feedbacks

Fig: Stevens and Bony, 2013

Scales of Atmospheric Processes



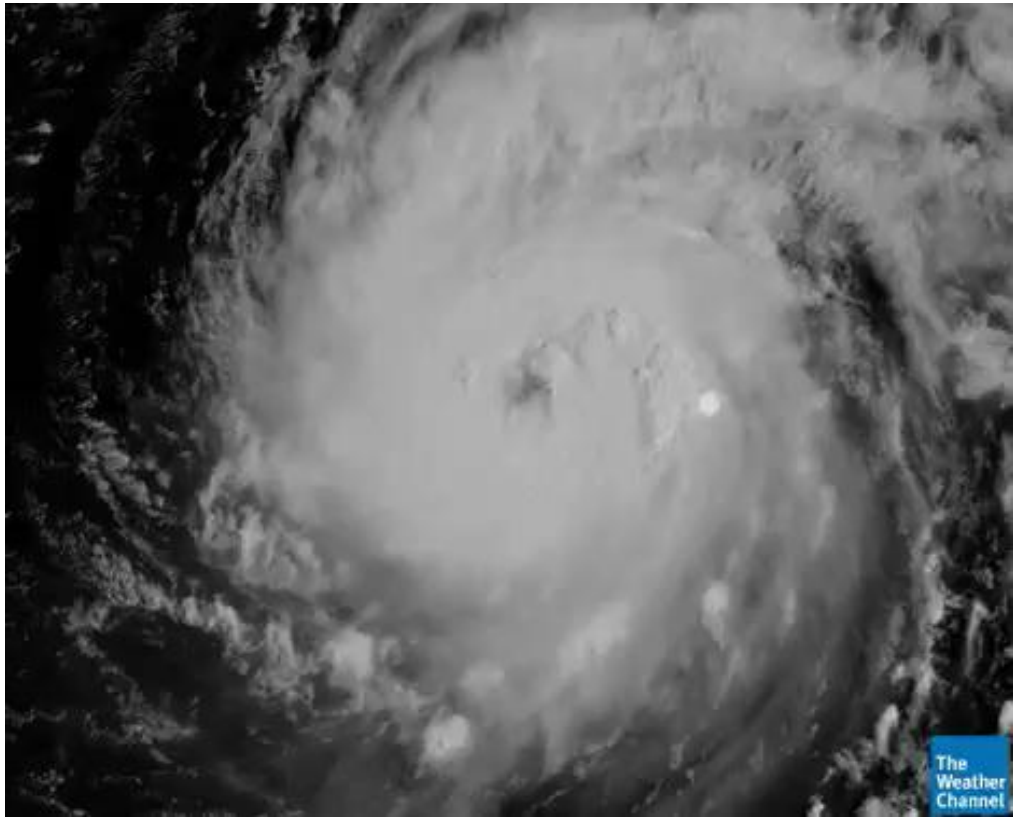
Modification of the figure from Andrew Gettleman, NCAR

Cloud-Circulation coupling on different time-scales

- Small scales: Microphysics – Turbulence coupling
- Synoptic scales: Convection – Circulation feedbacks
- Planetary scales: Cloud radiation – Circulation feedbacks
- Convective momentum transport feedbacks

Credits: Stu Ostro's twitter handle

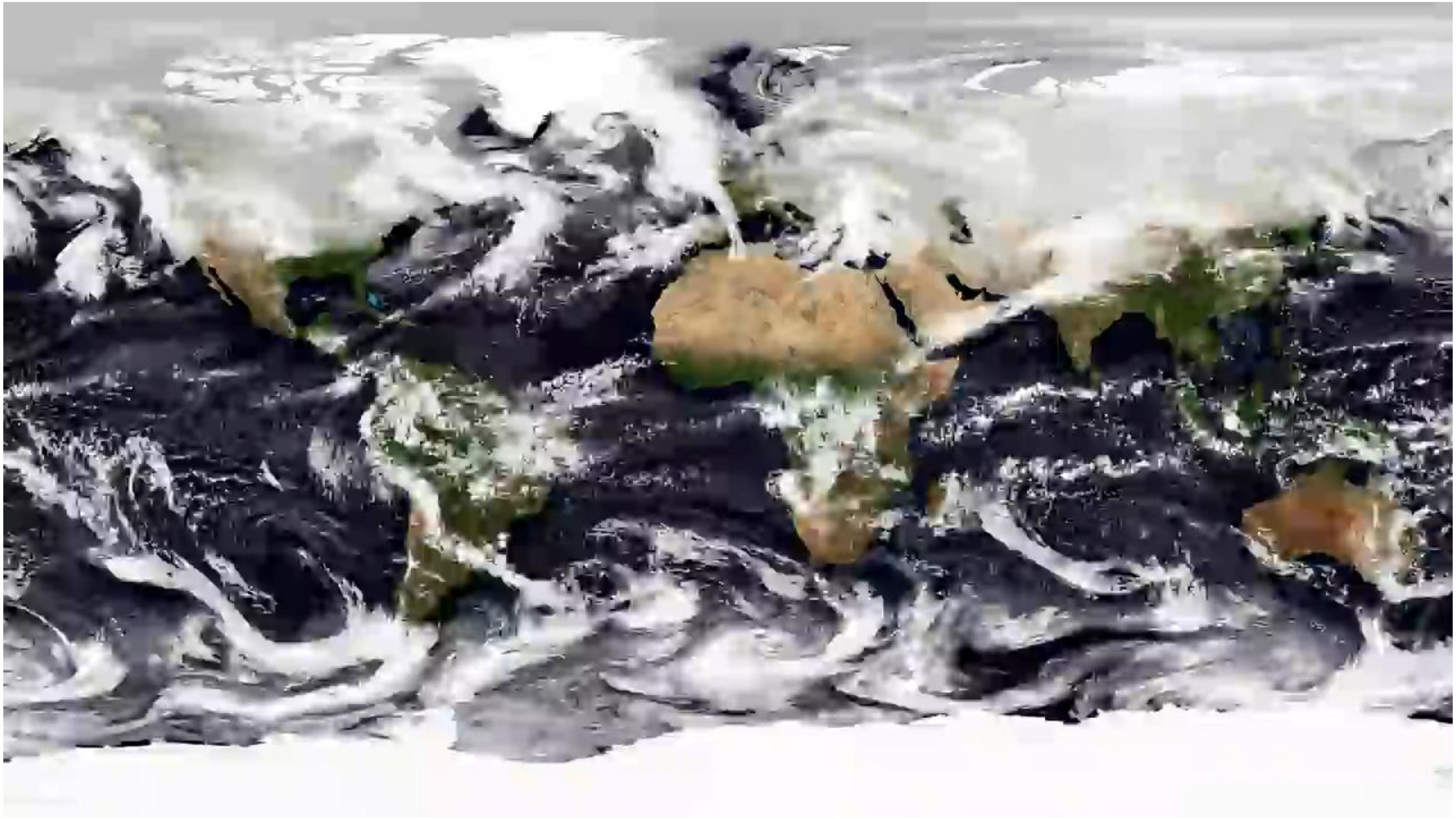
Satellite's view



Credits: Twitter handle of "The weather Channel"

What we see

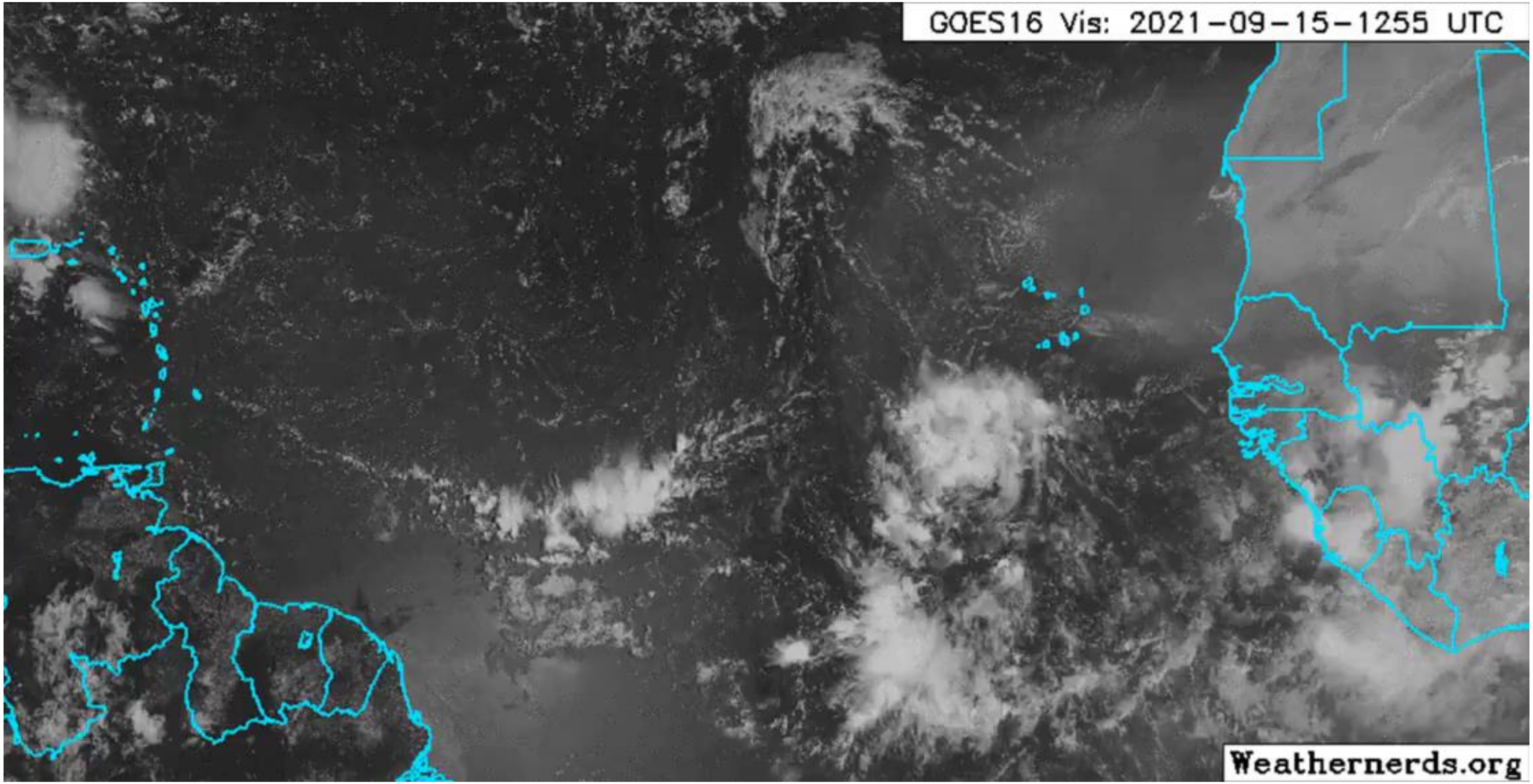
Credits: Stu Ostro's Twitter handle



Source : NASA

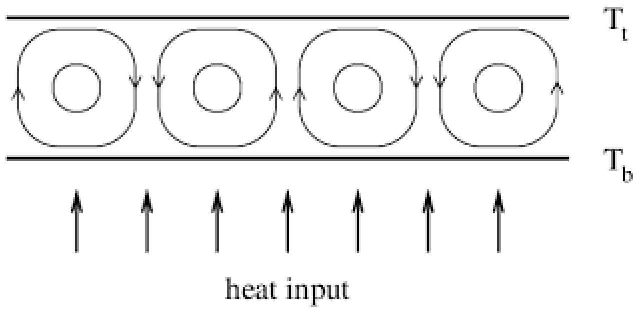
Stu Ostro’s twitter

Stu Ostro's twitter

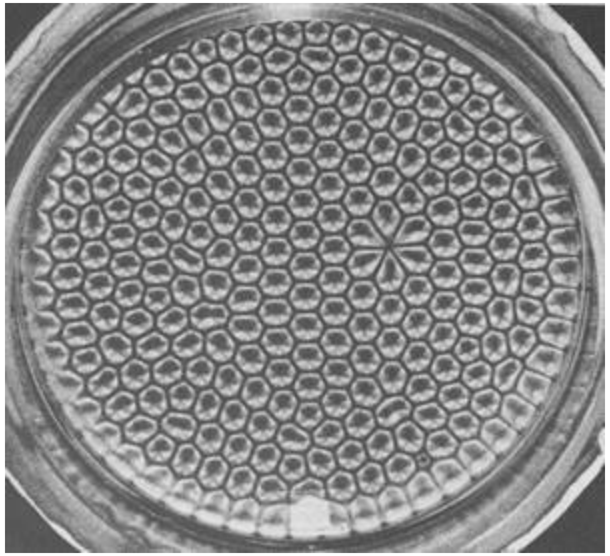

GOES16 Vis: 2021-09-15-1255 UTC
Weathernerds.org

How do we understand this variability in cloud-circulation coupling?

Thermodynamics of Clouds and Convection

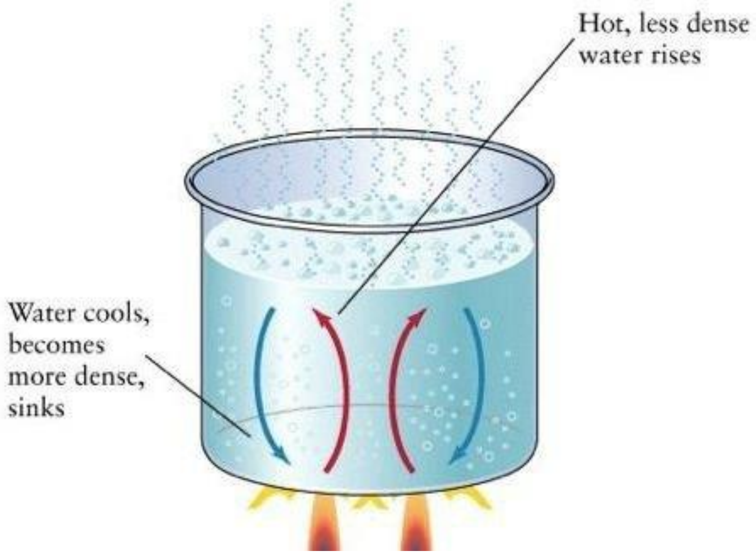


Two plate heated from bottom and cooled from top



Korenic et al. 2019

Note: Upper surface is not a plate



Ra ~ 2000

Ra ~ 10^4-10^8

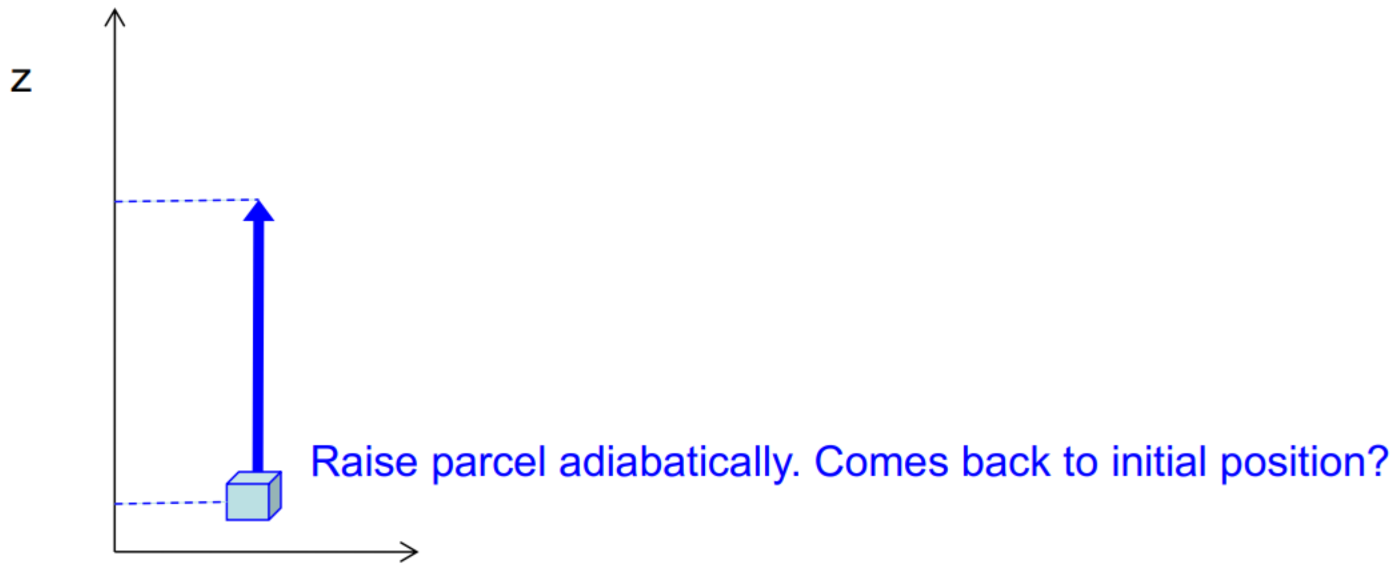
$$\mathrm{Ra} = \frac{\text{time scale for thermal transport via diffusion}}{\text{time scale for thermal transport via convection at speed } u}.$$

Thermodynamics of Clouds and Convection

Atmospheric dry convection Ra > 10^12

Unlike the dishpan case or Rayleigh-Benard rolls, both T and P decrease with height in the atmosphere!

Density Rho = f (T,P) : How to determine if a particular airmass will rise-up or not?
Clue – Parcel Method



Thermodynamics of Clouds and Convection

- Dry Convection : Potential temperature is conserved under Adiabatic displacement of parcel
- If one can make hydrostatic approximation, then one can show that dry static energy is conserved as well.
- How do we decide the stability of dry atmosphere?
- Dry Adiabatic lapse rate

Dry convection

Potential temperature $\theta = T\,(p_0 / p)^{R/cp}$ conserved under adiabatic displacements :

Adiabatic displacement

1st law thermodynamics: d(internal energy) = ΔQ (heat added) – ΔW (work done by parcel)

$$c_v\, dT = -\; p\, d(1/\rho)$$

Since $p = \rho R T$, $\quad c_v\, dT = -\, p\, d(R\,T / p) = -\, R\, dT + R\,T\, dp / p$

Since $c_v + R = c_p$, $\quad c_p\, dT / T = R\, dp / p$

$$\Rightarrow d \ln T - R / c_p\, d \ln p = d \ln (T / p^{R/cp}) = 0$$

$$\Rightarrow T / p^{R/cp} = \text{constant}$$

$\Rightarrow \theta = T\,(p_0 / p)^{R/cp}$ potential temperature is conserved under adiabatic (reversible) displacement

Remark1: ideal gaz law: $pV = Nkt \Leftrightarrow p = p = \rho R T$, $R=k/m$ where m=molecular mass

Remark2: $c_p = c_v + R > c_v$

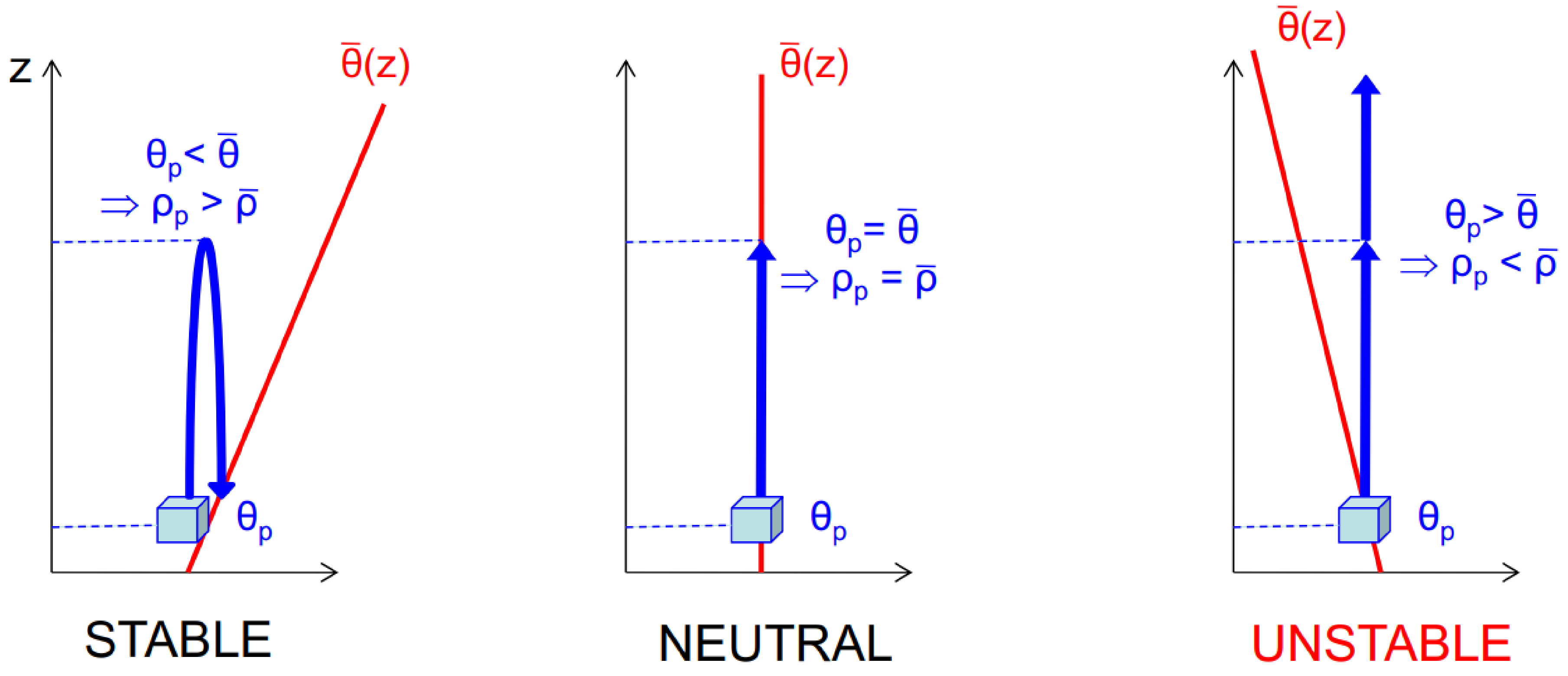
Remark3: We assumed $p_{parcel}=p_{environment} \Leftrightarrow$ quasistatic displacement

Remark4: If we make the hydrostatic approximation, dry static energy $h= c_p\, T + g\, z$ is conserved :
$c_p\, dT / T = R\, dp / p \Leftrightarrow c_p\, dT = R\,T\, dp / p = -\, g\, dz \Leftrightarrow c_p\, T + g\, z = \text{constant}$

Slide from Caroline Muller's Les Houche Talk

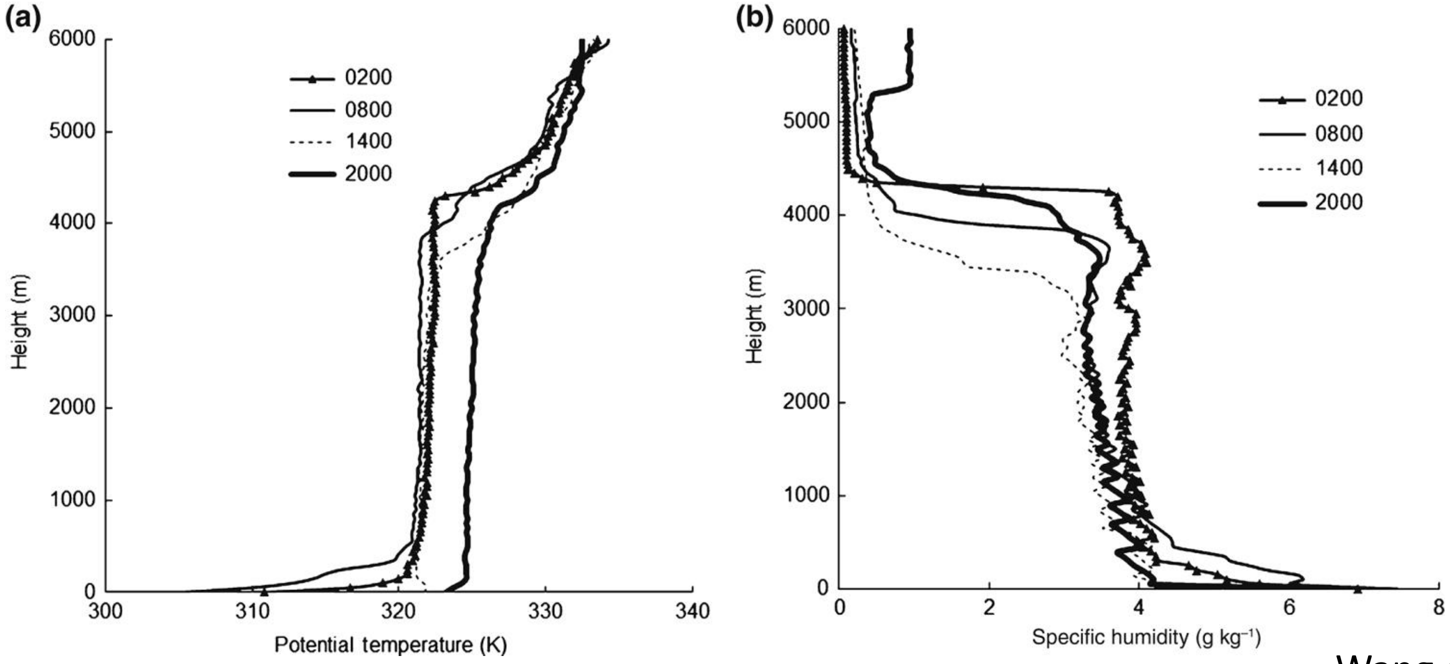
The parcel method:

Small vertical displacement of a fluid parcel adiabatic (=> θ = constant).
During movement, pressure of parcel = pressure of environment.



Thermodynamics of Clouds and Convection

Observations from Taklamakan desert in central Asia



Wang et al, 2016

Desert boundary layer is almost in a neutral state. The dry convection develops very rapidly in response to day-time heating!

Atmospheric Dry Convection

- Buoyancy driven circulation : Gives rise to ‘thermals’ in the boundary layer and clouds in the free troposphere
- Consider the equations of vertical motion (departure from hydrostatic balance) and potential temperature / dry static energy (s) conservation.
- Assume resting, horizontally uniform ‘basic state’

$$\overline{\rho}\frac{\partial w'}{\partial t} = -\frac{\partial p'}{\partial z} - \rho' g \, ,$$

$$\frac{\partial s'}{\partial t} = -w'\frac{\partial \overline{s}}{\partial z} \, .$$

Overbar – Horizontal average

Prime – perturbation from base state

Dry adiabatic motion

Pressure term reduces buoyancy effect

Atmospheric dry convection

- Perturbation density scales with dry static energy for parcel

$$-\left(\frac{\rho'}{\overline{\rho}}\right) \cong \frac{T'}{\overline{\overline{T}}} = \frac{s'}{c_p\overline{\overline{T}}} \,. \quad \Rightarrow \quad \frac{\partial w'}{\partial t} = \frac{gs'}{c_p\overline{\overline{T}}} \,.$$

$$w'(t) = w'(0)\,\mathrm{Re}\{e^{\sigma t}\} \,,$$

$$s'(t) = s'(0)\,\mathrm{Re}\{e^{\sigma t}\} \,,$$

$$\sigma^2 = -\frac{g}{c_p\overline{\overline{T}}}\frac{\partial \bar{s}}{\partial z} \,.$$

$\partial \bar{s}/\partial z < 0$, σ is real.

$\frac{\partial \bar{s}}{\partial z} < 0$ is the criterion for dry convective instability .

What happens when air is moist?

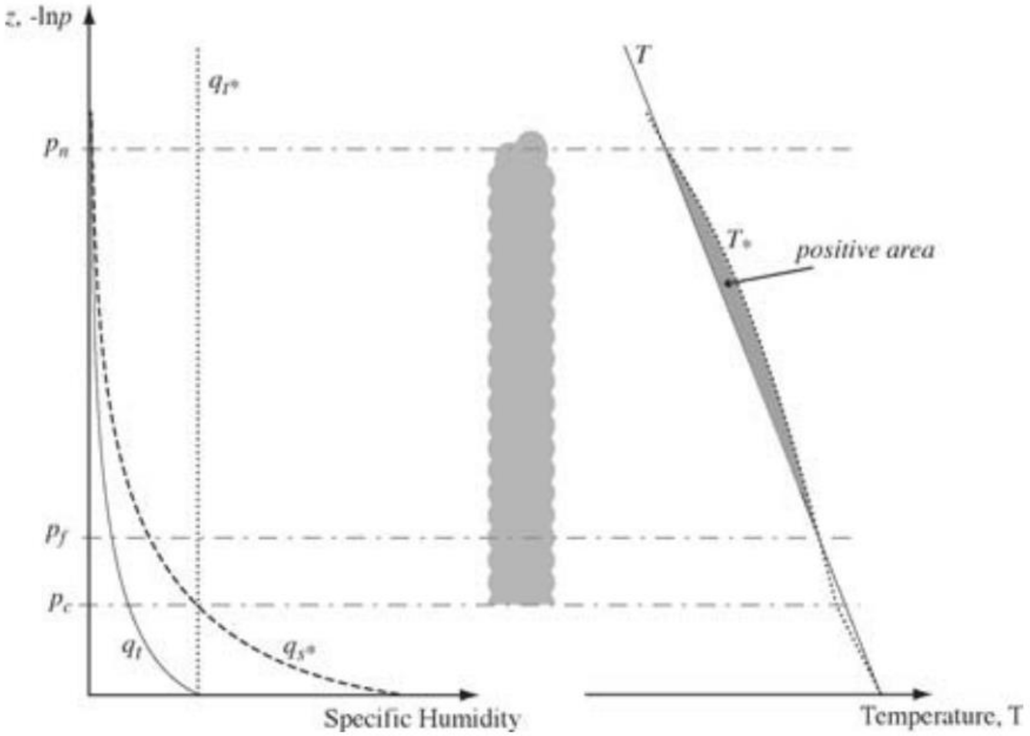
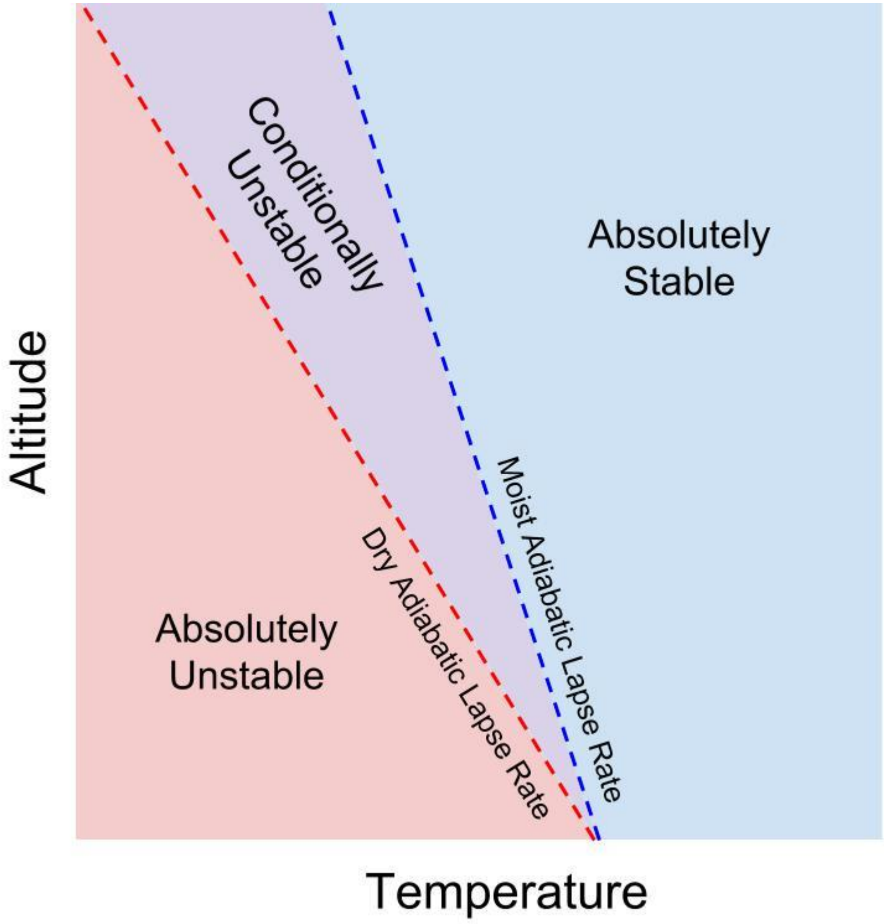


Figure 3 State diagram for an atmosphere stable to infinitesimal, but unstable to finite amplitude, displacements of near surface air.



Stevens, 2005 (Review)

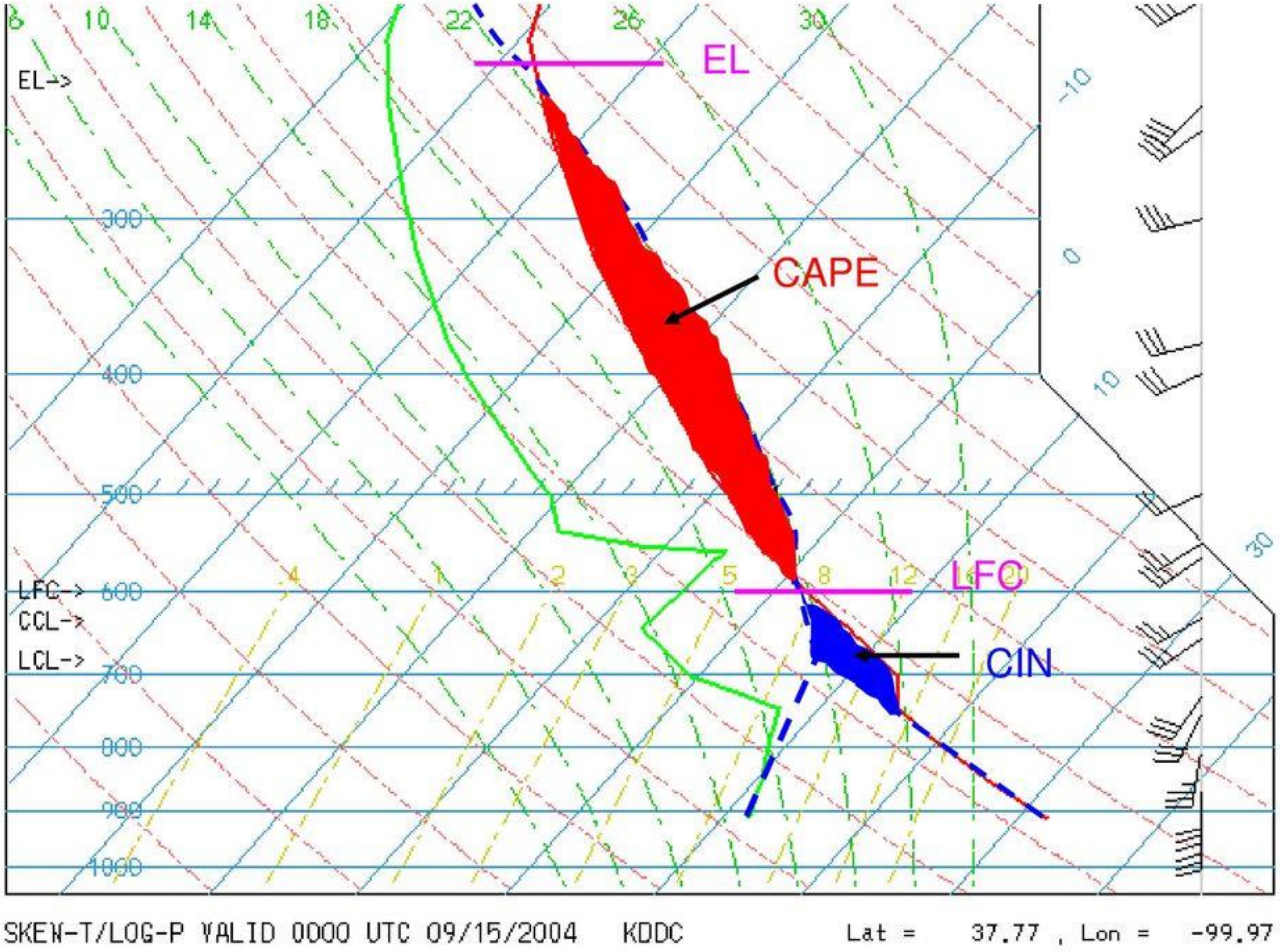


Figure 3: Skew-T Ln-P plot from Dodge City, KS at 0000 UTC on 15 September 2004

Image: Dr. Heevar

Thermodynamics of Clouds and Convection

- Conditional instability

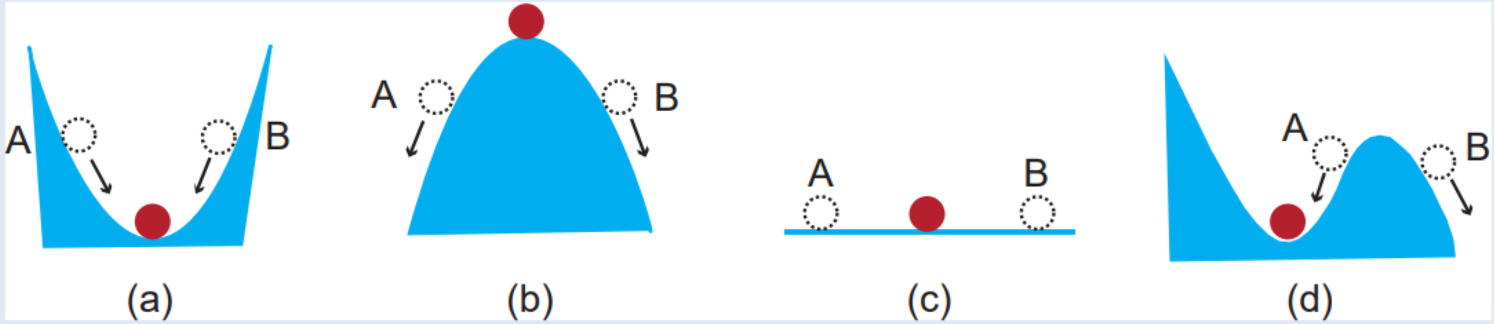


Fig. 3.17 Analogs for (a) stable, (b) unstable, (c) neutral, and (d) conditional instability. The red circle is the original position of the ball, and the white circles are displaced positions. Arrows indicate the direction the ball will move from a displaced position if the force that produced the displacement is removed.

Unlike QG theory a linear stability analysis of this system becomes difficult due to 2 main reasons:

1. The perturbation and stability depends both on temperature and humidity
2. The stability conditions depends on finite amplitude perturbations

What happens when air is moist?

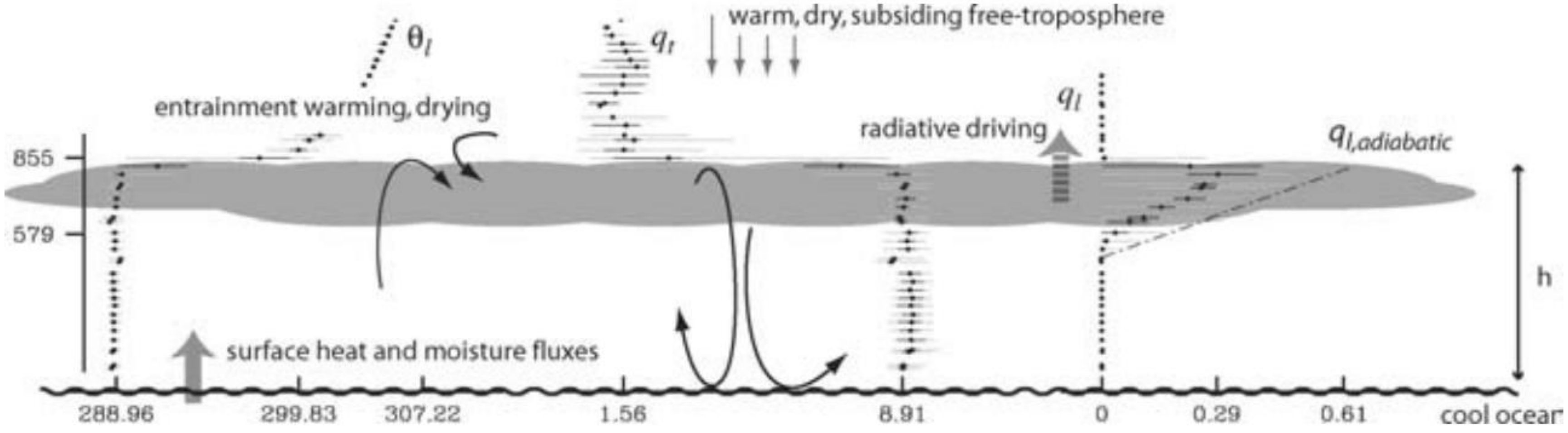
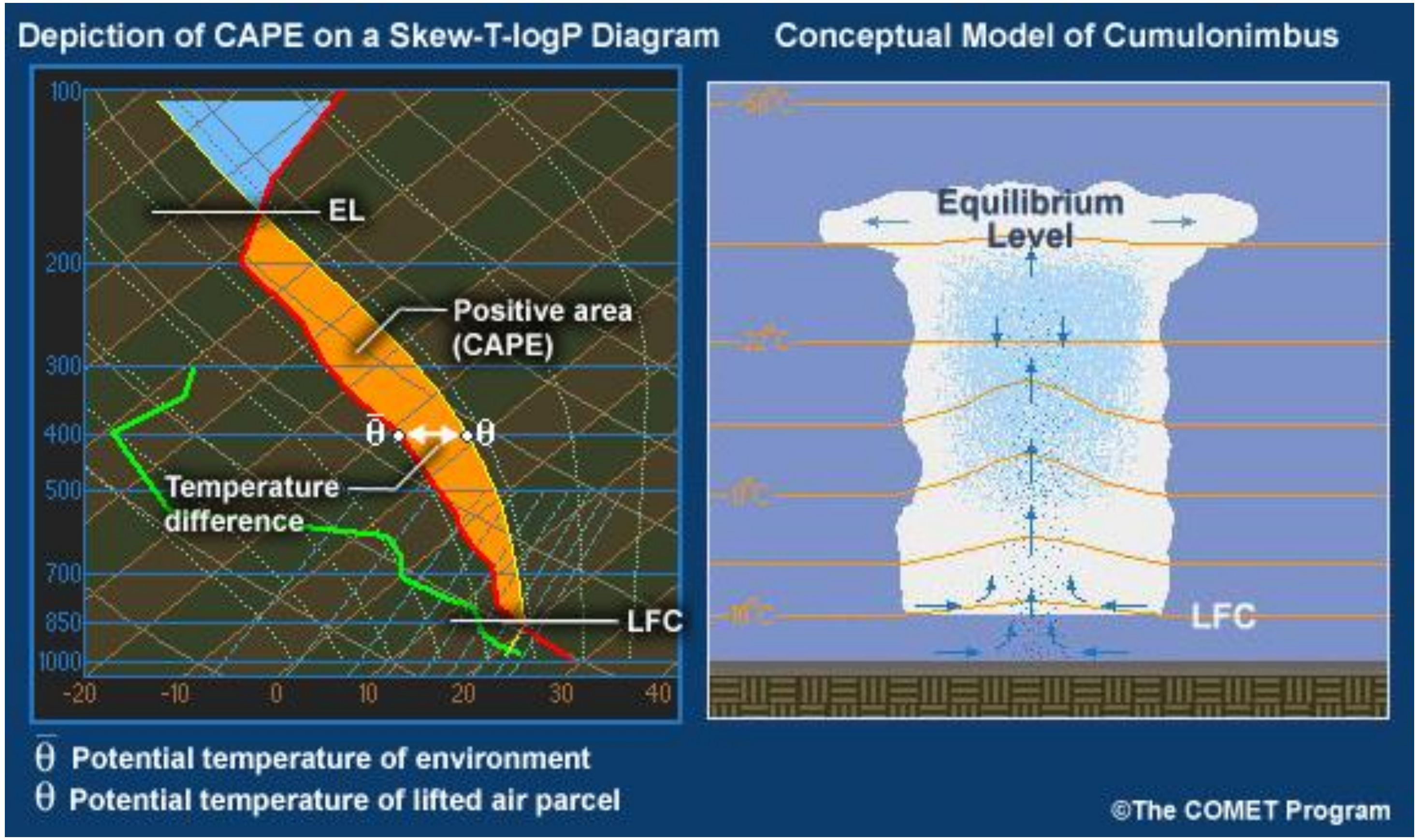


Figure 4 Cartoon of well-mixed, nonprecipitating, stratocumulus layer, overlaid with data from research flight 1 of DYCOMS-II. Plotted are the full range, middle quartile, and mean of θ_l, q_t, and q_l from all the data over the target region binned in 30-m intervals. Heights of cloud base and top are indicated, as are mixed layer values and values just above the top of the boundary layer of various thermodynamic quantities. The adiabatic liquid water content is indicated by the dash-dot line.

Stevens, 2005 (Review)

Thermodynamics of Clouds and Convection

- How to determine stability of moist atmosphere?



Keeping track of Energy in the Atmosphere

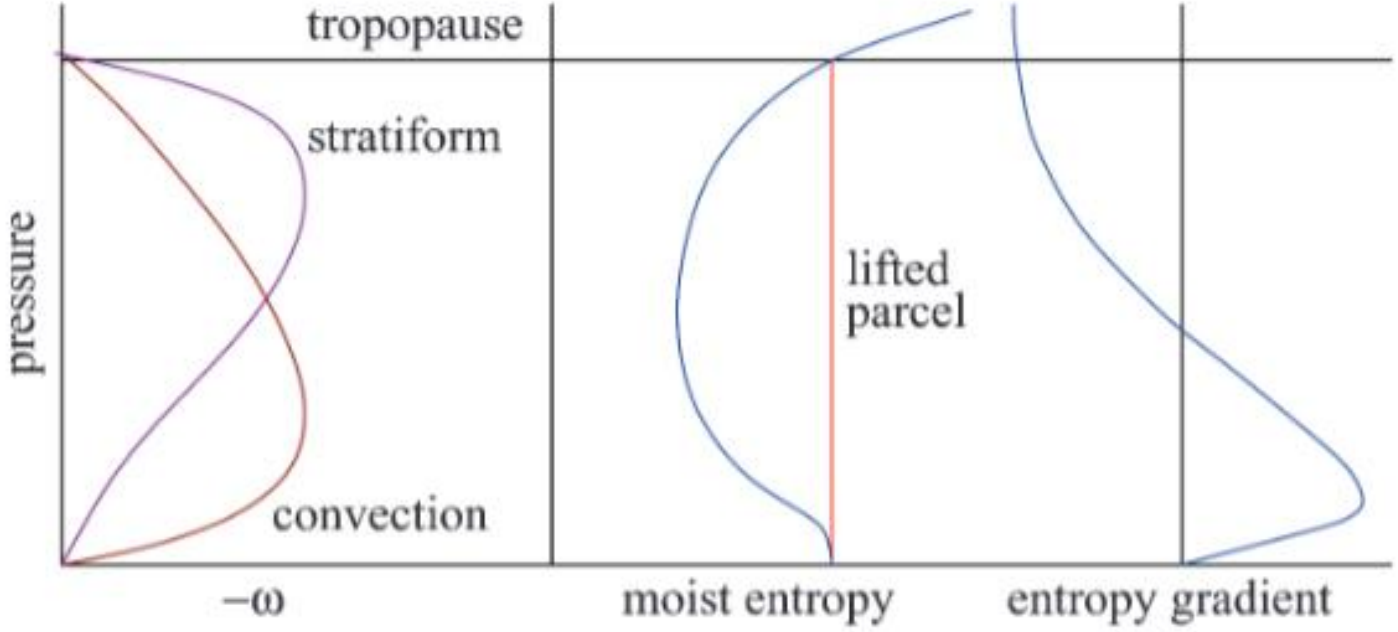
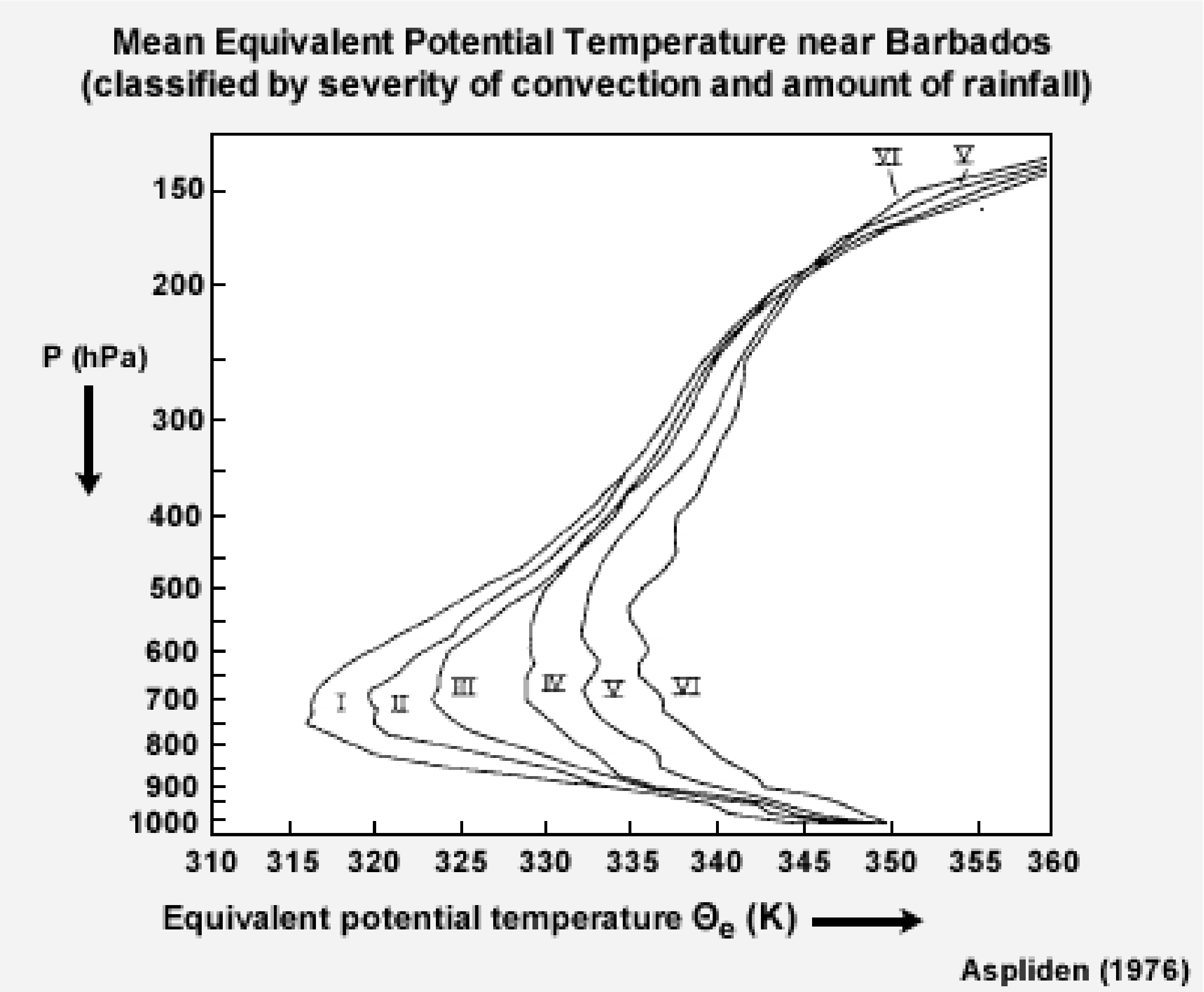


Figure 6. Schematic diagram of a typical tropical profile of moist entropy (middle panel) and its pressure gradient (right panel) with the entropy of a lifted parcel illustrated. Two typical mass flux profiles are illustrated (left panel), a convective profile with a low-level maximum and a stratiform profile with a high-level maximum.

Raymond et al., 2009

Vertical structure of Equivalent Potential Temperature / Moist Static Energy



- Notice that neither mean upward circulation nor diffusion can transport energy upwards.

For fully saturated atmosphere:

$$\frac{\partial h'_{sat}}{\partial t} = -w'\frac{\partial \bar{h}_{sat}}{\partial z} \ .$$

$$\sigma^2 = -\frac{g}{c_p \overline{T}\,(1+\gamma)}\frac{\partial \overline{h_{sat}}}{\partial z} \ . \qquad \gamma \equiv \frac{L}{c_p}\left(\frac{\partial q_{sat}}{\partial T}\right)_p$$

Energy in the Atmosphere

The total energy per unit mass in the atmosphere is given by

$$E = \underbrace{c_V\, T}_{\mathrm{I}} + \underbrace{g\, z}_{\mathrm{P}} + \underbrace{L\, q}_{\mathrm{L}} + \underbrace{\frac{1}{2}\left(u^2 + v^2\right)}_{\mathrm{K}}, \qquad (4.1)$$

Table 4.1 Amount and distribution of energy per unit surface area in the global atmosphere (from Peixoto and Oort 1992).

		$10^6\ \mathrm{J\,m^{-2}}$	Fraction (%)
Internal energy	I	1,800	70.2
Potential energy	P	700	27.3
Latent energy	L	64	2.5
Kinetic energy	K	1.2	0.05
Total		2,565	100

Energy Transports

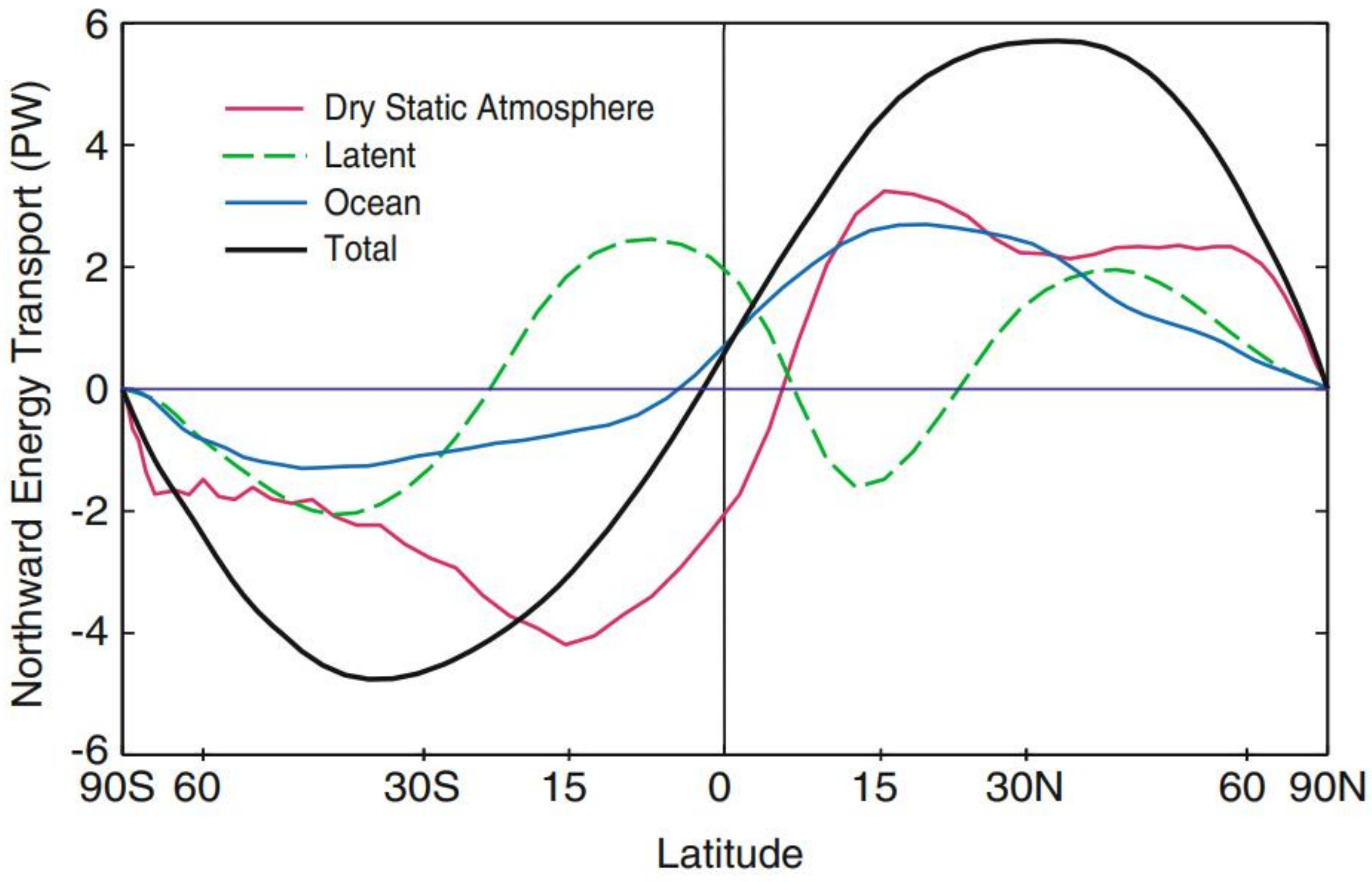


Fig. 4.2 Annual mean meridional heat transport in the atmosphere (latent and dry) and in the ocean. Figure from Siedler et al. (2001).

Source : Siedler et al. 2001

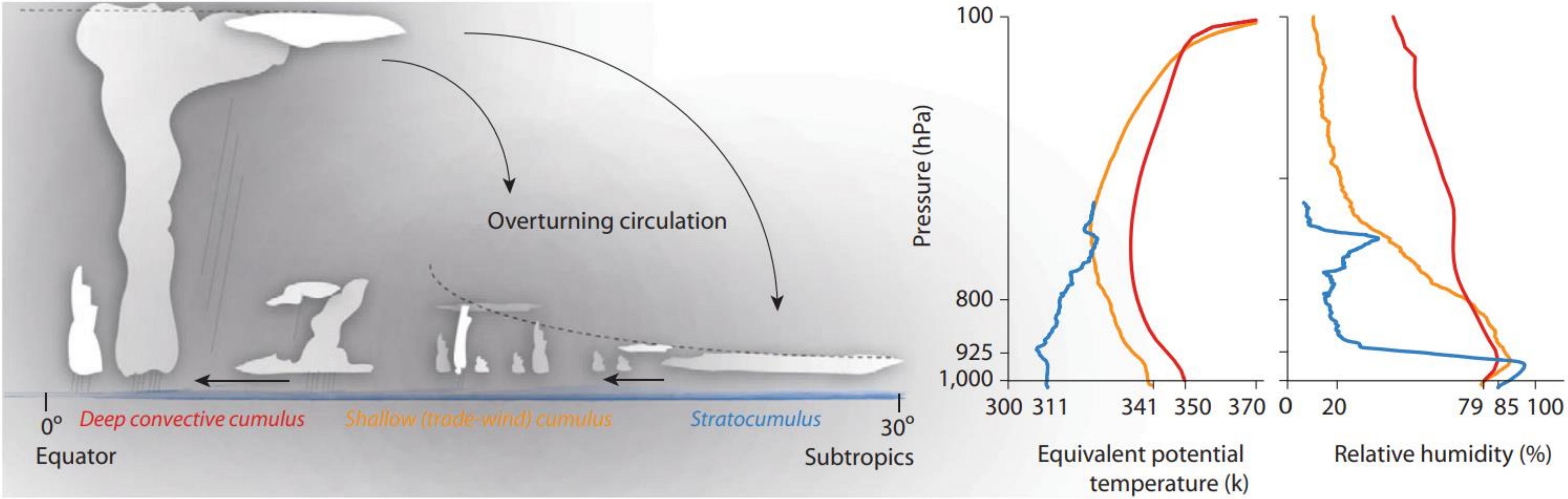


FIGURE 1.15: The zonal-mean large-scale overturning circulation between the subtropics and tropics (the Hadley circulation), along with representative profiles of (saturation) equivalent potential temperature and relative humidity that are typical of the three cloud regimes found throughout the Hadley circulation: in blue, low-level stratocumulus over the eastern ocean boundaries; in orange, shallow (trade-wind) cumulus regime over warmer sea surface temperatures in the trades and, in red, deep cumulus clusters in the inner tropics.

Book chapter - Nuijens and Jackob, 2020

Energy in the Atmosphere

The total energy per unit mass in the atmosphere is given by

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Energy Transports

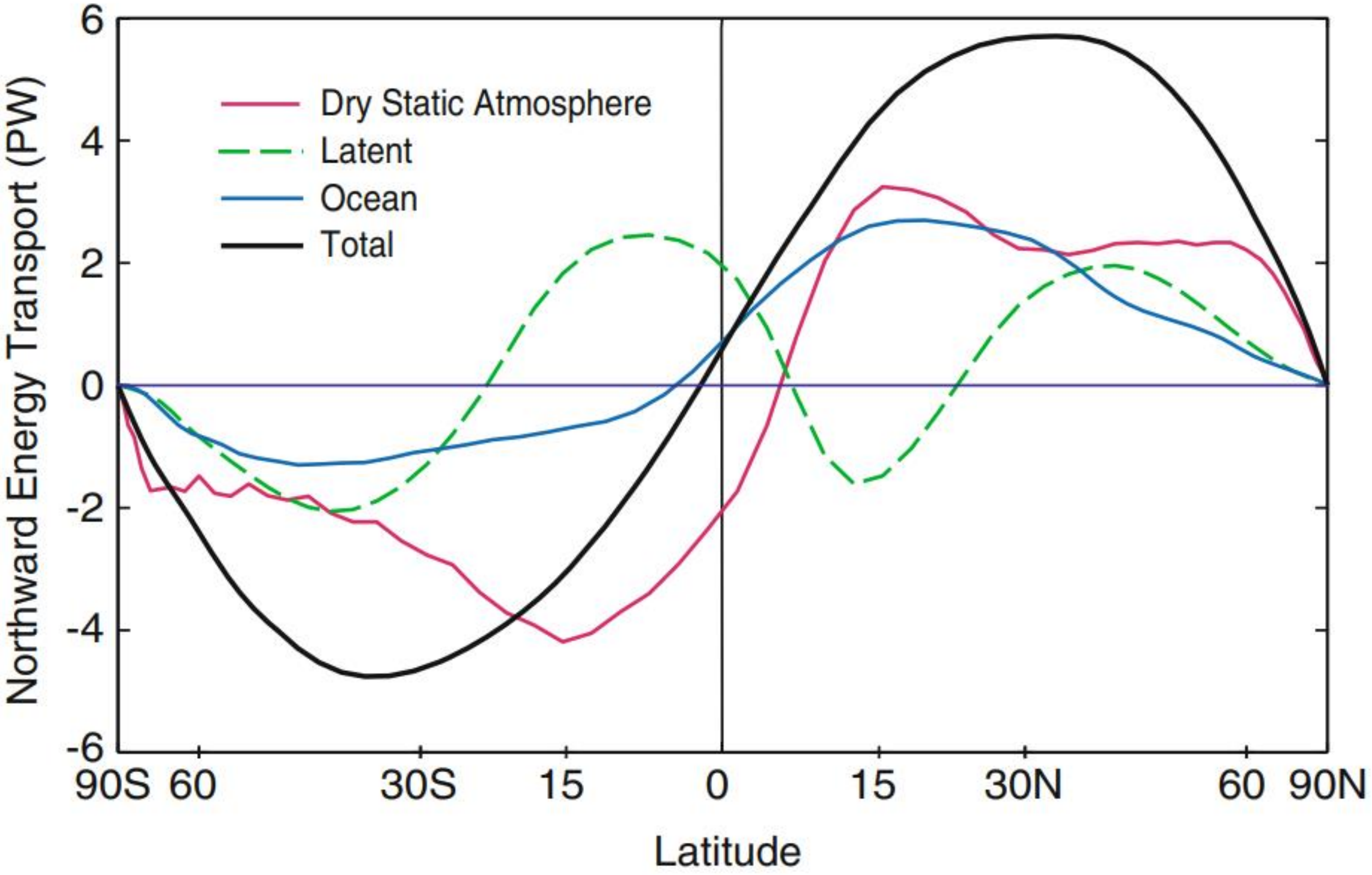

Fig. 4.2 Annual mean meridional heat transport in the atmosphere (latent and dry) and in the ocean. Figure from Siedler et al. (2001).

Source : Siedler et al. 2001

"Atmosphere" in the Climate model : **Simplified form**

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F}, \quad \textit{(horizontal momentum)}$$

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p, \quad \textit{(thermodynamic energy)}$$

$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0, \quad \textit{(mass continuity)}$$

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0, \quad \textit{(hydrostatic equilibrium)}$$

$$d\overline{q}/dt = S_q. \quad \textit{(water vapor mass continuity)}$$

Harmless looking terms F, Q, and $S_q \Longrightarrow$ "physics"

Representation of Physics

- Terms F, Q and S_q represent physical processes.

- **Equation of motion, F**

Turbulent transport, generation and dissipation of momentum

- **Equation of thermodynamic energy, Q**

Convective-scale transport of heat, Sources and Sinks due to phase changes, Radiative sources and sinks

- **Equation of water vapor mass continuity, S_q**

Convective-scale transport of water, Sources and Sinks due to phase changes

Modeling Convection-Circulation Coupling

$$\frac{\partial s}{\partial t} + \nabla \vec{v}_h s + \frac{\partial \omega s}{\partial p} = Q_R + L_v(c-e),$$

$$\frac{\partial q}{\partial t} + \nabla \vec{v}_h q + \frac{\partial \omega q}{\partial p} = -(c-e)$$

$$\frac{\partial \vec{v}_h}{\partial t} + \nabla \vec{v}_h \vec{v}_h + \frac{\partial \omega \vec{v}_h}{\partial p} + \nabla \Phi + f k \times \vec{v}_h = 0$$

$$\bar{\chi} = \frac{1}{A}\int_A \chi dA; \quad \chi = \bar{\chi} + \chi'$$

$$\underbrace{\frac{\partial \bar{s}}{\partial t} + \bar{\vec{v}}_h \nabla \bar{s} + \bar{\omega}\frac{\partial \bar{s}}{\partial p}}_{\text{large-scale observable}} = \bar{Q}_R + \underbrace{L_v(\bar{c}-\bar{e}) - \frac{\partial \overline{\omega' s'}}{\partial p}}_{\text{subgrid convective}}$$

$$\underbrace{\frac{\partial \bar{q}}{\partial t} + \bar{\vec{v}}_h \nabla \bar{q} + \bar{\omega}\frac{\partial \bar{q}}{\partial p}}_{\text{large-scale observable}} = \underbrace{-(\bar{c}-\bar{e}) - \frac{\partial \overline{\omega' q'}}{\partial p}}_{\text{subgrid convective}}$$

$$\underbrace{\frac{\partial \bar{\vec{v}}_h}{\partial t} + \bar{\vec{v}}_h \nabla \bar{\vec{v}}_h + \bar{\omega}\frac{\partial \bar{\vec{v}}_h}{\partial p}}_{\text{large-scale observable}} = \underbrace{-\frac{\partial \overline{\omega' \vec{v}_h'}}{\partial p}}_{\text{subgrid transport}},$$

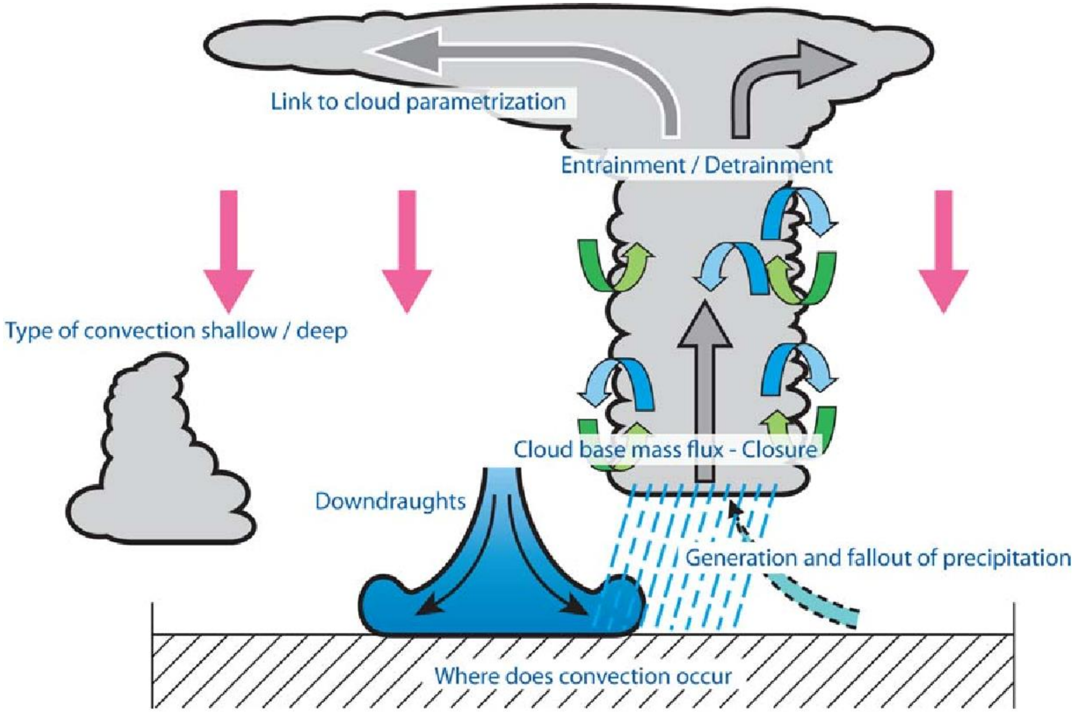

Figure 3. Schematic of a bulk convection scheme with a shallow and deep entraining/detraining cloudy

Park and Bechtold, 2009

Questions?