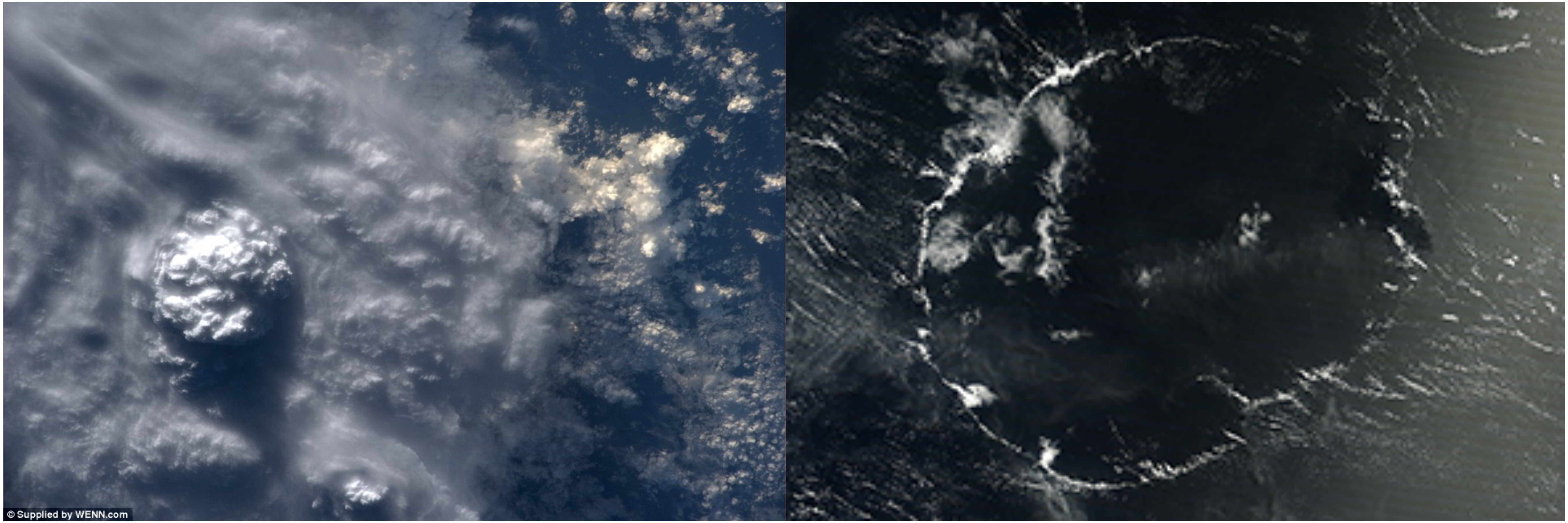
Clouds and climate sensitivity

Nicolas Rochetin



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Many thanks to Jean-Louis Dufresne, Sandrine Bony, Jessica Vial and Raphaela Vogel for the helpful discussions, enlightening advices and some of the slides !

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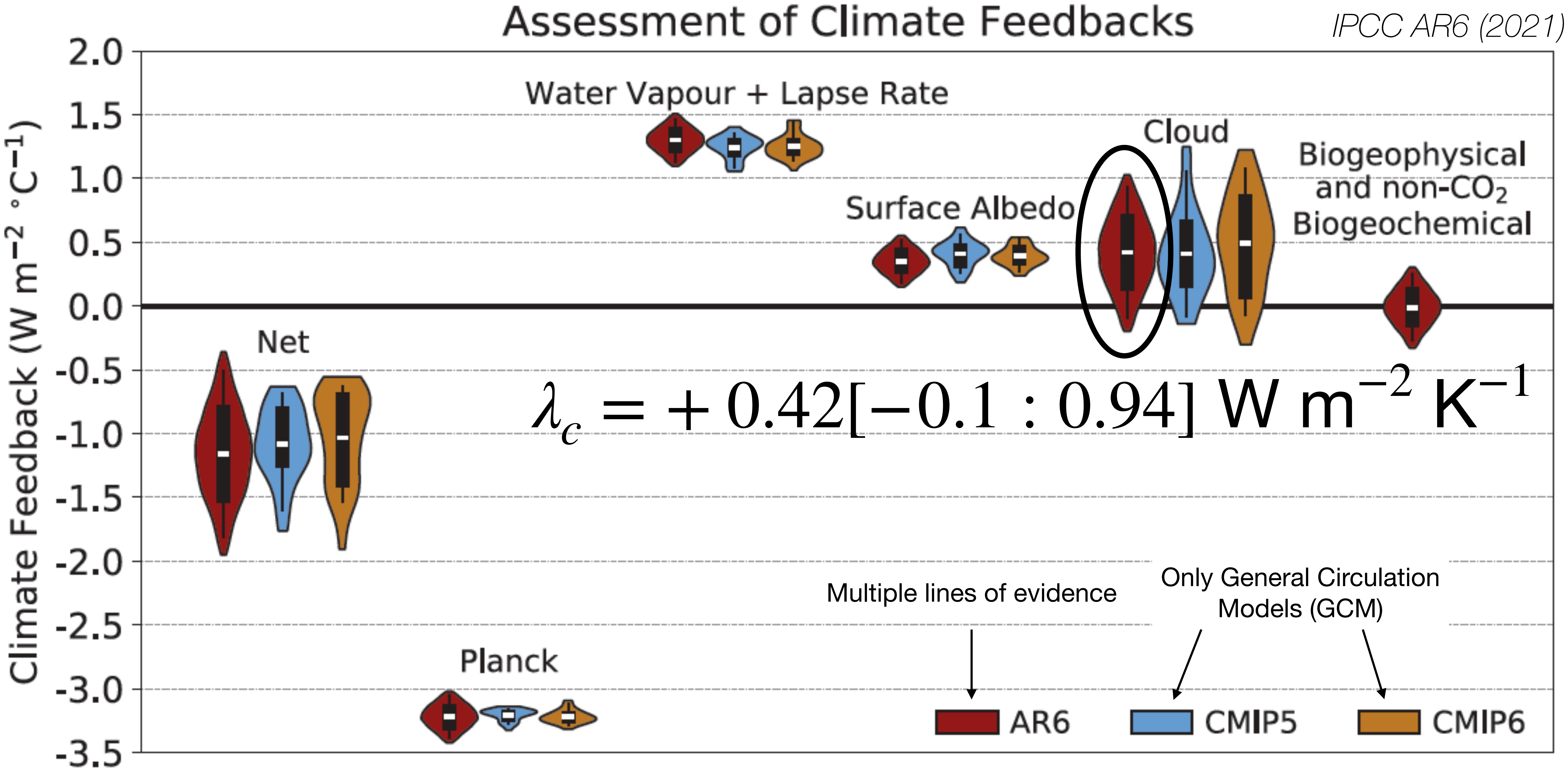
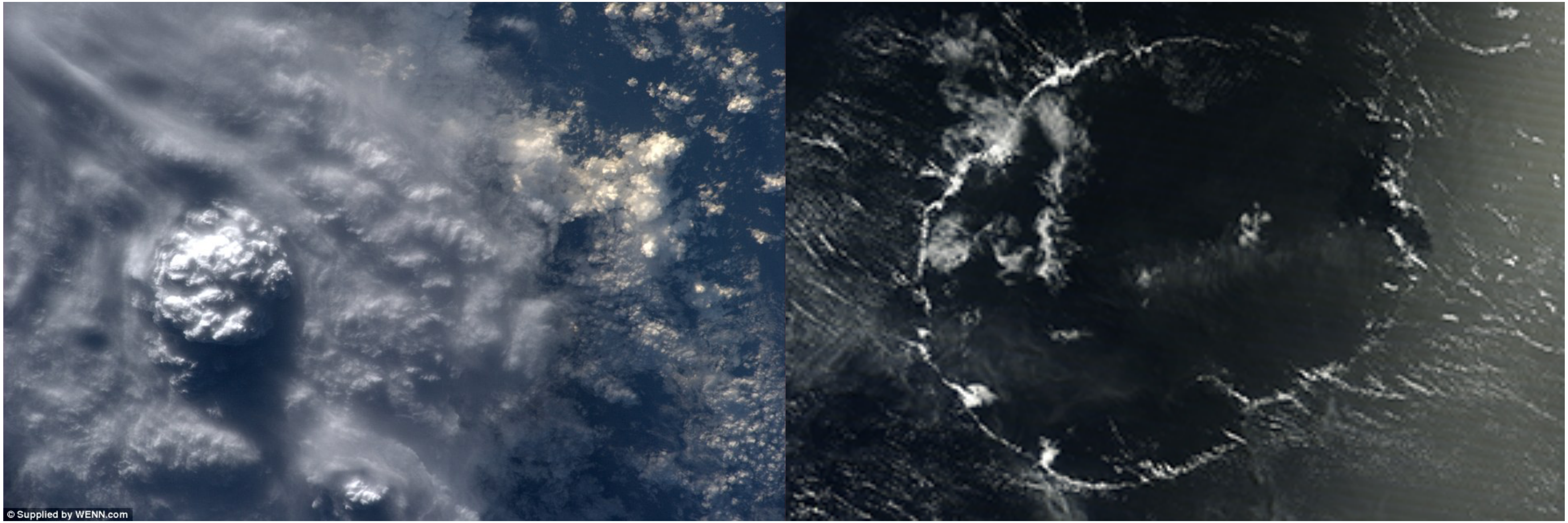


$$\lambda_c = +0.42[-0.1 : 0.94]\ \mathrm{W\ m^{-2}\ K^{-1}}$$

Why clouds are the first contributors to the climate feedback uncertainty ?

Part 1 - Clouds are full components of the general circulation



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Part 1 - Clouds are full components of the general circulation

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- 1.1 Generalities about clouds
  - 1.1.1 Clouds are multiscale
  - 1.1.2 Cloud Atlas
  - 1.1.3 Cloud climatology
  - 1.1.4 Cloud response to warming
- 1.2 Cloud interactions with radiation and the large scale circulation
  - 1.2.1 Cloud composition effect
  - 1.2.2 Cloud altitude effect
  - 1.2.3 Cloud Radiative Effect (CRE)
- 1.3 Sum up

1.1.1 Clouds are multiscale

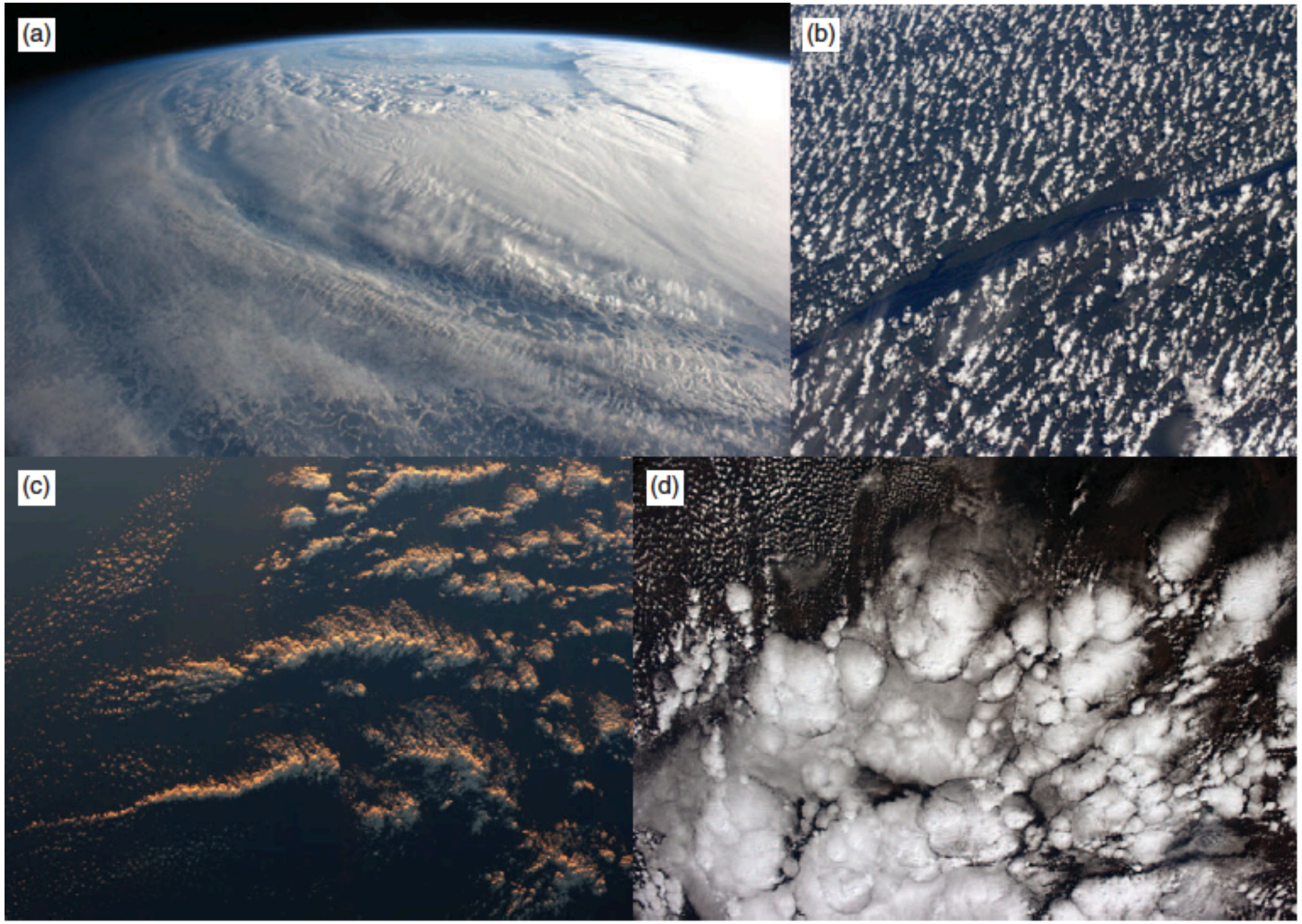

FIGURE 1.1: Photographs taken by the astronaut Alexander Gerst from the International Space Station (Gerst, 2017). (a) Cloud fields in an extratropical cyclone; (b) cumulus streets over land; (c) field of cumulus over the ocean; (d) organised convective cells. Copyright © [2014] ESA/NASA

Clouds do not only materialize the multiscale circulations in which they are embedded: they are tightly coupled to these circulations !

Part 1 - Clouds are full components of the general circulation

1.1.2 Cloud Atlas: attempt to define clouds by Luke Howard (1803)

A cloud is a collection of liquid and/or solid hydrometeors (visible by the human eye) in a given volume of air, which can be described through 3 key properties referring to their radiative properties:

1. **Cloud altitude**: emission temperature
2. **Cloud amount (or cloud fraction)**: the fraction of sky covered by a certain type of clouds in a certain layer of atm.
3. **Optical thickness**: the degree to which the cloud prevents sunlight from passing through it

2 families of clouds:

1. **Stratiform clouds**: horzontal development
2. **Cumuliform clouds**: vertical development

Their lifetime depends mainly:

1. **'Feeding' fluxes**: moist updrafts
2. **'Depleting' fluxes**: precipitation
3. (Relative) **Humidity of the near-environment**: droplets formation and re-evaporation
4. **Large-scale moisture transport**: warm conveyor belts in strom-tracks, moisture convergence …

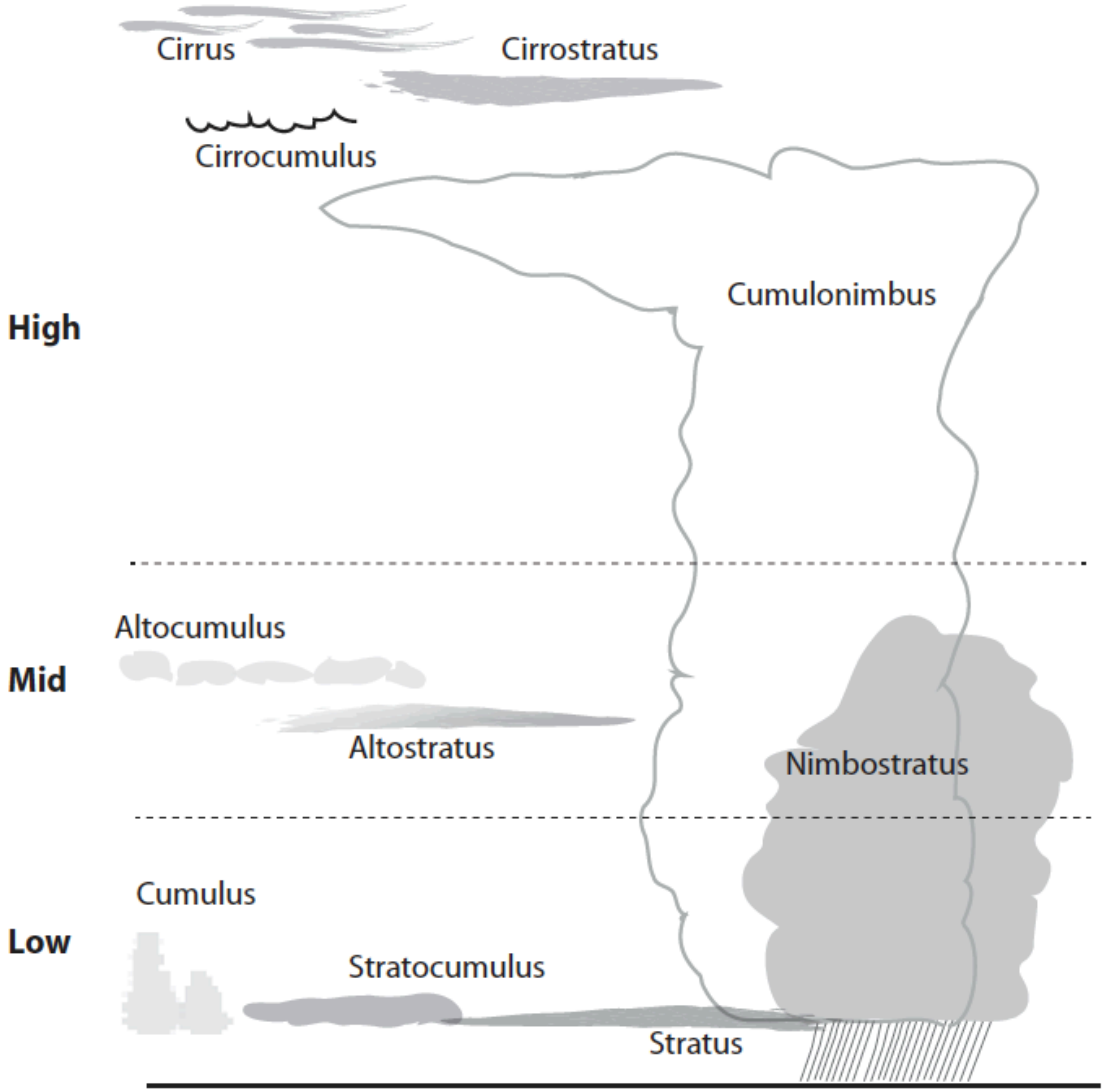

FIGURE 1.2: A schematic of Luke Howard's cloud classification.

Clouds exhibit various shapes and colors which largely determine their radiative properties

1.1.2 Cloud Atlas: how do clouds form ?

1. **Condensation of water vapor on Cloud Condensation Nuclei (CCN)**, when reaching the saturation vapor pressure $p_{e,s}$, whose variations with ambiant temperature is given by the **Clausius-Clapeyron equation**: $\frac{d \ln p_{e,s}}{dT} = \frac{L_v}{R_v T^2} \implies p_{e,s} = Ae^{\beta T}$

    - Latent heat of vaporisation: $L_v = 2.3\ 10^6$J kg^{-1}
    - Gas constant of water vapor: $R_v = 461.5$ J kg^{-1} K^{-1}

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2. Formation of clouds differing by their condensed phased

- **Liquid (or warm) clouds**
- **Ice (or cold) clouds**
- **Mixed-phased clouds**

… whose important property is **Particle Size Distribution (PSD)** : $PSD = (N, r)$ = **Number of particle of size r**

→ **Liquid water content:** $LWC = \frac{4}{3}\pi \bar{r} \rho_L h N$ (kg kg^{-1}) **Liquid water path:** $LWP = \int_{p_{top}}^{p_{sfc}} LWC dp$ (kg m^{-2}) **Optical depth:** $\tau = \dfrac{3LWP}{2\rho_L \bar{r}}$

1.1.2 Cloud Atlas: how do clouds form ?

3. **Liquid drops are spherical** (overall) created by **activation**
    - $\bar{r} < 30\ \mu$m $\implies$ Droplets
    - $\bar{r} < 300\ \mu$m $\implies$ Drizzle
    - $\bar{r} > 300\ \mu$m $\implies$ Raindrops

… resulting from **Condensation + Collision + Coalescence** processes

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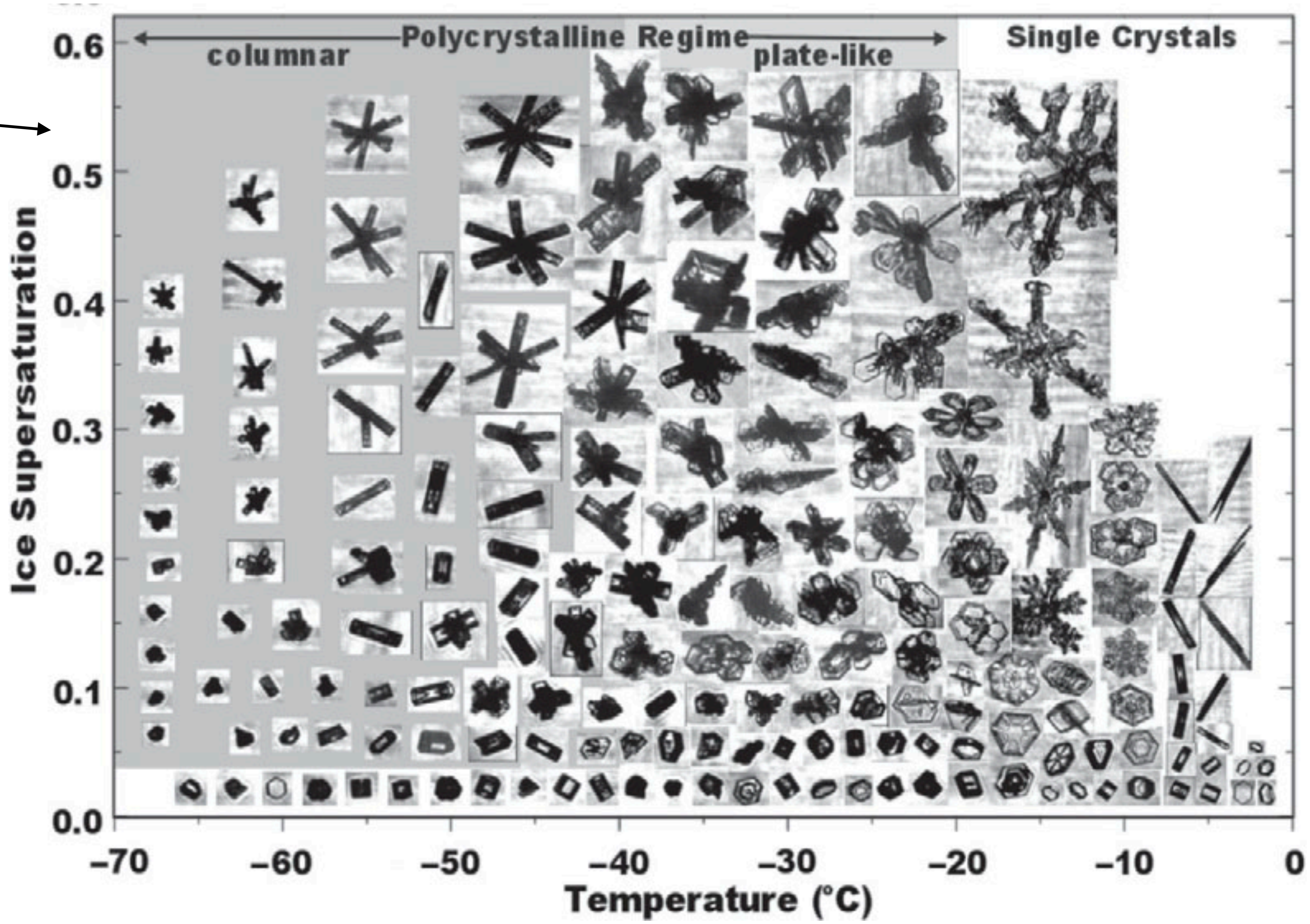
… resulting from **Condensation** + **Collision** + **Coalescence** processes

4. **Ice particles** created by **nucleation**
   - much more various shapes and sizes !
   - $\bar{r} \sim 40\ \mu$m



1.1.2 Cloud Atlas: attempt to define clouds by Luke Howard (1803)

‘Official’ classification of the cloud ‘Etages’ by the WMO in 2017

Étages	Polar	Temperate	Tropical
High	3–8 km	5–13 km	6–18 km
Mid	2–4 km	2–7 km	2–8 km
Low	0–2 km	0–2 km	0–2 km

Annual means from surface observations *(Hahn and Warren 2007)*

			Cloud amount (%)	
Étages	Genus	Abbreviation	Land	Ocean
High	Cirrus	Ci	—	—
	Cirrocumulus	Cc	22	12
	Cirrostratus	Cs	—	—
Mid	Altocumulus	Ac	17	17
	Altostratus	As	4	6
	Nimbostratus	Ns	5	5
Low	Cumulus	Cu	5	13
	Cumulonimbus	Cb	4	6
	Stratus	St	5	12
	Stratocumulus	Sc	12	22
	Fog	*Fo*	*1*	*2*
	Total cloud cover	**Tc**	**54**	**68**
	Clear sky	Cr	—	—
	Precipitation	Pt	—	—

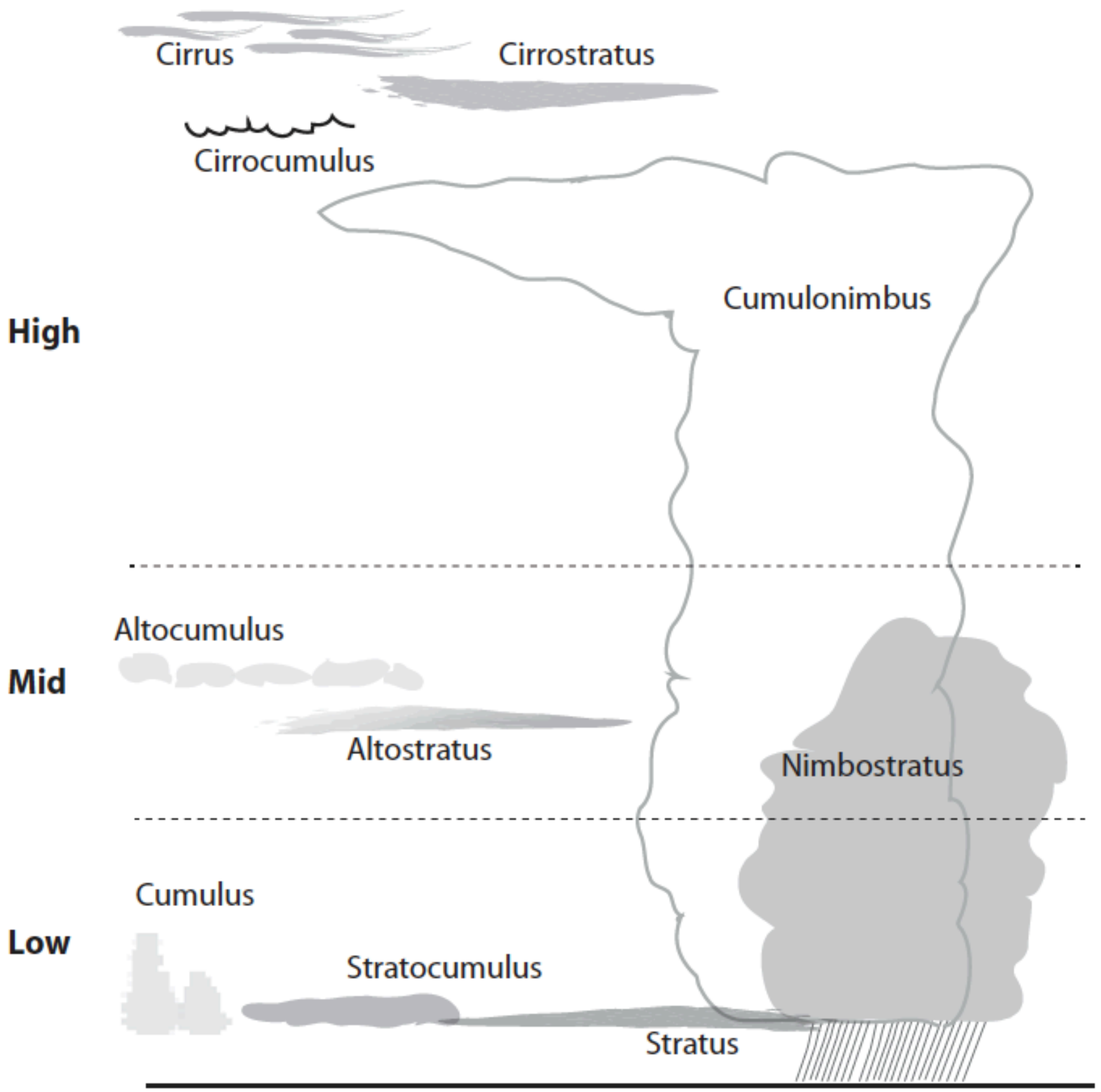


FIGURE 1.2: A schematic of Luke Howard’s cloud classification.

These ‘naturalistic’ considerations taken from Howard largely set current days standards

Part 1 - Clouds are full components of the general circulation

1.1 Generalities about clouds

- 1.1.1 Clouds are multiscale
- 1.1.2 Cloud Atlas
- 1.1.3 Cloud climatology
- 1.1.4 Cloud response to warming

1.2 Cloud interactions with radiation and the large scale circulation

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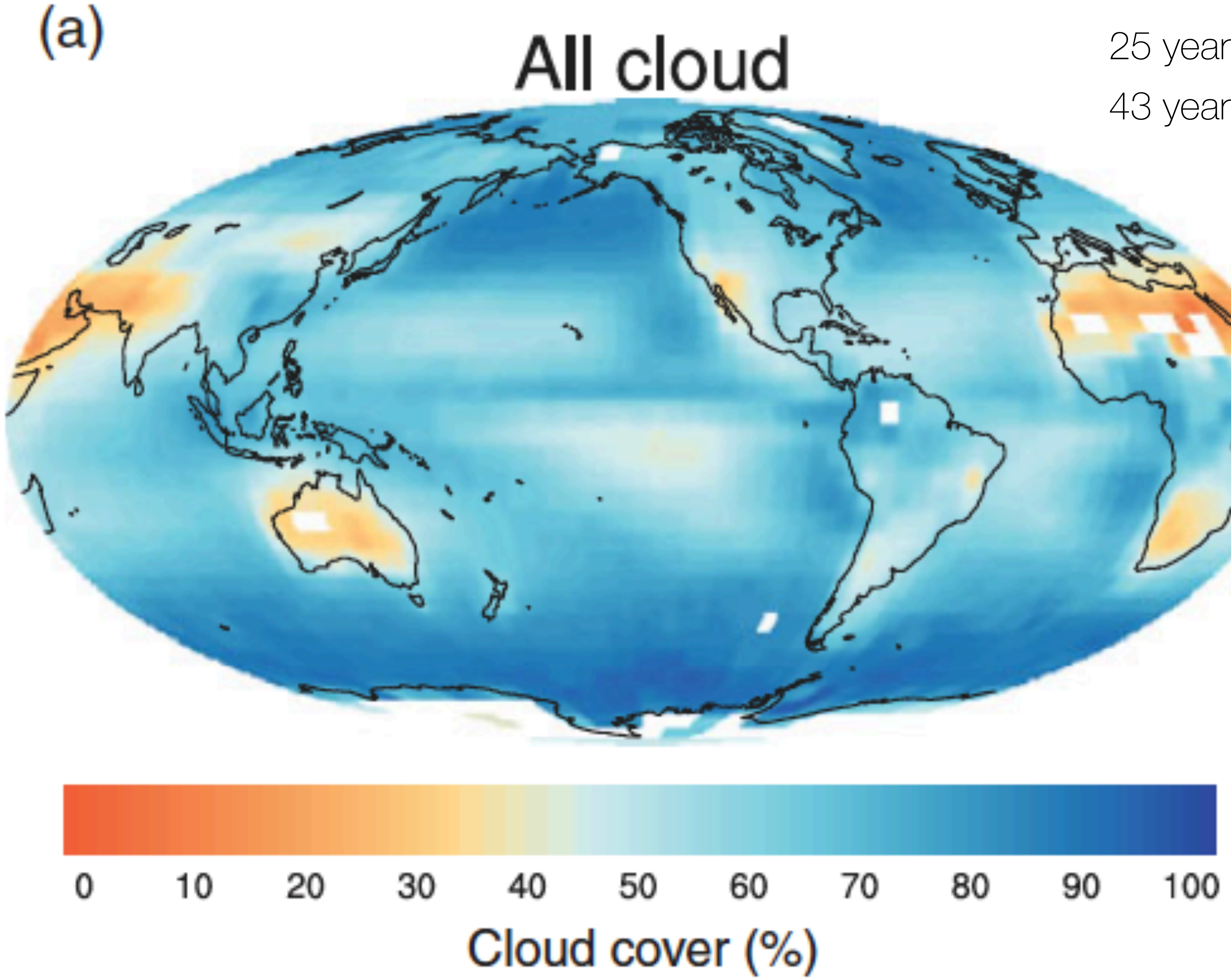
1.3 Sum up

1.1.3 Cloud climatologies: surface-based measurments

Annual means from surface observations



Hahn and Warren 2007: longest surface-based cloud climatology record

25 years of obs. over lands (1971-1996)

43 years of obs. over oceans (1954-1997)

The Earth is remarkably cloudy: few regions exhibits less than 40% cloud fraction

1.1.3 Cloud climatologies: space-based measurements

CTP diagram (Cloud Top Pressure)

International Satellite Cloud Climatology Project

ISCCP (started in 1983)

→

Visible and Infra-red radiances measurements from radiometers to derive:

- Cloud amount (or cloud fraction)
- Cloud optical depth
- Cloud top pressure (CTP)

Rossow and Schiffer 1999

Effect on the

Infrared radiation absorbed/emitted

towards space

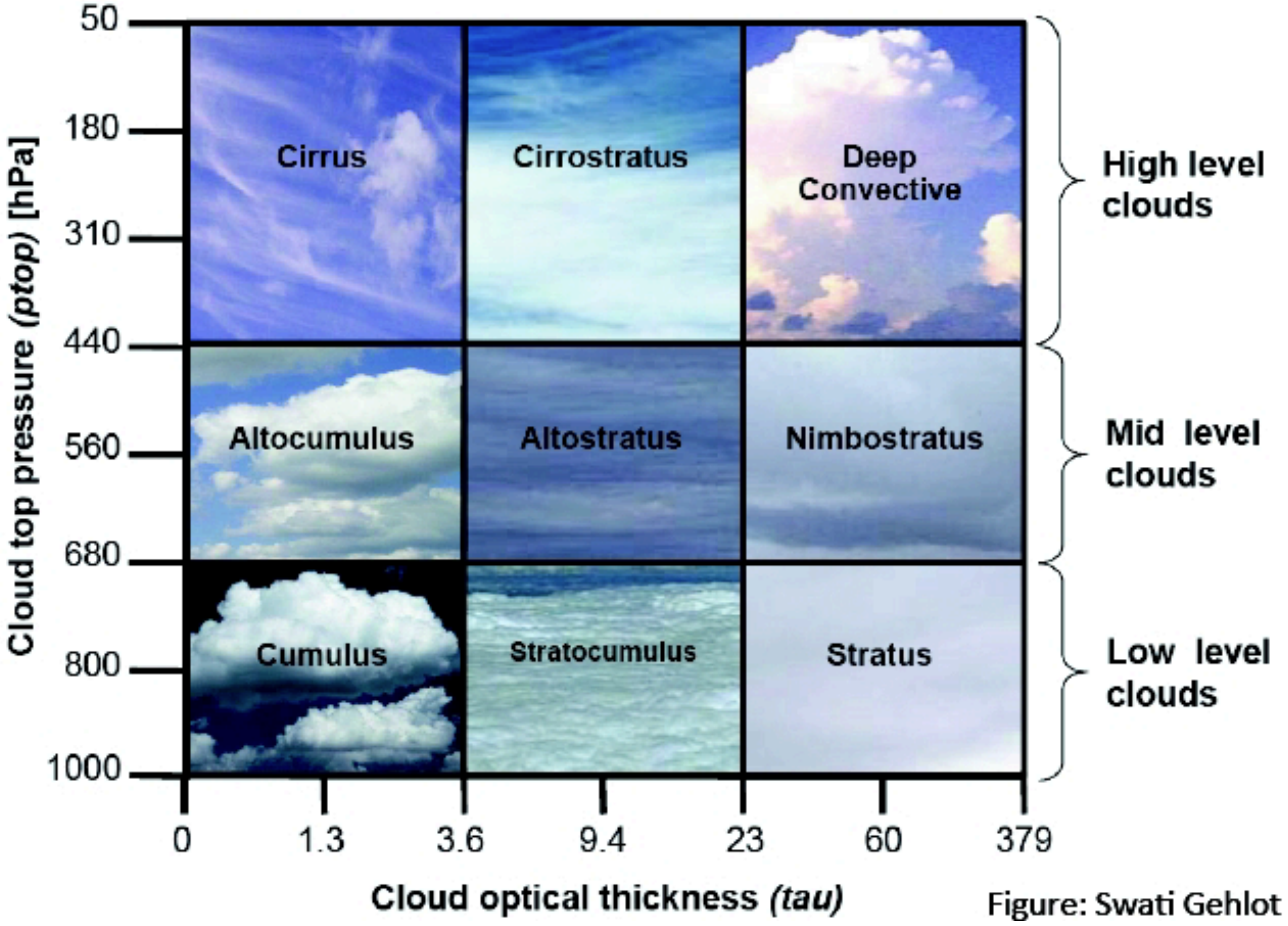


Figure: Swati Gehlot

Effect on the **Shortwave radiation scattered/reflected**

1.1.3 Cloud climatologies: space-based measurements

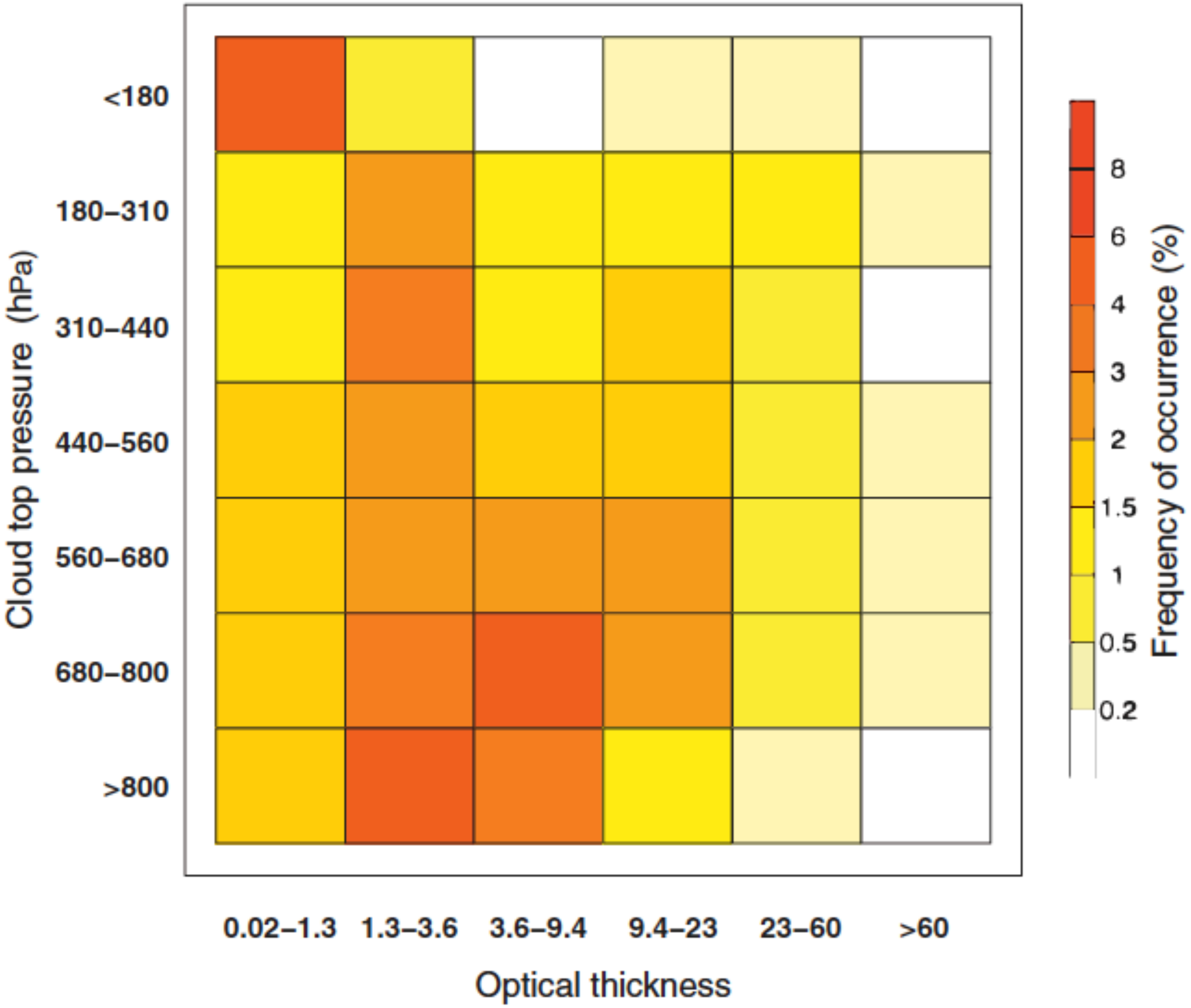
Annual and global means from space

Tselioudis et al., 2013

Visible and Infra-red radiances measurements from radiometers to derive:

- Cloud amount (or cloud fraction)
- Cloud optical depth
- Cloud top pressure (CTP)

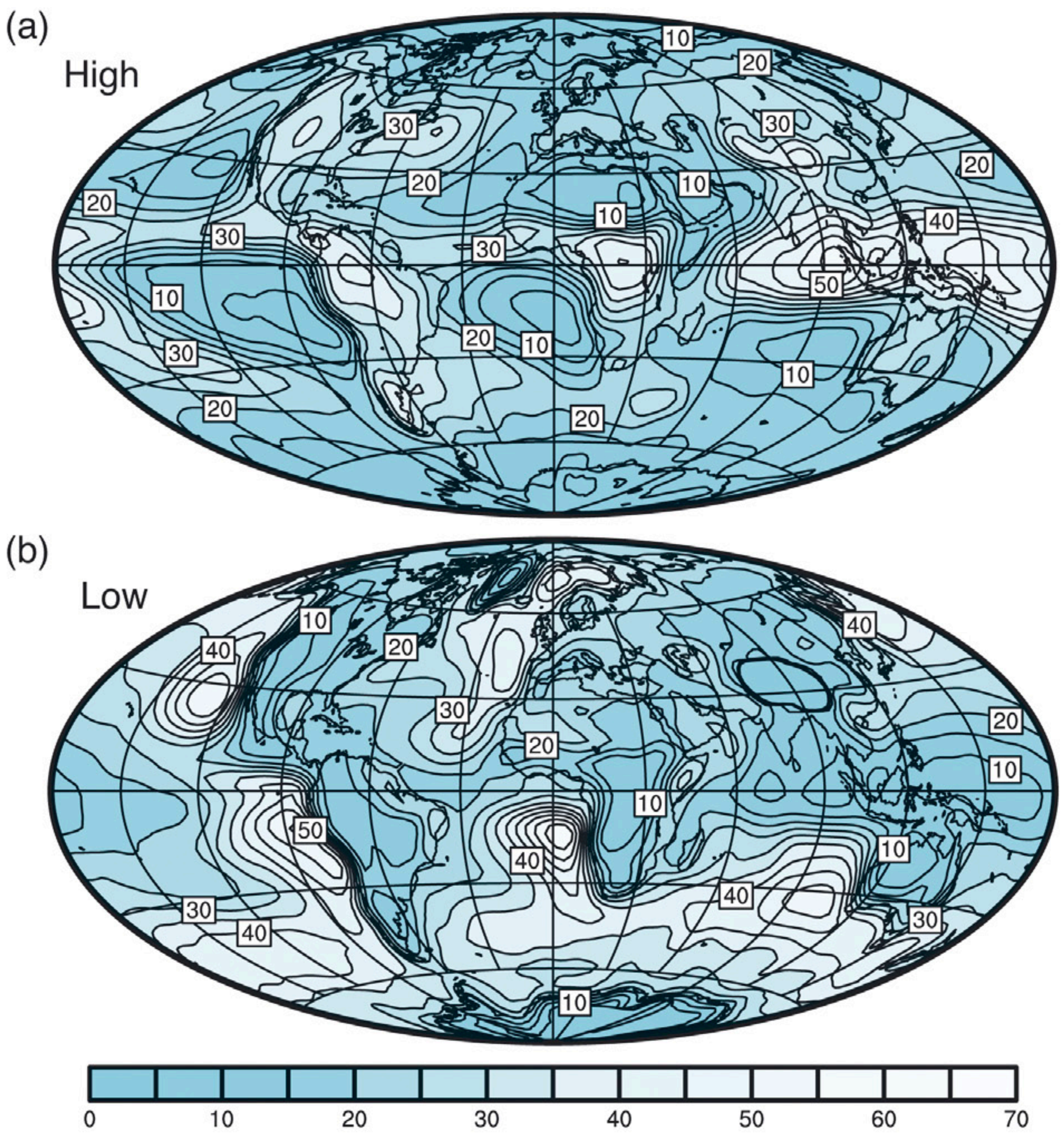
Effect on the **Infrared radiation absorbed/emitted** towards space



Effect on the **Shortwave radiation scattered/reflected**

1.1.3 Cloud climatologies: space-based measurments

Annual means from ISCCP

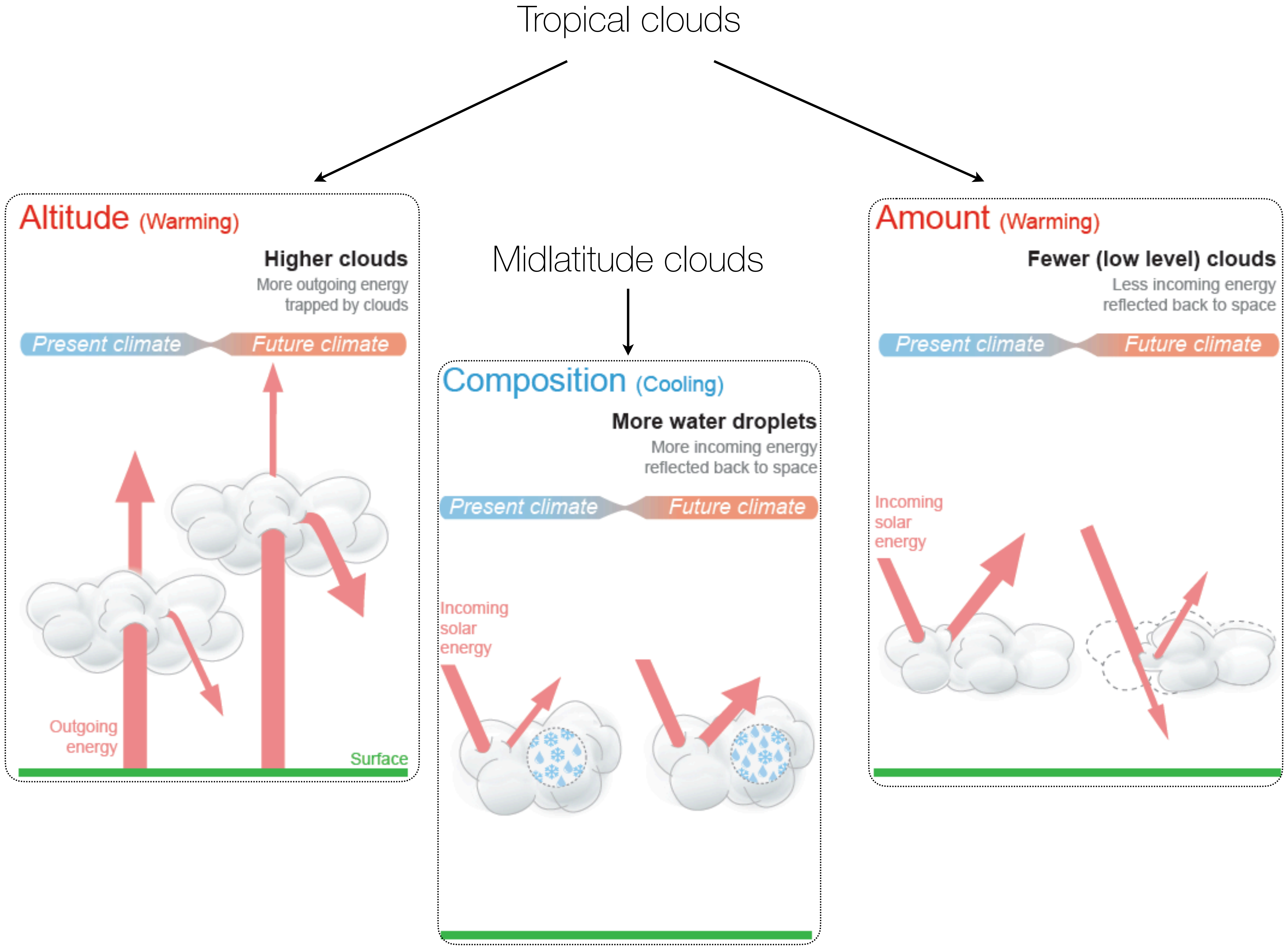


Clouds are not randomly distributed: they reveal the main features of the general circulation of the atmosphere

Part 1 - Clouds are full components of the general circulation

1.1.4 Cloud response to warming

Overall, scientists expect clouds to amplify future warming (IPCC AR6 2021)



Tropical clouds

Midlatitude clouds

Effect on the **Infrared radiation absorbed/emitted** towards space

Cloud fraction (or cloud amount)

Effect on the **Shortwave radiation scattered/reflected**

Part 1 - Clouds are full components of the general circulation

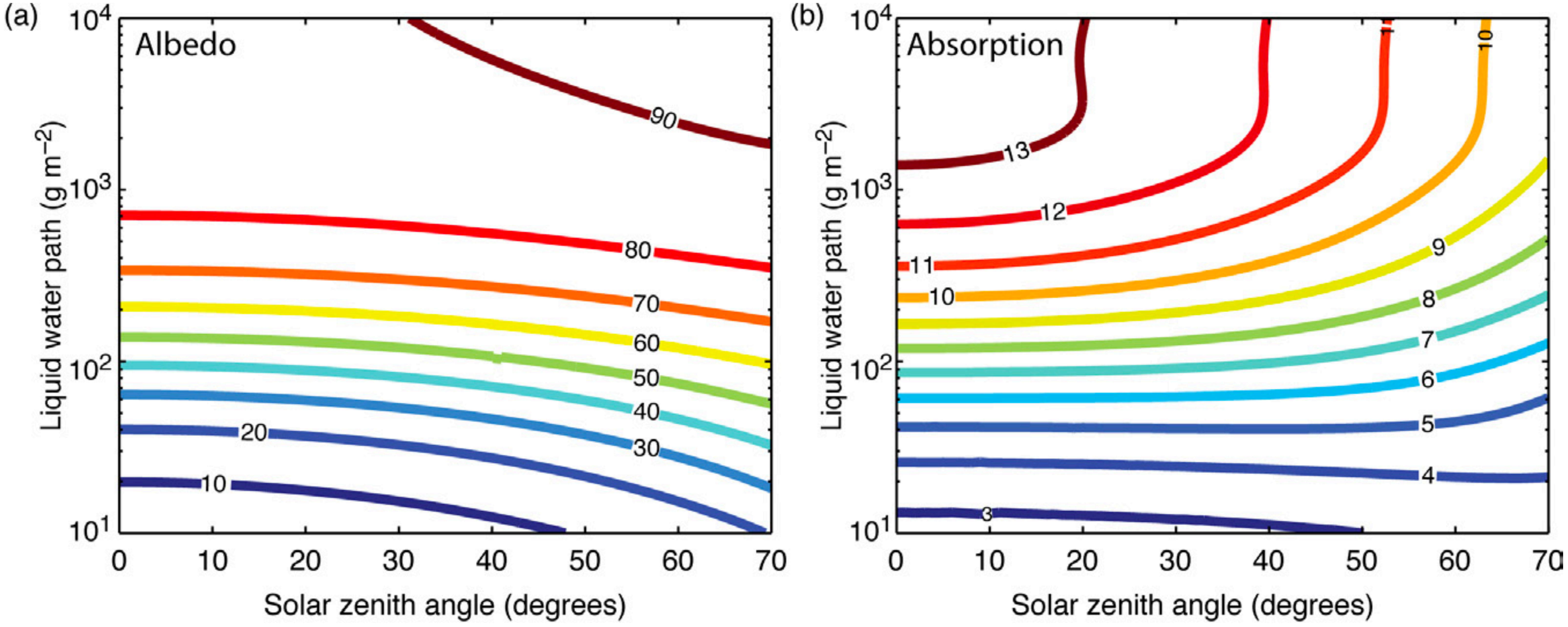
1.2.1 Cloud composition effects on the reflected Shortwave radiation (SW)

Sensitivity to the Liquid Water Path LWP and the solar zenith angle

➡ Fixed particle number N

Cloud albedo sensitivity to LWP

Cloud absorption sensitivity to LWP



Liquid water content: $LWC = \frac{4}{3}\pi\bar{r}\rho_L hN$ (kg kg^{-1})

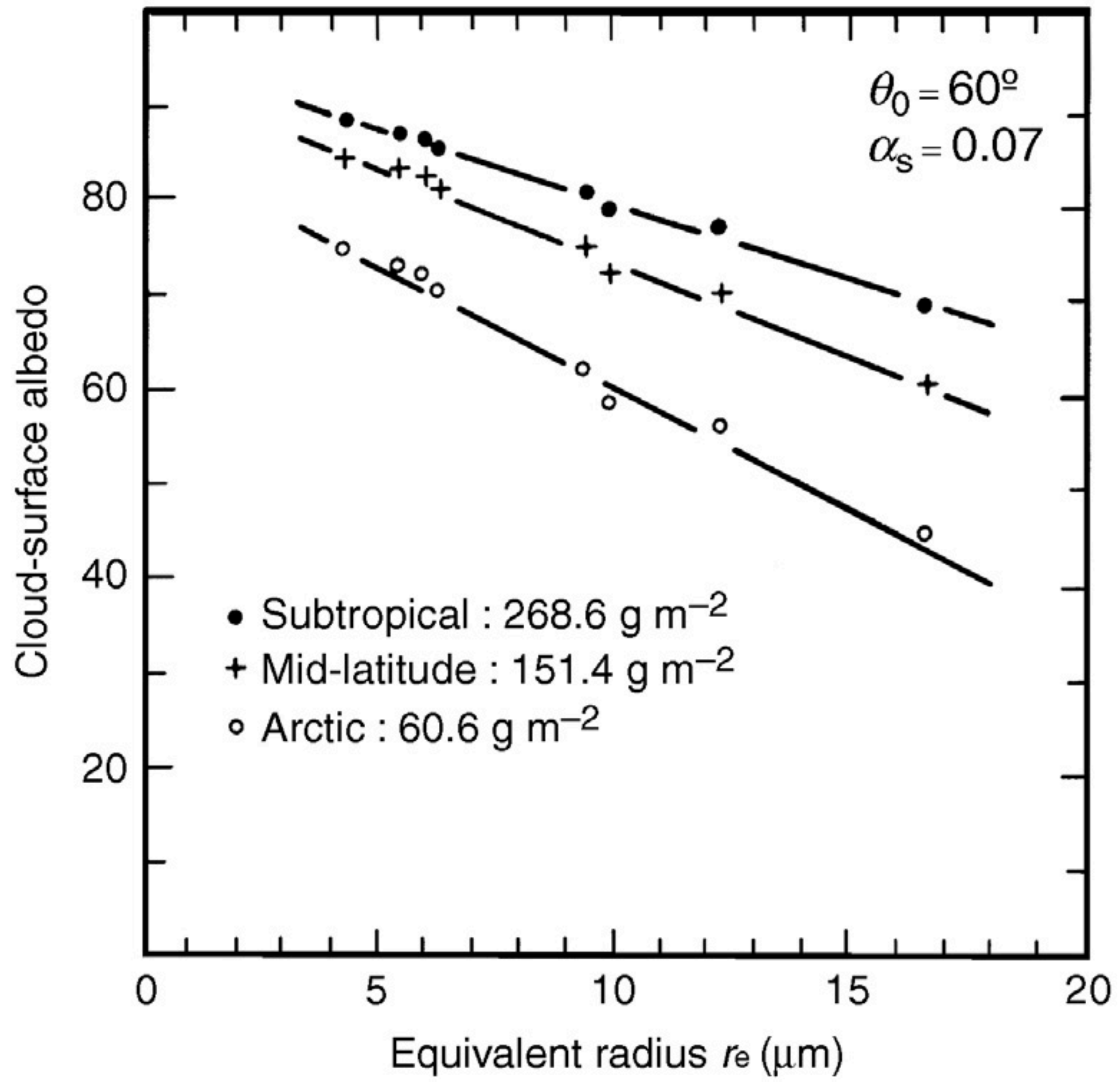
Liquid water path: $LWP = \int_{p_{top}}^{p_{sfc}} LWC dp$ (kg m^{-2})

Optical depth: $\tau = \frac{3LWP}{2\rho_L\bar{r}}$

Sensitivity to the droplet size $\bar{r}$

➡ Fixed liquid water content LWP

Cloud albedo



Smaller/more droplets increase cloud brightness

- Increased number of refractions at interfaces air/liquid

1.2.1 Cloud composition effects on the reflected Shortwave radiation (SW)

Sensitivity to the Liquid Water Path LWP and the solar zenith angle

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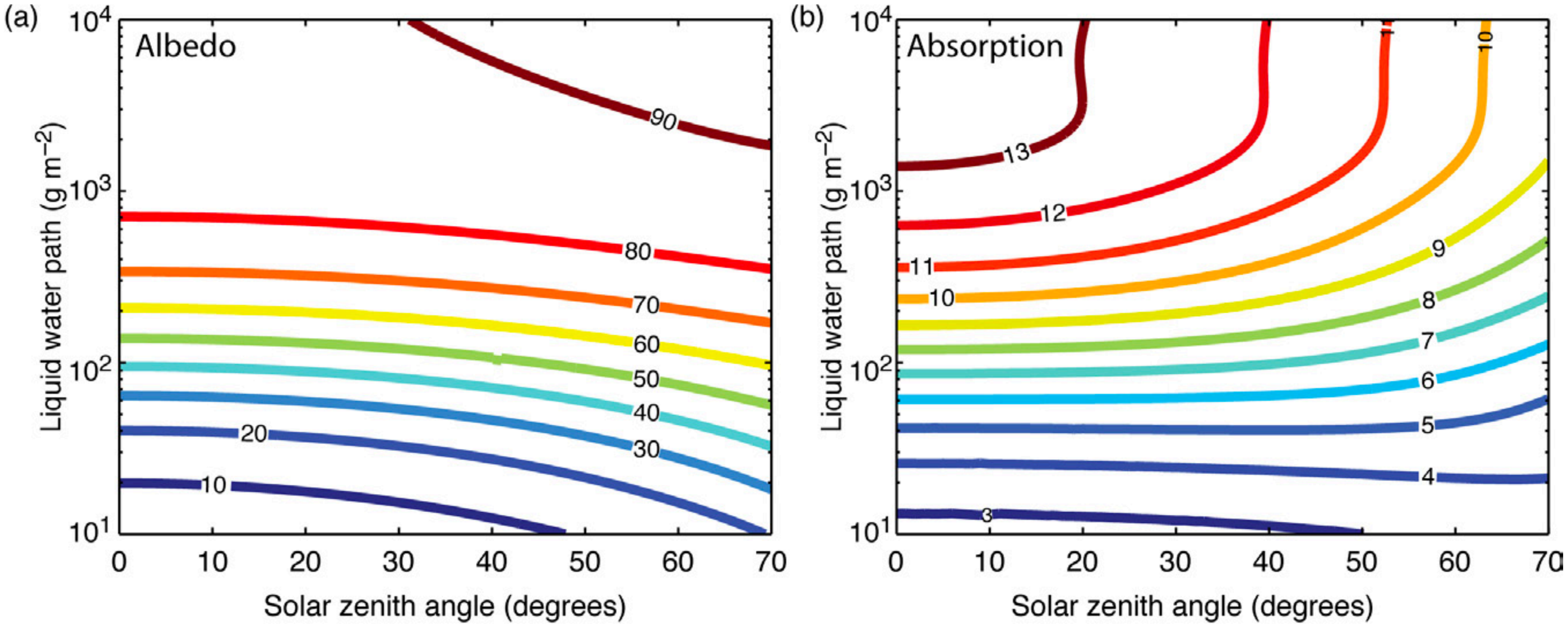
Cloud albedo sensitivity to LWP

Cloud absorption sensitivity to LWP



From space: **LWP increases cloud top brightness**

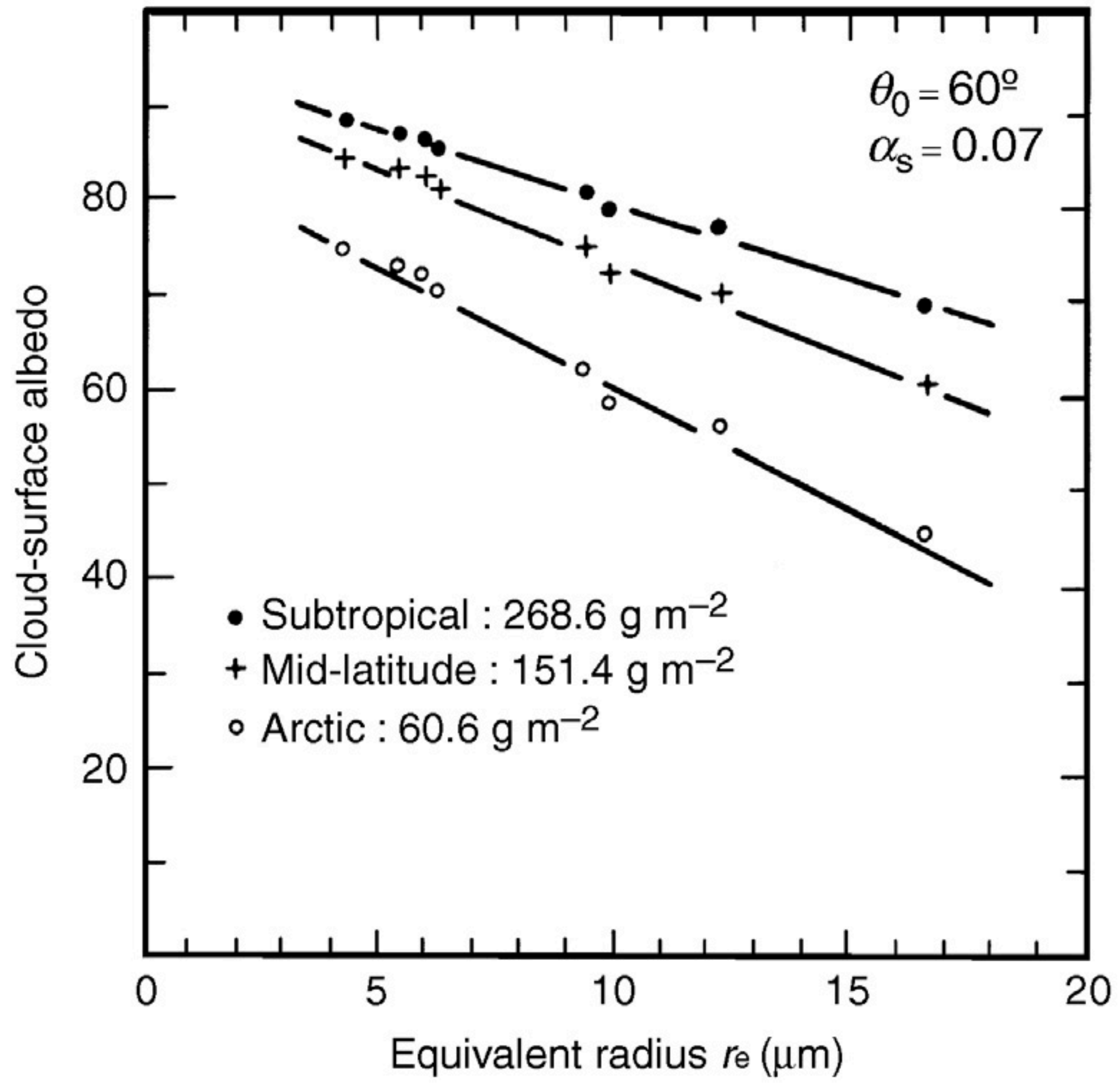
From the surface: **LWP increases cloud base darkness**

More reflection and less absorption with increasing zenith angle

Sensitivity to the droplet size $\overline{r}$

➡ Fixed liquid water content LWP

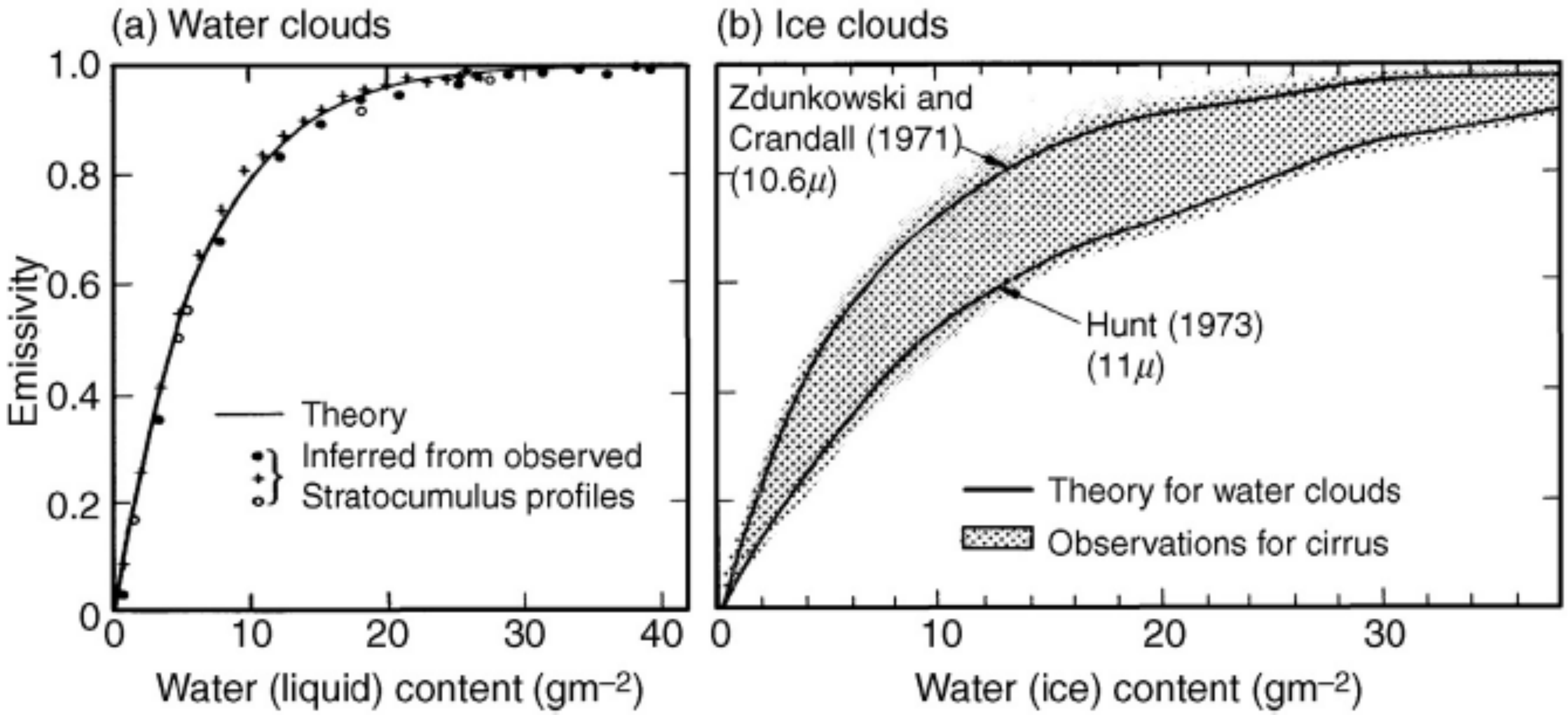
Cloud albedo



Smaller/more droplets increase cloud brightness

- Increased number of refractions at interfaces air/liquid

1.2.1 Cloud composition effects on the emitted Longwave radiation (LW)



Clouds are very efficient in absorbing/emitting LW (IR)

- ➡ As from ~ 20 g m^{-2} they are completely opaque to LW (IR)
- ➡ **Cloud surface ~ black body** (except cirrus)

Absoption and albedo are more sensitive to LWP

➡

Clouds are important greenhouse contributors !

- ➡ Especially elevated clouds (e.g cirrus)

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1.2.2 Cloud altitude effect: the Earth's radiative-convective equilibrium (RCE)

Equilibrium at TOA

$R^{net}_{TOA} = 0$

$$=$$

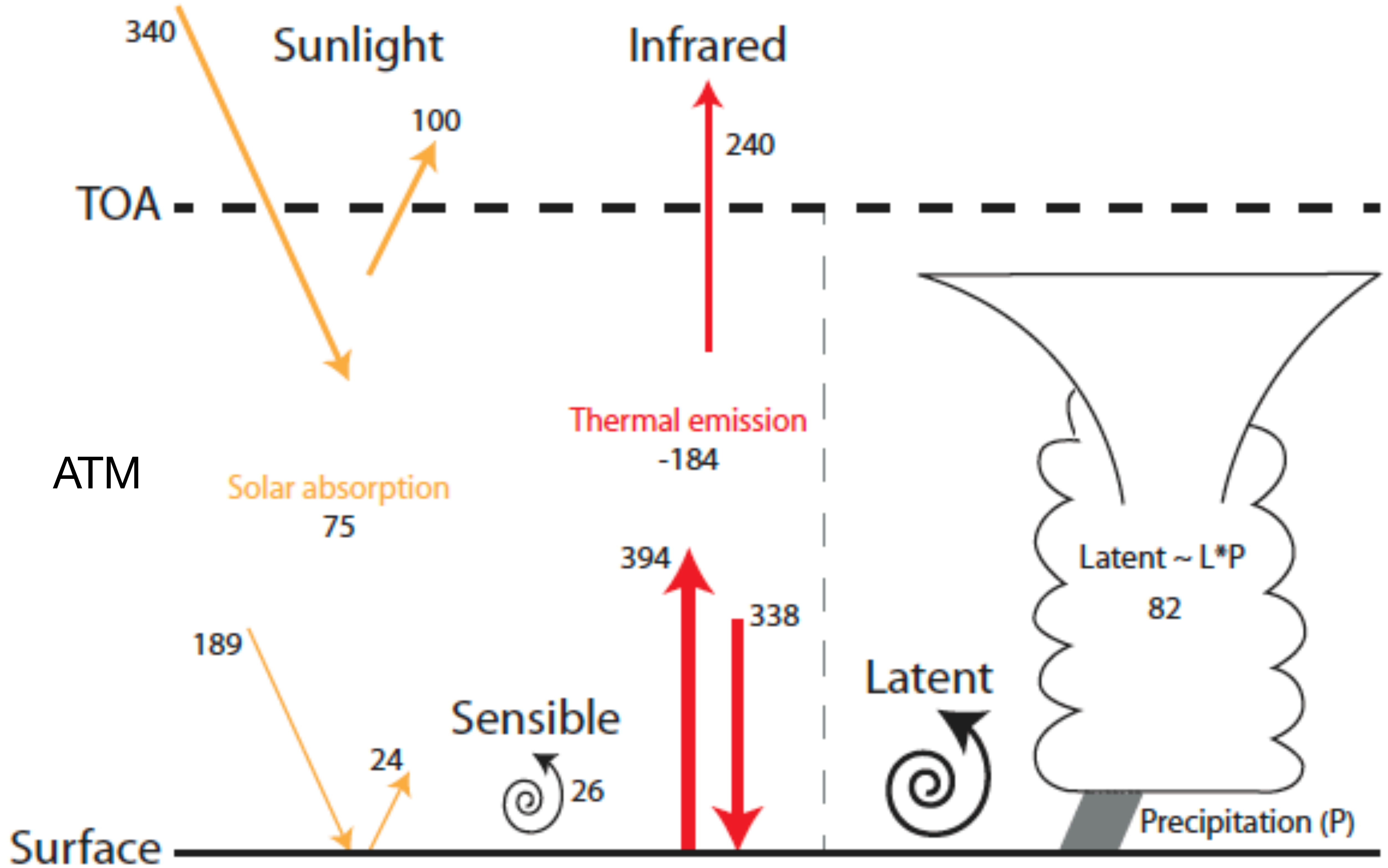
Net radiative cooling of the atmosphere

$R^{net}_{atm} = SW^{net}_{atm} + LW^{net}_{atm} = -\ 108\ \mathrm{W\ m^{-2}}$

$$+$$

Net radiative heating of the surface (land+oceans)

$R^{net}_{sfc} = SW^{net}_{sfc} + LW^{net}_{sfc} = +\ 108\ \mathrm{W\ m^{-2}}$



$F_{sens} = 26\ \mathrm{W\ m^{-2}}$ $F_{lat} = L_v P = 82\ \mathrm{W\ m^{-2}}$

Heat transfer surface → atmosphere by convection

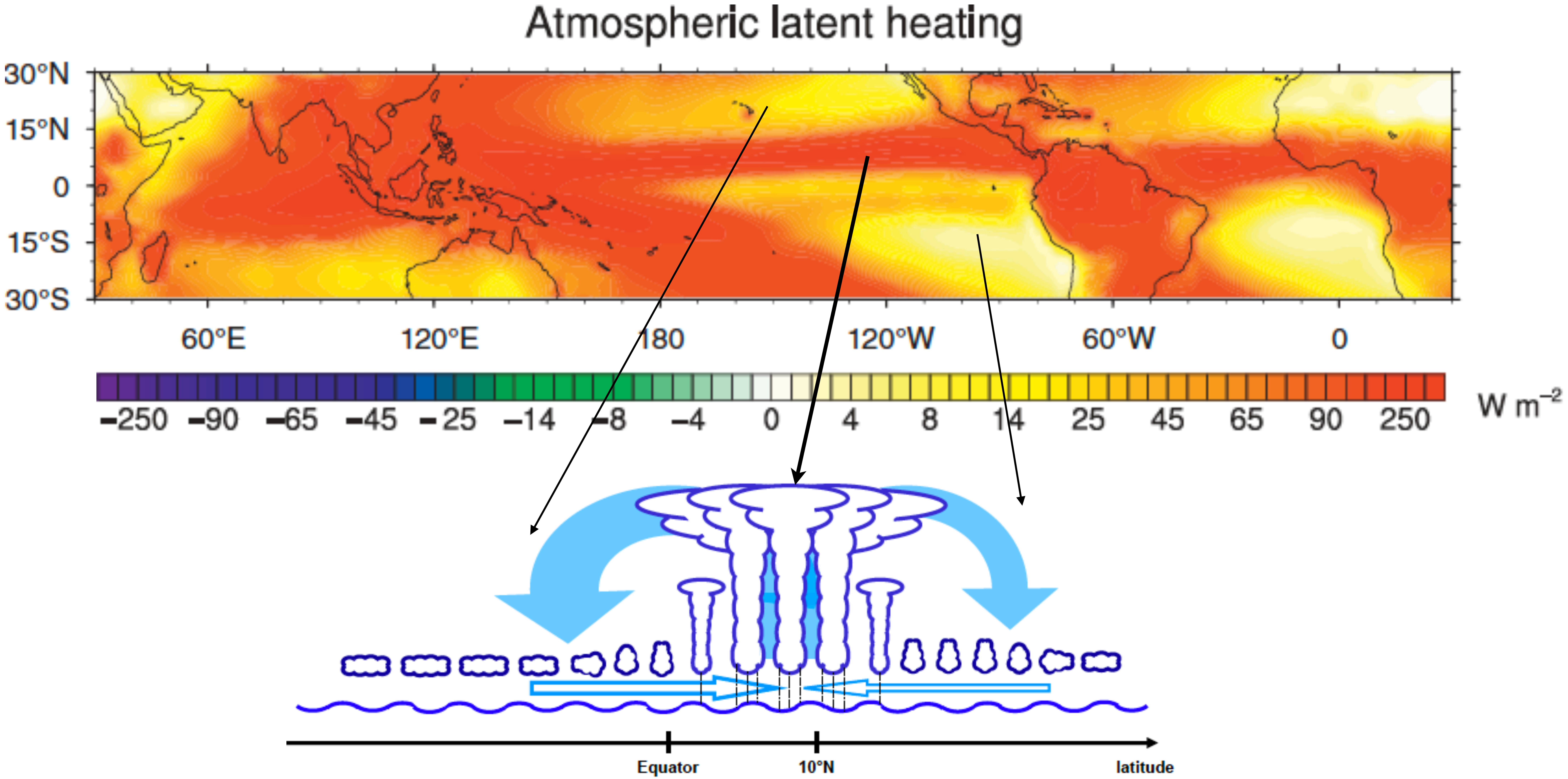
- Sensible heat $F_{sens} = 26$ W m^{-2}
- Latent heat (water cycle) $F_{lat} = L_v E = L_v P = 82$ W m^{-2}

Clouds heat the atmosphere by condensation/precipitation processes

➡ $\sim 80\,\%$ of the atmospheric heating !

Convection compensates radiative losses by the atmosphere

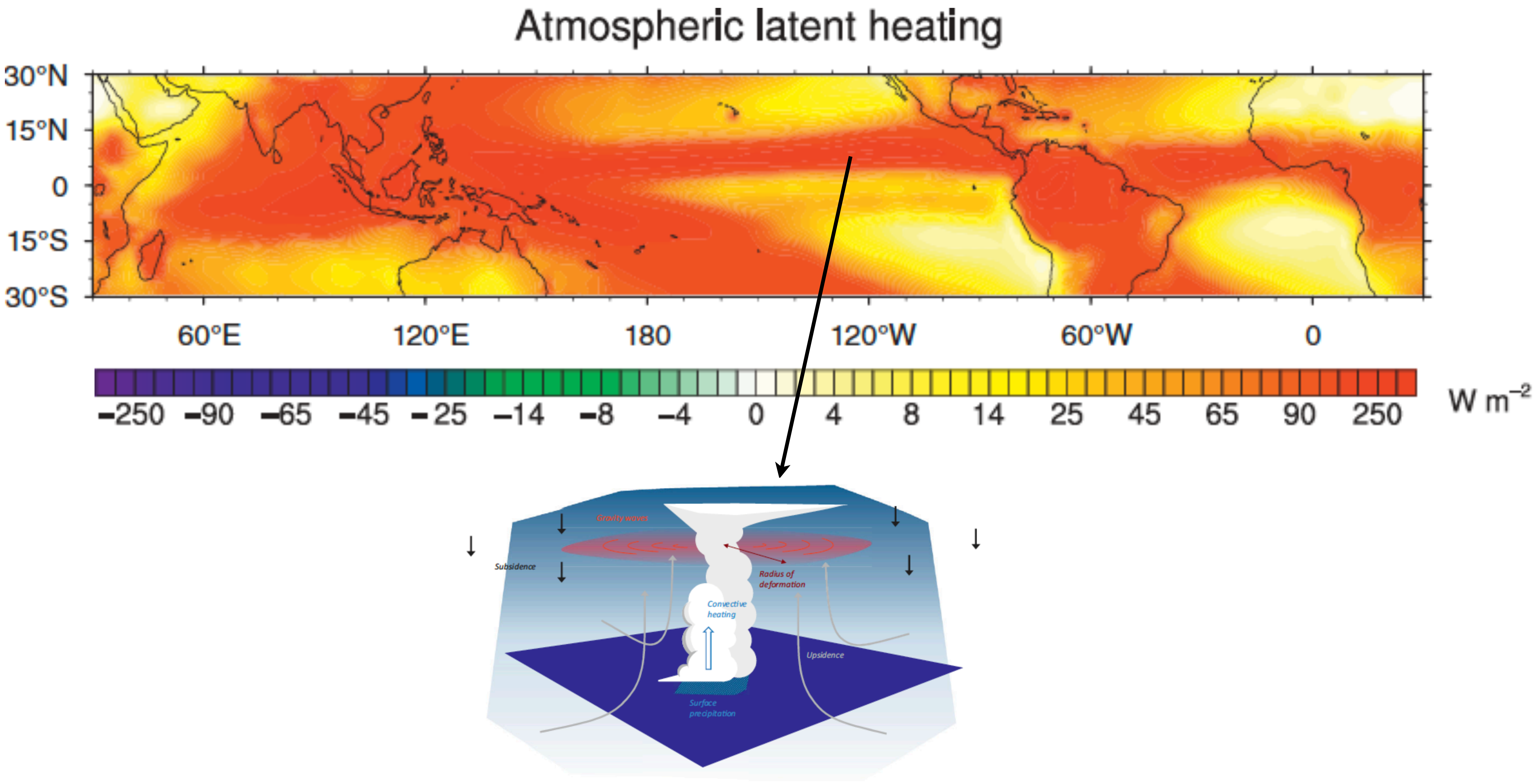
1.2.2 Latent heating effect on the circulation: large scale convergence and subsidence



Strong heating in deep clouds drives large scale ascendance and subsiding motions around cloud systems

➡ Mean Hadley-cell in the tropics

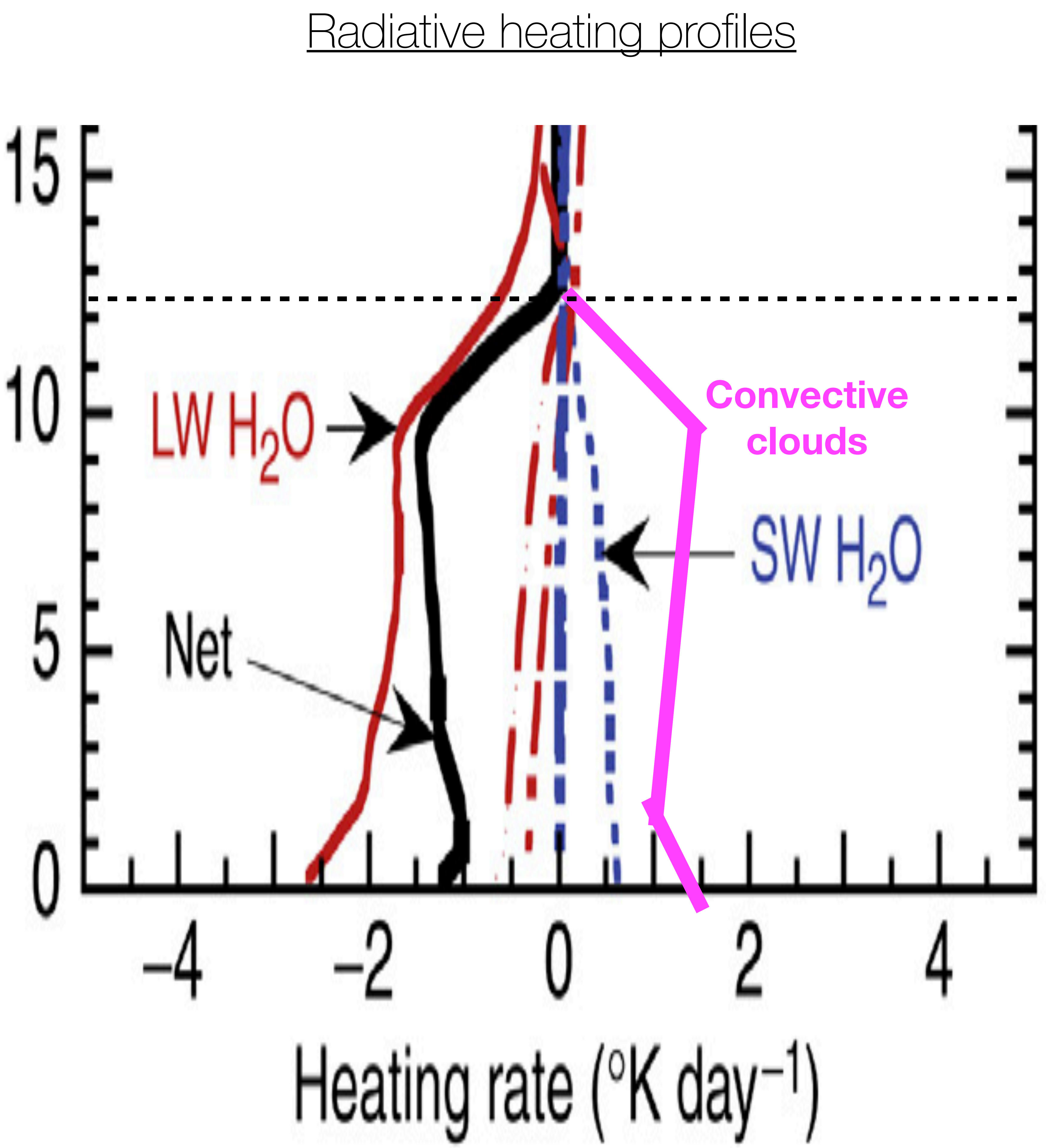
1.2.2 Latent heating effect on the circulation: wave disturbances

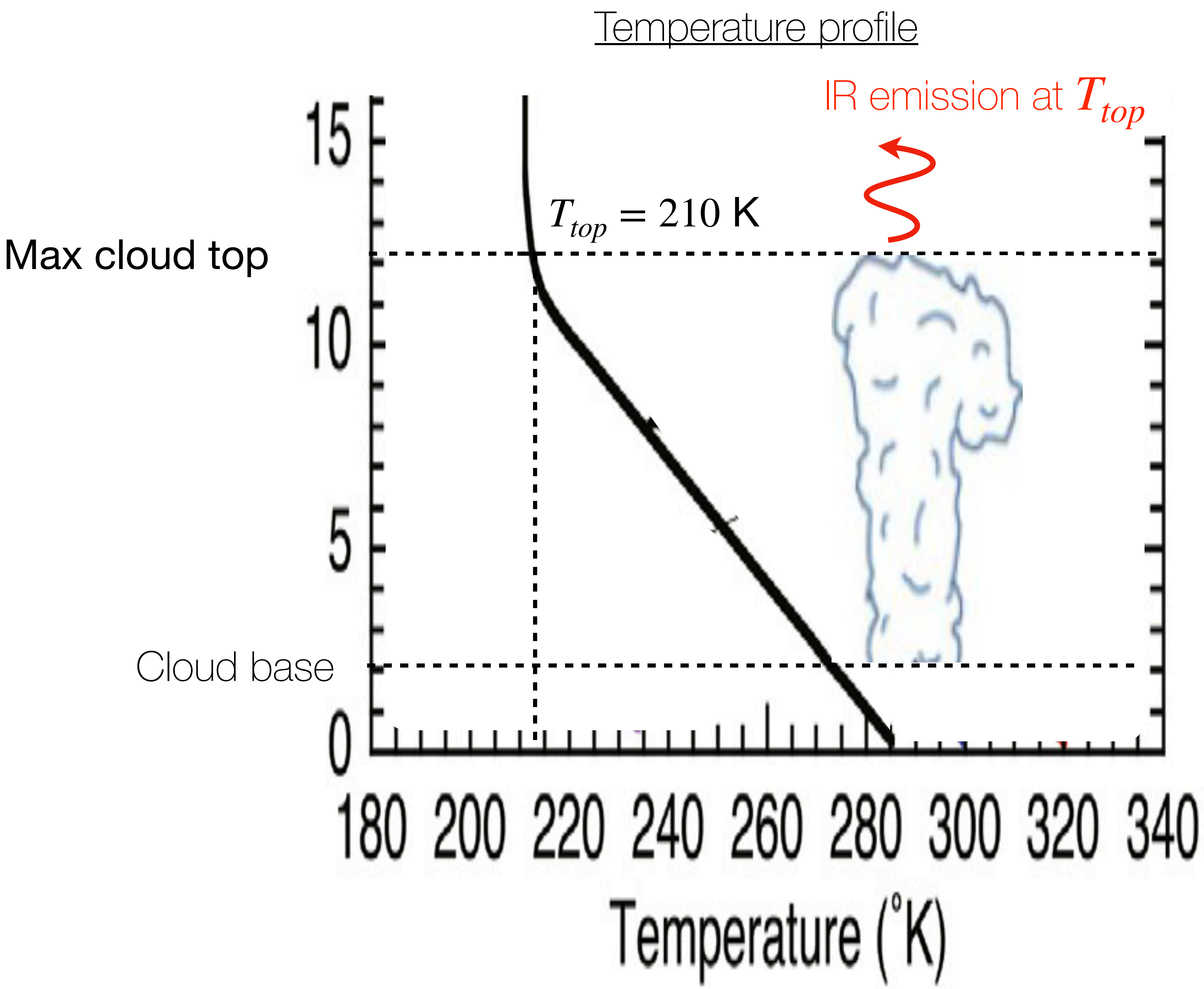


Strong heating in deep clouds trigger gravity waves in the free troposphere

➡ Smoothering of the temperature gradient in the free atmosphere in the tropics

1.2.2 Cloud altitude effect on the emitted Longwave radiation (LW)





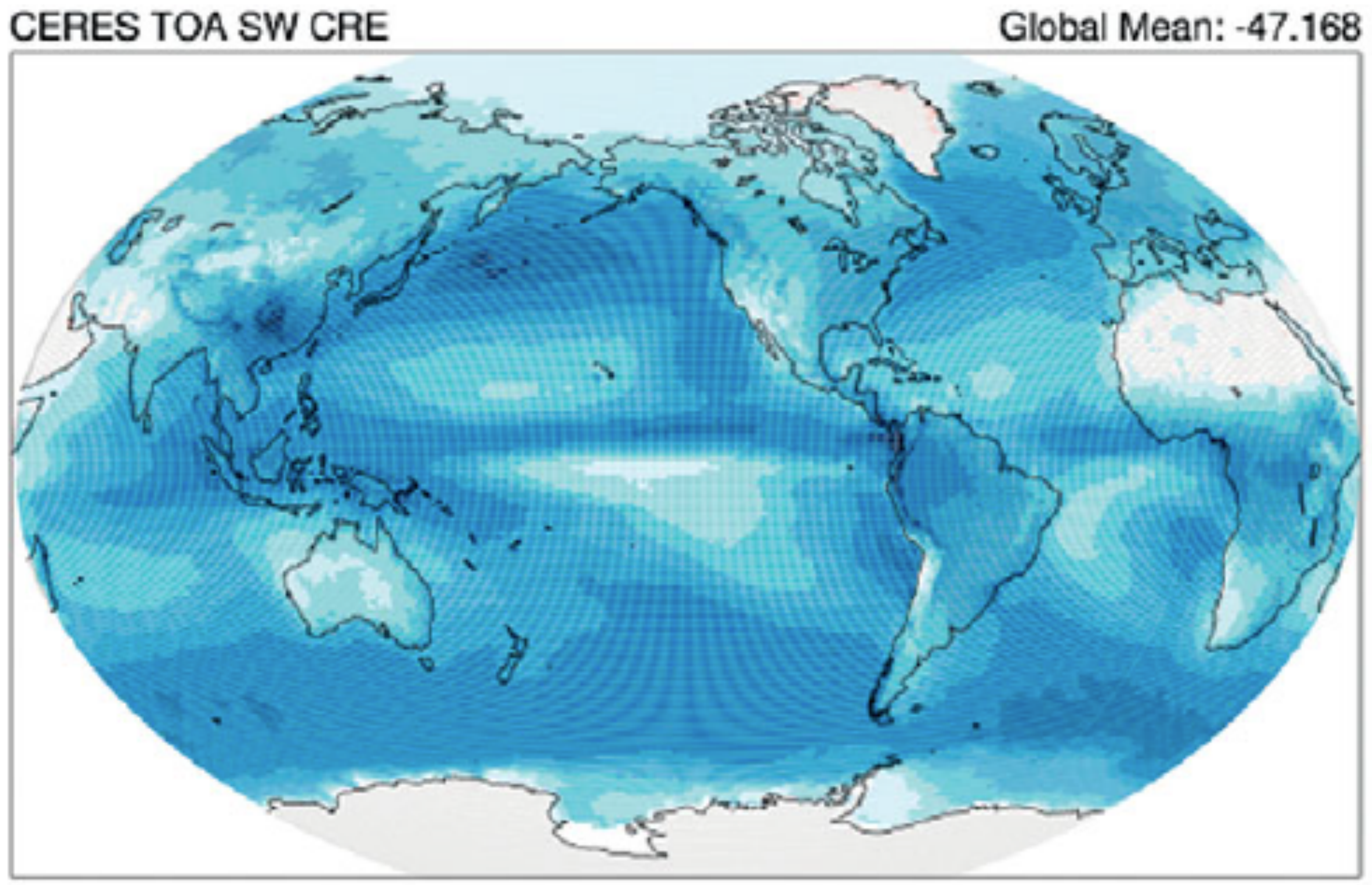
1. Water vapor vertical profile sets the radiative cooling rate profile
2. The radiative cooling profile sets the convective heating profile
3. The convective heating profile sets the cloud top altitude
4. The cloud top altitude sets the IR emission at cloud top

Ultimately, T_{top} (deep clouds) is strongly constrained by T_{surf} through water vapor (Clausius-Clapeyron)

Part 1 - Clouds are full components of the general circulation

1.2.3 Cloud Radiative Effet: CRE at the Top of the Atmosphere (TOA)

ShortWave (SW) CRE at TOA



Bright clouds scatter/reflect sunlight

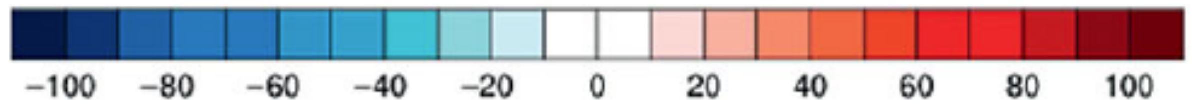
➡ Earth cooling ~ 47 W m^{-2}

Global cloud albedo effect

$\sim +15\,\%$

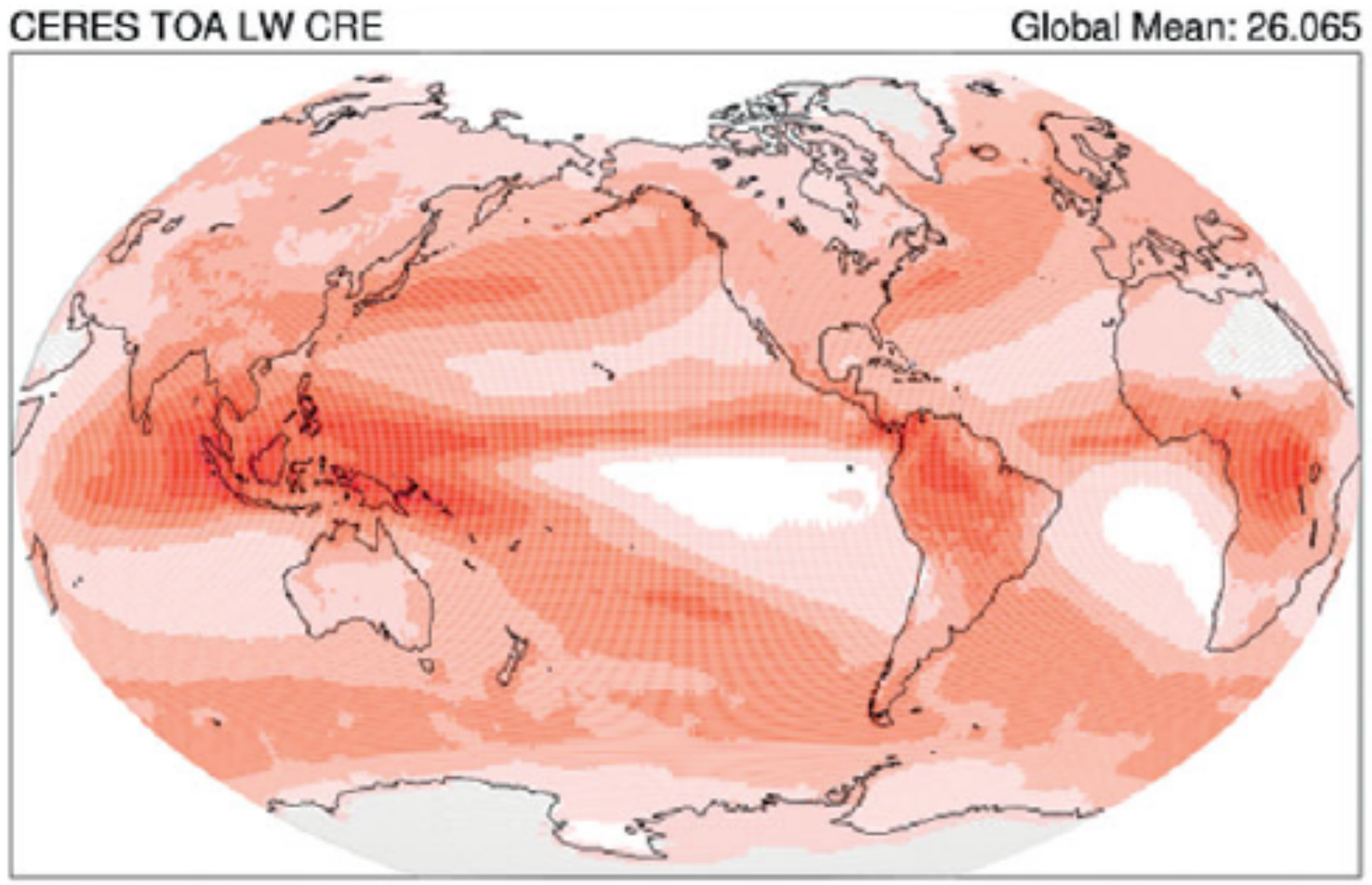
$$CRE = F^{net}_{allsky} - F^{net}_{clear}$$

with (T_s, q) constants



W m^{-2}

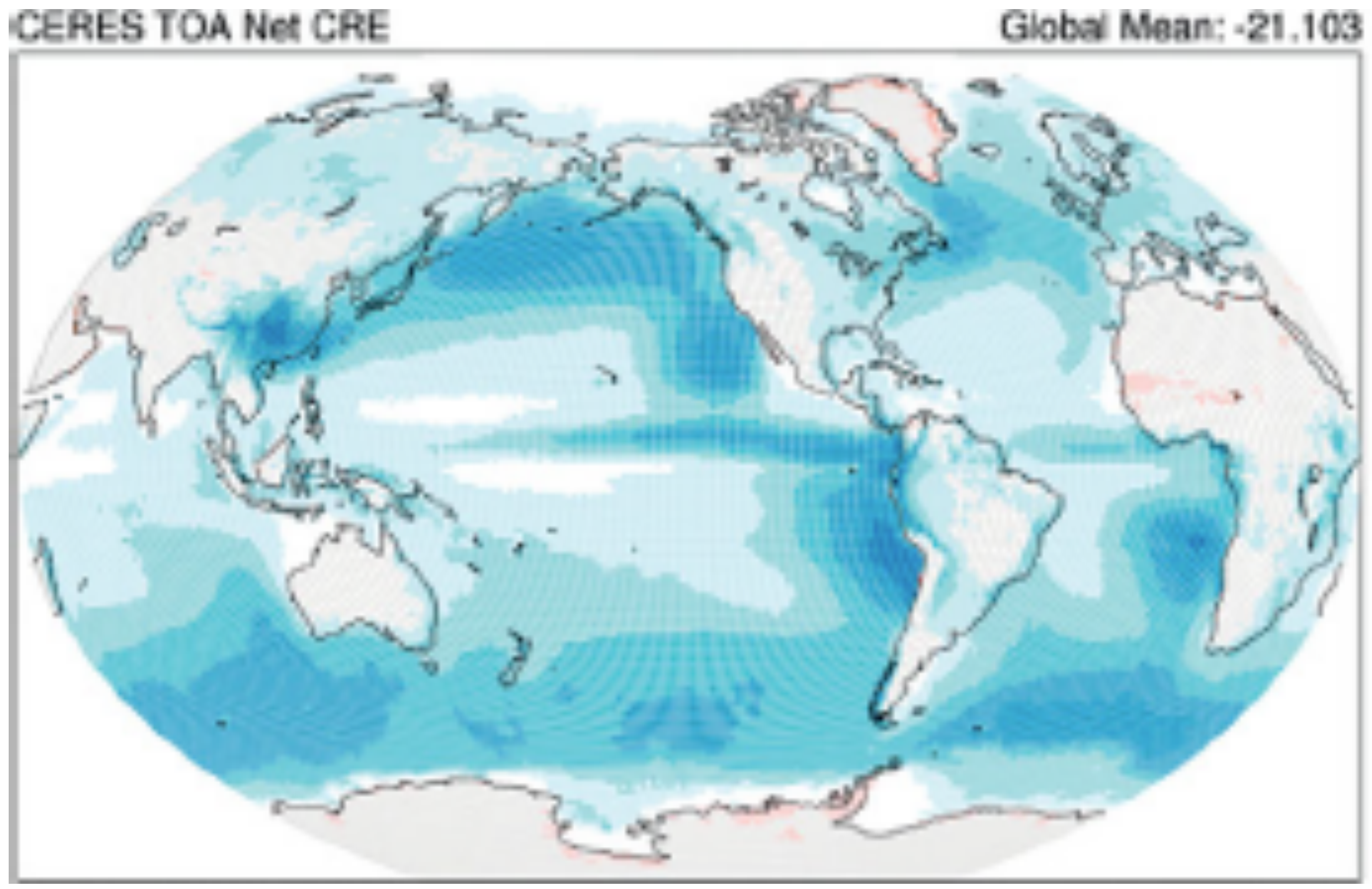
LongWave (LW) CRE at TOA



Clouds absorb/emit LW (IR) upward and downward

➡ Earth warming ~ 26 W m^{-2}

Total CRE at TOA



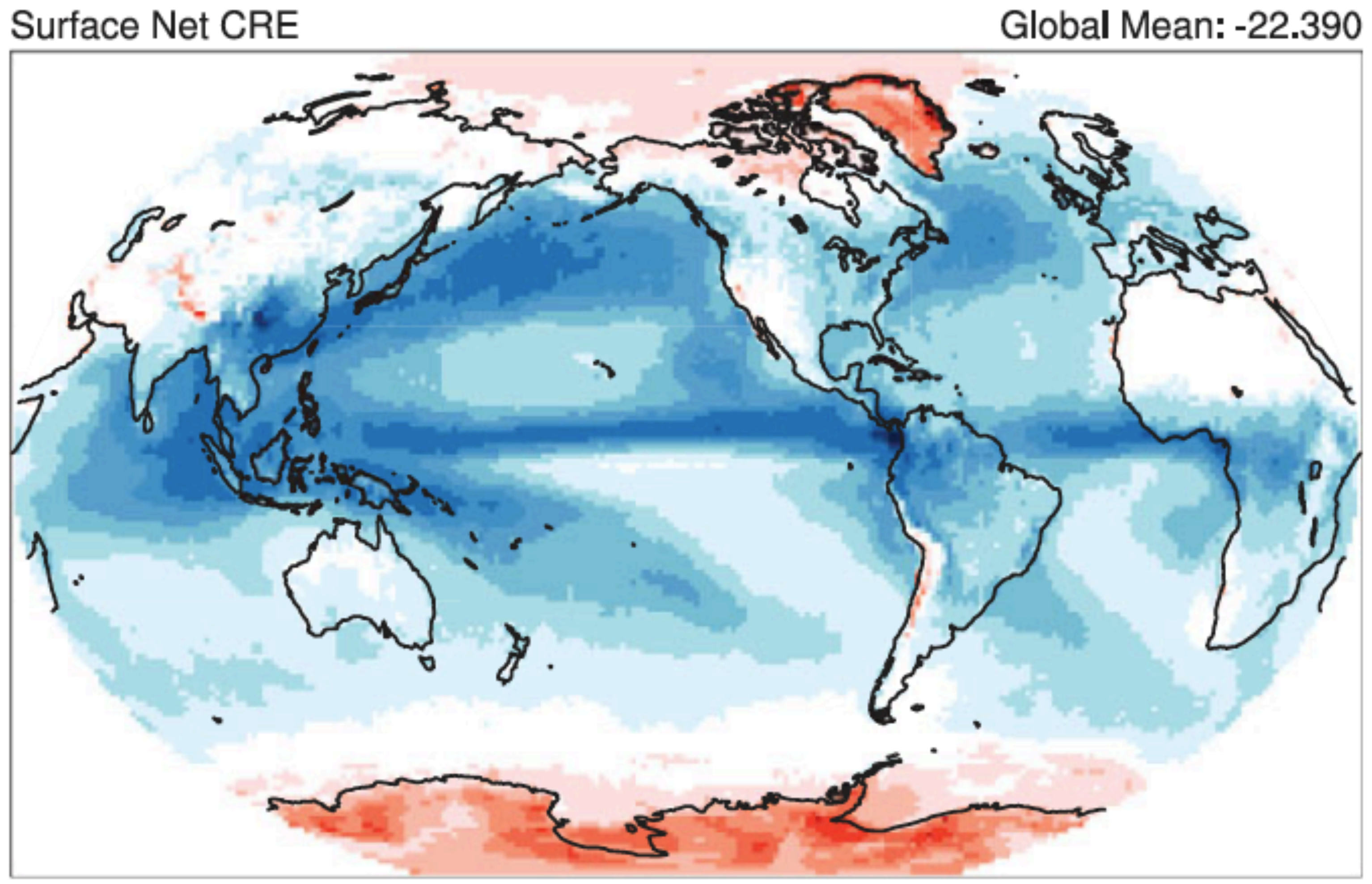
Overall cooling of the Earth ~ 21 W m^{-2}

Cloud and Earth Radiant Energy System

CERES (started in 2000)

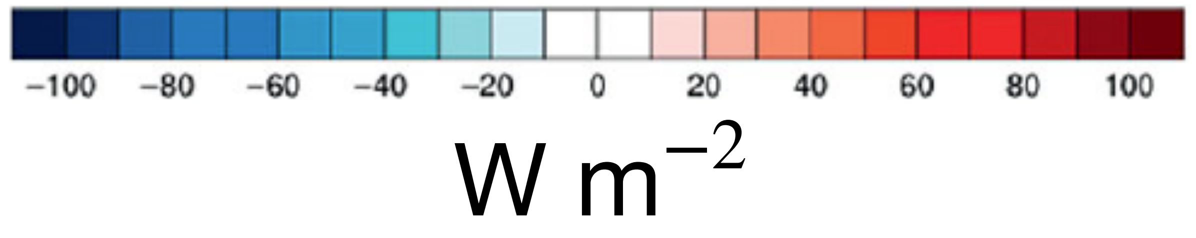
1.2.3 Cloud Radiative Effet: CRE in the atmosphere and at the surface

Surface CRE

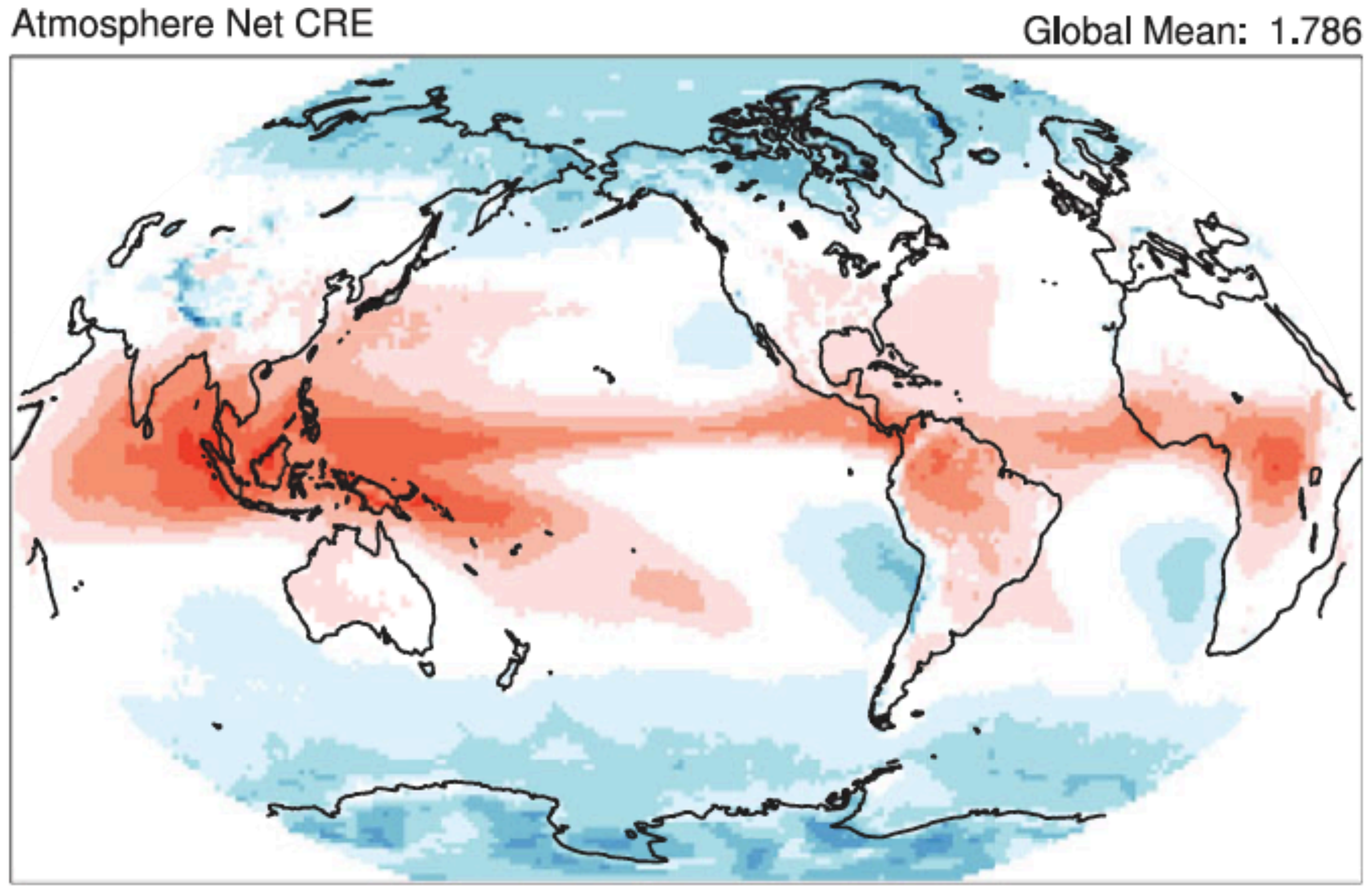


$$CRE = F^{net}_{allsky} - F^{net}_{clear}$$

with (T_s, q) constants



Atmosphere CRE



Clouds reduce incoming SW

Clouds increase downwelling LW

➡ Surface cooling by ~ 22 W m^{-2}

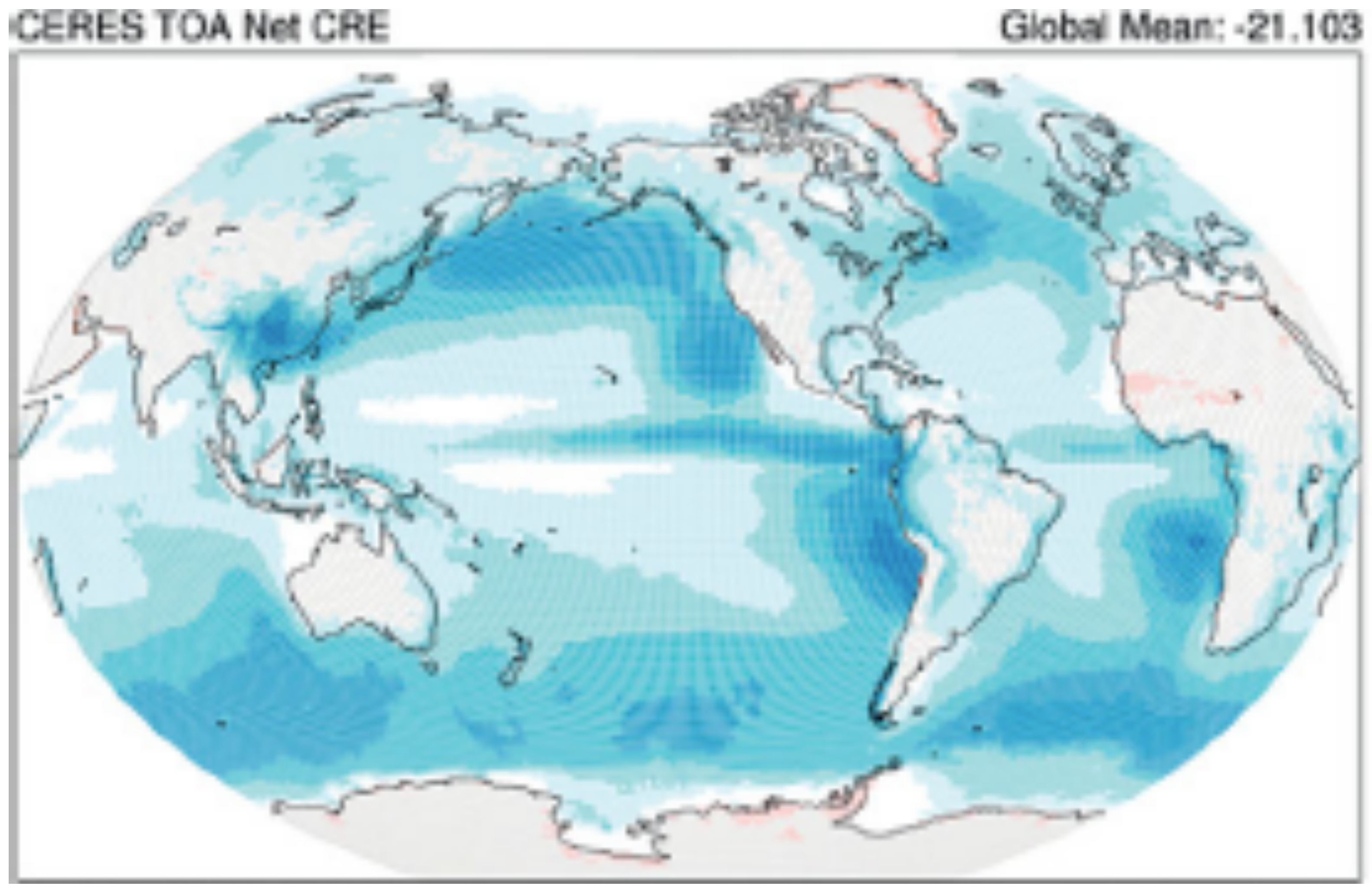
Clouds reduce SW absorption by water vapor

Clouds increase LW heating in the upper levels

Clouds decrease LW heating in the low-levels

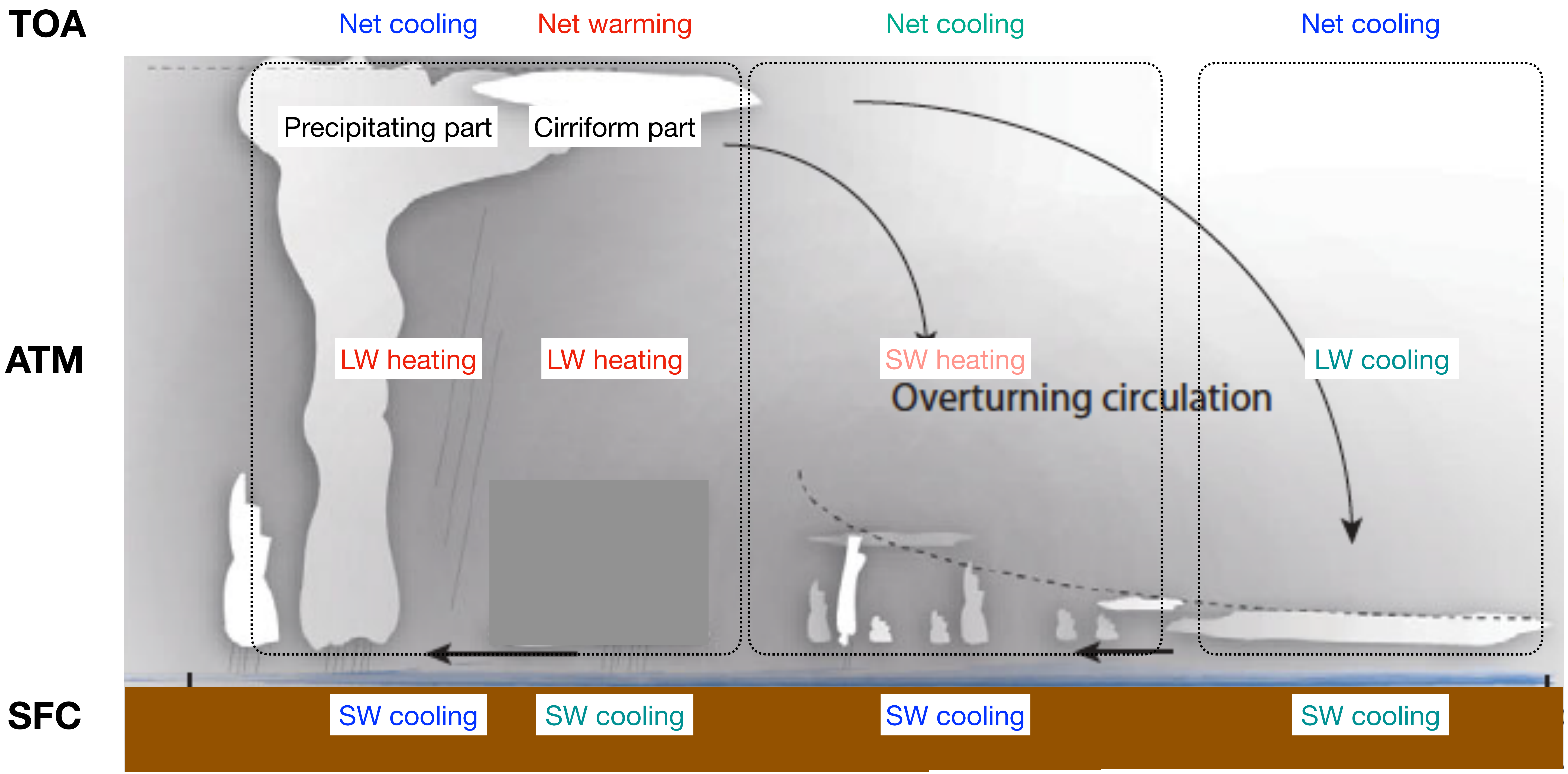
➡ Atmosphere warming ~ 1 W m^{-2}

Total CRE at TOA



Overall cooling of the Earth ~ 21 W m^{-2}

1.2.3 CRE effect on the circulation: modulation of surface fluxes and temperature profile



Deep clouds

$\Longrightarrow \text{CRE}_{Cb}^{TOA} \sim 0\ \text{W m}^{-2}$

Cumulus

$\Longrightarrow \text{CRE}_{Cu}^{TOA} \sim -15\ \text{W m}^{-2}$

Strato-Cumulus

$\Longrightarrow \text{CRE}_{Sc}^{TOA} \sim -50\ \text{W m}^{-2}$

TOA

Net cooling

Net warming

Net cooling

Net cooling

Precipitating part

Cirriform part

ATM

LW heating

LW heating

SW heating

LW cooling

SFC

SW cooling

SW cooling

SW cooling

SW cooling

1. At the surface, CRE modulate the atmosphere/surface energy imbalance → CRE control on surface fluxes
2. In the atmopshere, CRE modulate the rad-cooling profile → CRE control on temperature profile

CRE control on convective motions (i.e vertical transport of heat, momentum, water and mass)

Part 1 - Clouds are full components of the general circulation

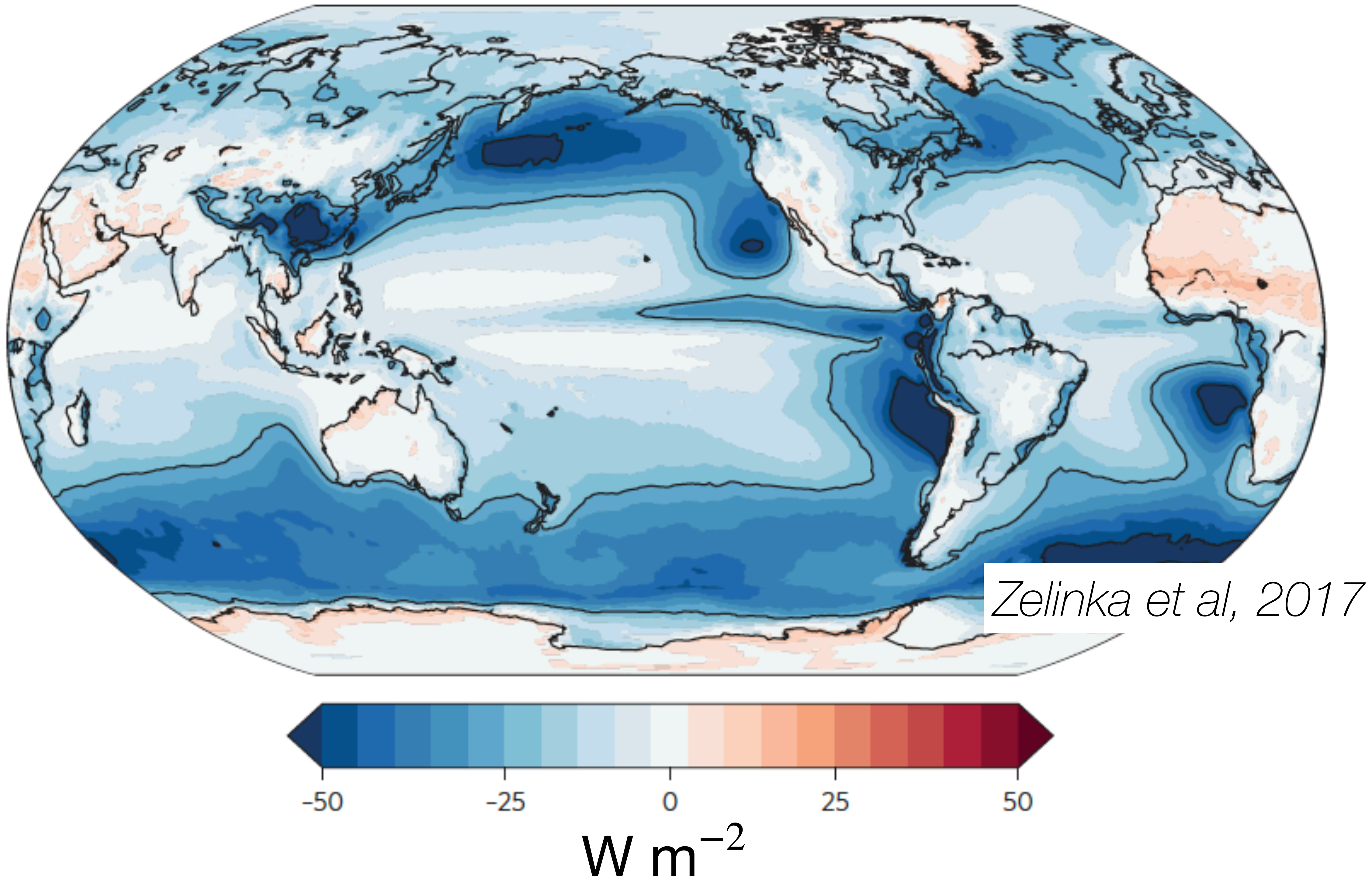
1.3 Sum up

From CRE to cloud feedback λ_c

Obseved present climate (observations)

$$CRE = -21 \text{ W m}^{-2}$$

Net CRE at TOA

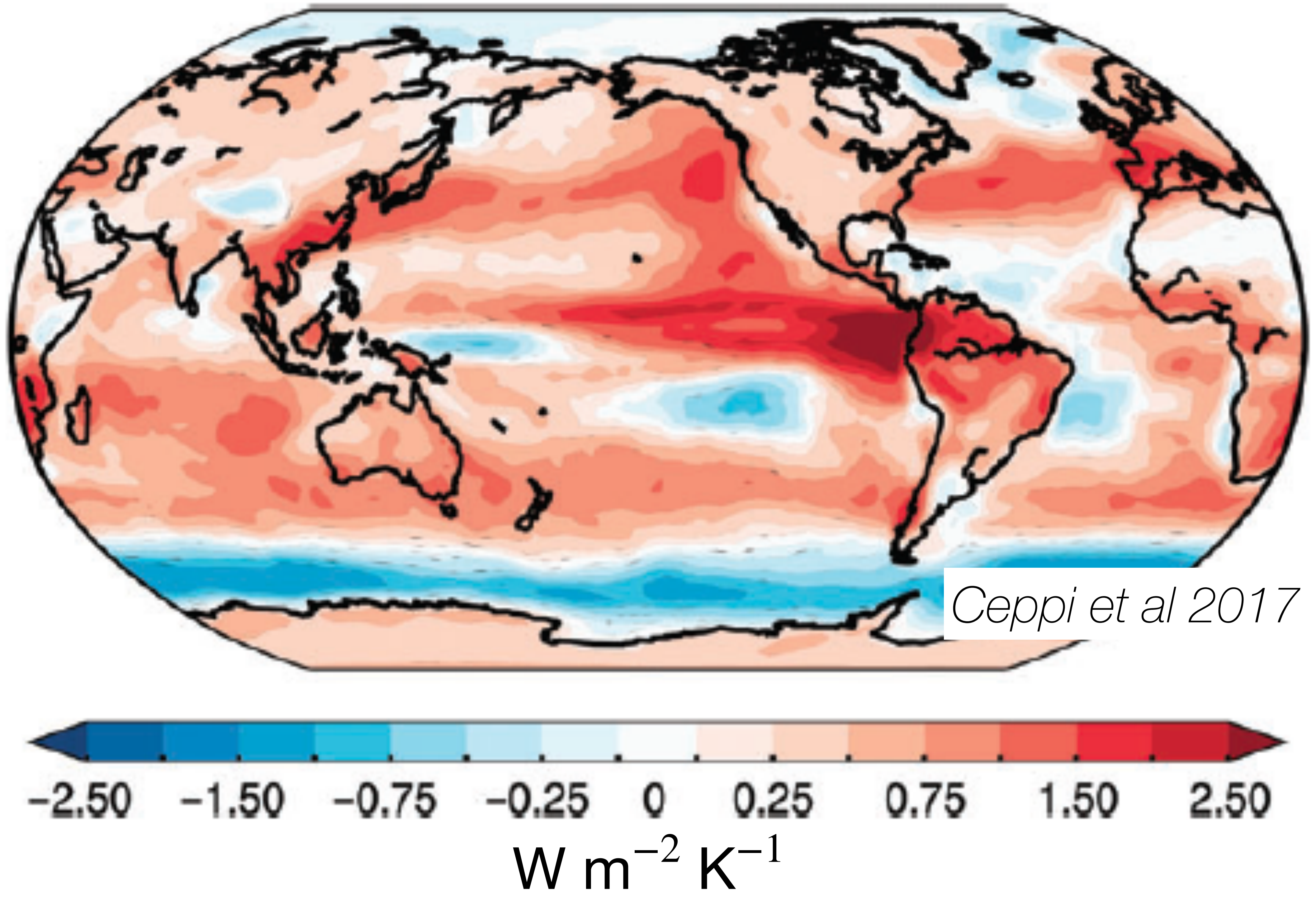


Zelinka et al, 2017

Projected future climate (models)

$$\lambda_c = \frac{dCRE}{dT_s} = +0.42[-0.1 : 0.94] \text{ W m}^{-2} \text{ K}^{-1}$$

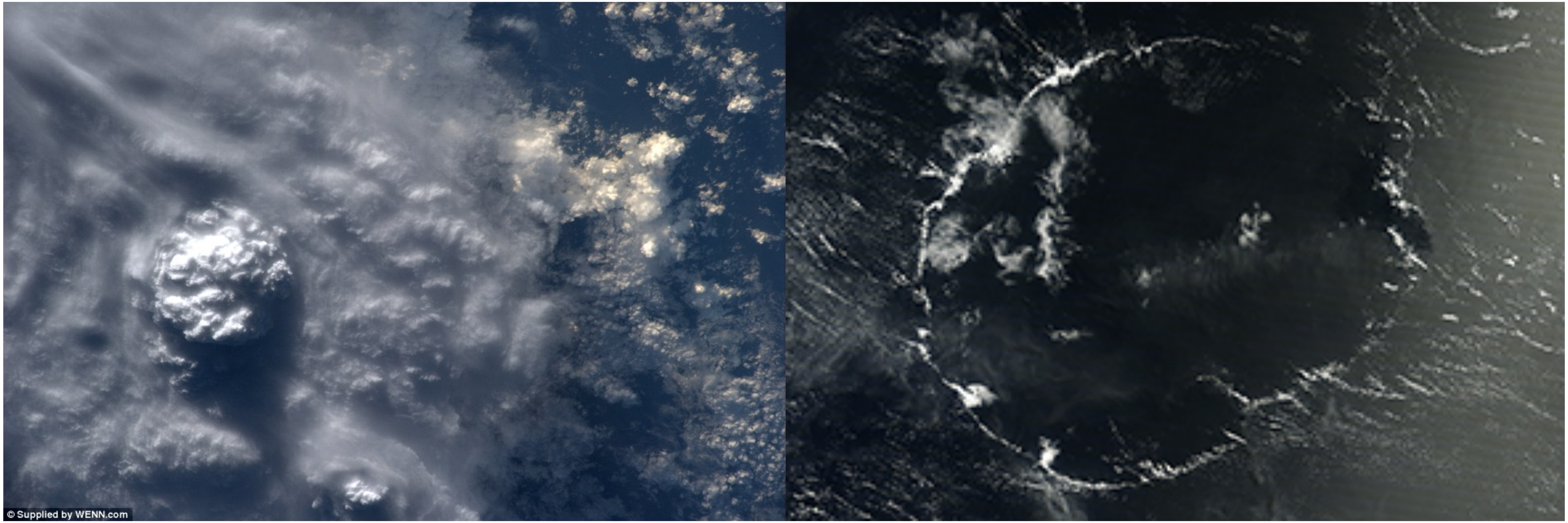
Multimodel mean net cloud feedback computed from 18 climate models



Ceppi et al 2017

Hard to interpret $\Longrightarrow$ necessity to decompose cloud feedbacks by cloud types, by regimes, SW, LW, etc …

Part 2 - Clouds in a changing climate



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Part 2 - Clouds in a changing climate

IPCC, AR6 (2021)

Feedback	AR5	AR6
High-cloud altitude feedback	Positive (*high confidence*)	Positive (*high confidence*)
Tropical high-cloud amount feedback	N/A	Negative (*low confidence*)
Subtropical marine low-cloud feedback	N/A (*low confidence*)	Positive (*high confidence*)
Land cloud feedback	N/A	Positive (*low confidence*)
Mid-latitude cloud amount feedback	Positive (*medium confidence*)	Positive (*medium confidence*)
Extratropical cloud optical depth feedback	N/A	Small negative (*medium confidence*)
Arctic cloud feedback	Small positive (*very low confidence*)	Small positive (*low confidence*)
Net cloud feedback	Positive (*medium confidence*)	Positive (*high confidence*)

Feedback assessment by

Cloud regimes

- Tropical deep clouds
- Sub-tropical shallow clouds
- Mid-latitude clouds
- Polar clouds

Cloud key characteristics

- Cloud amount (fraction)
- Cloud thickness
- Cloud altitude

Combination of obs., high-res. models and climate models led to

Significant progresses

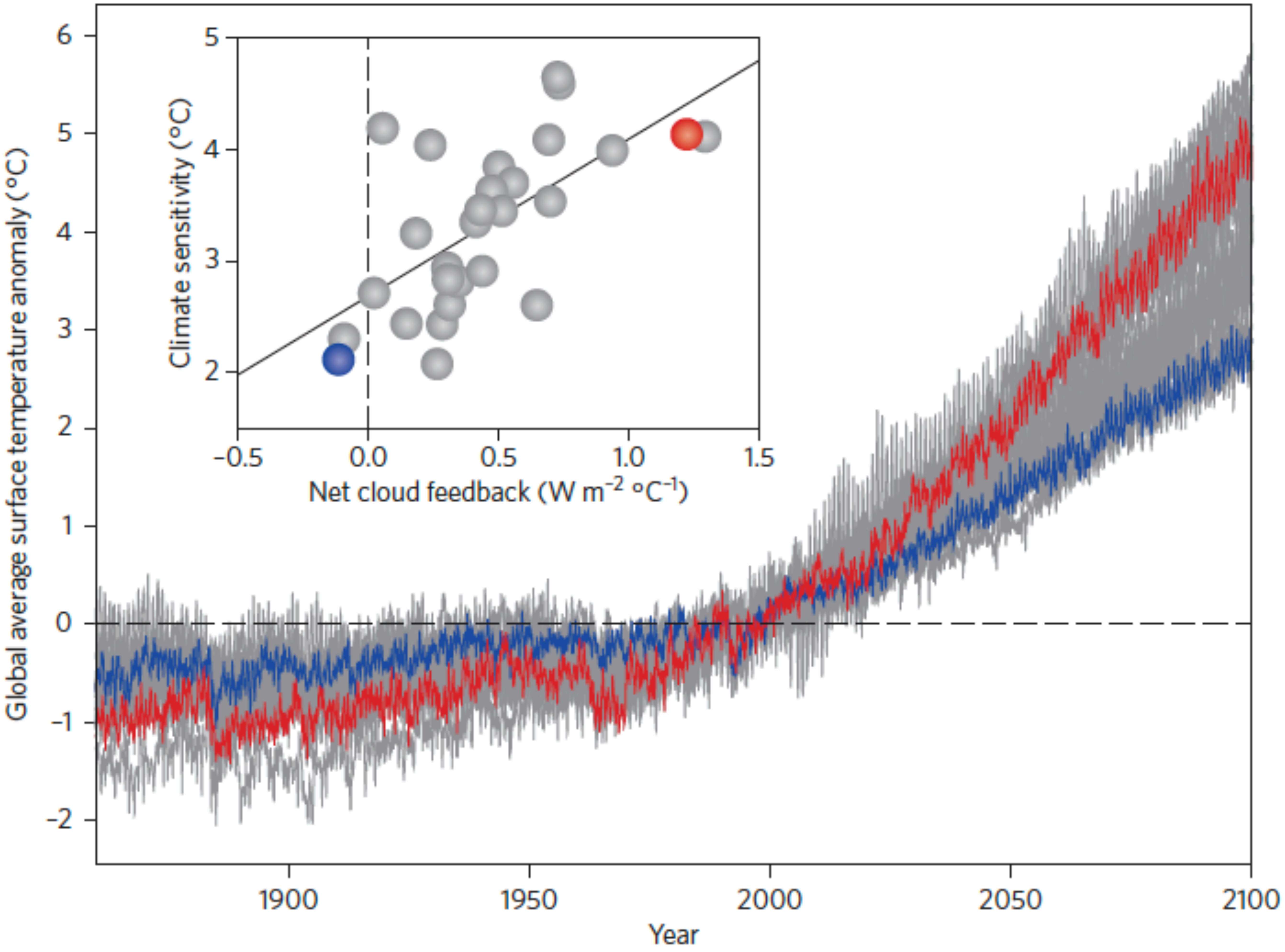
- Marine low-clouds
- Mid-latitude cloud fraction

Although some uncertainties

- Arctic clouds
- Tropical anvil fraction

Part 2 - Clouds in a changing climate

Zelinka et al., (2017)



In a large part, cloud feedbacks discrimate models with low-sensitivity from models with high-sensitivity

Part 2 - Clouds in a changing climate

+ Positive feedback

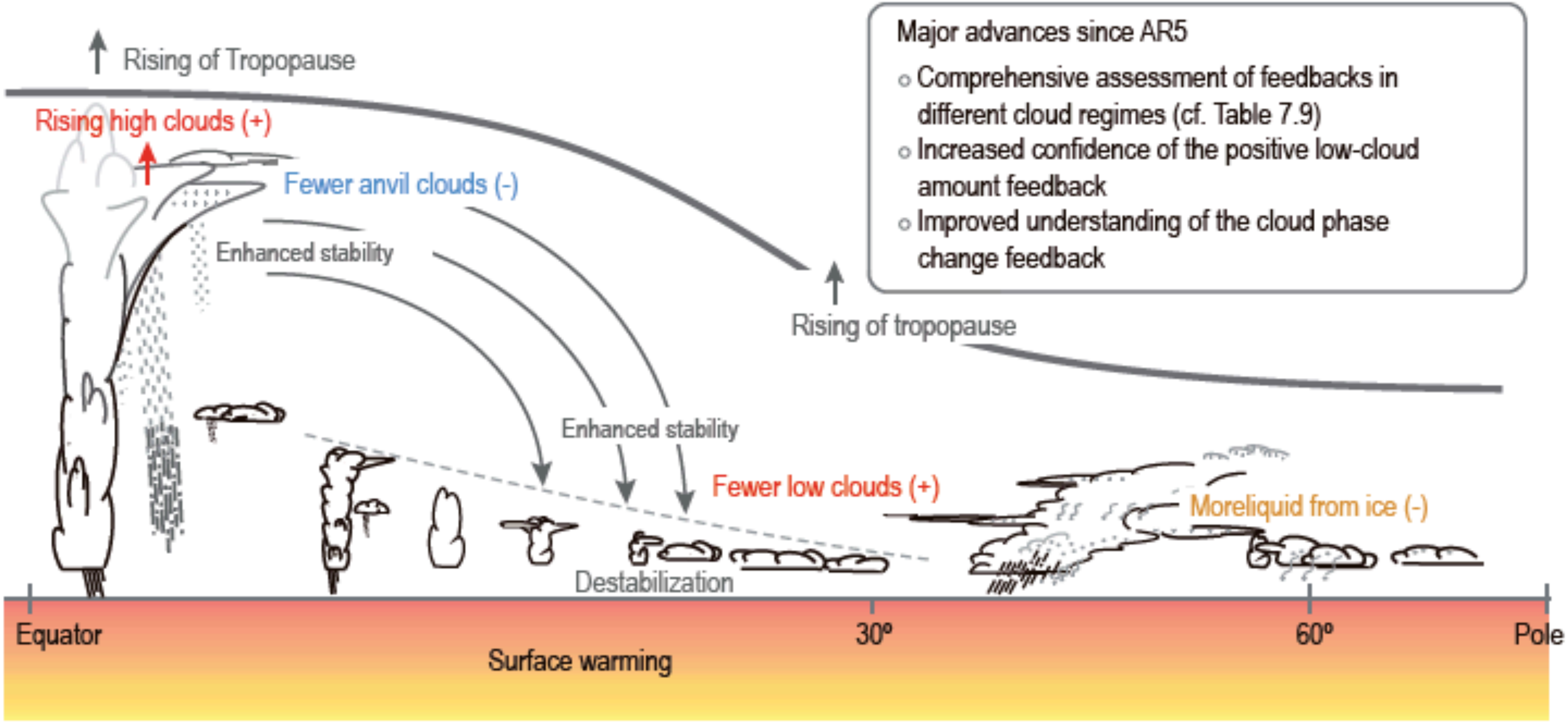
— Negative feedback

🟥 High confidence

🟧 Medium confidence

🟦 Low confidence

IPCC, AR6 (2021)



Major advances since AR5

- ○ Comprehensive assessment of feedbacks in different cloud regimes (cf. Table 7.9)
- ○ Increased confidence of the positive low-cloud amount feedback
- ○ Improved understanding of the cloud phase change feedback

Part 2 - Clouds in a changing climate

2.1 Tropical high clouds altitude feedback
2.2 Tropical high clouds amount feedback
2.3 Tropical low clouds feedback
2.4 Midlatitude cloud amount feedback
2.5 Extratropical cloud optical depth feedback
2.6 Sum up

Part 2 - Clouds in a changing climate

2.1 Tropical high clouds altitude feedback

2.2 Tropical high clouds amount feedback

2.3 Tropical low clouds feedback

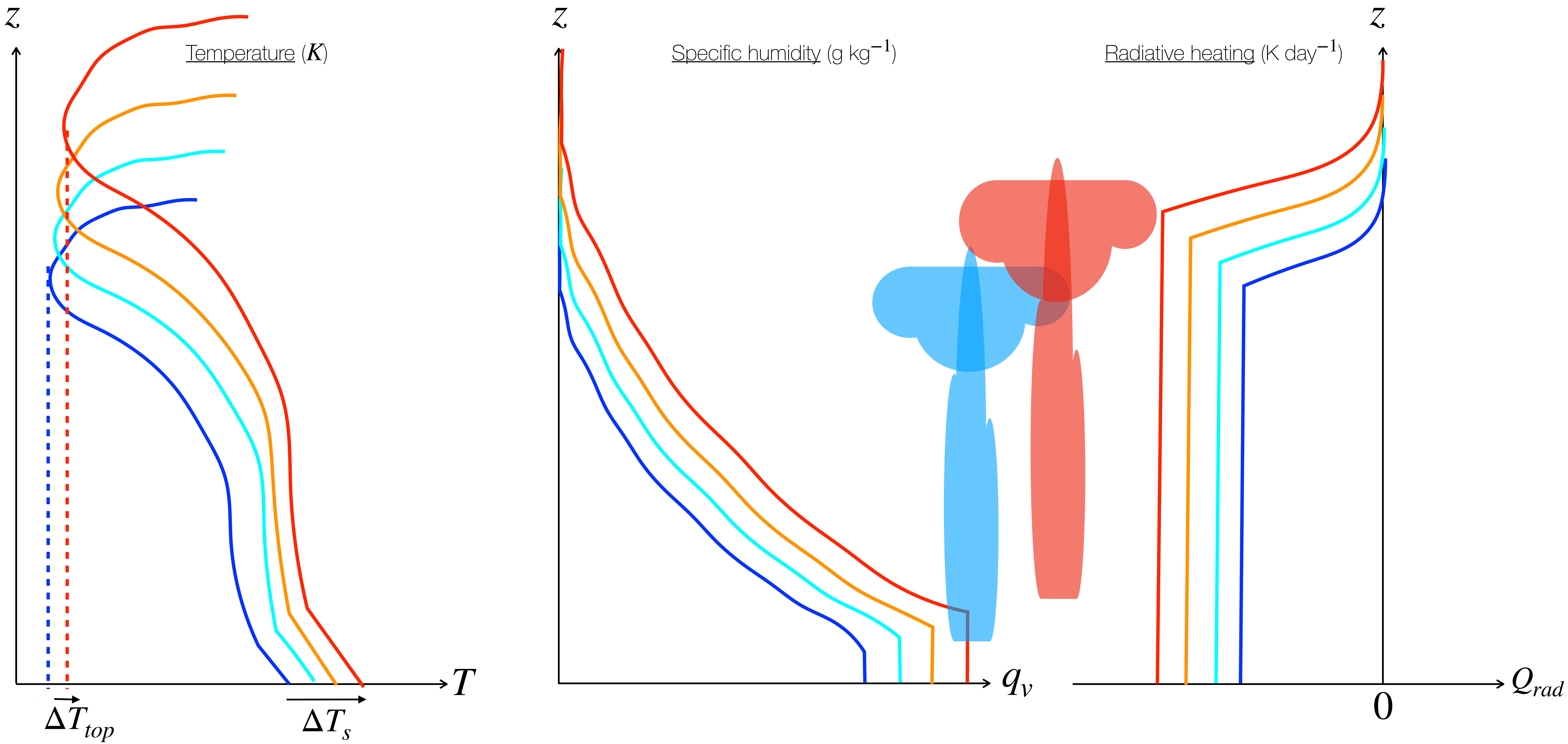
2.4 Midlatitude cloud amount feedback

2.5 Extratropical cloud optical depth feedback

2.6 Sum up

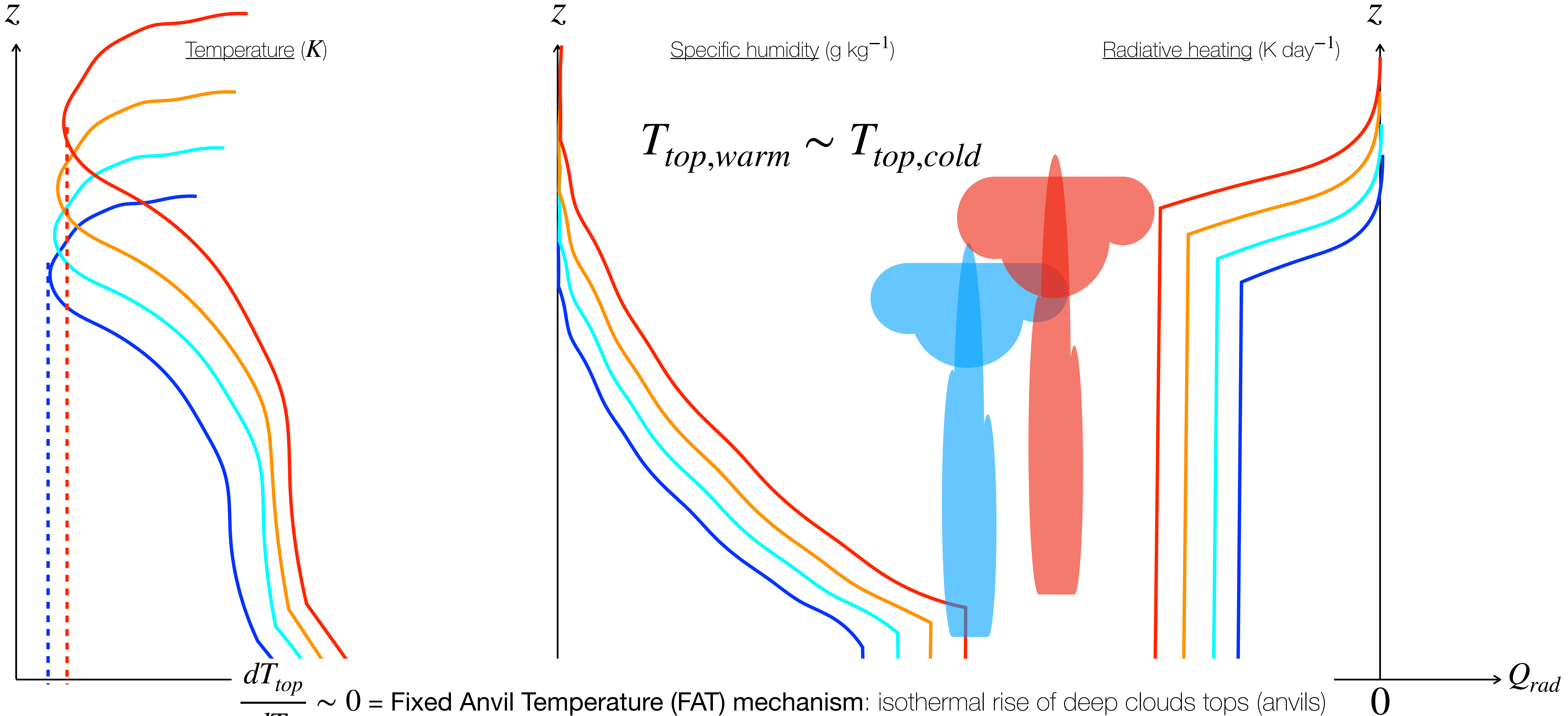
2.1 Tropical high cloud altitude feedback: clear sky control on deep clouds

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}



2.1 Tropical high cloud altitude feedback: FAT mechanism

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}



$\frac{dT_{top}}{dT_s} \sim 0$ = **Fixed Anvil Temperature (FAT) mechanism**: isothermal rise of deep clouds tops (anvils)

$\Longrightarrow$ **Positive Feedback**: cloud IR emission remains nearly unchanged with warming

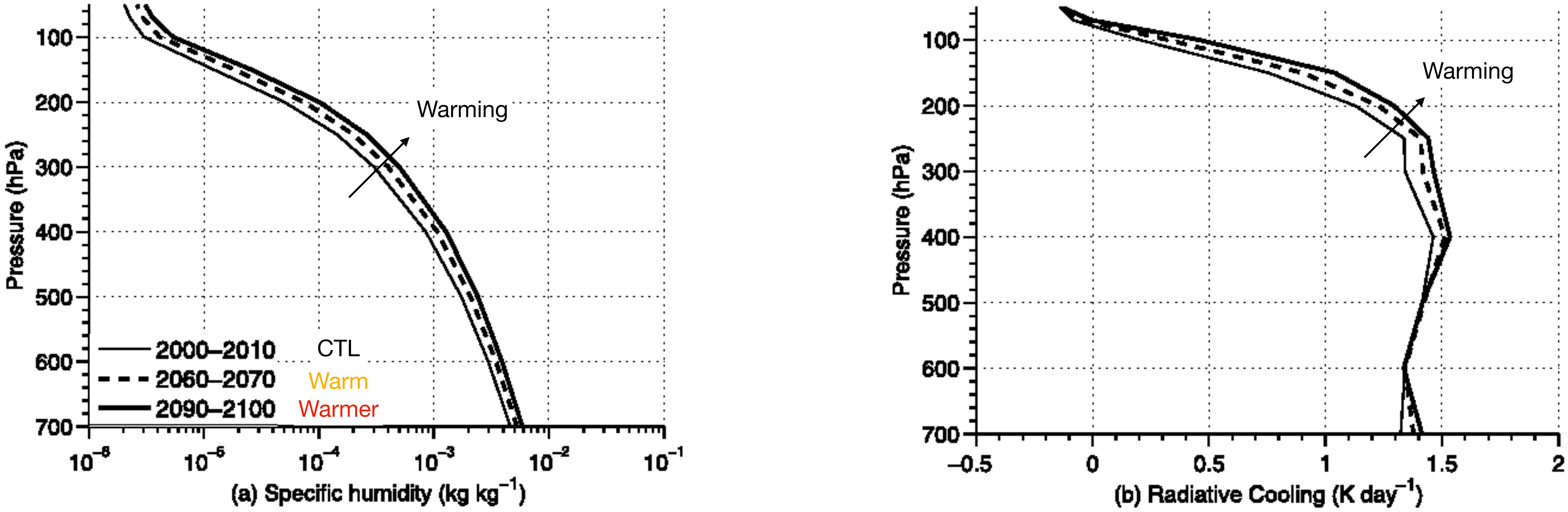
2.1 Tropical high cloud altitude feedback: clear sky control on deep clouds

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6	0.22 ± 0.12 W m^{-2} $°C^{-1}$

Zelinka and Hartmann, 2010

Specific humidity q

Radiative cooling Q_{rad}



1 - Dependance of radiative cooling to water vapor

In clear-sky tropical atmosphere the radiative cooling profile strongly depends on water vapor

Because water vapor decreases as vapor pressure decreases, at some altitude water molecule become too scarce to emit LW

- ▸ The drop of water vapor concentration at some altitude is entirely driven by temperature through Clausius-Clapeyron

2.1.1 Tropical high cloud altitude feedback: clear sky control on deep clouds

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}

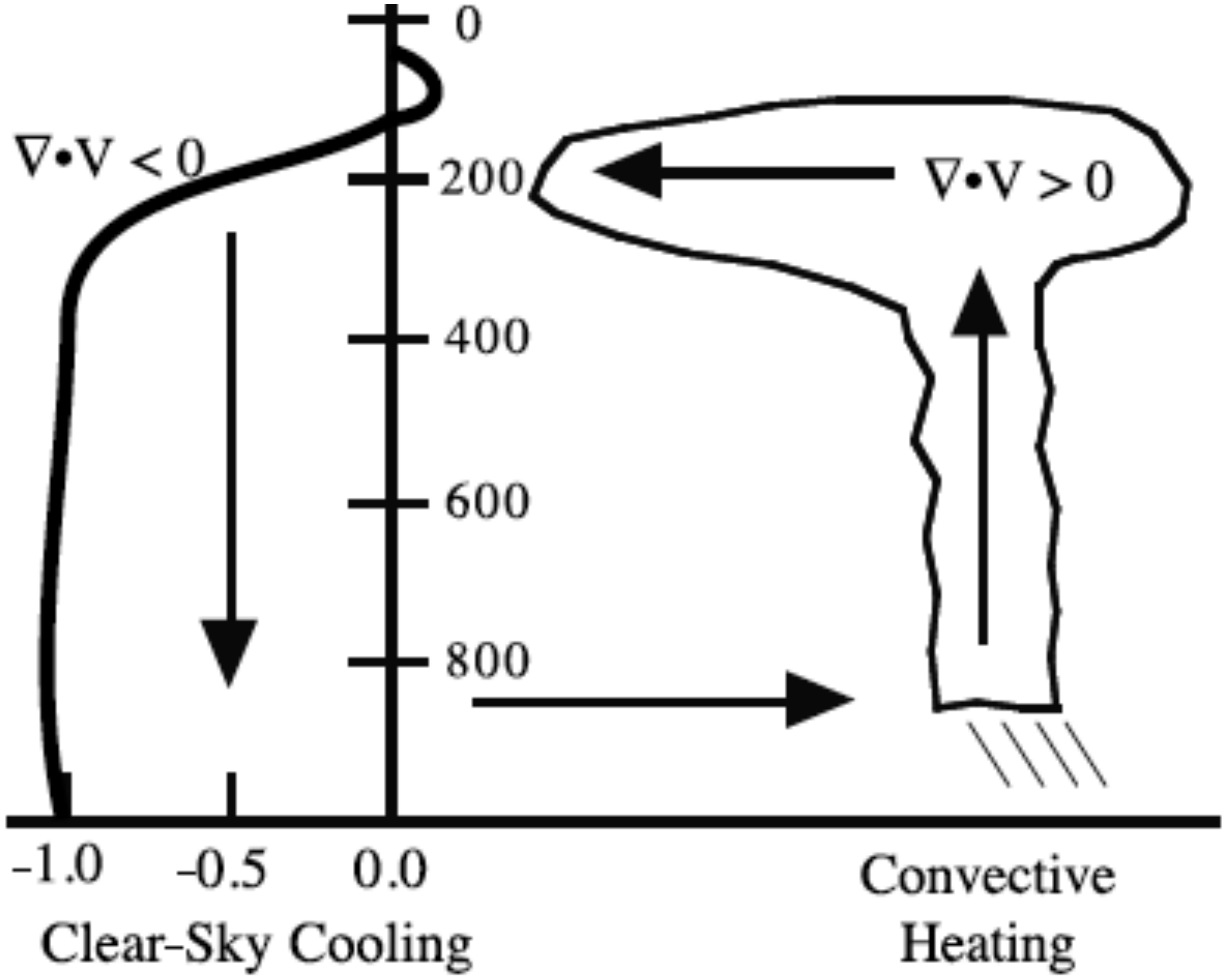
Hartmann and Larson., 2002

Mass convergence

➡ Level of origin of large scale subsidences

Mass divergence

➡ Detrainment layer of deep clouds



Water vapor profile sets LW cooling profile in clear sky regions

The minimum LW cooling sets the detrainement layer of deep clouds

- **Strong connection between clear sky regions and cloudy (connvective) regions !**

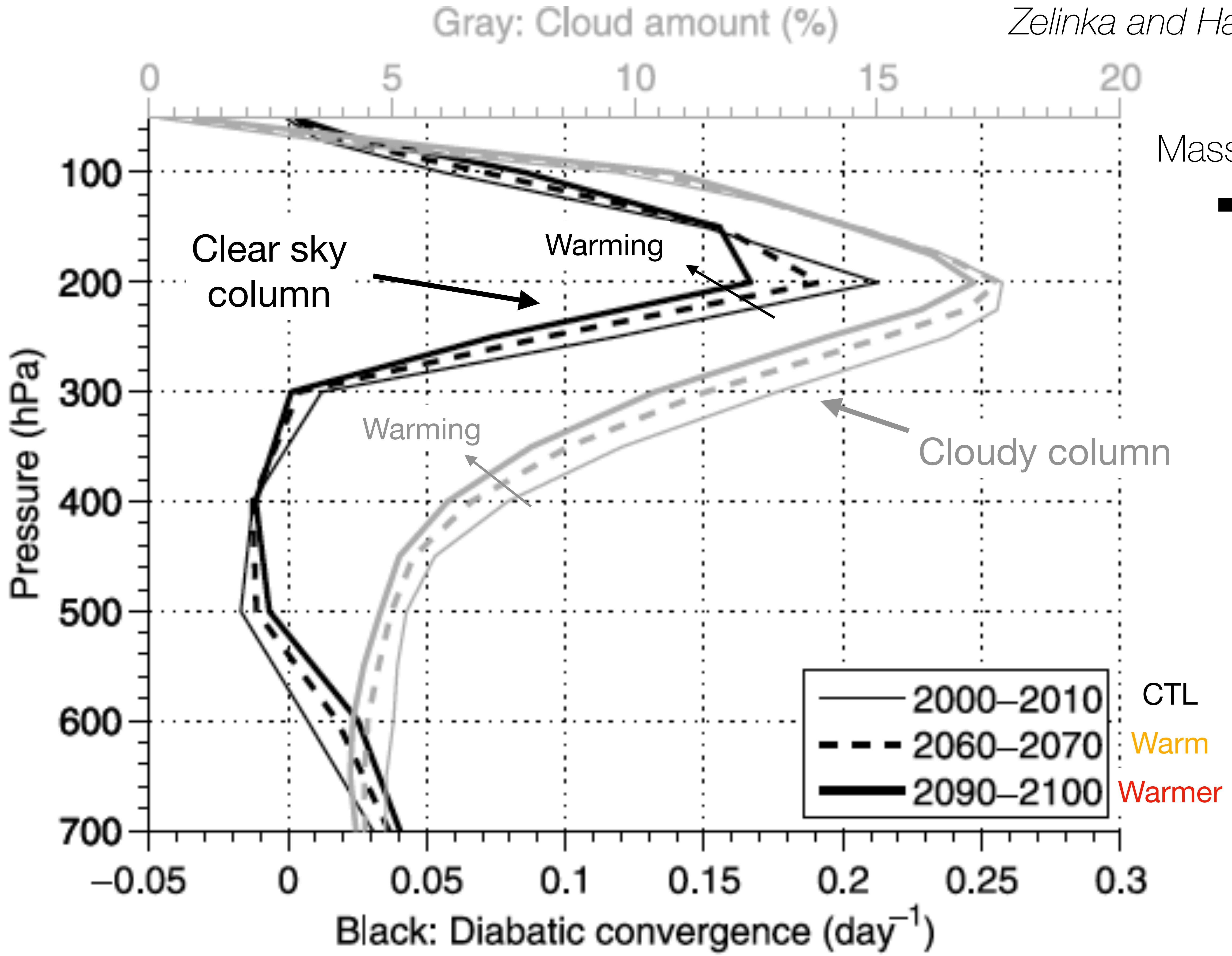
2.1.1 Tropical high cloud altitude feedback: clear sky control on deep clouds

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}

Zelinka and Hartmann, 2010

Mass convergence

➡ Level of origin of large scale subsidences



Mass divergence

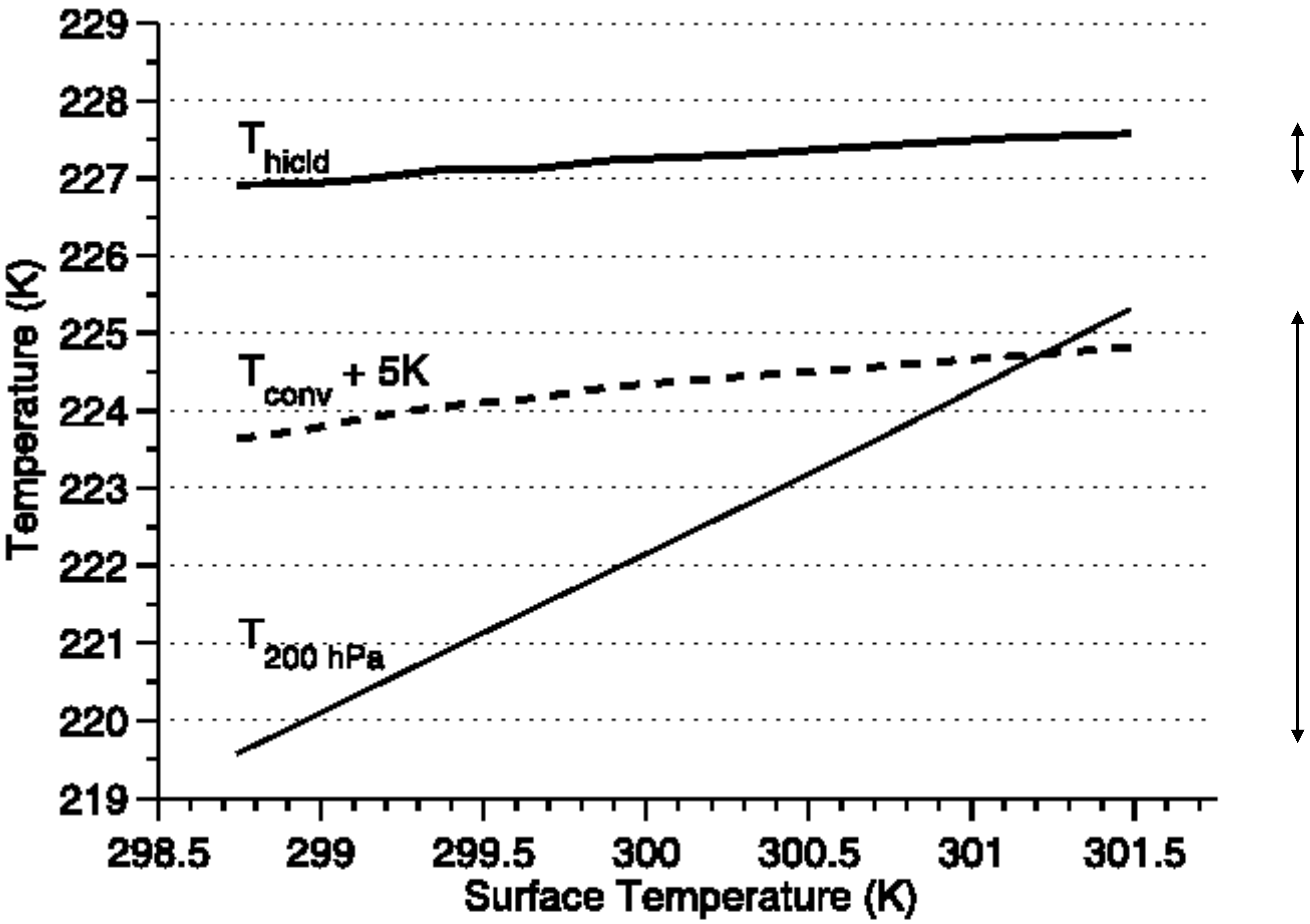
➡ Detrainment layer of deep clouds

Strong connection between clear sky regions and cloudy regions !

2.1 Tropical high cloud altitude feedback: FAT hypothesis in GCM

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}

Zelinka and Hartmann, 2010



$\Delta T_{top} < 1$ K

$\Delta T_{tropo} \sim 6$ K

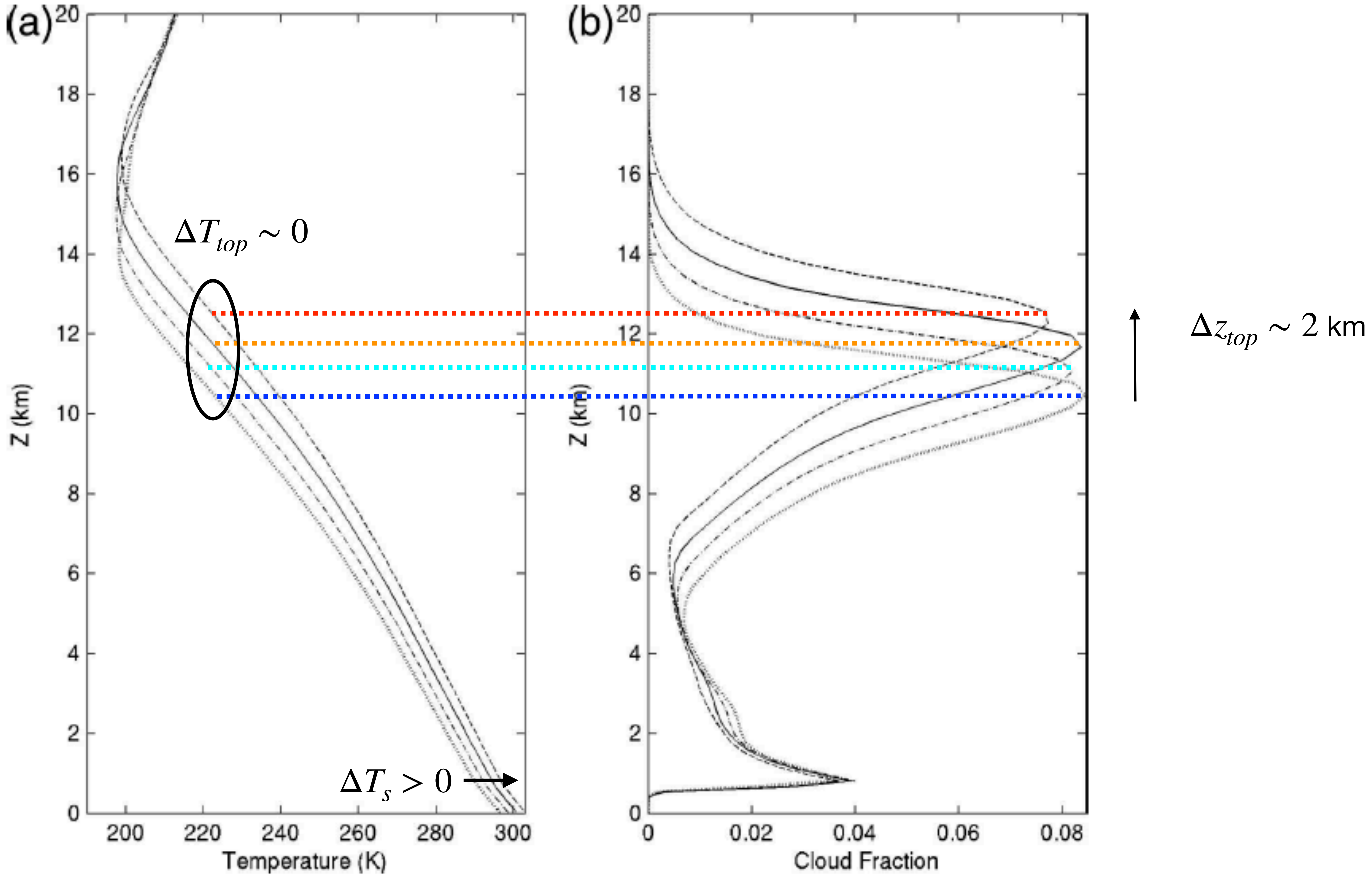
General Cirulation Model (GCM) experiments support FAT constraint

2.1 Tropical high cloud altitude feedback: FAT hypothesis in CRM

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}

Kuang and Hartmann, 2007

Isothermal rise of the cloud detrainment layer with waring



$\Delta T_{top} \sim 0$

$\Delta T_s > 0$

$\Delta z_{top} \sim 2$ km

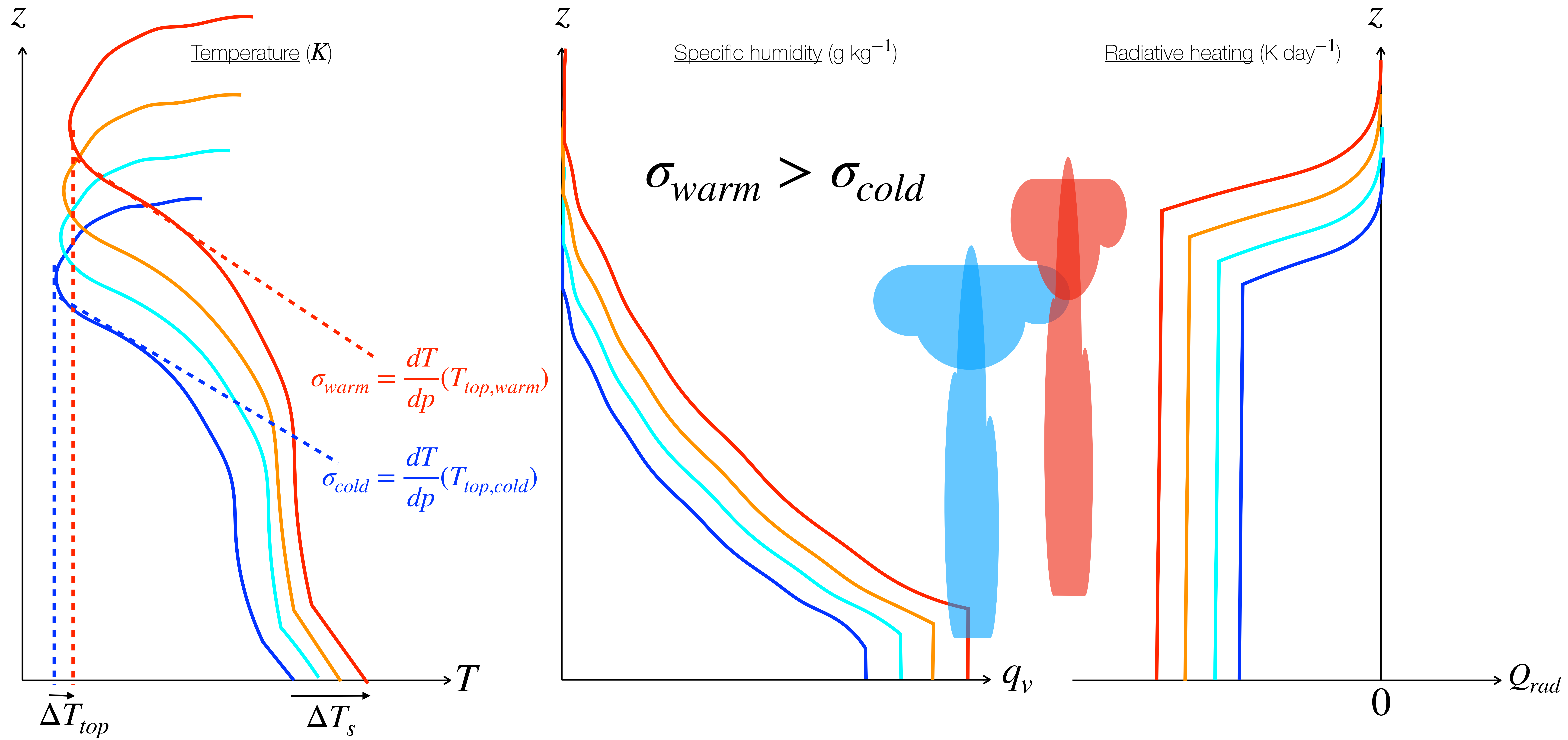
Cloud Resolving Model (CRM) simulations also support FAT

Part 2 - Clouds in a changing climate

- 2.1 Tropical high clouds altitude feedback
- 2.2 Tropical high clouds amount feedback
- 2.3 Tropical low clouds feedback
- 2.4 Midlatitude cloud amount feedback
- 2.5 Extratropical cloud optical depth feedback
- 2.6 Sum up

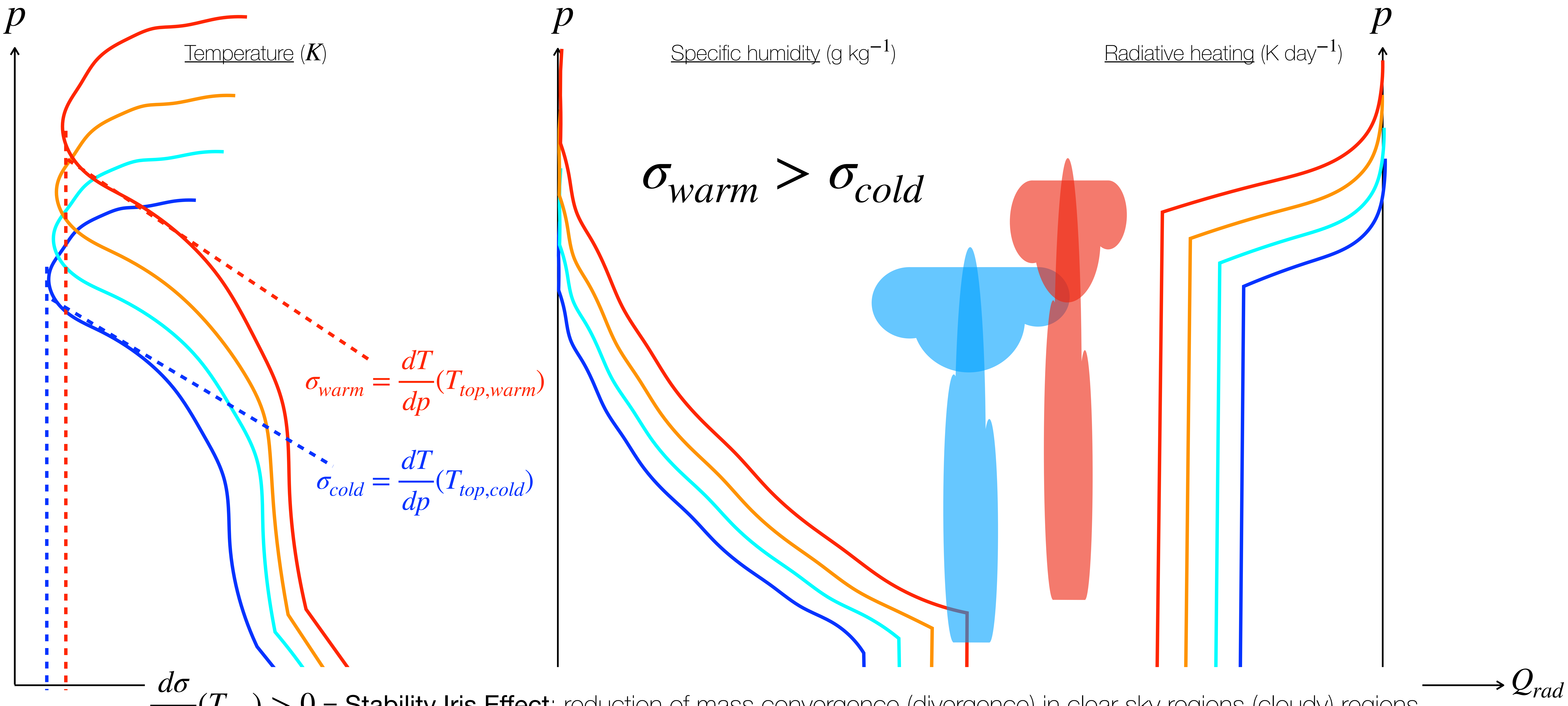
2.2 Tropical high cloud amount feedback: clear sky control on deep clouds

Tropical high-cloud amount feedback	N/A	AR5	Negative (*low confidence*)	AR6	-0.15 ± 0.2 W m^{-2} °C^{-1}



2.2 Tropical high cloud amount feedback: stability iris mechanism

Tropical high-cloud amount feedback	N/A	AR5	Negative (*low confidence*)	AR6	-0.15 ± 0.2 W m^{-2} °C^{-1}



$\frac{d\sigma}{dT_s}(T_{top}) > 0$ = **Stability Iris Effect**: reduction of mass convergence (divergence) in clear sky regions (cloudy) regions

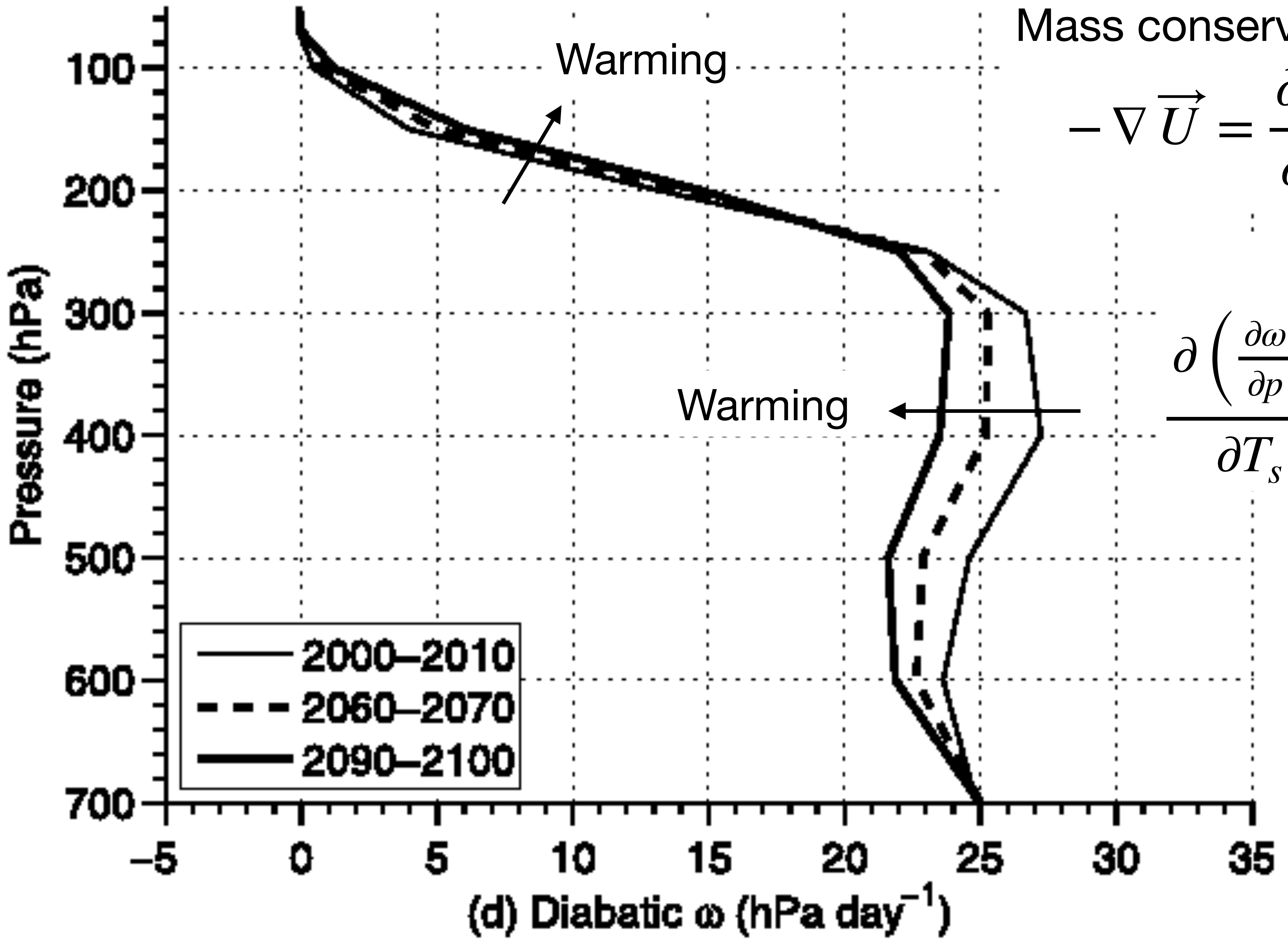
$\Longrightarrow$ **Negative feedback (a priori)**: deep cloud fraction decreases with warming

2.2 Tropical high cloud amount feedback: stability iris mechanism

High-cloud altitude feedback	Positive (*high confidence*) AR5	Positive (*high confidence*) AR6 0.22 ± 0.12 W m^{-2} °C^{-1}

Zelinka and Hartmann, 2010

Vertical velocity ω



Mass conservation

$$-\nabla \vec{U} = \frac{\partial \omega}{\partial p}$$

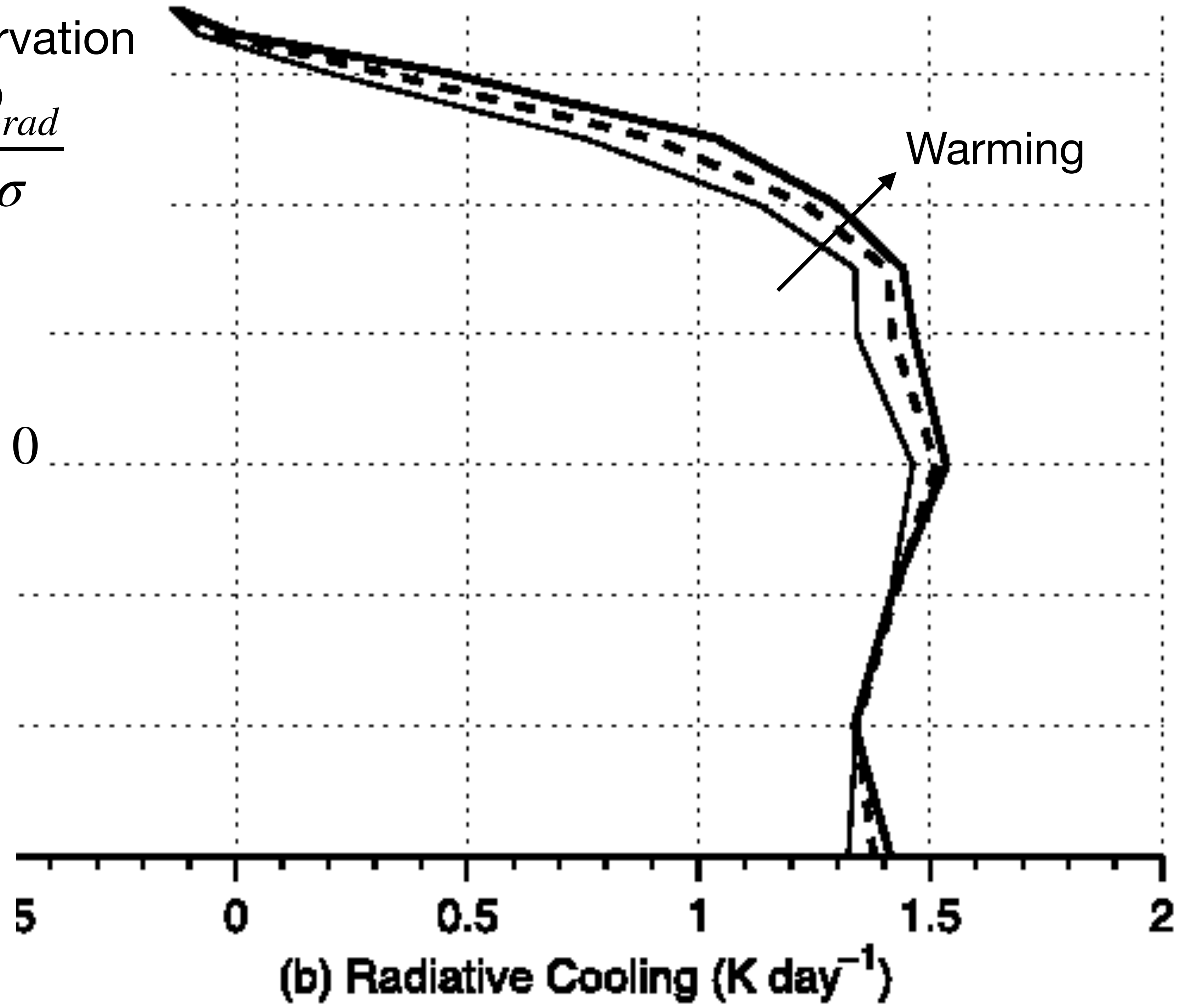
Energy conservation

$$\omega = \frac{Q_{rad}}{\sigma}$$

Under warming

$$\frac{\partial\left(\frac{\partial \omega}{\partial p}\right)}{\partial T_s} < 0 \implies \frac{\partial\left(-\nabla \vec{u}\right)}{\partial T_s} < 0$$

Radiative cooling Q_{rad}



2 - Rad. Conv. Equilibrium (RCE) in clear-sky regions

In clear-sky tropical atmosphere the radiative cooling is compensated by adiabatic compression

Static stability

The radiative cooling profile and the temperature profile then set the large scale vertical velocity profile $\omega = \frac{Q_{rad}}{\sigma}$ with $\sigma = \frac{dT}{dp}$

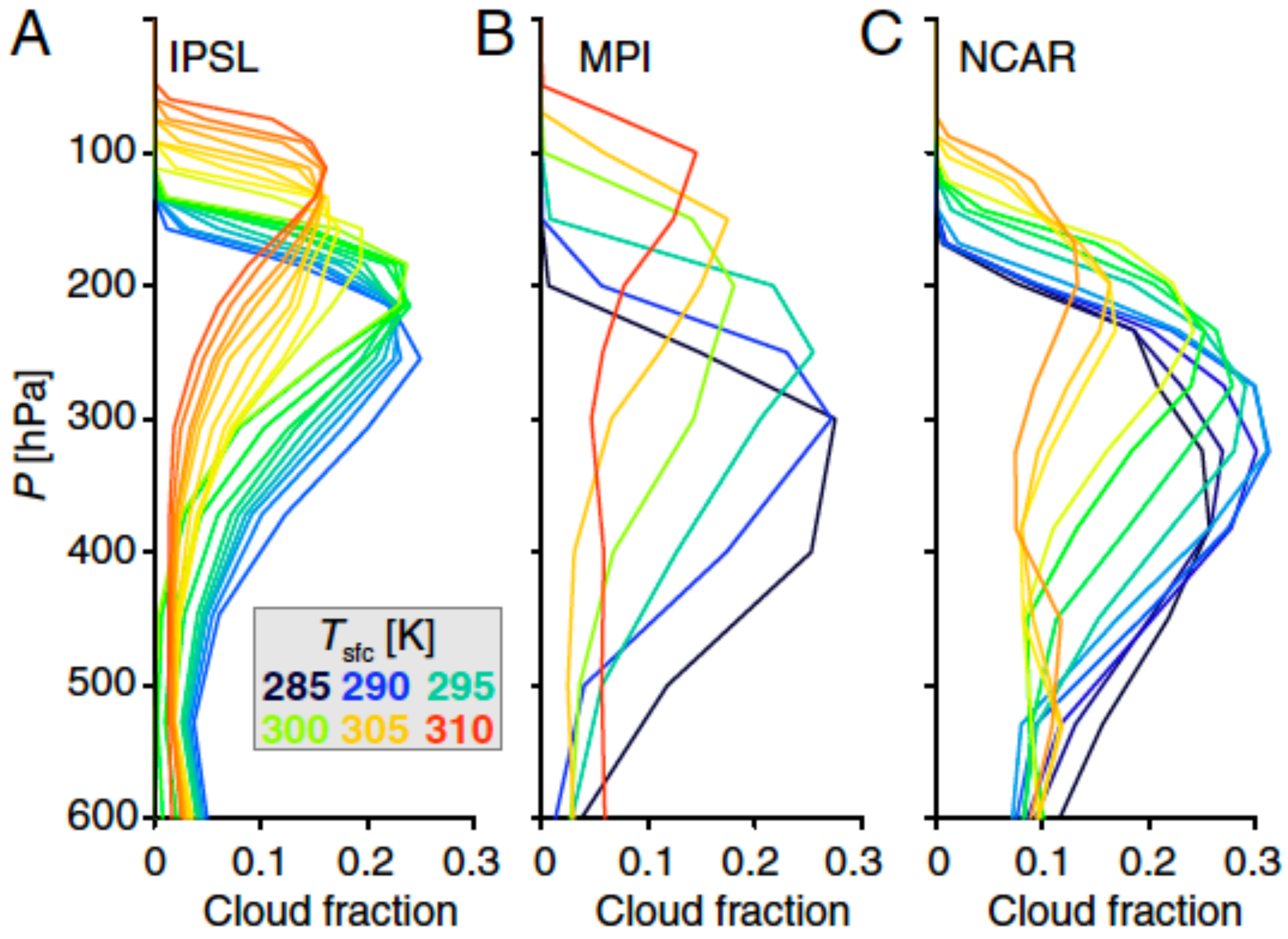
Mass conservation !

Convergence of mass at the level of Q_{rad} drop $\Longrightarrow$ Divergence of mass in cloudy regions

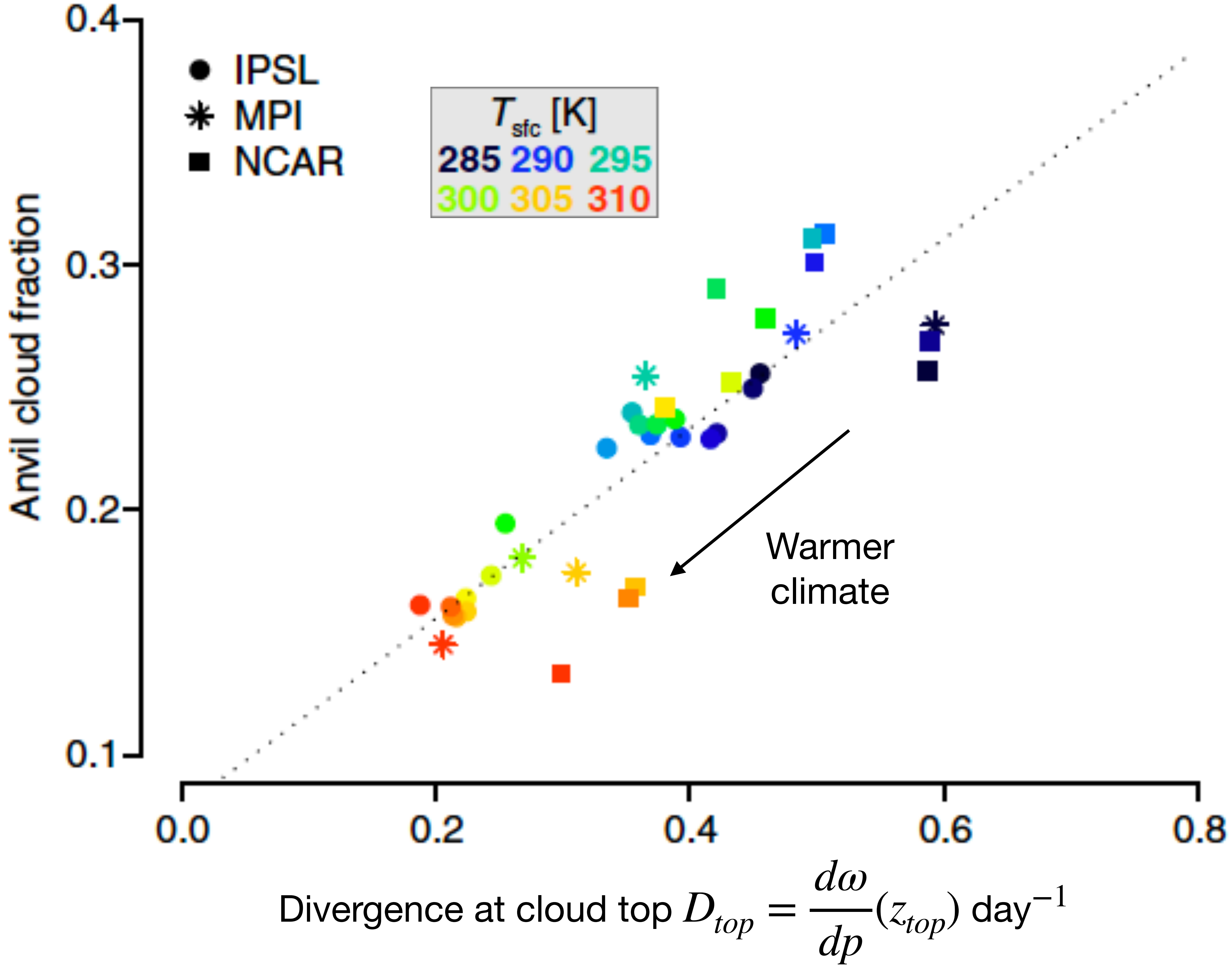
2.2 Tropical high cloud amount feedback: stability iris effect in GCMs

Tropical high-cloud amount feedback	N/A AR5	Negative (*low confidence*) AR6 -0.15 ± 0.2 W m^{-2} °C^{-1}

Bony et al, 2016



Reduction of anvil cloud fraction with warming in 3 different GCMs



Strong correlation between cloud fraction reduction and divergence reduction under climate change

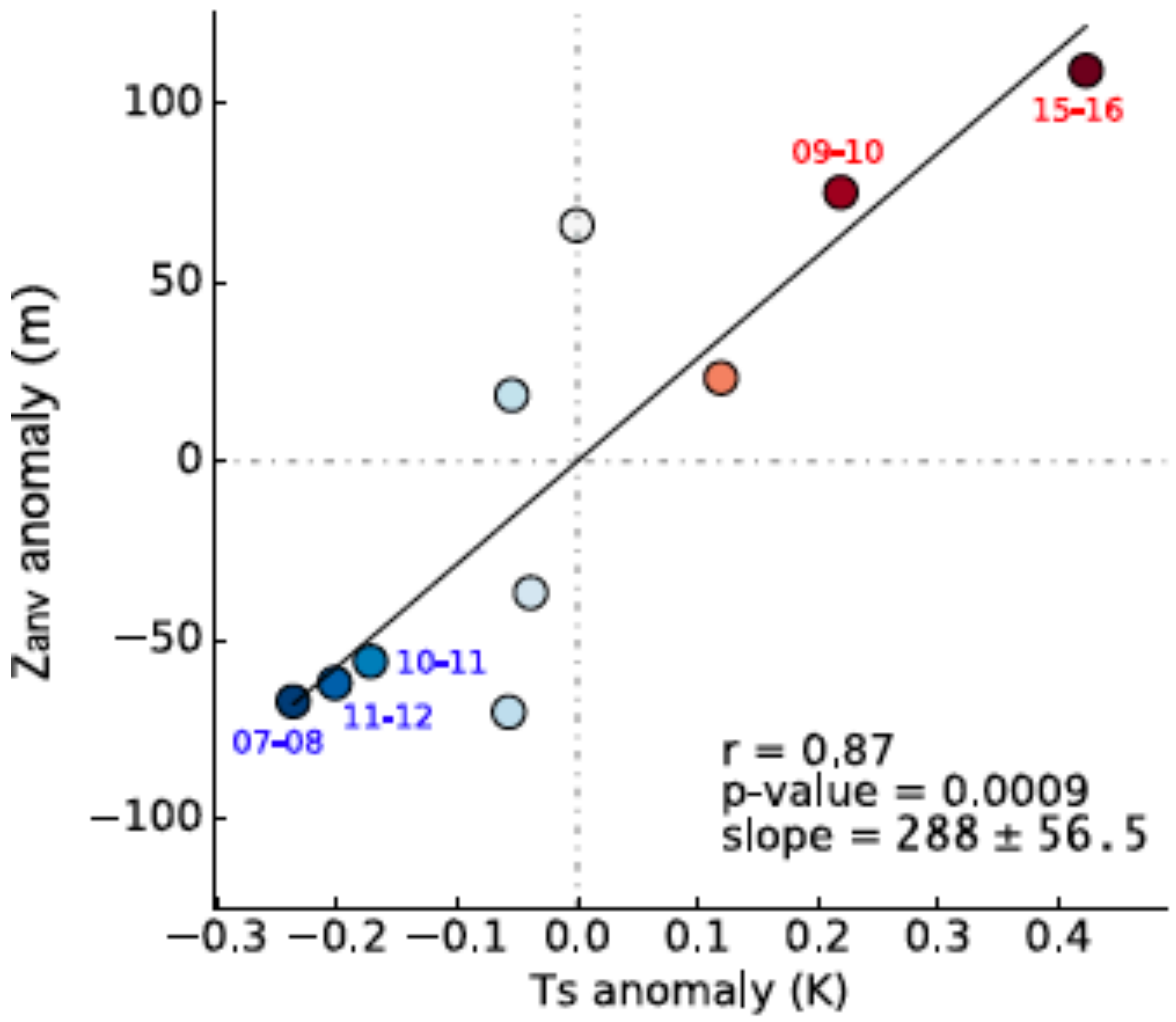
General Cirulation Model (GCM) experiments support stability iris mechanism

2.2 Tropical high cloud amount feedback: stability iris effect in observations

Tropical high-cloud amount feedback	N/A AR5	Negative (*low confidence*) AR6 -0.15 ± 0.2 W m^{-2} °C^{-1}

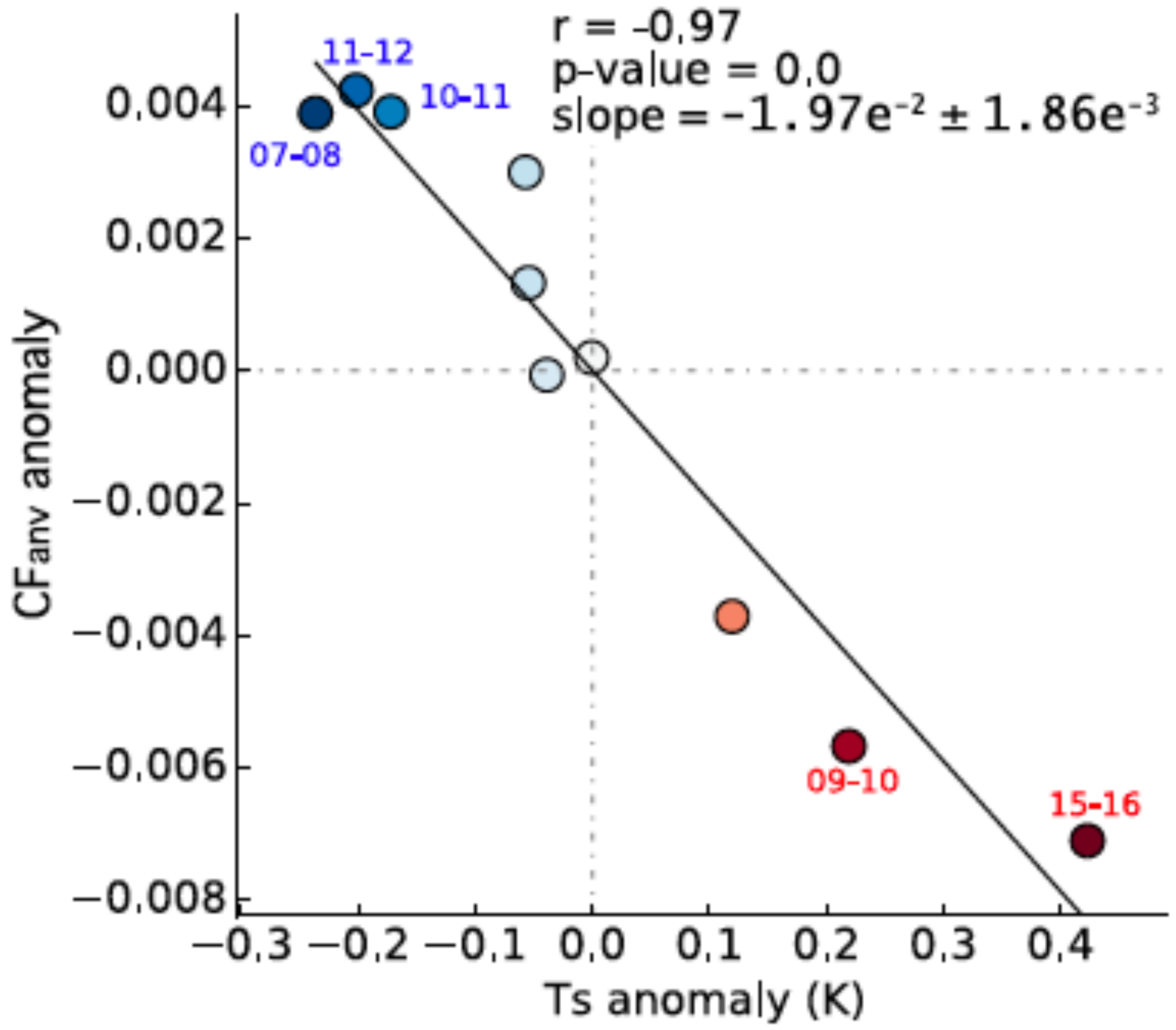
Saint-Lu et al, 2020

z_{top} against T_s interannual variations



Rise of anvil cloud top with observed warming (ENSO years)

CF_{top} against T_s interannual variations



Reduction of anvil cloud fraction with observed warming (ENSO years)

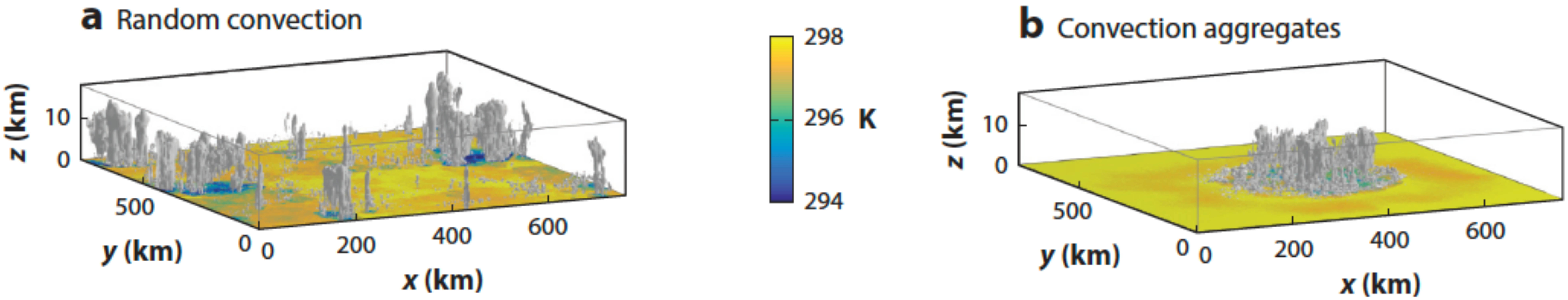
10-year timeseries of satellite observations support stability iris mechanism (and FAT)

2.2 Tropical high cloud amount feedback: deep convection aggregation

Tropical high-cloud amount feedback	N/A AR5	Negative (*low confidence*) AR6 –0.15 ± 0.2 W m^{-2} °C^{-1}

Clouds and near-air temperature

Muller et al, 2022



When convection aggregates:

- Dryer atmosphere ⟹ more LW emitted to space (increased OLR)
- Reduced cloud cover ⟹ less SW reflected to space (decreased albedo)
  - ➡ Near compensation of these two effects

Increased aggregation in a warmer climate (Coppin and Bony 2015)

BUT

Large discrepancies in anvil cloud cover response to warming *(Wing et al, 2020)*

Large uncertainties related to convective aggregation

2.2 Tropical high cloud amount feedback

Tropical high-cloud amount feedback	N/A	AR5	Negative (*low confidence*)	AR6	-0.15 ± 0.2 W m^{-2} °C^{-1}

Why then a low confidence ?

Many **GCMs** misreprensent convective clouds (*Ceppi et al, 2017)*

- Underestimation of anvil clouds
- Underestimation of cirrus clouds

CRMs exhibit large discrepacies in the simulated deep clouds because of their treatment of microphysical processes

Large uncertainties related to convective aggregation in models and theories

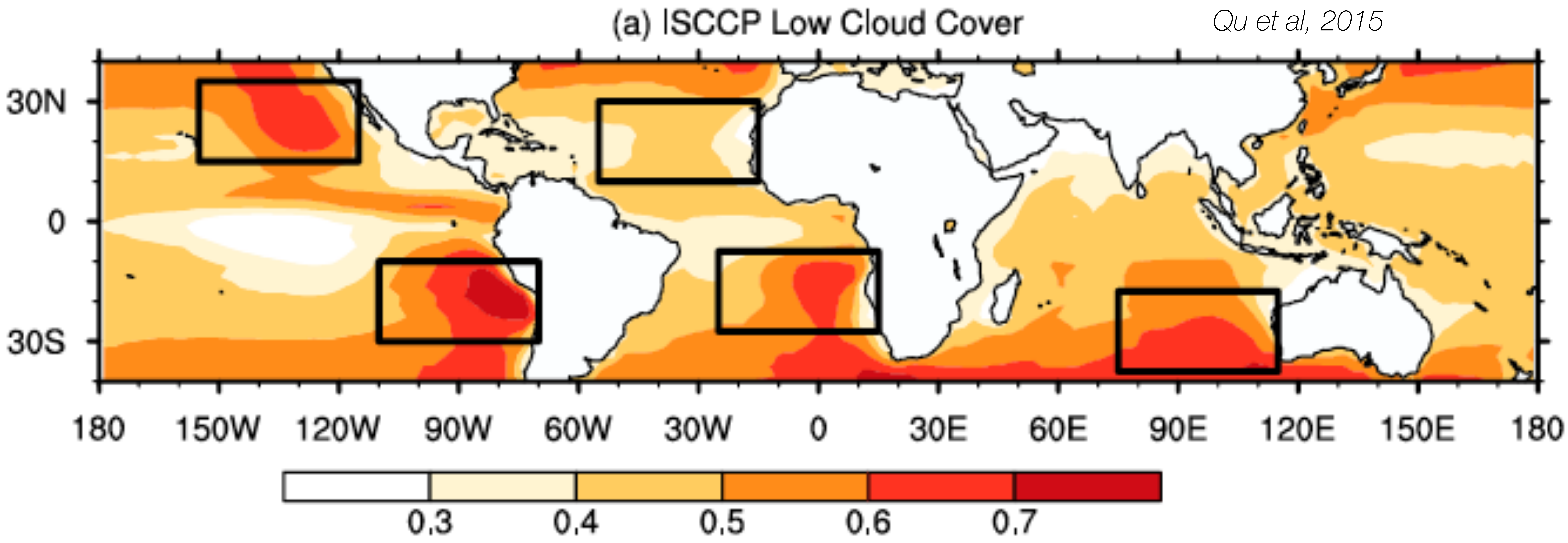
Still lack of modeling evidences !

➡ New model evidences from IPSL GCM: *Saint-Lu, Dufresne, Bony et al., submitted !*

Part 2 - Clouds in a changing climate

2.3 Tropical low clouds feedbacks: low clouds are ubiquitous in the subtropics

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}



Qu et al, 2015

- Low clouds - i.e Strato-Cumulus (Sc) and Cumulus (Cu) - covers very a very large fraction of the Subtropics
- Their cloud cover exceeds 0.6 over very large areas

➡ Strong impact on the radiative budget of the Earth

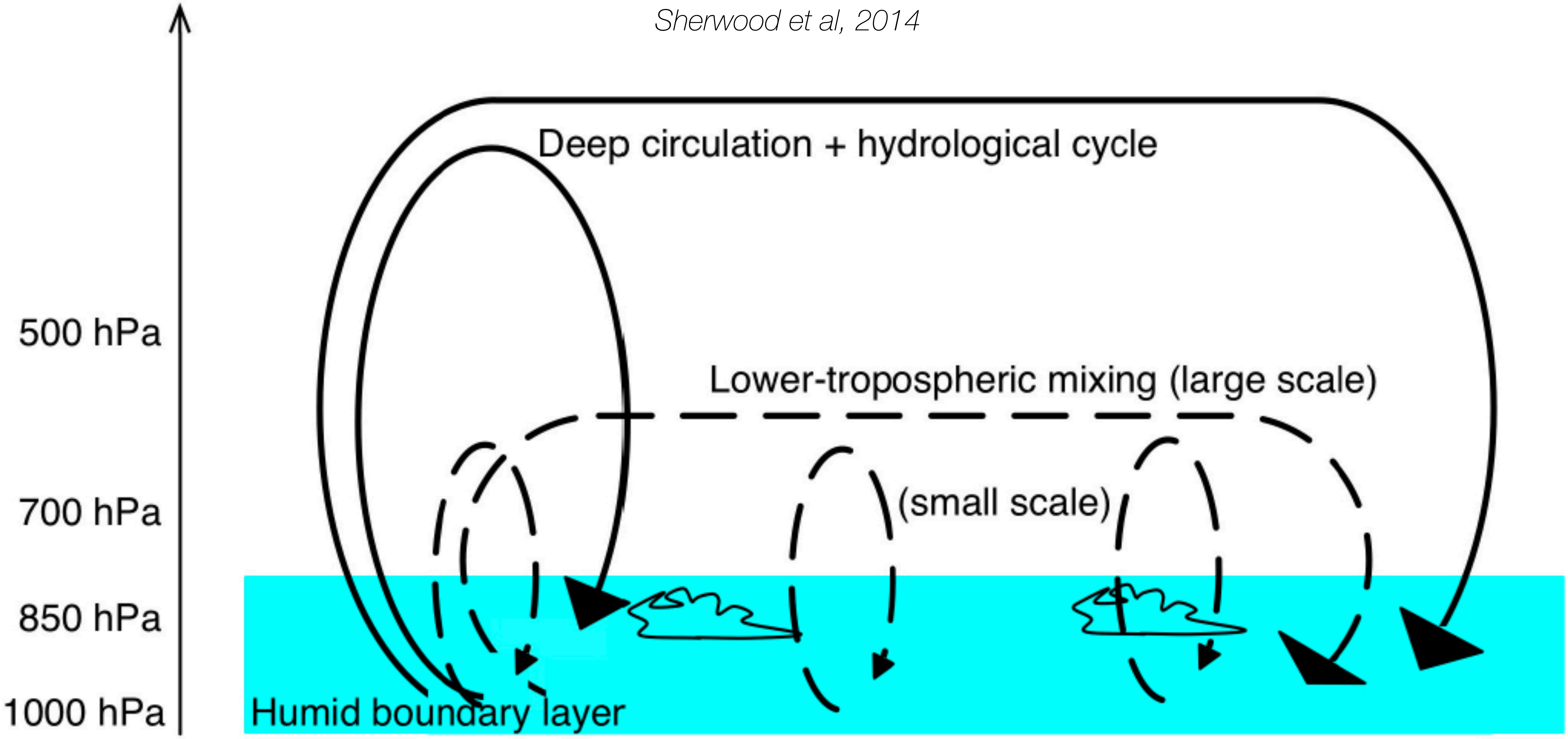
2.3 Tropical low clouds feedbacks: low clouds cool the Earth

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

Shallow clouds reflect efficiently sunlight towards space and cool the planet, especially stratocumulus

2.3 Tropical low clouds feedbacks: Bouday Layer (BL) processes are complex

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} $°C^{-1}$


Sherwood et al, 2014

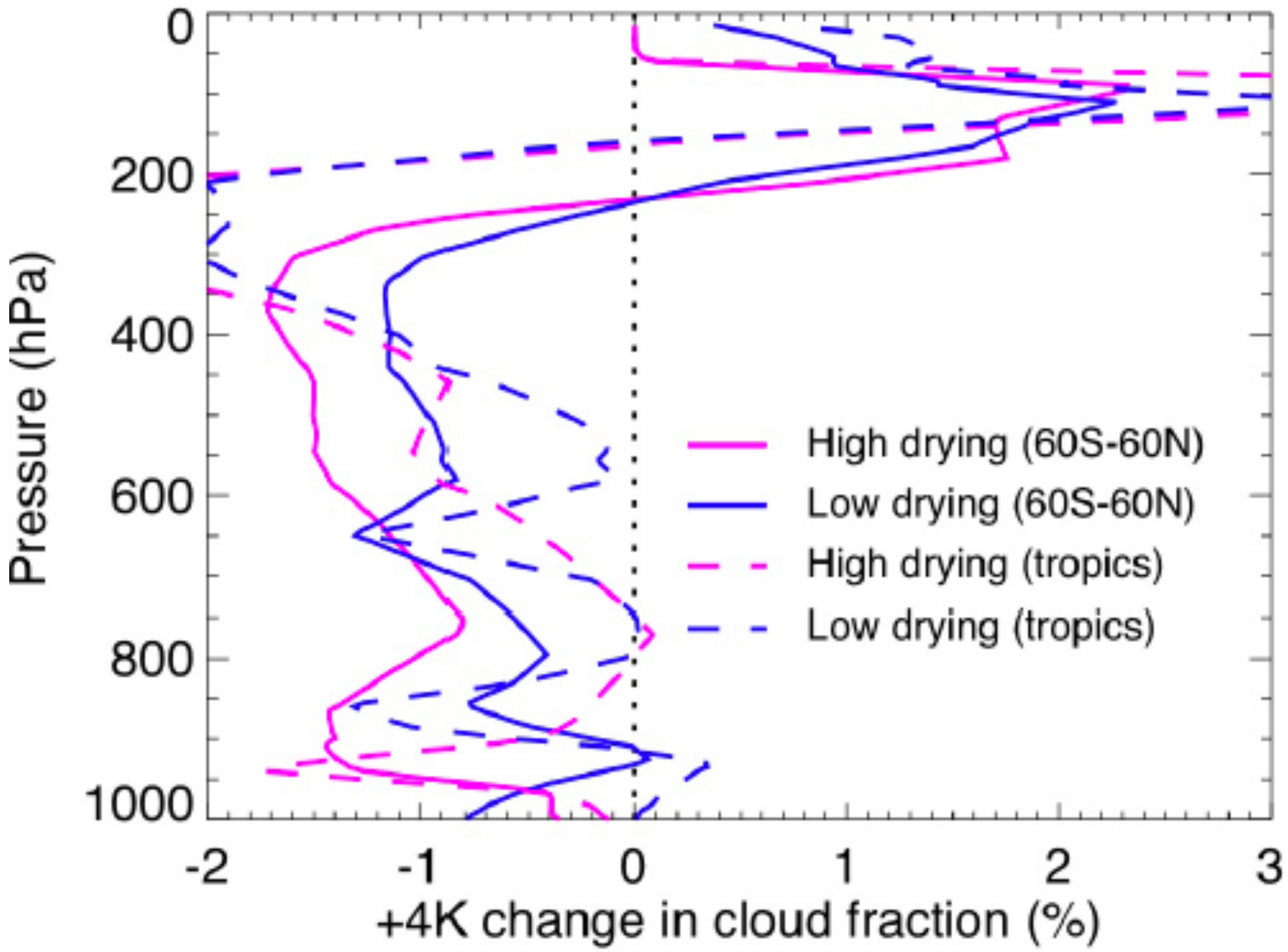
Boundary layer moisture budget results from a subtle balance between different scales

2.3 Tropical low clouds feedbacks: decreasing cloud cover under global warming

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} $°C^{-1}$

Sherwood et al, 2014

Cloud cover response to a $\Delta T_s = 4$ K forcing in 2 climate models

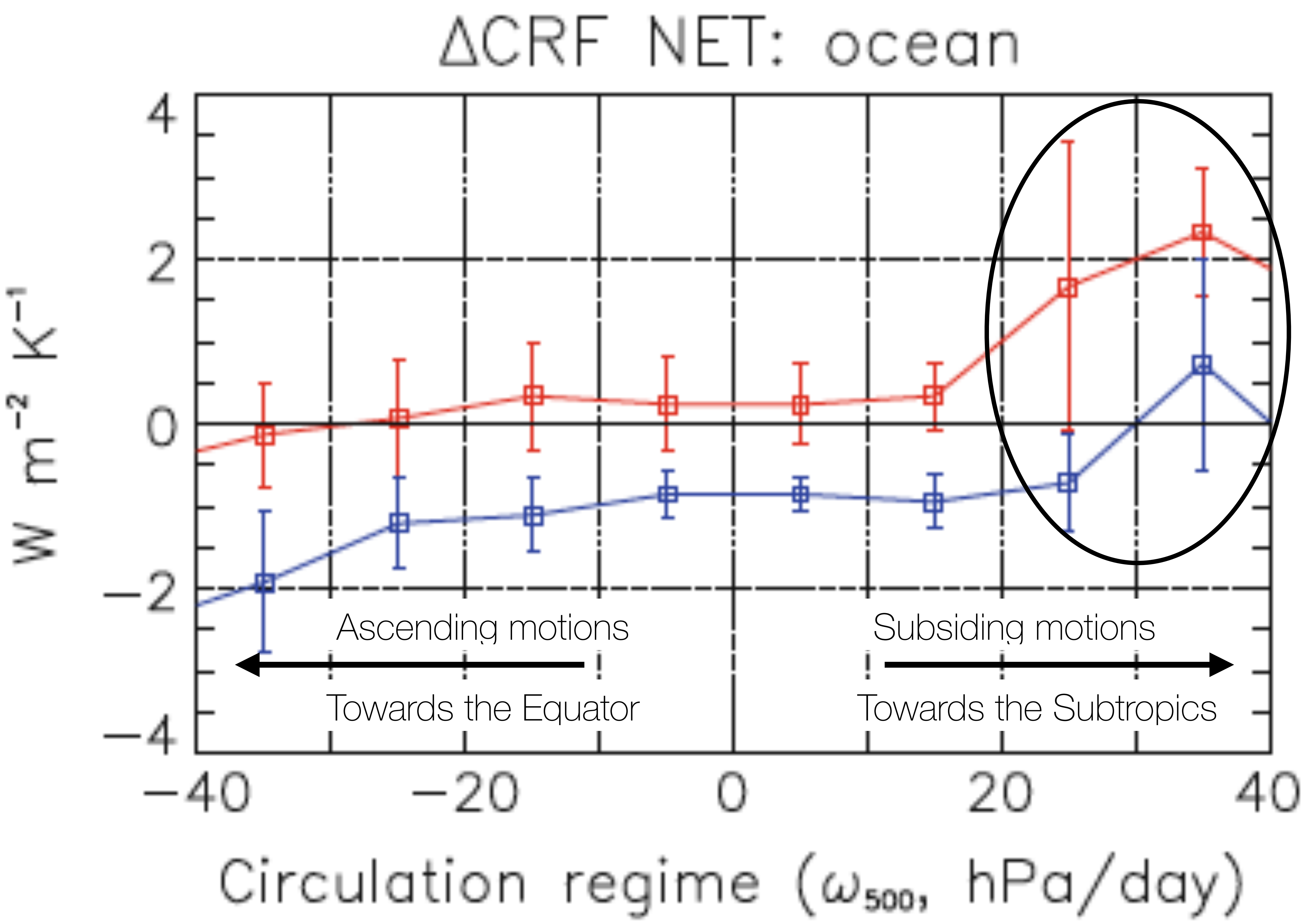


All models predicts a decreasing low-cloud cover in response to a +4 K warming

2.3 Tropical low clouds feedbacks: long-terms uncertainties

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} $°C^{-1}$

Cloud feedbacks sorted by circulation regime over tropical oceans in CMIP5 GCMs



Vial et al, 2013

Cumulus and stratocumulus regions

Until AR6, trade winds low clouds were assessed as :

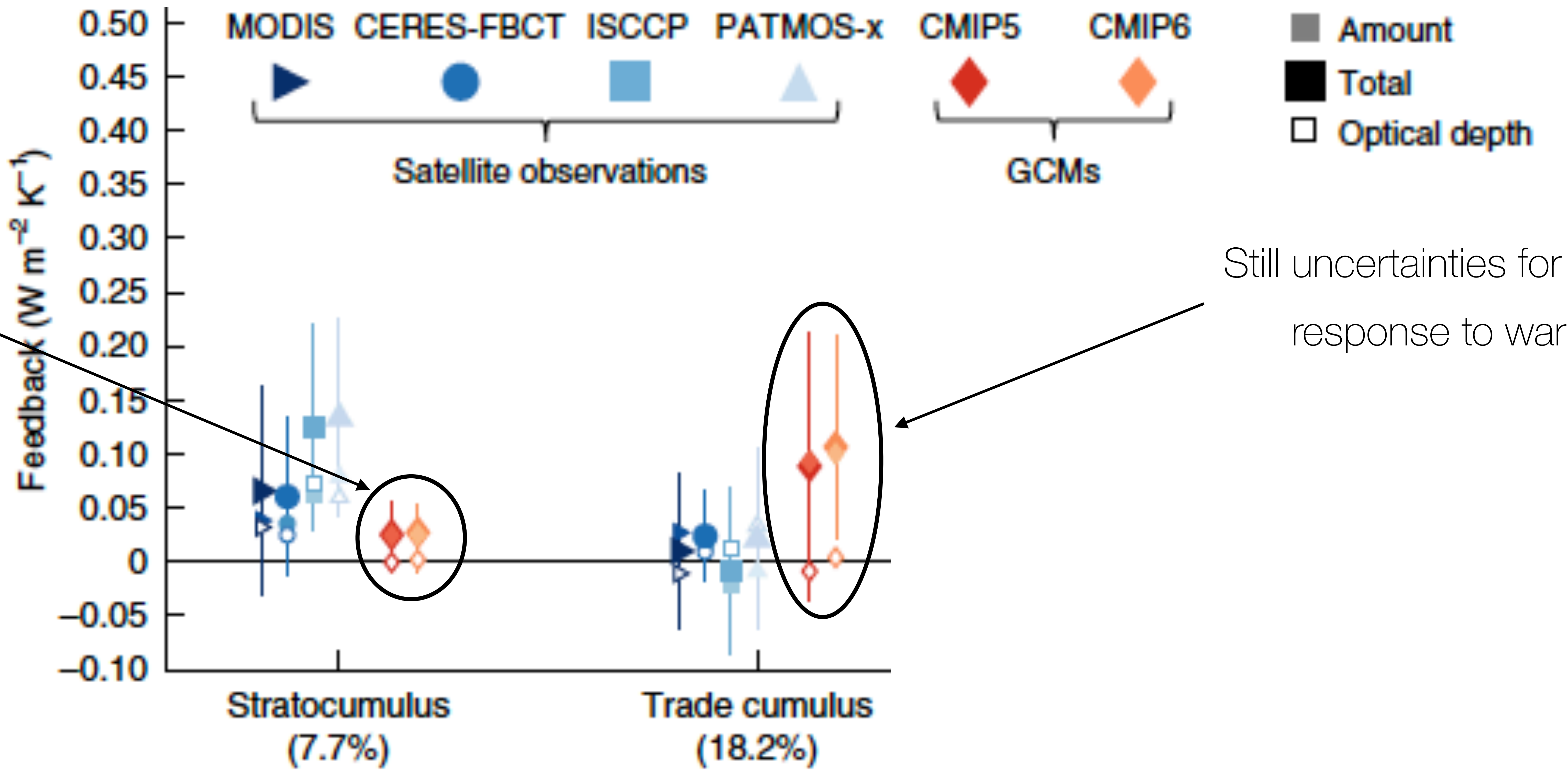
- main contributors of the overall positive cloud feedback
- main contributors of the inter-model spread in cloud feedbacks

2.3 Tropical low clouds feedbacks: recent progresses

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

Myers et al, 2021

Scaled marine low cloud feedbacks



Stratocumulus clouds response better constrained in climate models (GCM)

Still uncertainties for cumulus response to warming

- **Modest positive feedback from stratocumulus clouds** (when scaled by their area coverage)
- **Near zero cumulus feedback suggested in observations, but positive in climate models**
- **Spread in the response of cumulus simulated but climate models**

2.3 Tropical low clouds feedbacks: cloud controlling factors

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

Decomposition of the low cloud cover response in climate models into a sum of 2 local controlling factors: *Qu et al, 2014*

$$\Delta LCC = \left(\frac{\partial LCC}{\partial EIS}\right)\Delta EIS + \left(\frac{\partial LCC}{\partial SST}\right)\Delta SST \text{ with:}$$

1. EIS: Estimated Inversion strength
2. SST: Sea Surface Temperature

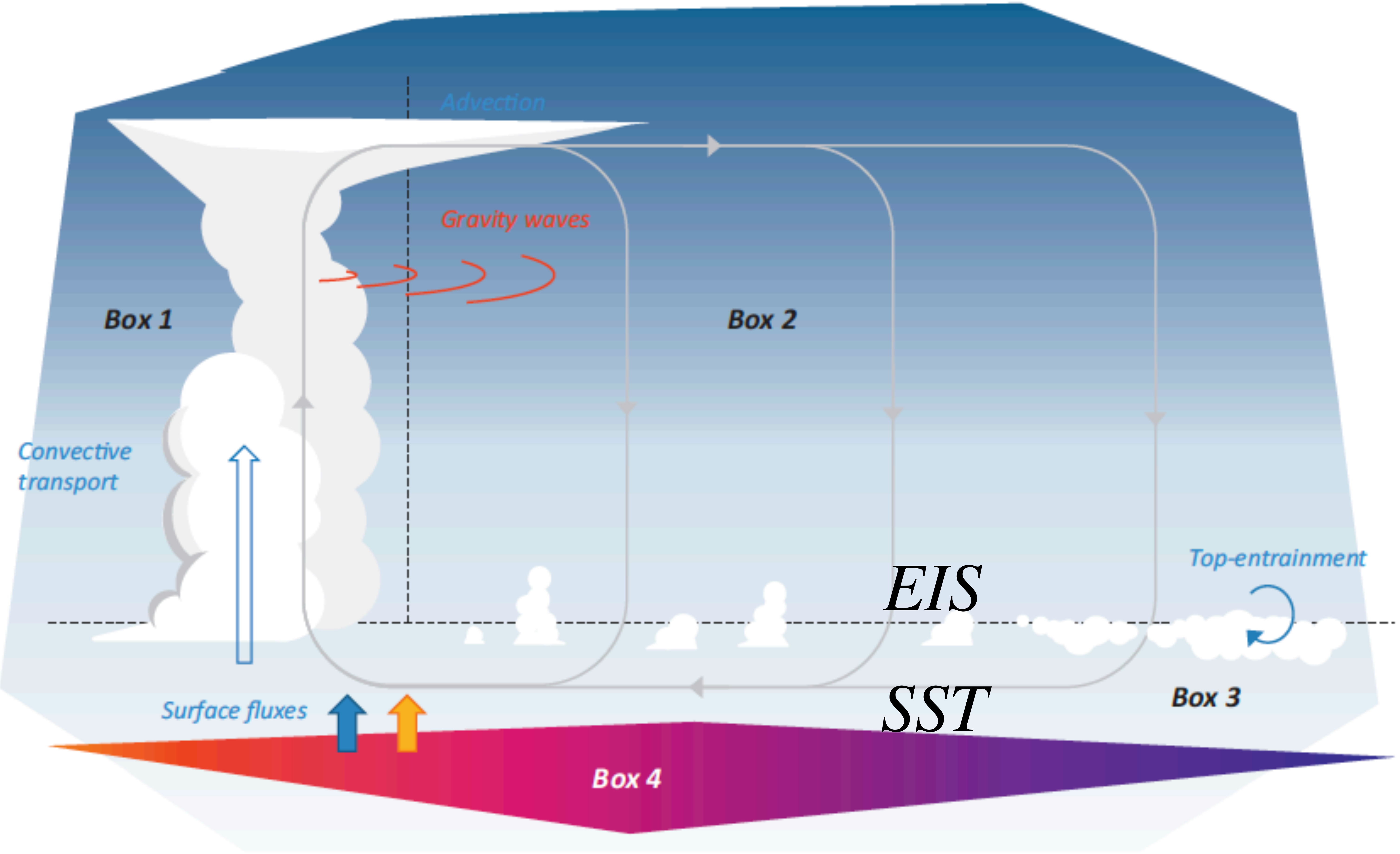
Increasing EIS under global warming

- Increased cloud cover in models (+ stratocumulus)
  - ➡ Negative feedback

Increasing SST under global warming

- Decreased cloud cover in models
  - ➡ Positive feedback

Slightly positive low cloud feedback
with important inter-model spread



Need for a process-level understanding !

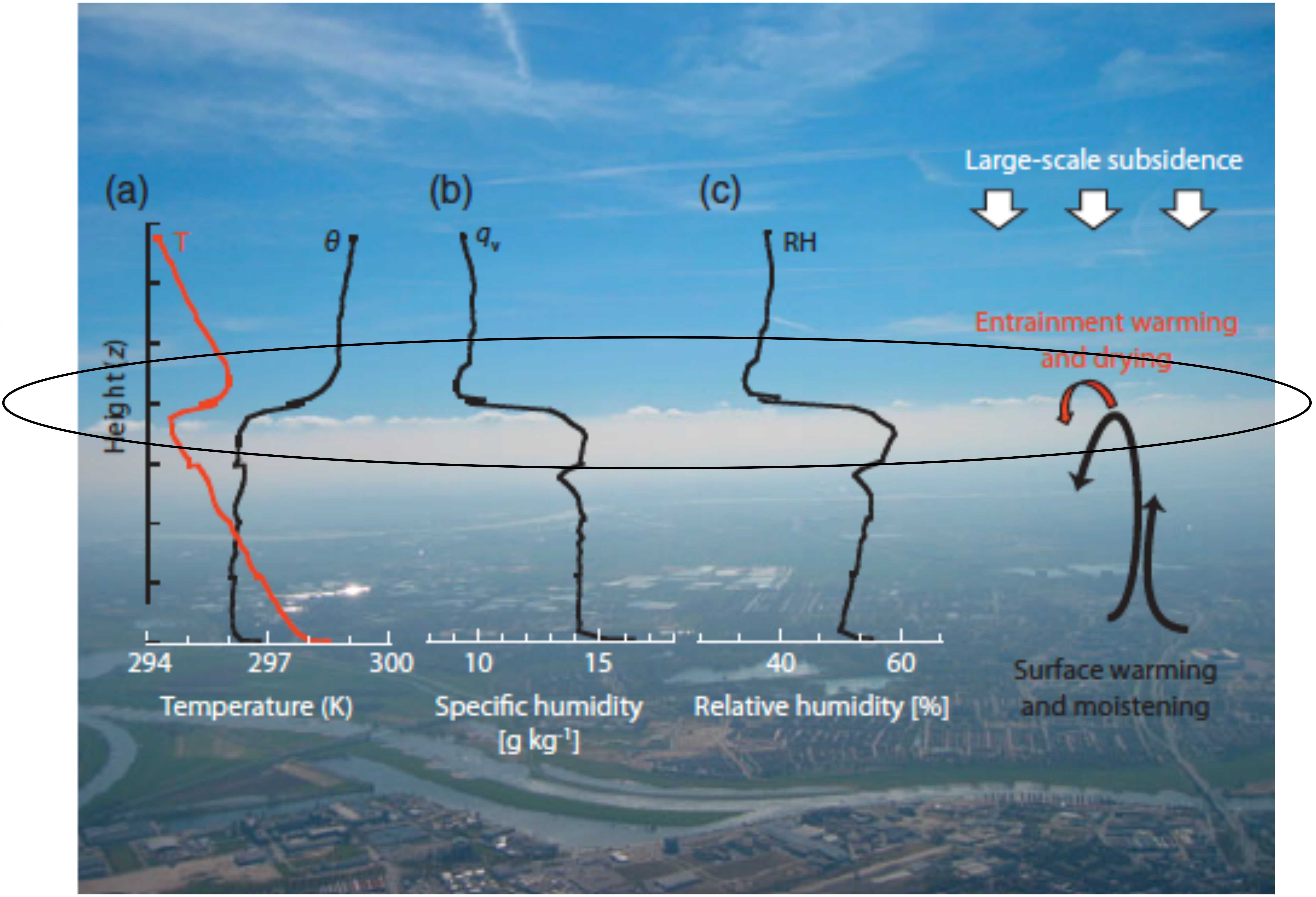
2.3 Tropical low clouds feedbacks: inversion strenght

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

Inversion strenght = Amplitude of

- Temperature increase
- Humidity drop

… at BL top



2.3 Tropical low clouds feedbacks: cloud controlling factors

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	$0.2 \pm 0.16\ \mathrm{W\ m^{-2}\ °C^{-1}}$

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2. SST: Sea Surface Temperature

Increasing EIS under global warming *Wood and Bretherton, 2006*

- Increased cloud cover in observations (+ stratocumulus)

  ➡ Negative feedback

\+

Increasing SST under global warming

- Decreased cloud cover in models (-stratocumulus)

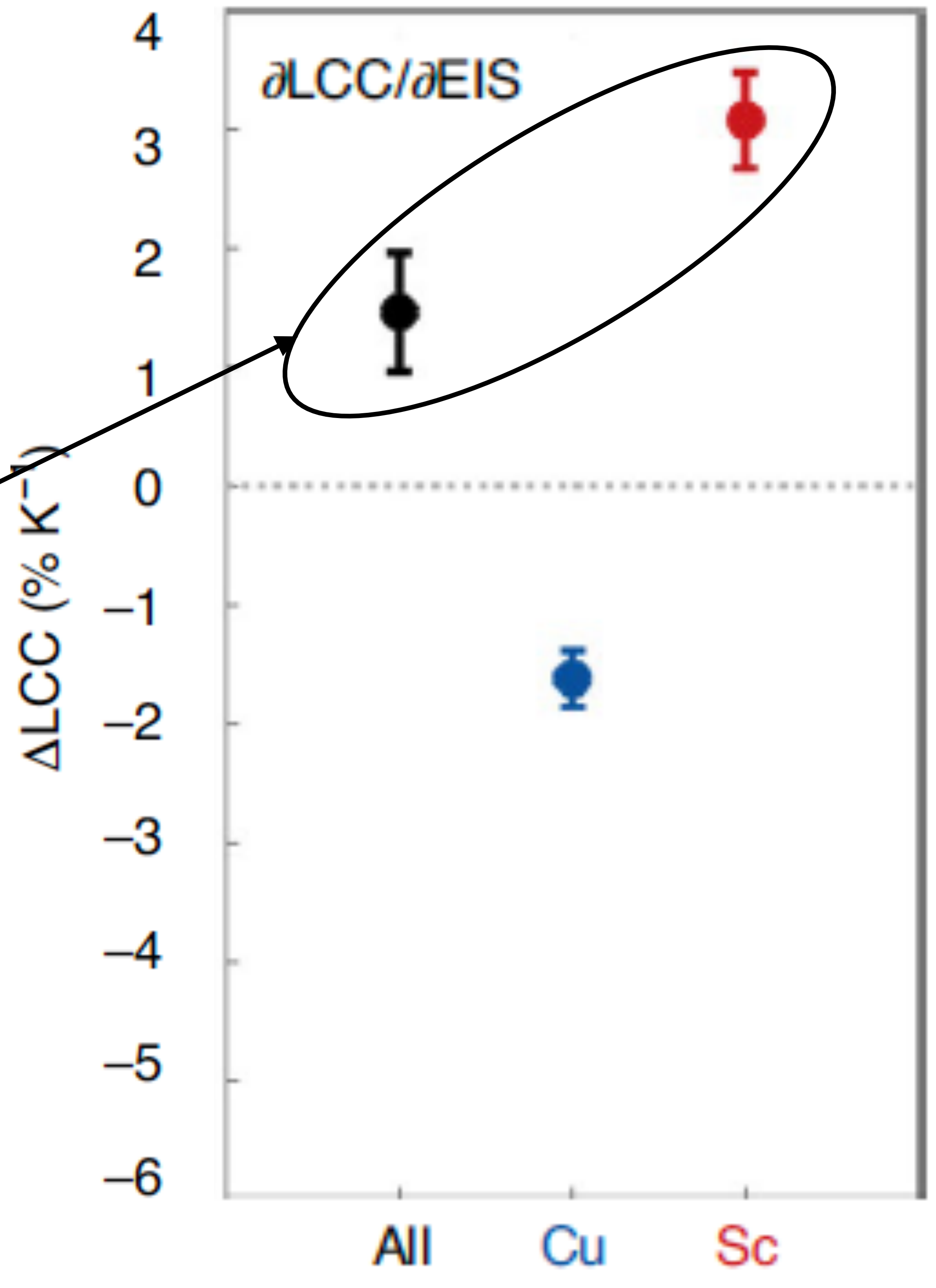
  ➡ Positive feedback

=

Slightly positive low cloud feedback
with important inter-model spread

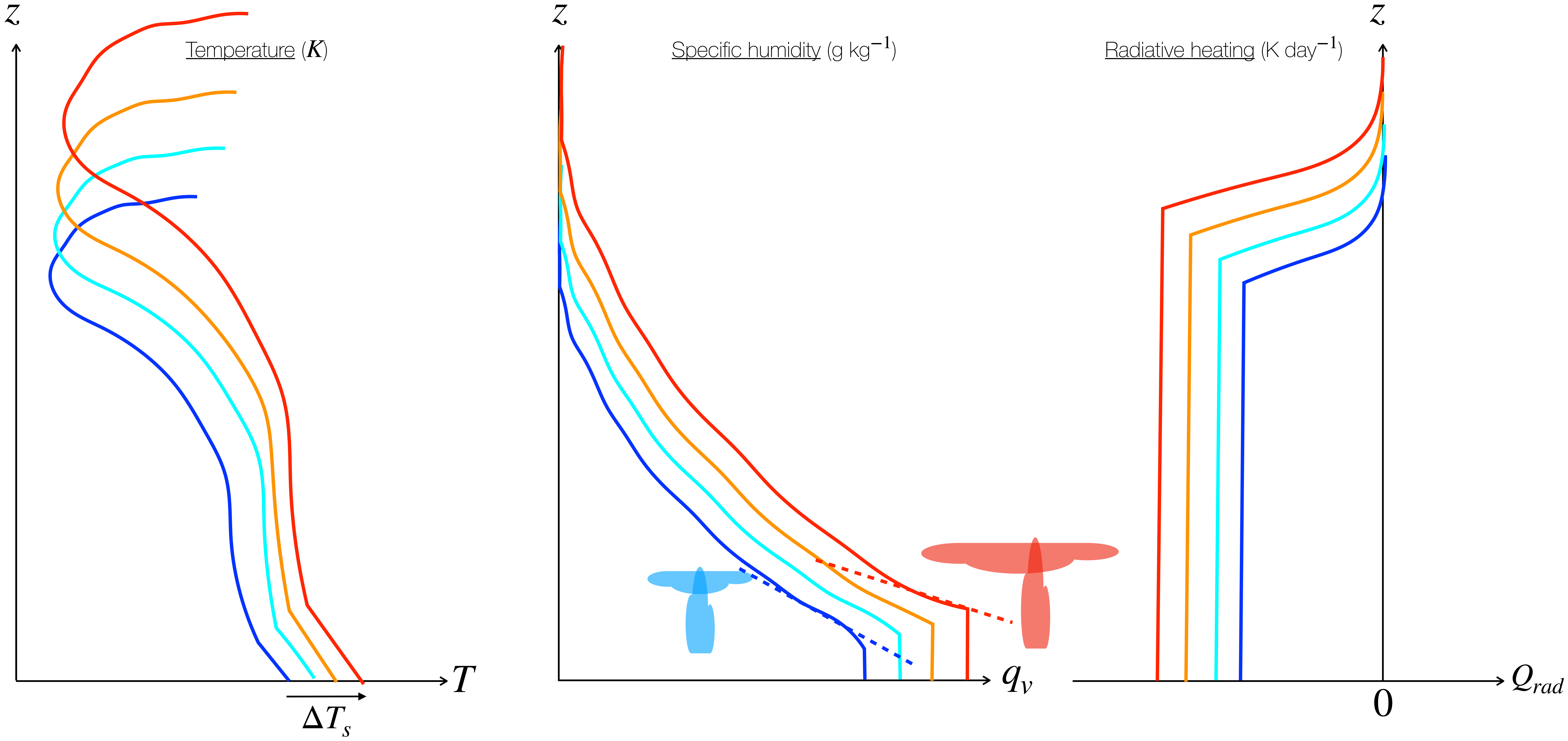
➡ Need for a process-level understanding !

Cesana et al, 2021



2.3 Tropical low clouds feedbacks: cloud controlling factors

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}



2.3 Tropical low clouds feedbacks: cloud controlling factors

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

2.3 Tropical low clouds feedbacks: cloud controlling factors

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Increasing EIS under global warming *Wood and Bretherton, 2006*

- Increased cloud cover in observations (+ stratocumulus)

➡ Negative feedback

+

Increasing SST under global warming

- Decreased cloud cover in obervations (-stratocumulus)

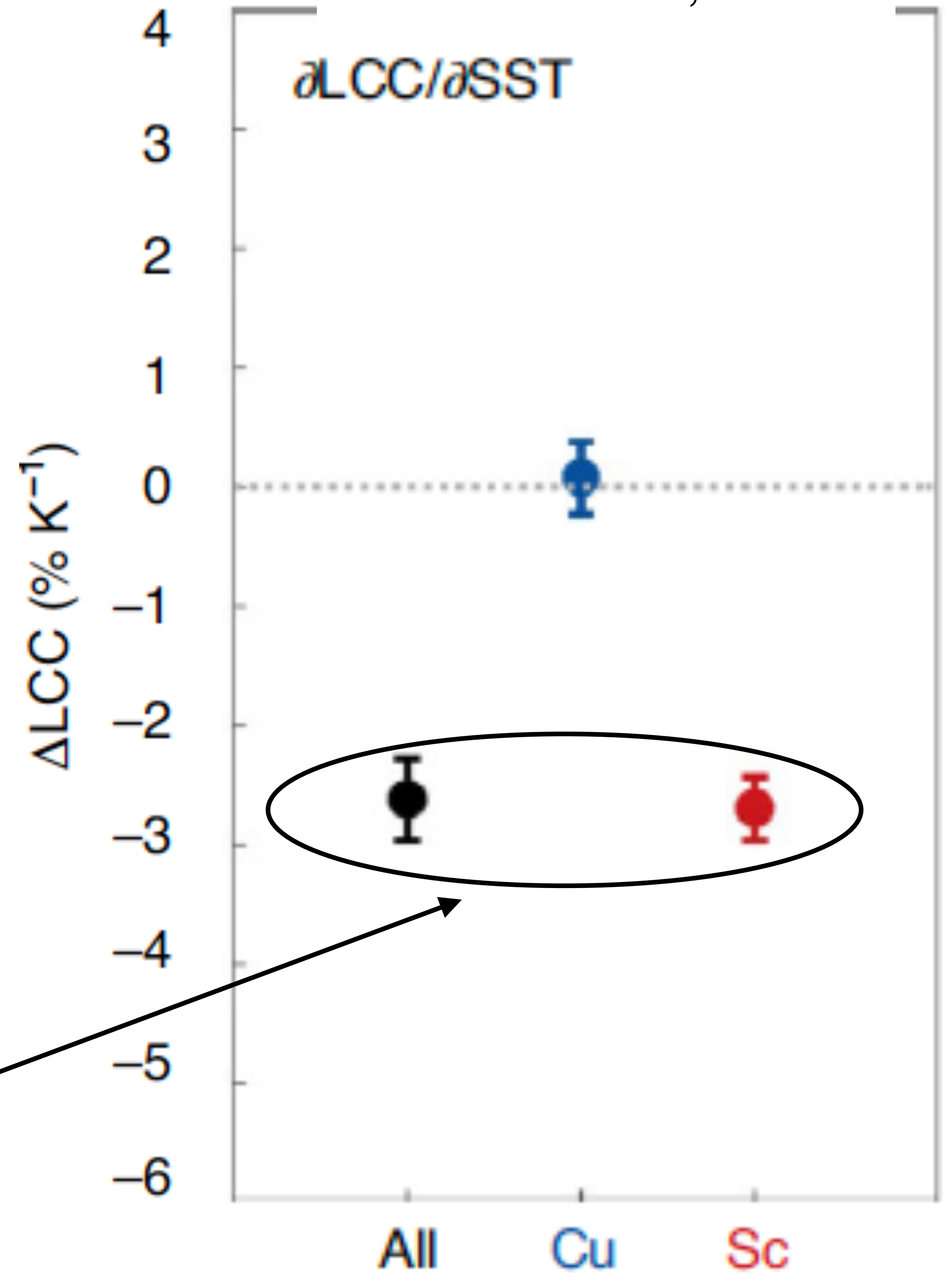
➡ Positive feedback

=

Slightly positive low cloud feedback
with important inter-model spread

➡ Need for a process-level understanding !

(Cesana et al, 2021



2.3 Tropical low clouds feedbacks: cloud controlling factors

Subtropical marine low-cloud feedback	N/A (*low confidence*) AR5	Positive (*high confidence*) AR6 $0.2 \pm 0.16\ \mathrm{W\ m^{-2}\ °C^{-1}}$

Decomposition of the low cloud cover response in climate models into a sum of 2 local controlling factors: *Qu et al, 2014*

$$\Delta LCC = \left(\frac{\partial LCC}{\partial EIS}\right)\Delta EIS + \left(\frac{\partial LCC}{\partial SST}\right)\Delta SST$$ with:

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2. SST: Sea Surface Temperature

Increasing EIS under global warming

- Increased cloud cover in observations (+ stratocumulus)

  ➡ Negative feedback

+

Increasing SST under global warming

- Decreased cloud cover in obervations (-stratocumulus)

  ➡ Positive feedback

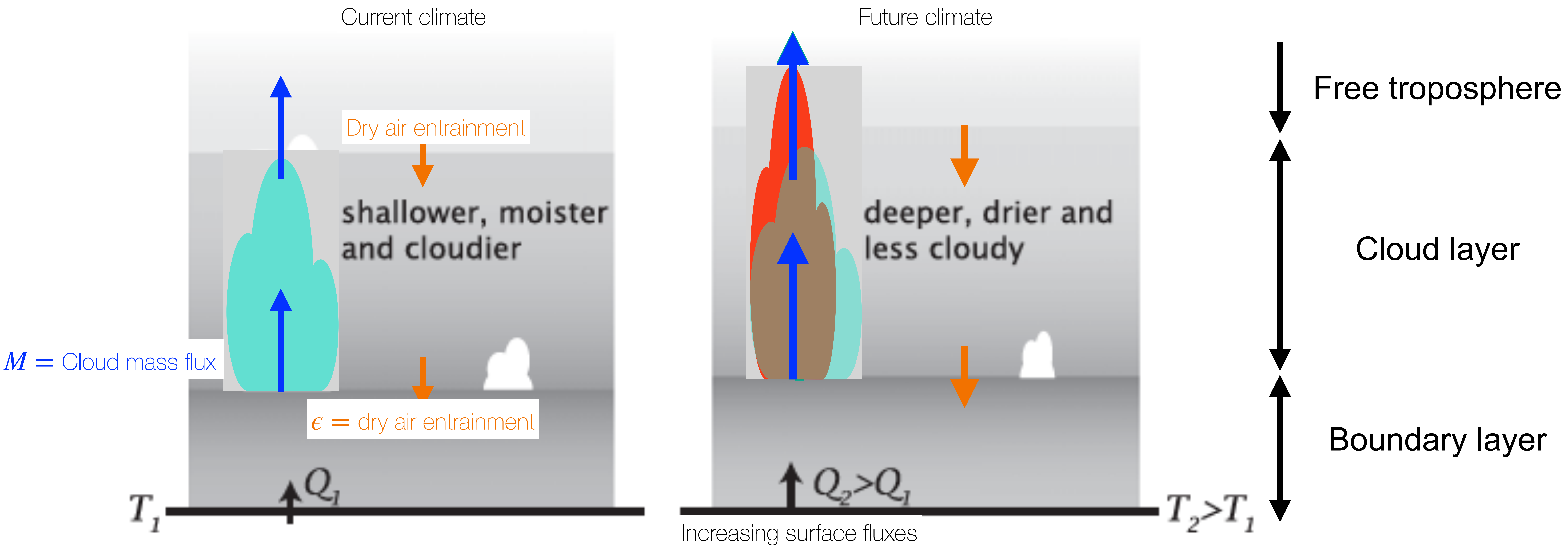
=

Slightly positive low cloud feedback with important inter-model spread ➡ **Need for a process-level understanding !**

2.3 Tropical low clouds feedbacks: surface flux dessication feedback

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

Sketch of the cumulus cloud response to warming *Rieck et al, 2012*



Increasing surface fluxes lead to more mixing between low levels and the troposphere

- BL deepening and drying
- Less cloud cover (LCC decrease)

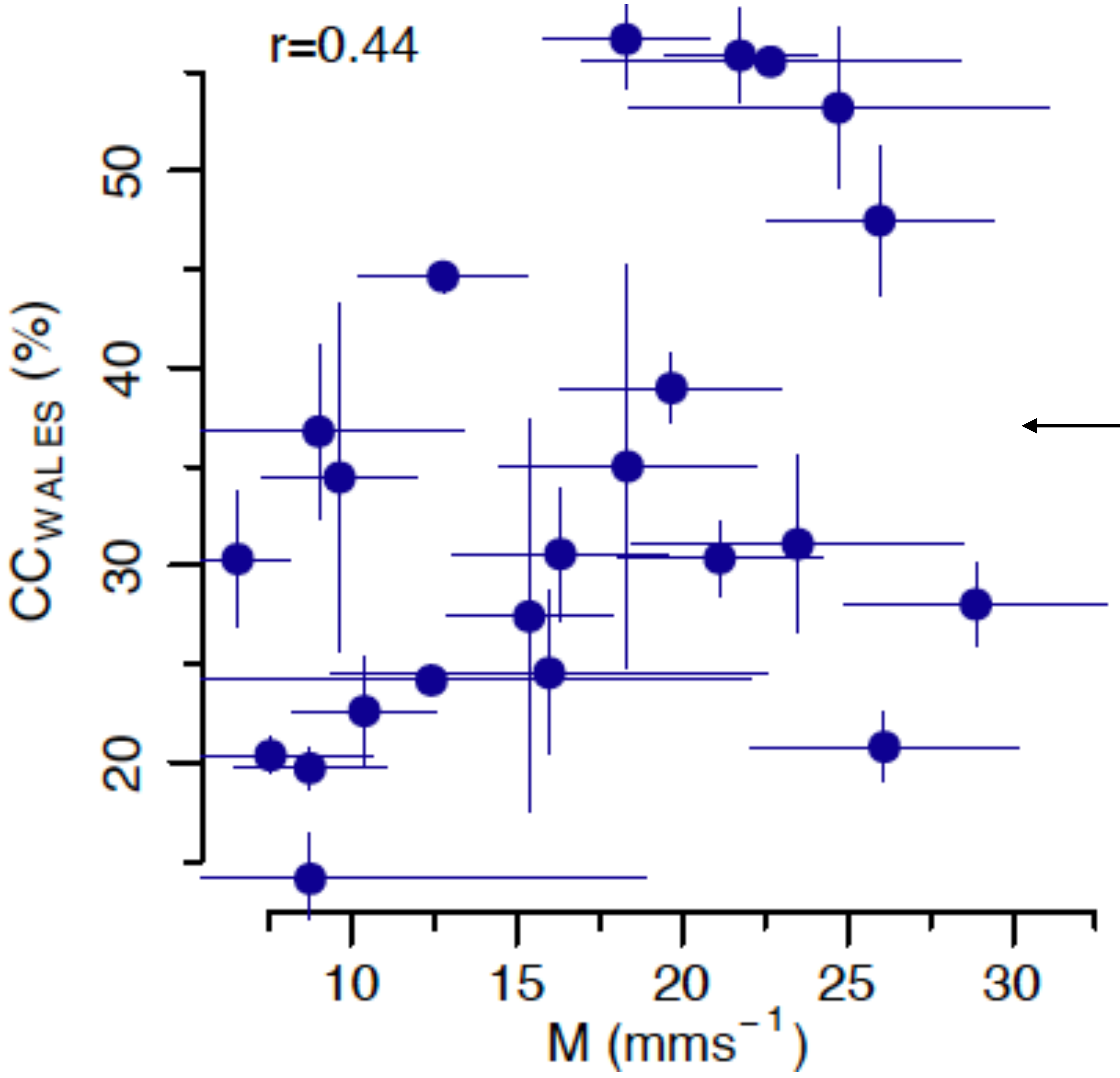
➡ Positive feedback

Suggests a negative correlation between M and LCC

2.3 Tropical low clouds feedbacks: refutation of the dessication mechanism for cumulus clouds

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} $°C^{-1}$

Scatterplot of cloud cover (CC) against cloud base mass flux (M) in observations



Vogel et al, 2022, accepted in Nature

Positive correlation between LCC and M in observations

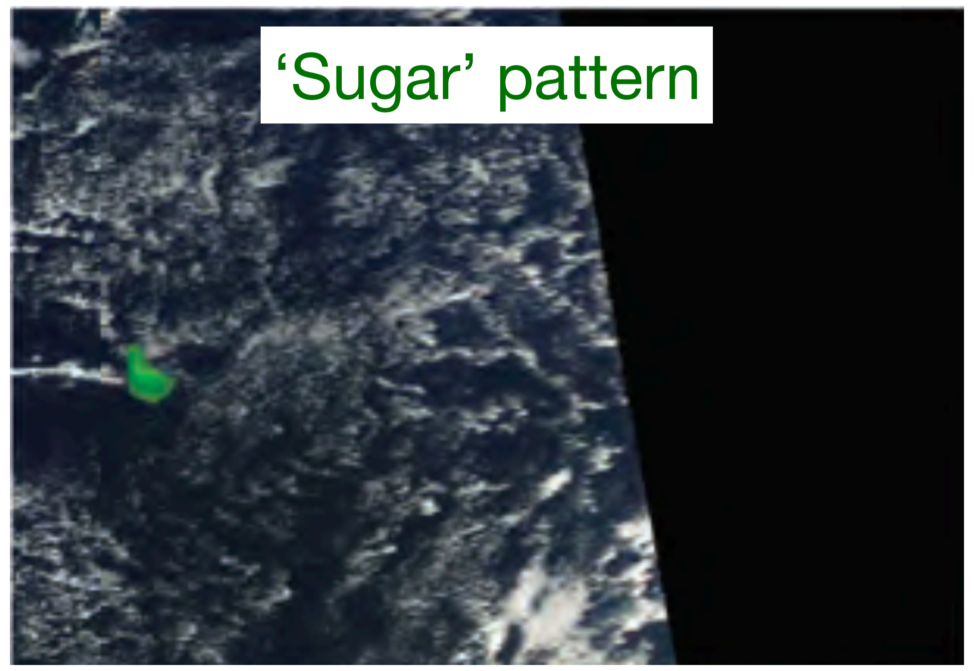
Recent observations refutes mixing dessication mechanism for cumulus clouds

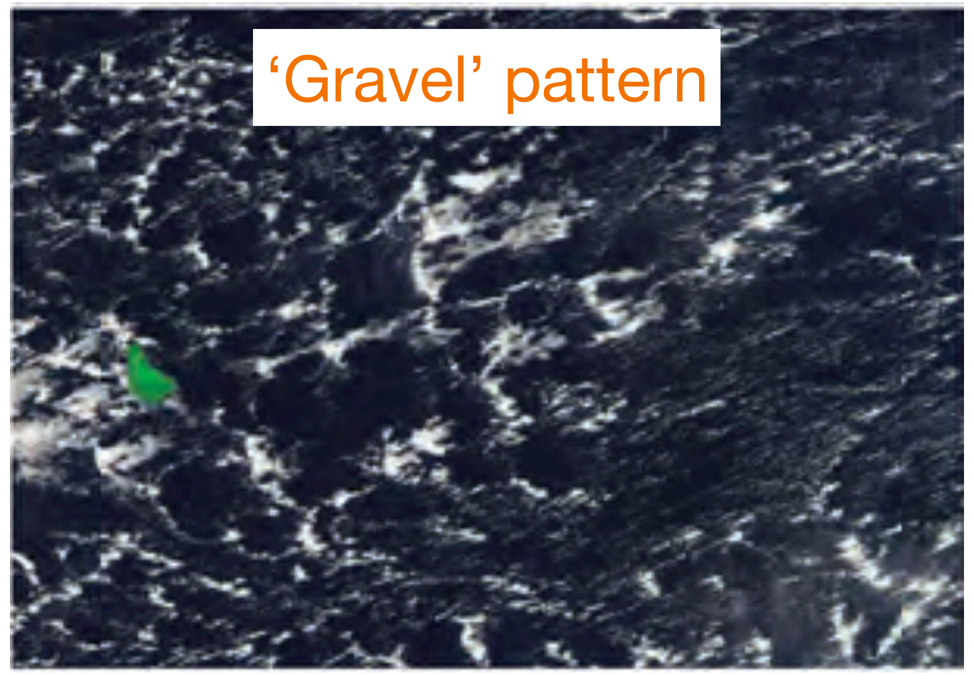
2.3 Tropical low clouds feedbacks: shallow convection aggregation

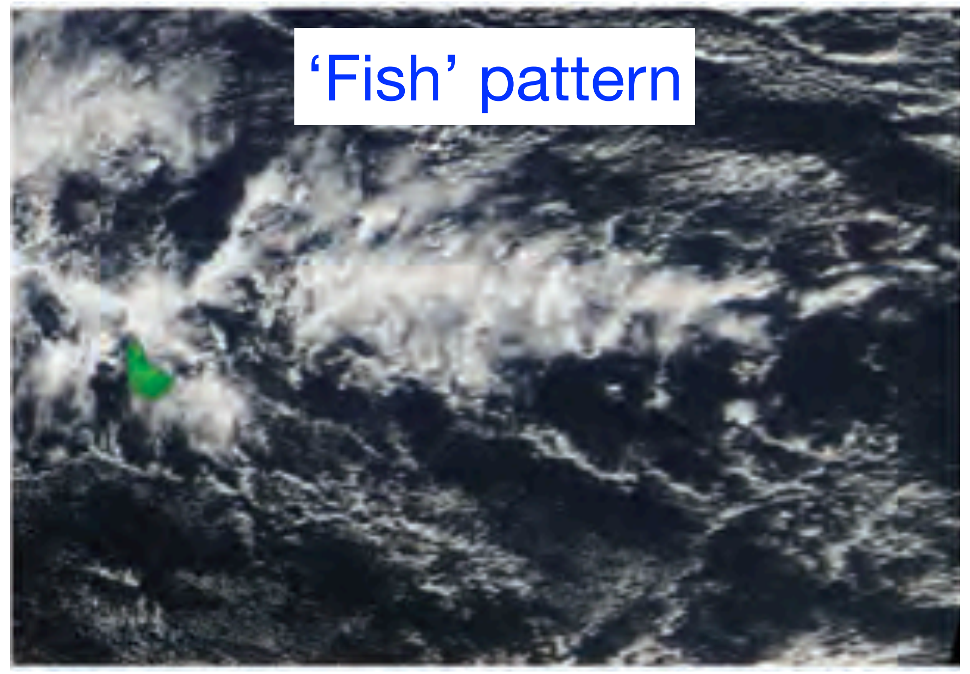
Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}

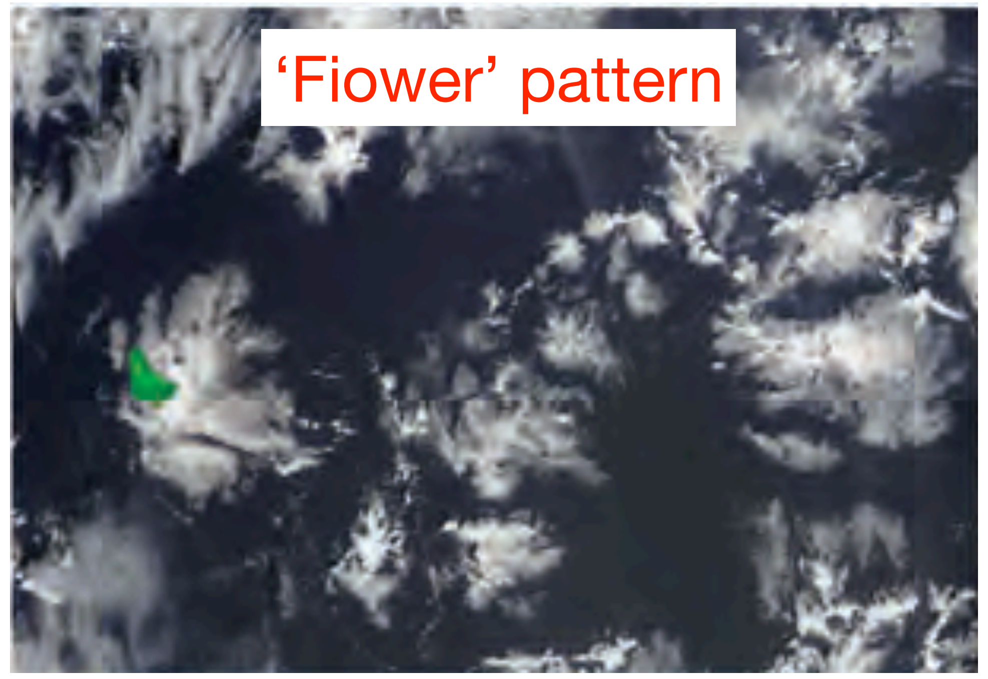
Mesoscale shallow cloud patterns identified during the EUREC4A campaign (Barbados Jan-Feb 2020)

Stevens et al, 2020

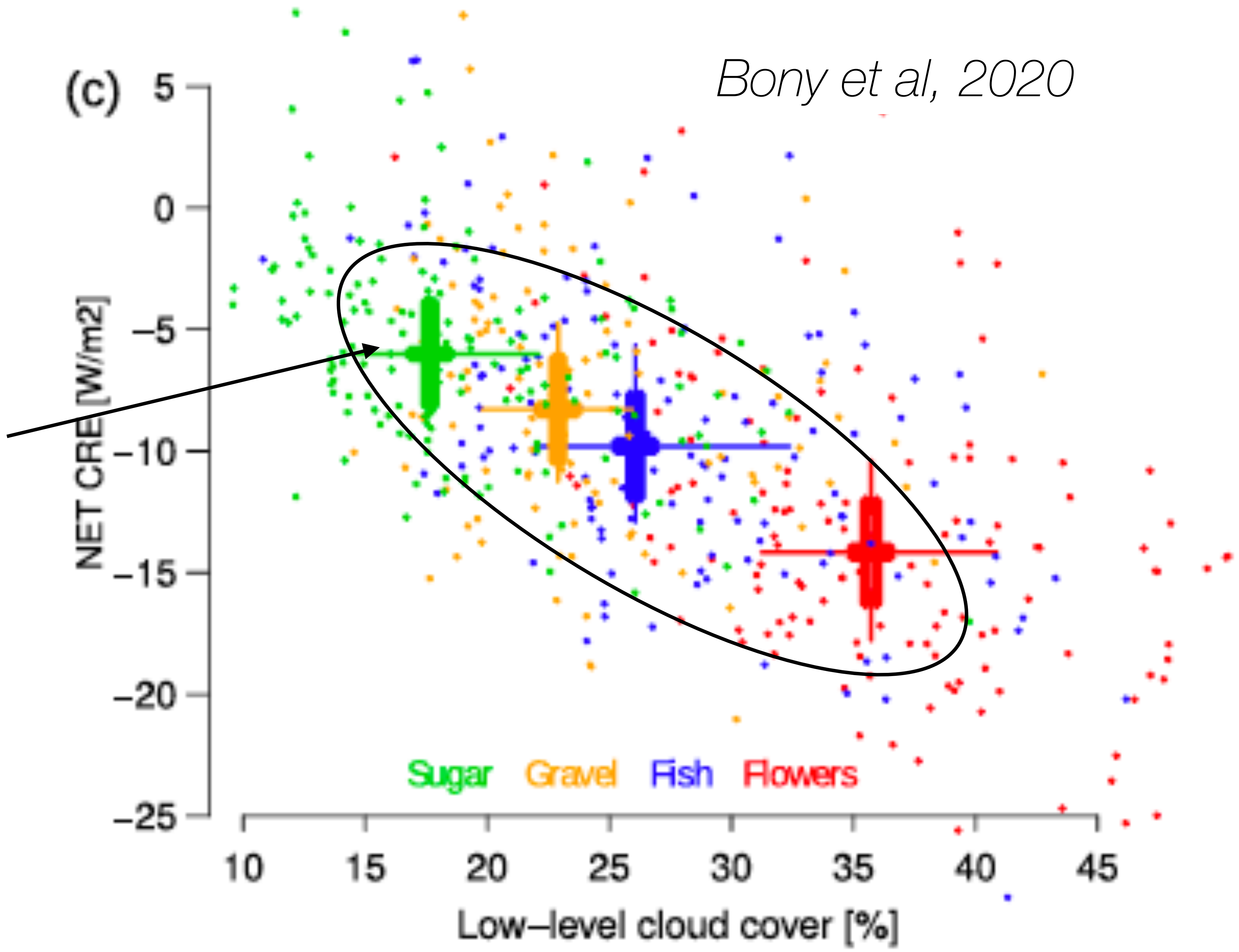








4 recurrent mesoscale coud patterns identified in recent observations



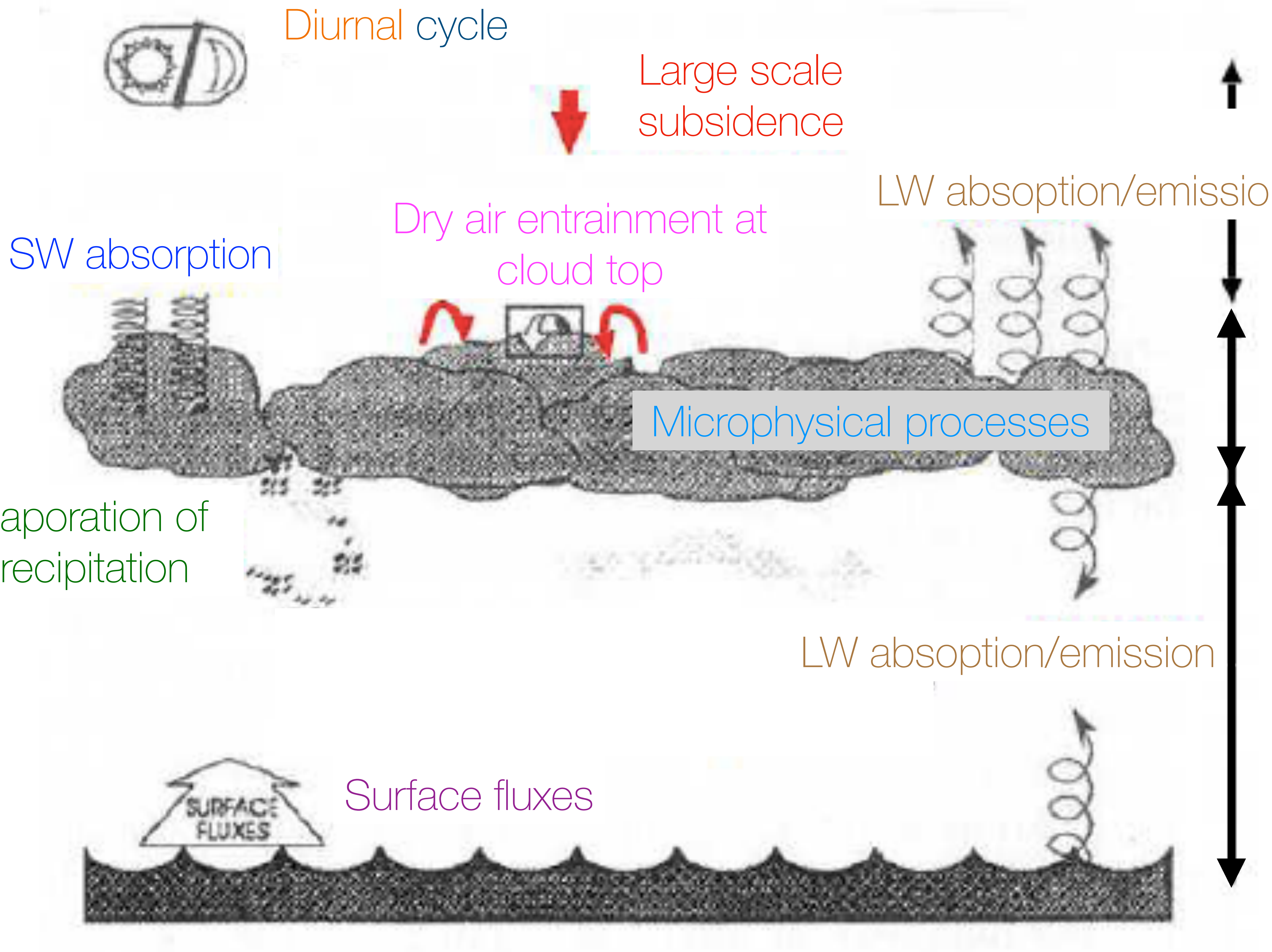
Bony et al, 2020

High sensitivity of the cloud radiative effect (CRE) to these patterns

➡ How these patterns will change under global warming ?

2.3 Tropical low clouds feedbacks: BL small scale processes

Subtropical marine low-cloud feedback	N/A (*low confidence*)	AR5	Positive (*high confidence*)	AR6	0.2 ± 0.16 W m^{-2} °C^{-1}



Diurnal cycle

Large scale subsidence

Free troposphere

LW absoption/emission

SW absorption

Dry air entrainment at cloud top

Cloud layer

Microphysical processes

Evaporation of precipitation

LW absoption/emission

Boundary layer

Surface fluxes

Very complex interactions between the surface, the boundary layer, the cloud layer et the free troposphere

- GCM struggle to represent these subtle couplings ⟹ model biases
- GCM represent these couplings in very various ways ⟹ inter-model spread

Part 2 - Clouds in a changing climate

2.1 Tropical high clouds altitude feedback

2.2 Tropical high clouds amount feedback

2.3 Tropical low clouds feedback

2.4 Midlatitude cloud amount feedback

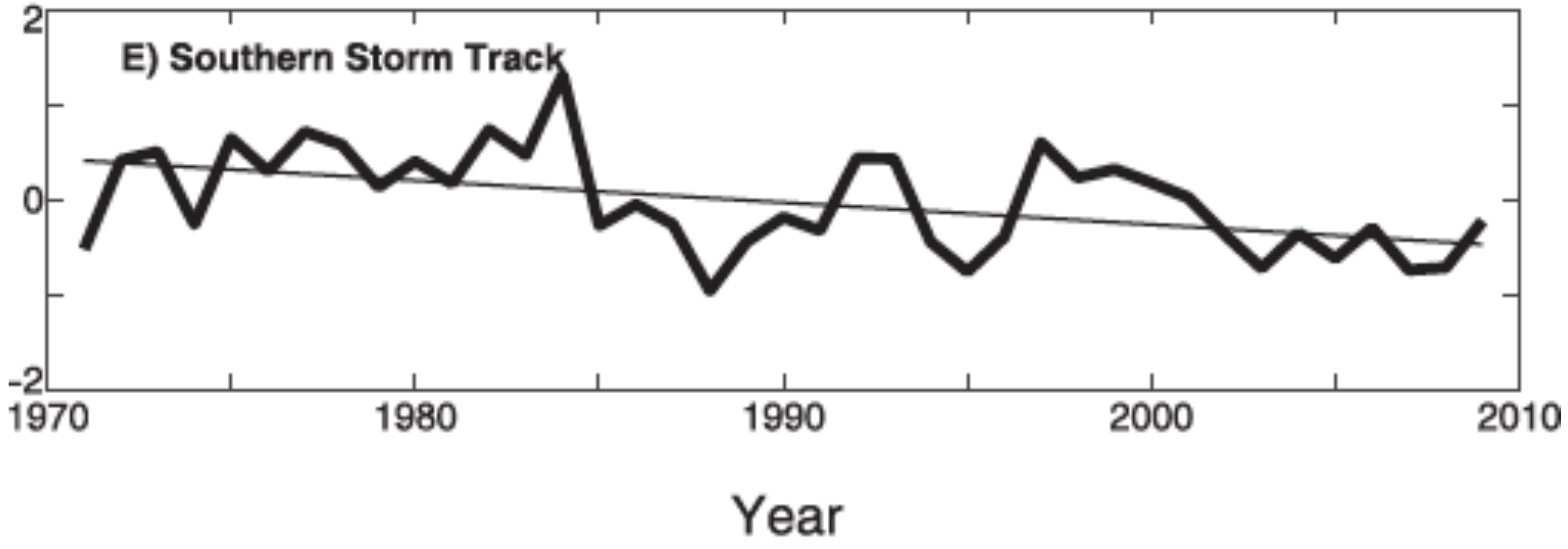
2.5 Extratropical cloud optical depth feedback

2.6 Sum up

2.4 Midlatitude cloud amount feedback: poleward shift of storm tracks

Latitudinal cloudiness 'center of mass' time evolution

Eastman and Warren, 2013



Tropical belt expansion and poleward shift of midlatitude jets in observations (satellite and ground based)

➡ Positive or negative feedback ?

2.4 Midlatitude cloud amount feedback: poleward shift of storm tracks

Latitudinal cloudiness 'center of mass' time evolution

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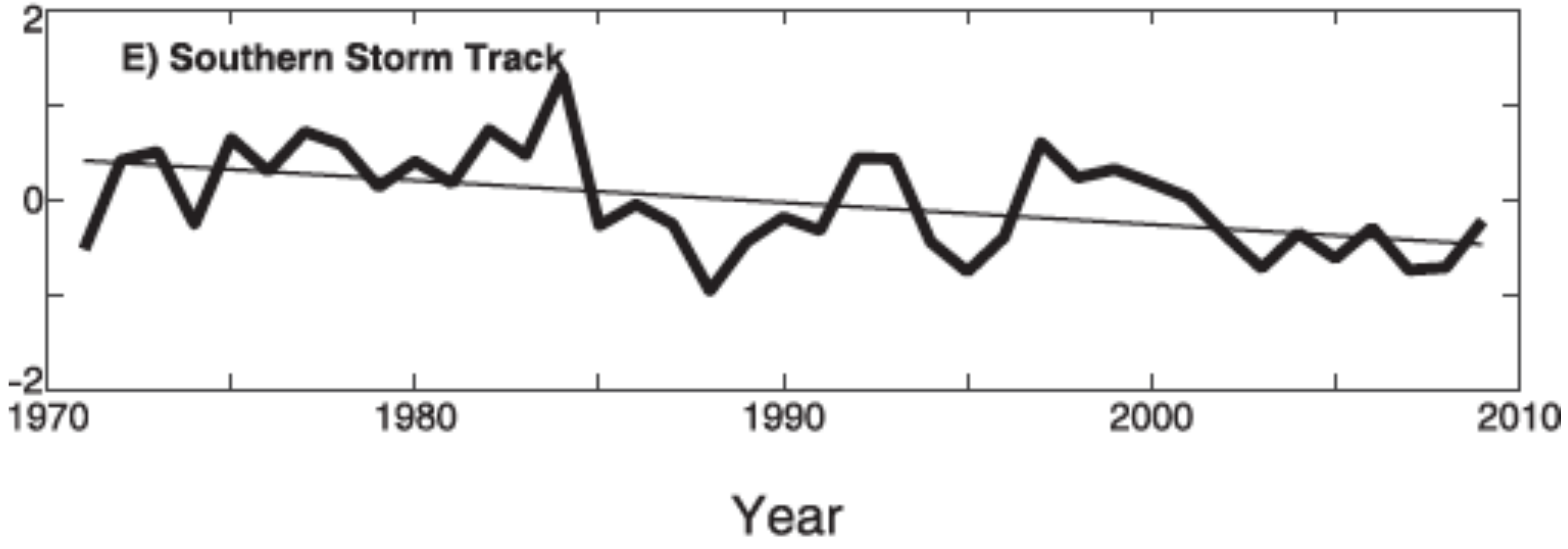


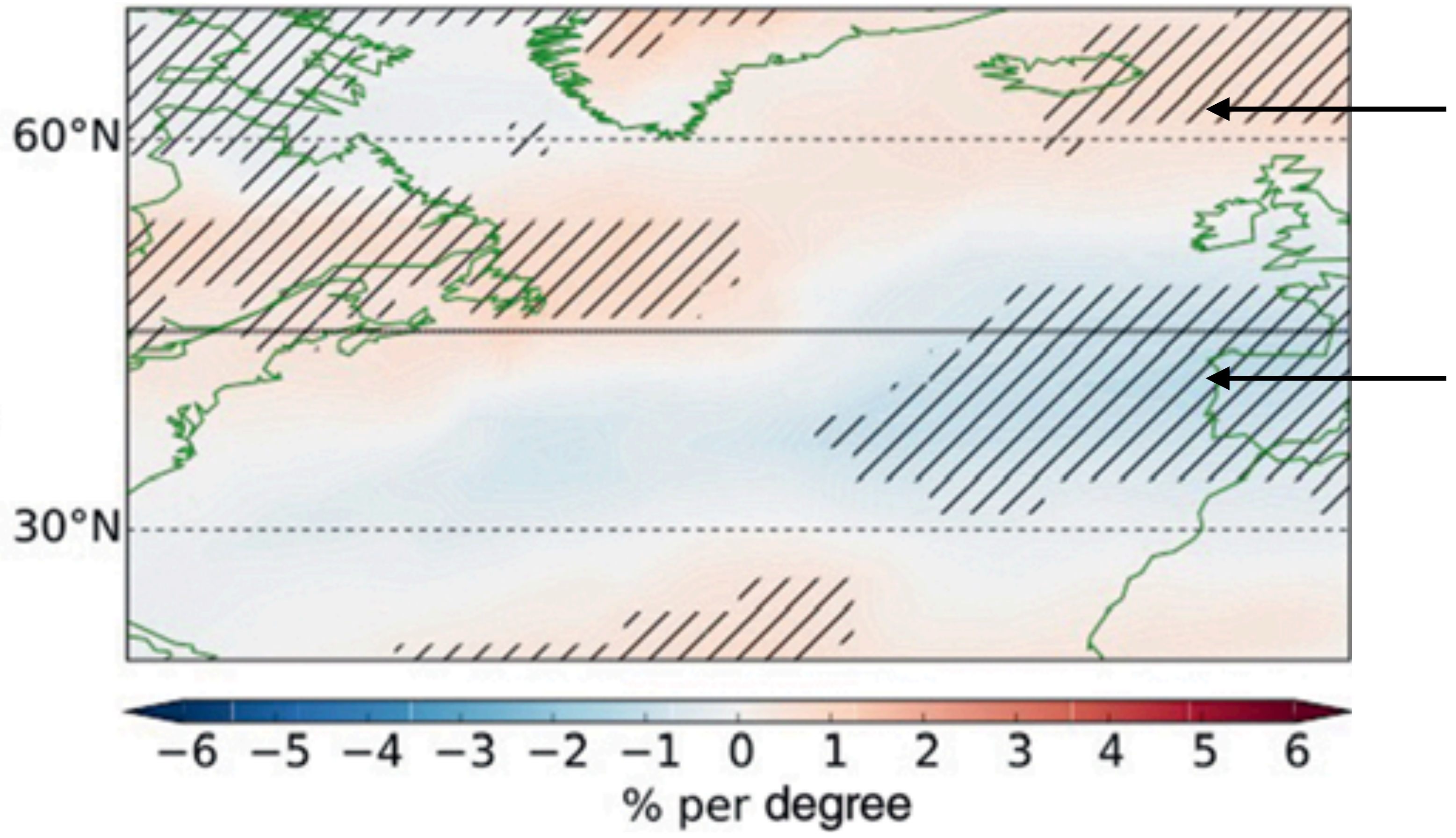
Tropical belt expansion and poleward shift of midlatitude jets in observations (satellite and ground based)

➡ Positive or negative feedback ? … quite subtle (again)

2.4 Midlatitude cloud amount feedback: poleward shift of storm tracks

Effect of a 1° poleward shift on the jet in long-term satellite observations *Tselioudis et al, 2016*

High cloud cover change

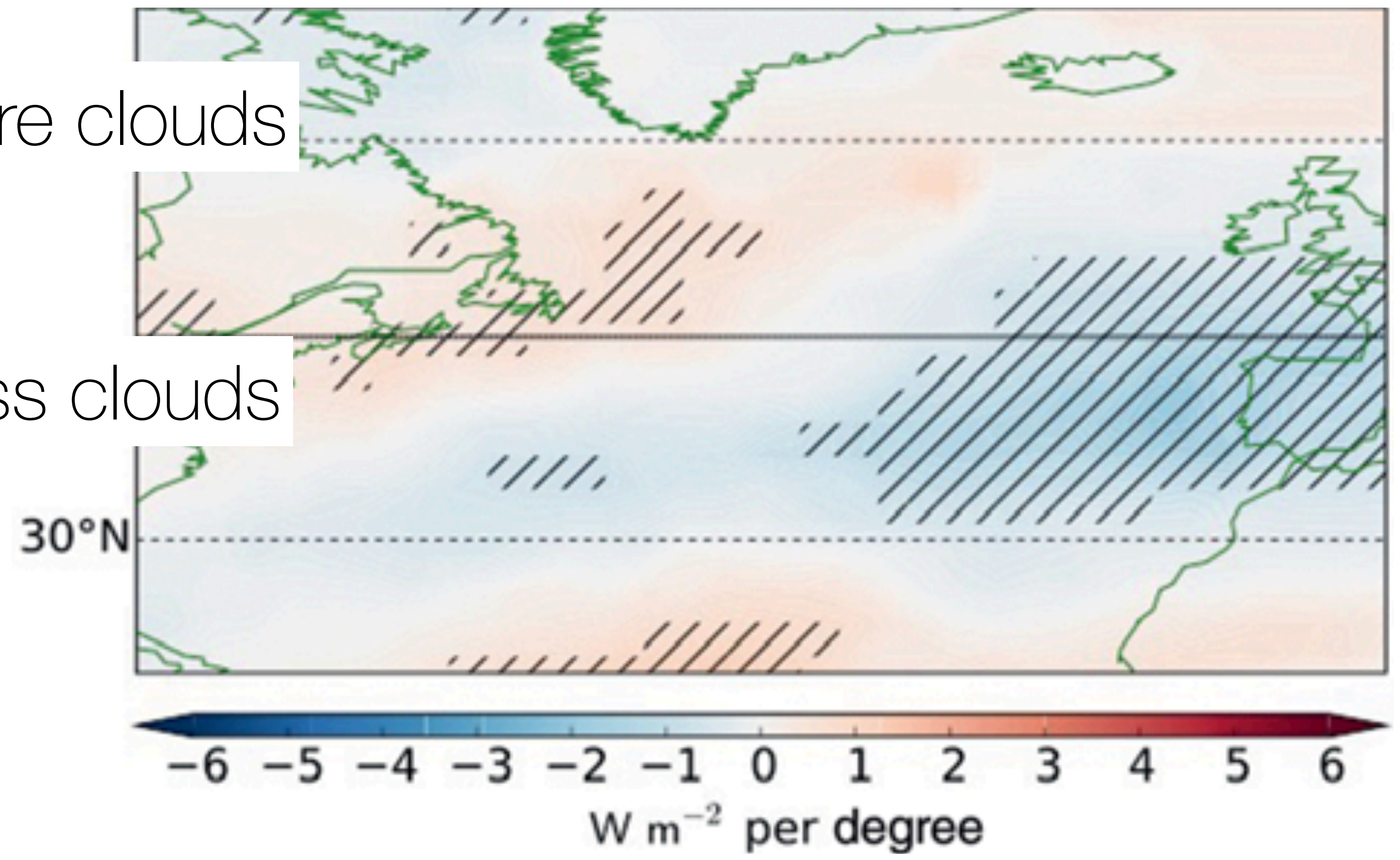


More clouds

Less clouds

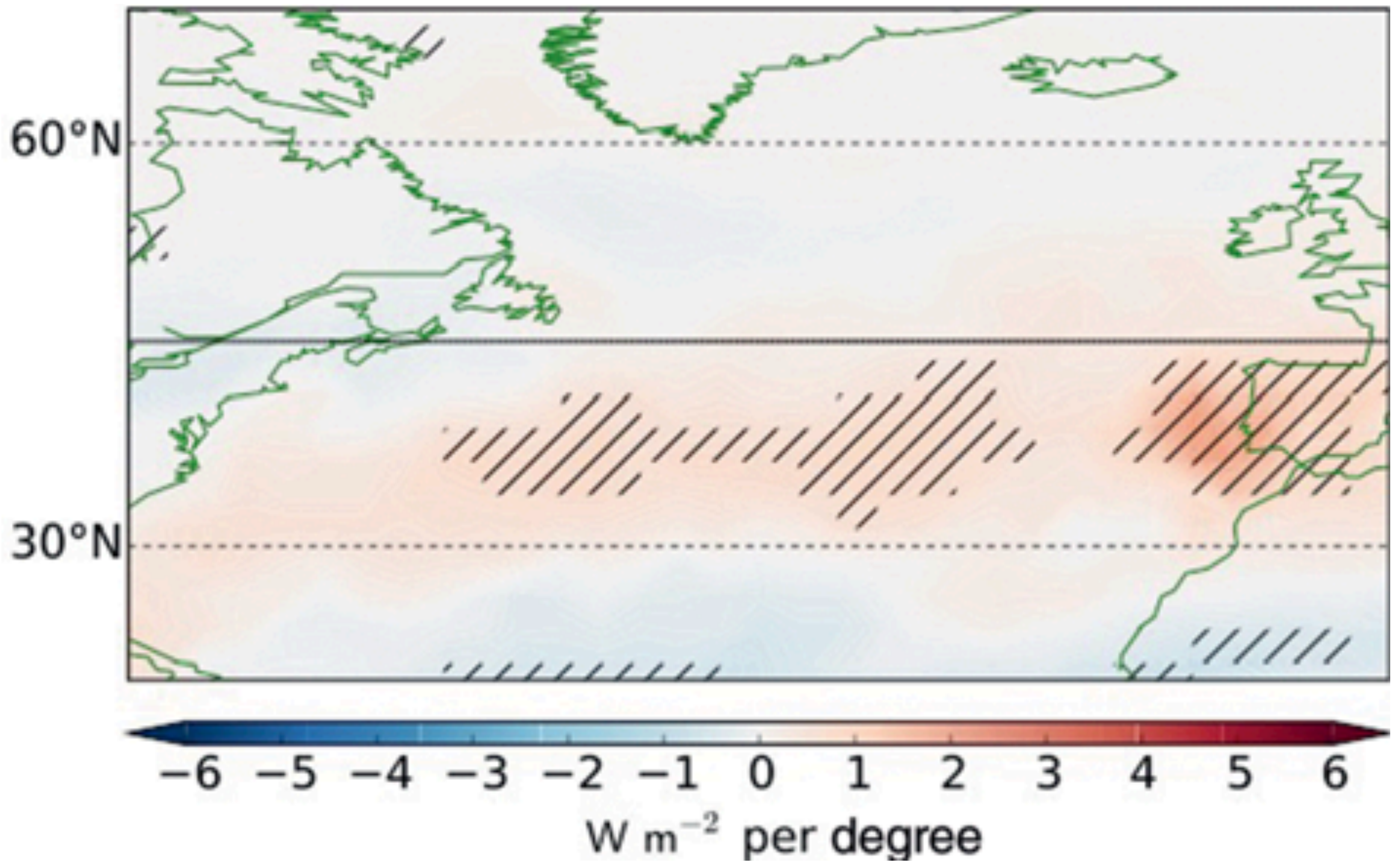
Poleward shift of storm tracks

LW CRE change



Poleward shift of LW CRE pattern

SW CRE change



Poleward shift of SW CRE pattern

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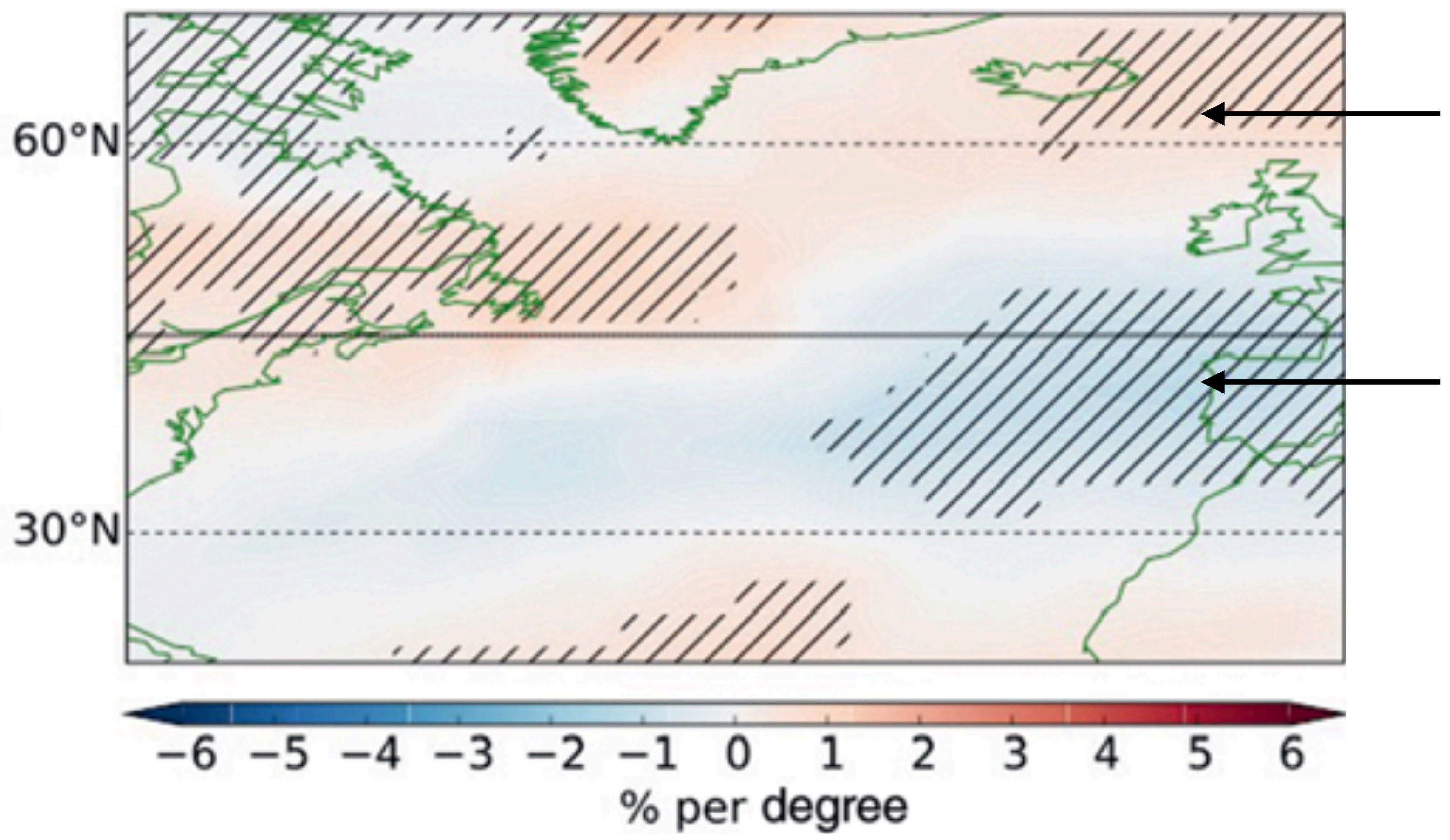

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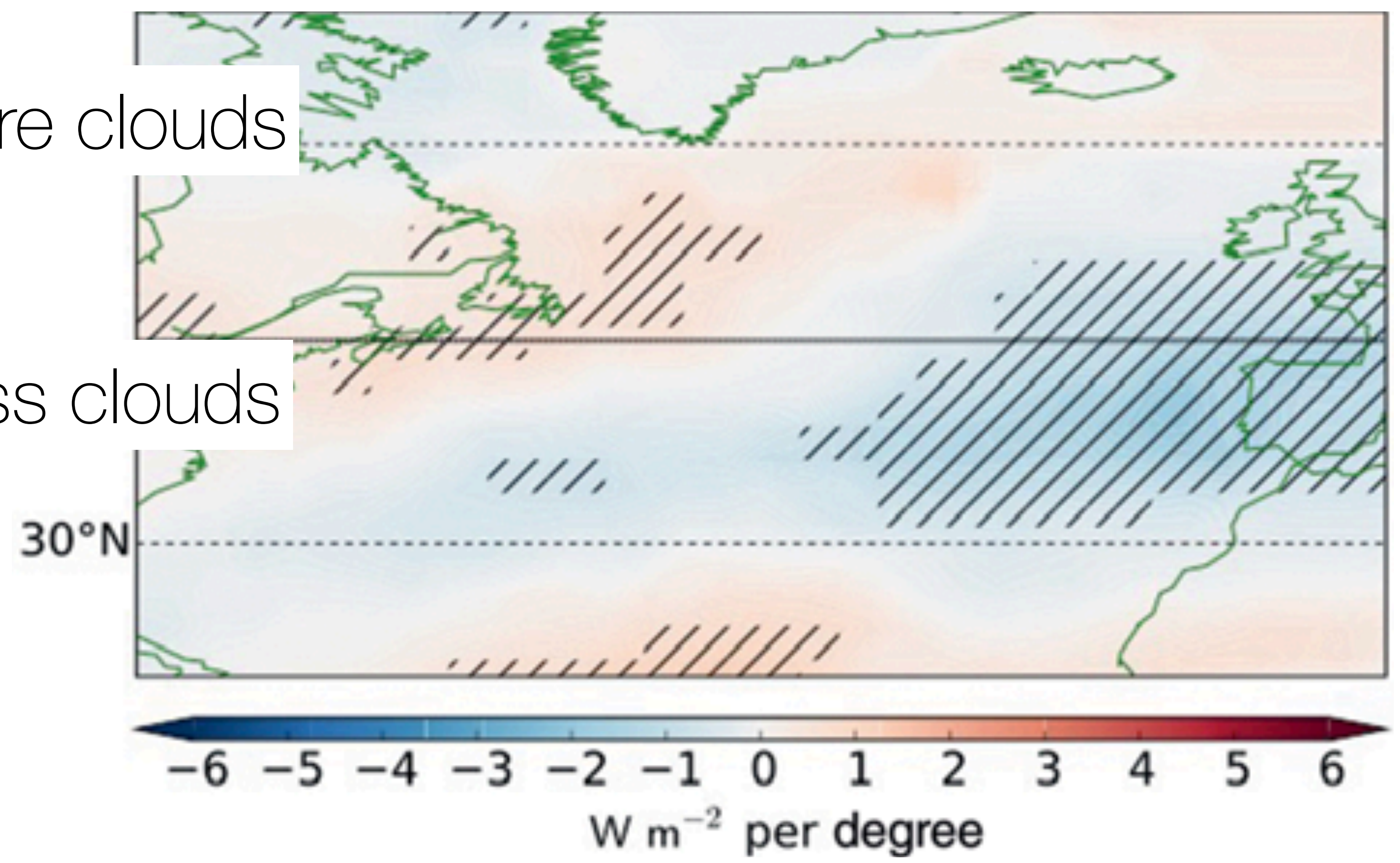

Poleward shift of LW CRE pattern

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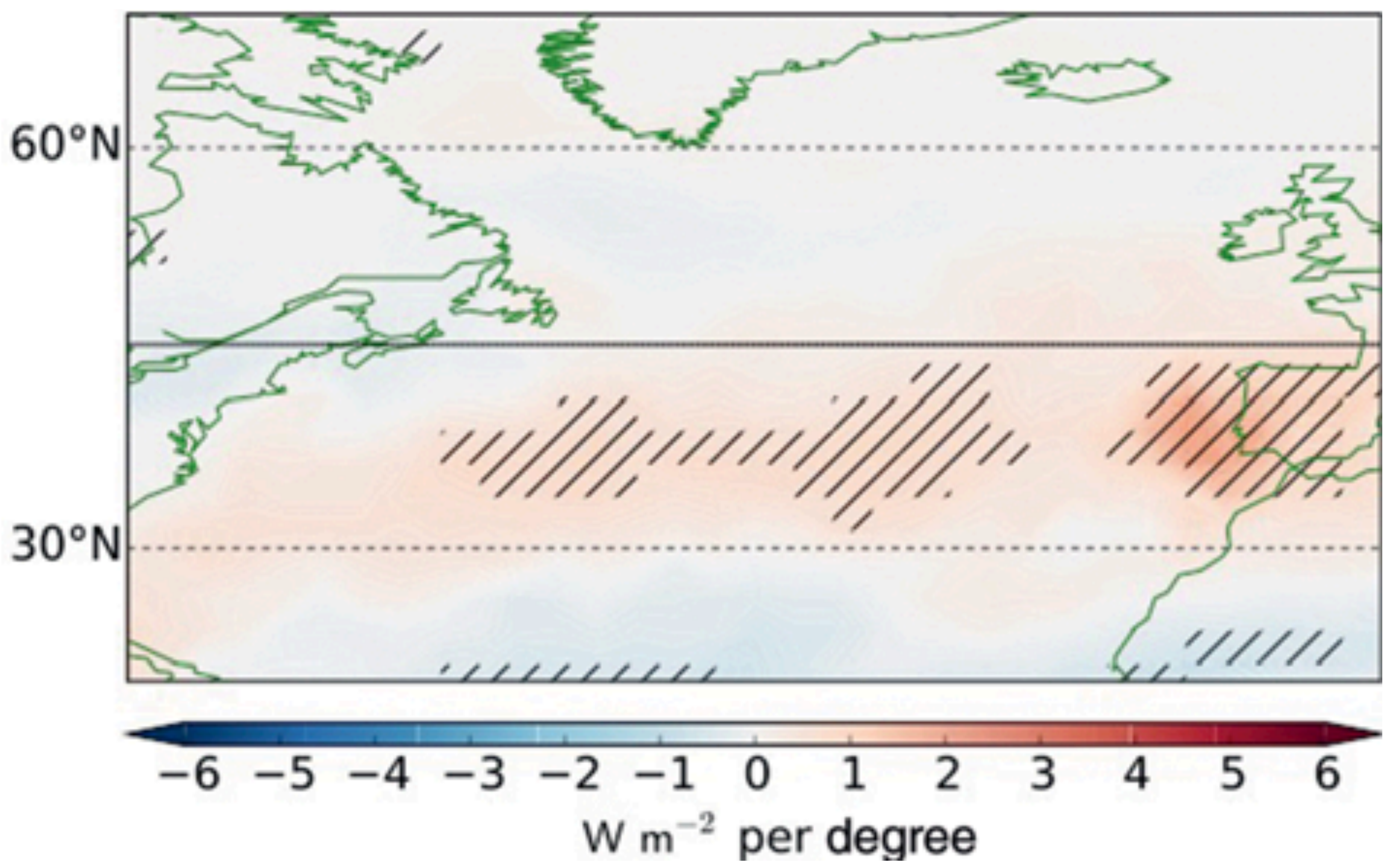


Poleward shift of SW CRE pattern

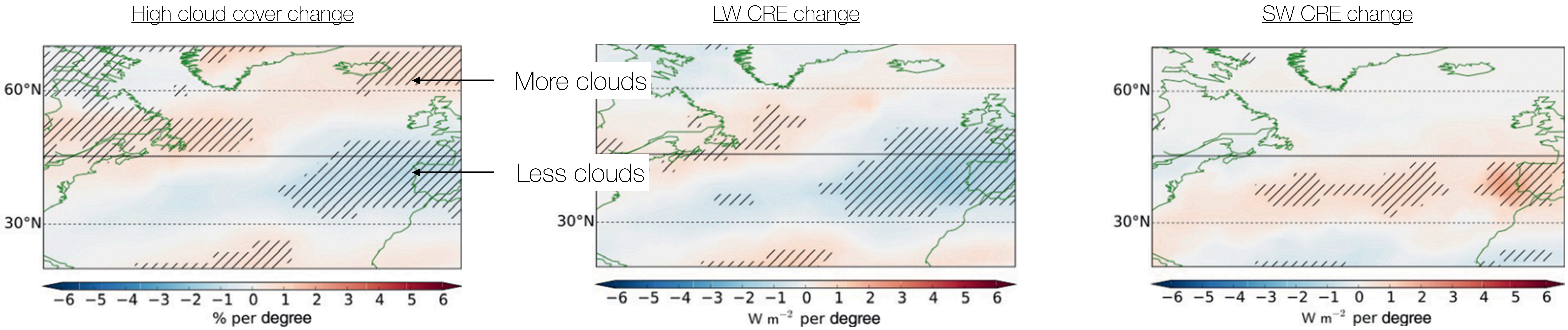
Near cancellation of these 2 effects in the mid-latitudes

⟹ **Very modest positive feedback**

2.4 Midlatitude cloud amount feedback: poleward shift of storm tracks

Mid-latitude cloud amount feedback	Positive (*medium confidence*)	AR5	Positive (*medium confidenc*	AR6	0.09 ± 0.1 W m^{-2} $°C^{-1}$

Effect of a 1° poleward shift on the jet in long-term satellite observations *Tselioudis et al, 2016*



Poleward shift of storm tracks

Poleward shift of LW CRE pattern

Poleward shift of SW CRE pattern

Near cancellation of these 2 effects in the mid-latitudes

⟹ Very modest positive feedback

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2.6 Sum up

2.5 Extratropical cloud optical depth feedback

From observations (Tan et al, 2019): more liquid water in clouds (and less ice particles) under surface warming

➡ Positive or negative feedback ?

2.5 Extratropical cloud optical depth feedback

Extratropical cloud optical depth feedback	N/A	AR5	Small negative (*medium confidence*) AR6 -0.03 ± 0.05 W m^{-2} °C^{-}

From observations (Tan et al, 2019): more liquid water in clouds (and less ice particles) under surface warming

➡ **Negative feedback** (increasing cloud optical depth with warming)

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From observations (Tan et al, 2019): more liquid water in clouds (and less ice particles) under surface warming

➡ Negative feedback (increasing cloud optical depth with warming)

BUT

Negative feedback exaggerated by climate models (AR5) due to a persistent bias related to microphysics (Zelinka et al, 2020)

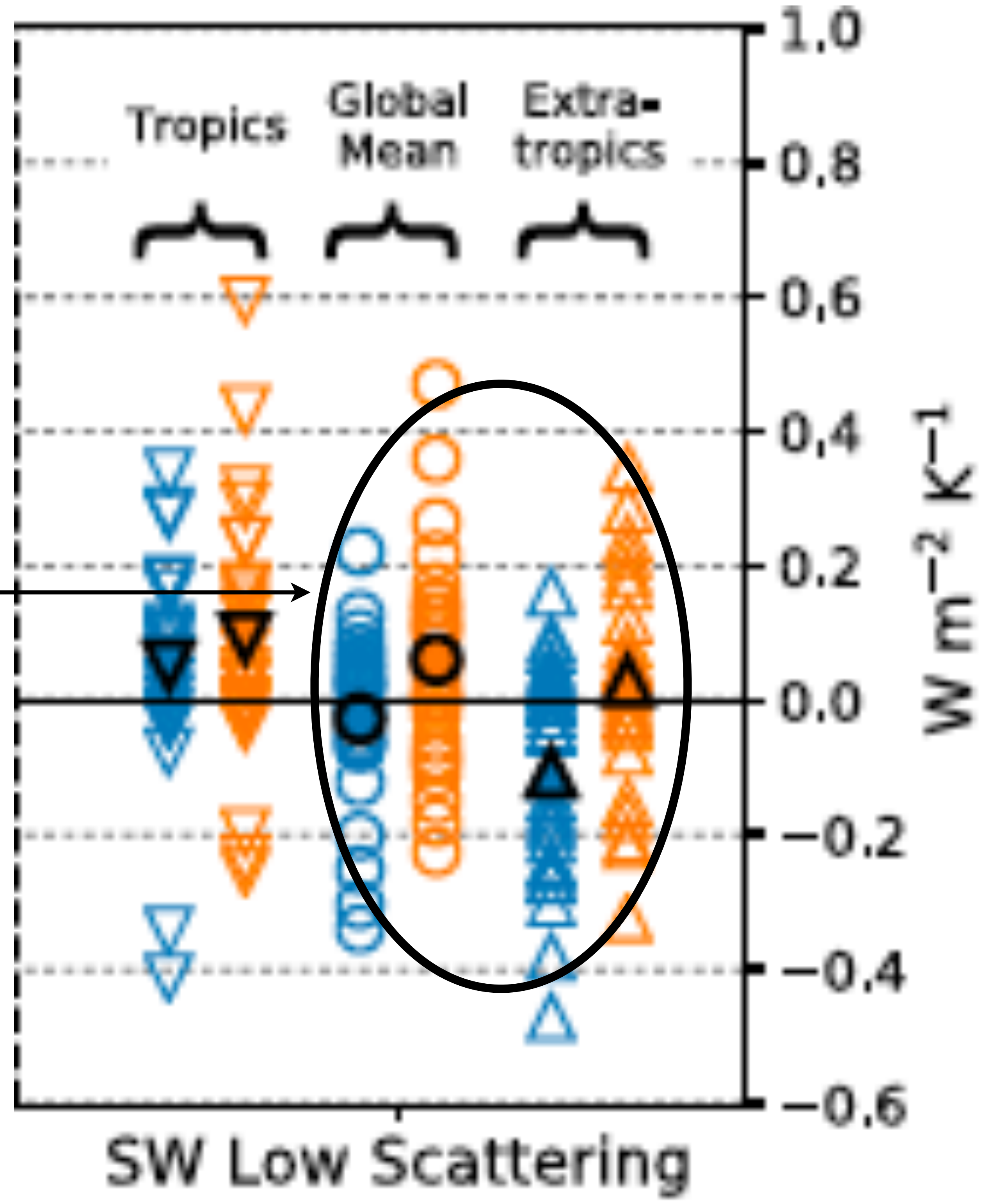
- lack of representation of supercooled liquid droplets
  - ➡ Overestimation conversion from ice to liquid

2.5 Extratropical cloud optical depth feedback

Extratropical cloud optical depth feedback	N/A AR5	Small negative (*medium confidence*) AR6 -0.03 ± 0.05 W m^{-2} °C^{-}

Regional mean SW cloud feedbacks in AR5 and AR6 climate models

Changes in the estimate of the SW cloud feedback mostly coming from extratropical mixed-phased clouds



Zelinka et al, 2020

AR5 models (IPCC 2013)

AR6 models (IPCC 2021)

Improvements in the representation of supercooled liquid droplets in AR6 models

- Less abrupt conversion from ice to liquid at the melting level
- Less increase of ‘warm’ droplets in mixed-phased clouds with warming
- Less increased cloud optical thickness (SW) with warming

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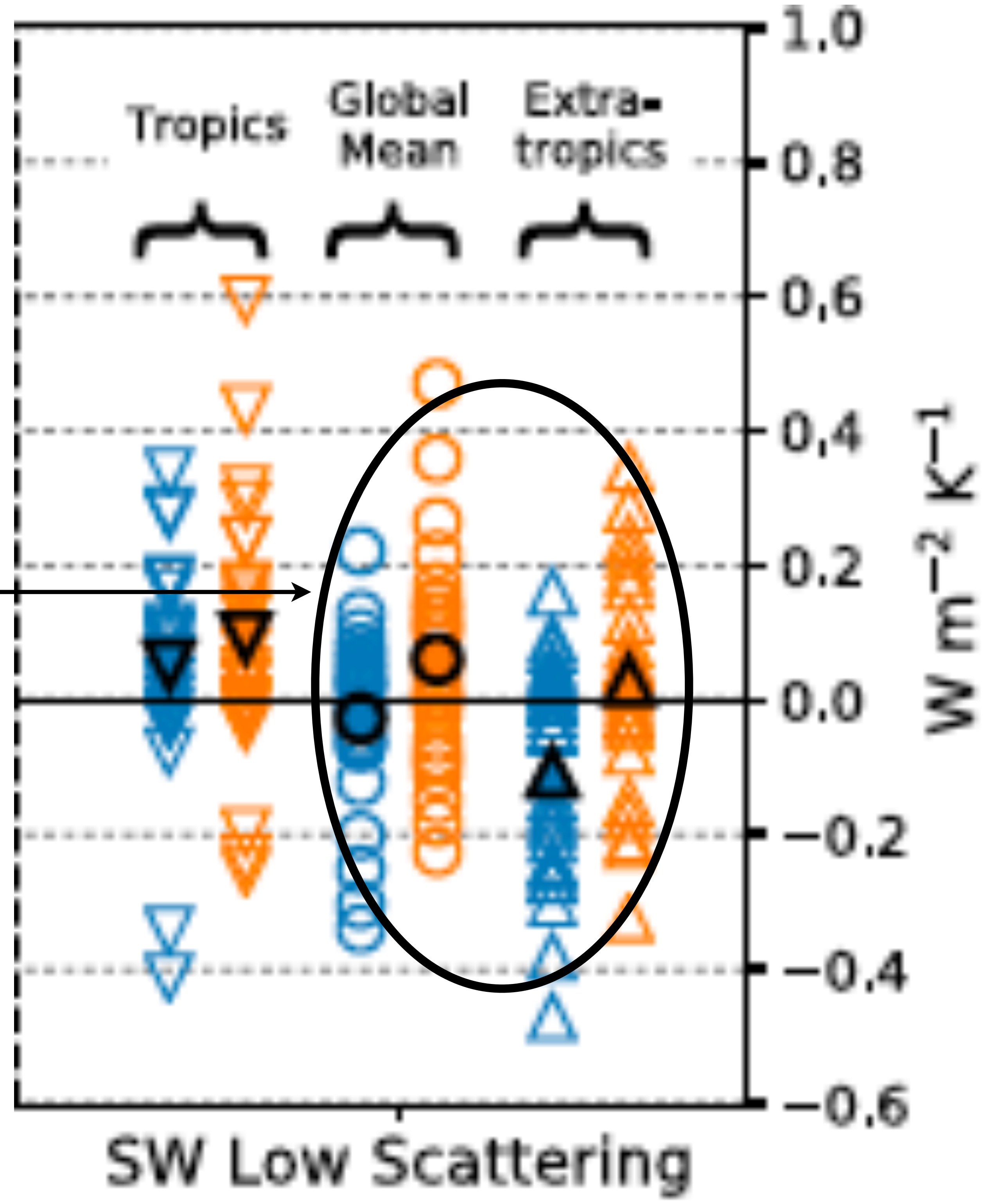

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Less negative feedback

- Acts to increase climate sensitivity of AR6 models !

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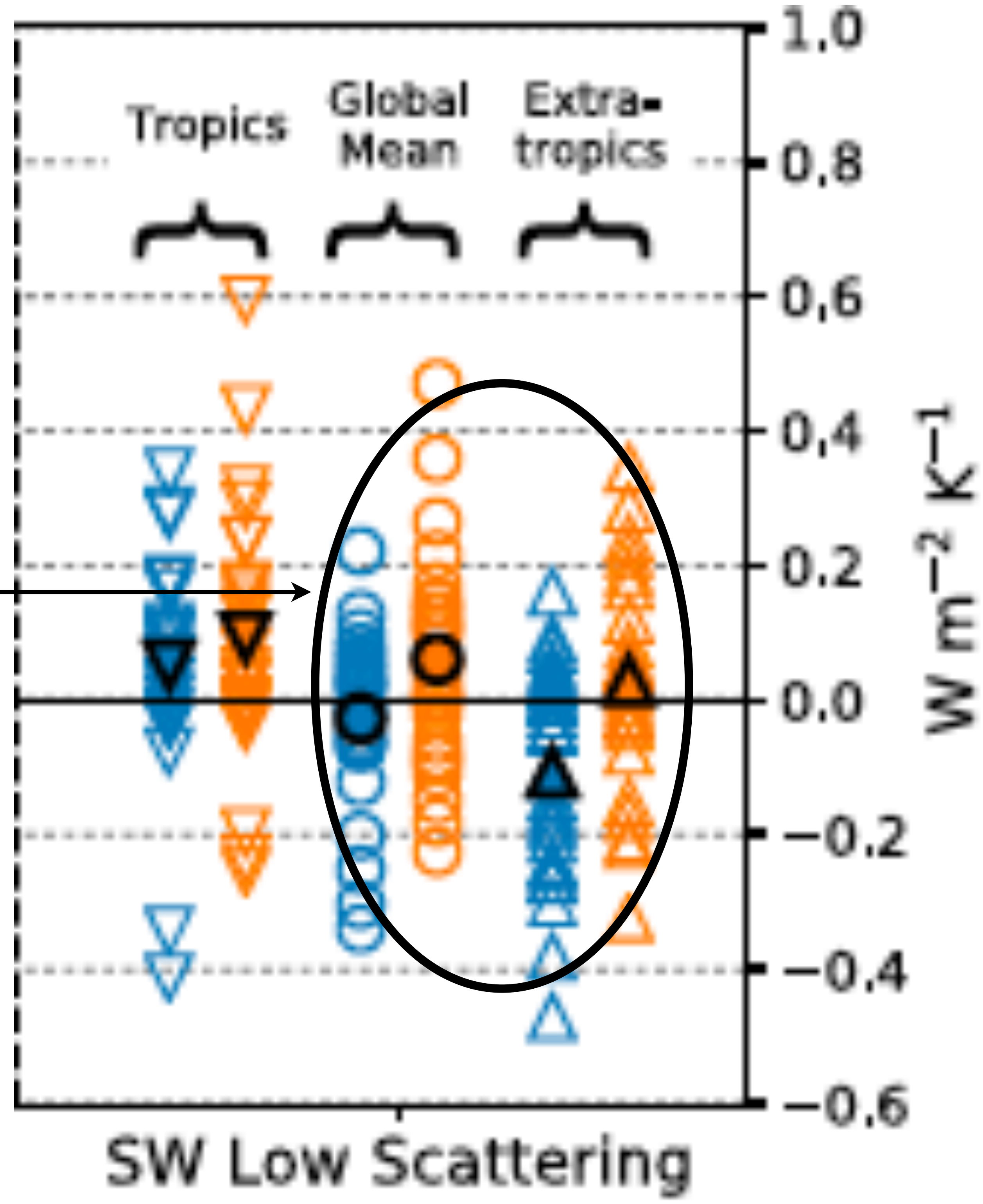

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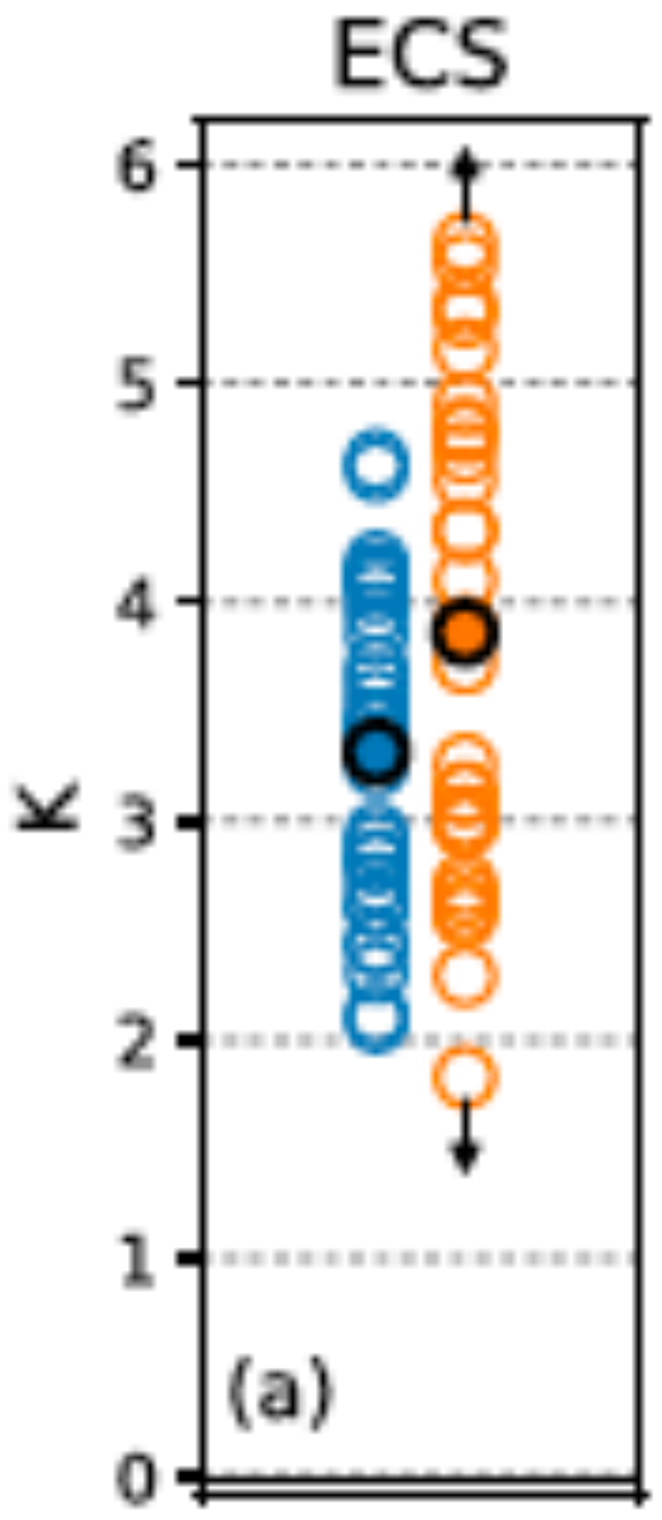

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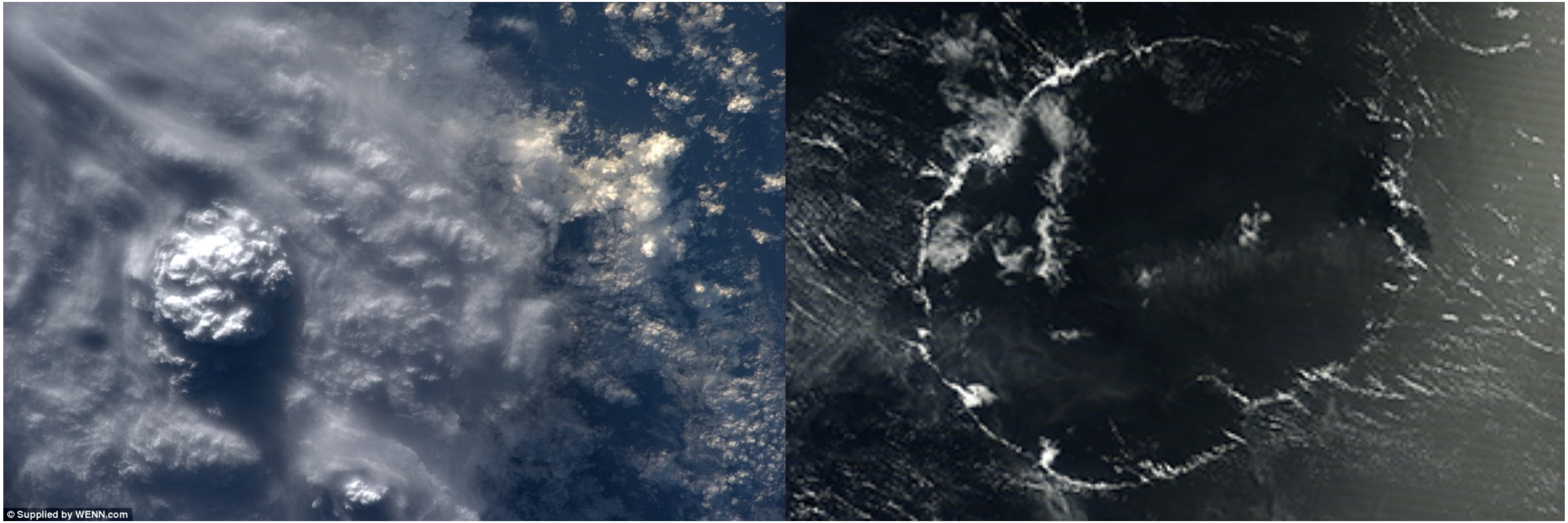
Part 3 - Clouds in models



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Part 3 - Clouds in models

3.1 Scale separation in the physical world

3.2 Scale separation in the numerical world

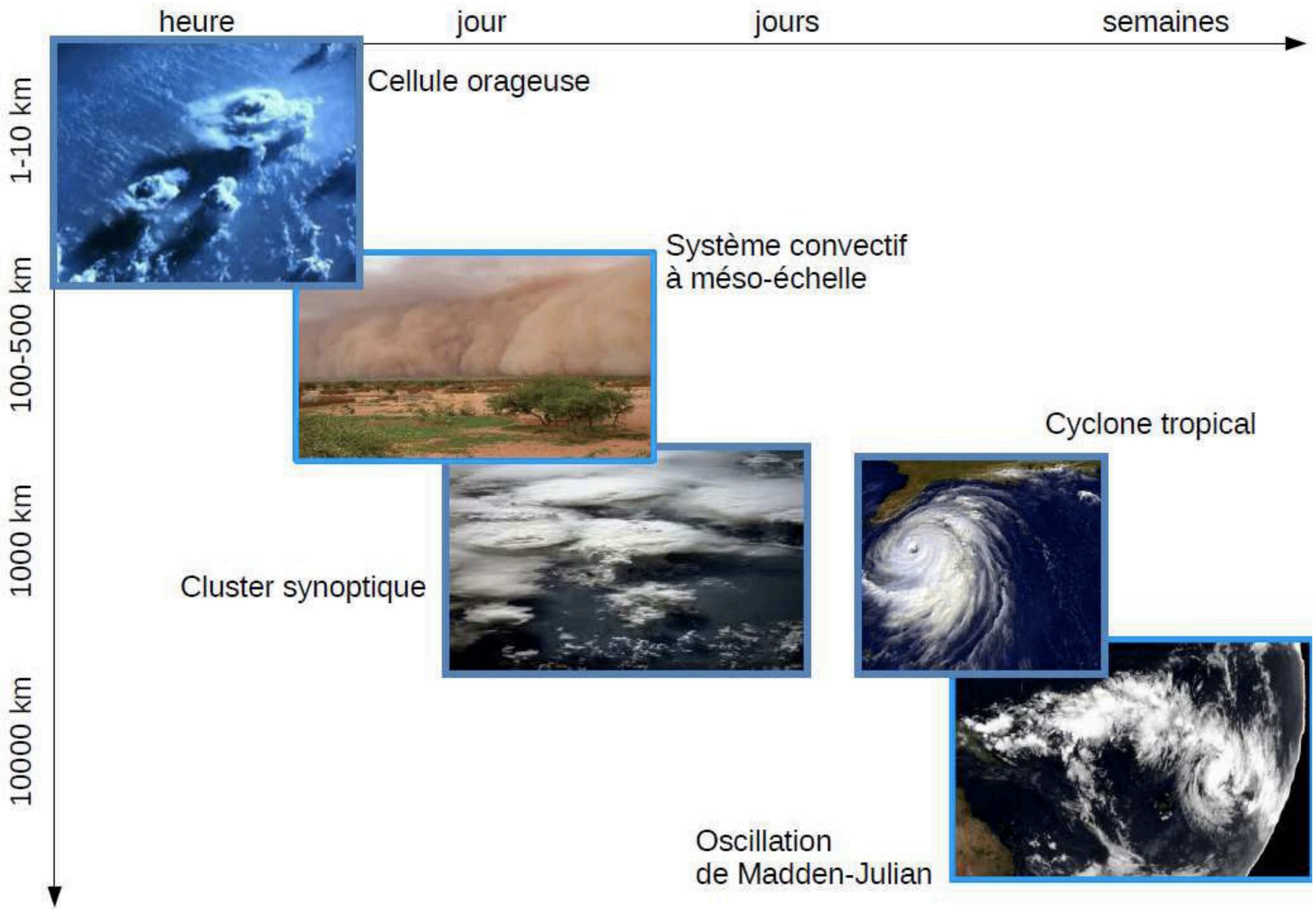
3.3 Between physics and numerics: parameterizations

3.4 What properties of clouds needs to be parameterized ?

3.5 What are climate models missing ?

3.6 Upcoming models and parameterizations

3.1 Scale separation in the physical world: the multiscale nature of clouds



3.1 Scale separation in the physical world: the multiscale nature of clouds

Mesoscake Convective system

$\tau \sim$ **heures and** $\mathscr{L} \sim 100$ **km**

Isolated storm cell

$\tau \sim$ **1 h and** $\mathscr{L} \sim 10$ **km**

Convective cluster

$\tau \sim$ **jours et** $\mathscr{L} \sim 1000$ **km**

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3.2 Scale separation in models: grid spacing as the reference scale

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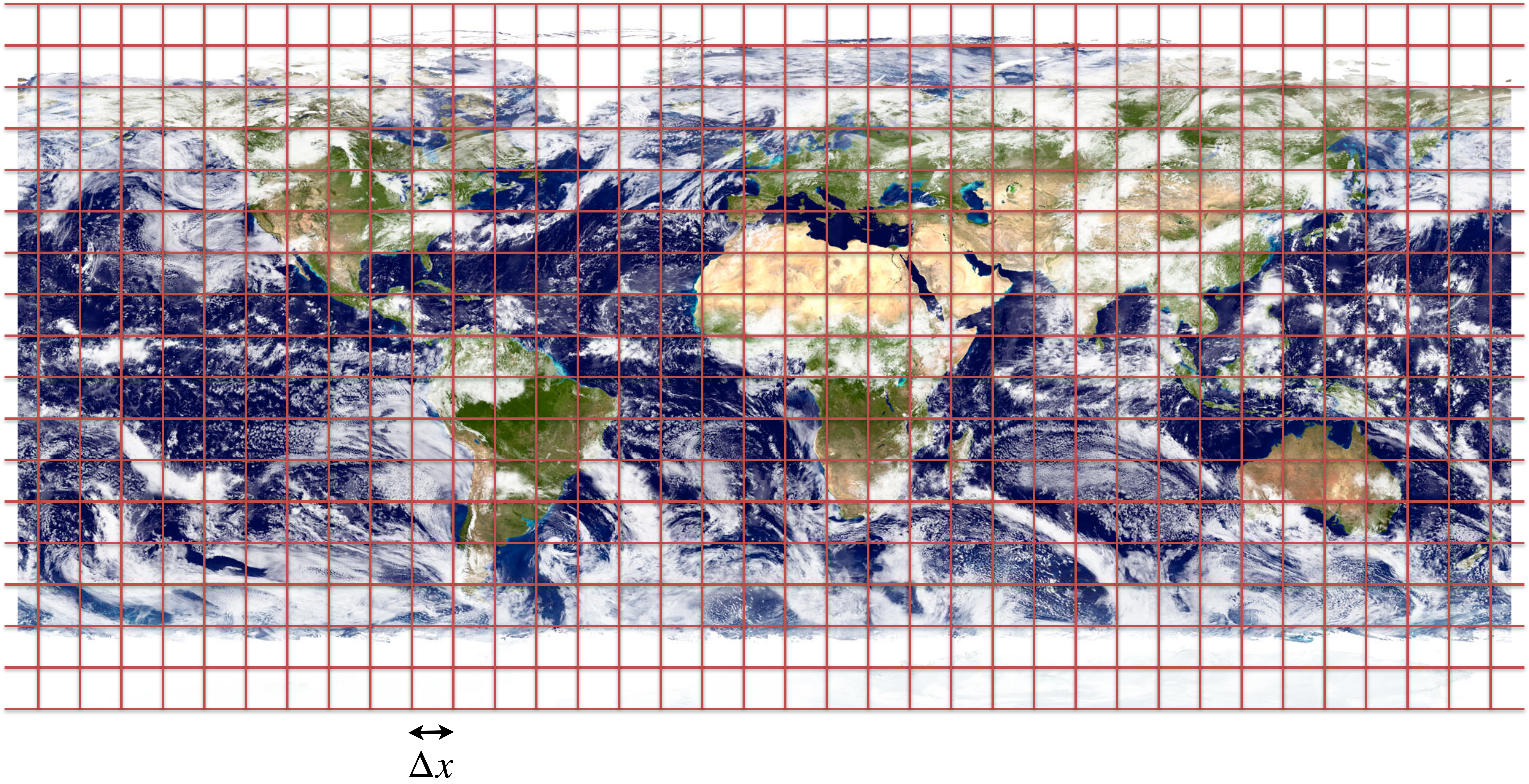

Grid spacing: Δx = minimum size of objects and flows 'explicitly' (i.e Navier-Stockes) resolved by models

Δx = Scale of reference which discriminates

- **'Resolved' processes** of scale $\mathscr{L} > \Delta x$ → 'Dynamical' core: direct resolution of **Navier-Stokes**
- **'Subgrid scale' processes** of scale $\mathscr{L} < \Delta x$ → 'Physical' core: implicit resolution through **parameterizations**

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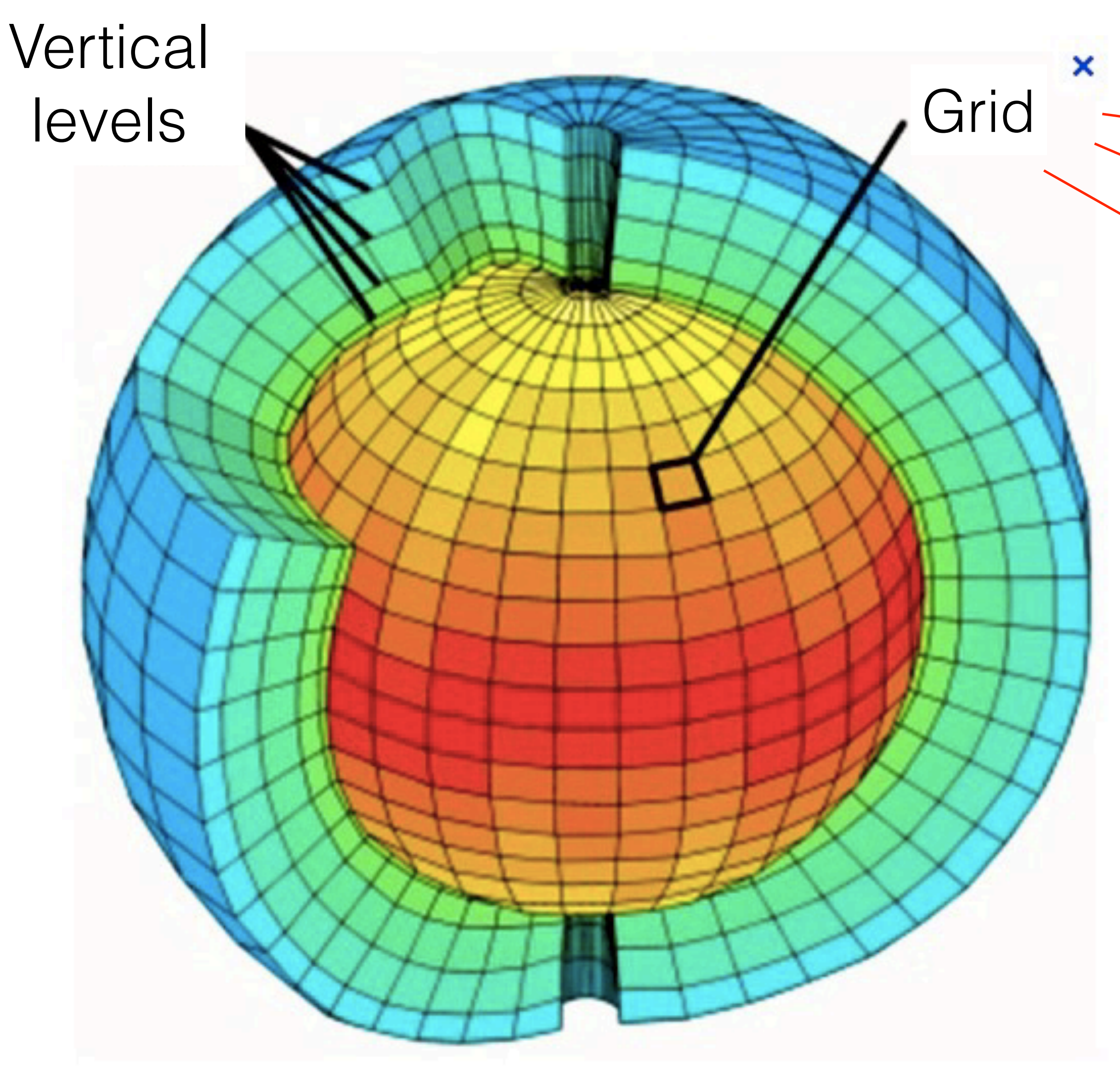
3.3 Between physics and numerics: parameterization of subgrid scale processes



Navier Stokes equations

Mass conservation

$$\boxed{\frac{\partial \rho}{\partial t} = -\vec{\nabla}\,.(\rho \vec{v})}$$

2nd law of Newton

$$\boxed{\frac{d\vec{v}}{dt} = \frac{\partial \vec{v}}{\partial t} + \vec{v}\,.\,\vec{\nabla}\vec{v} = -\frac{1}{\rho}\vec{\nabla}p - \vec{g}} + \boxed{\vec{F}_{fric}} - \boxed{2\vec{\Omega}\times\vec{v}}$$

Energy conservation

$$\boxed{Q} = c_p\frac{dT}{dt}\boxed{-\frac{1}{\rho}\frac{dp}{dt}}$$

Water conservation

$$\boxed{\frac{\partial(\rho q)}{\partial t} = -\vec{\nabla}\,.(\rho\vec{v}q)} + \rho\boxed{(E-C)}$$

Large scale terms

- Resolved scale

Source terms

- Subgrid scale

Grid spacing: Δx = minimum size of objects and flows 'explicitly' (i.e Navier-Stockes) resolved by models

Δx = Scale of reference which discriminates

- 'Resolved' processes of scale $\mathscr{L} > \Delta x$ ➡ 'Dynamical' core: direct resolution of Navier-Stokes
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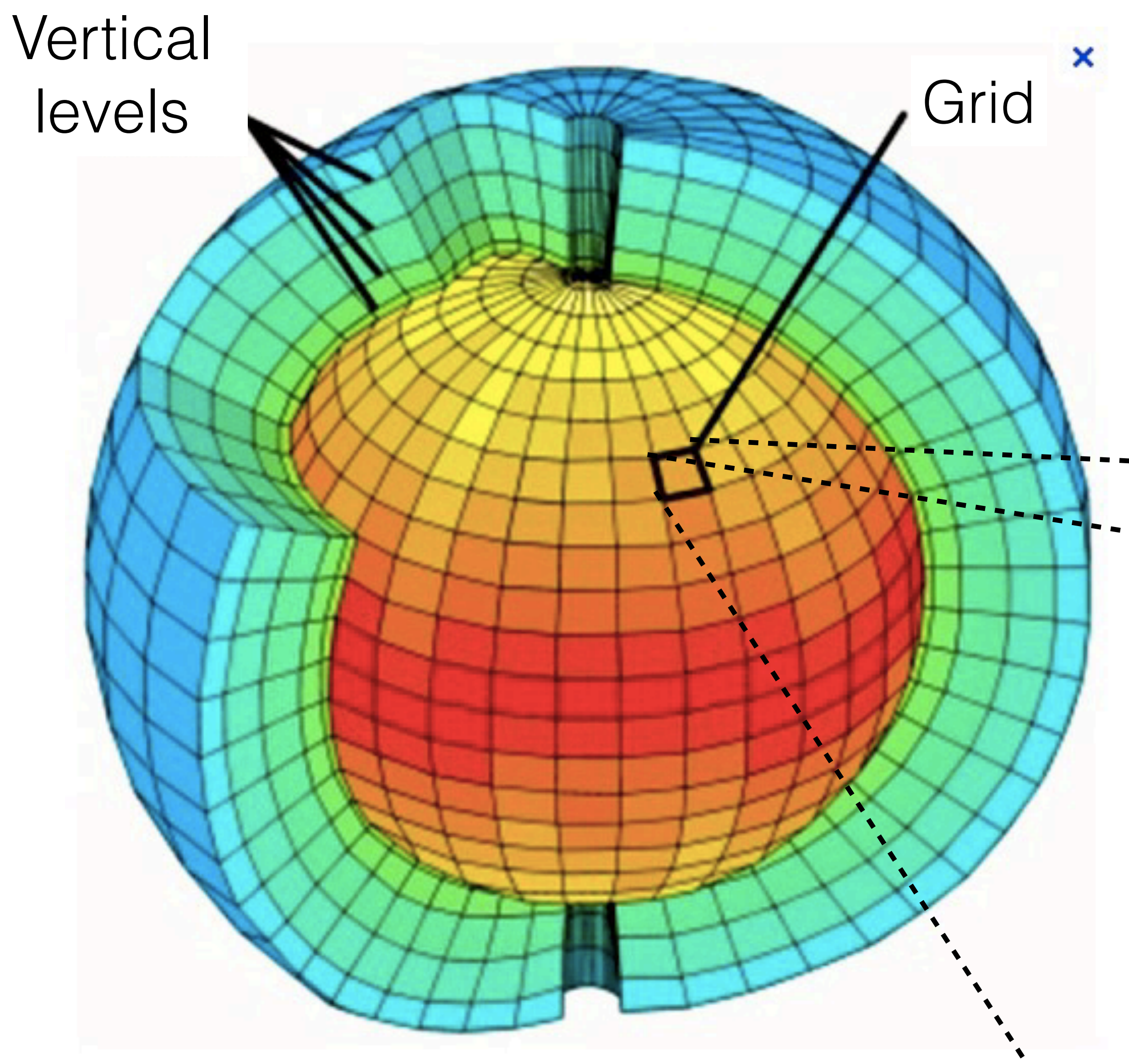
3.3 Between physics and numerics: parameterization of subgrid scale processes



Convection

Clouds

Surface fluxes

Turbulence

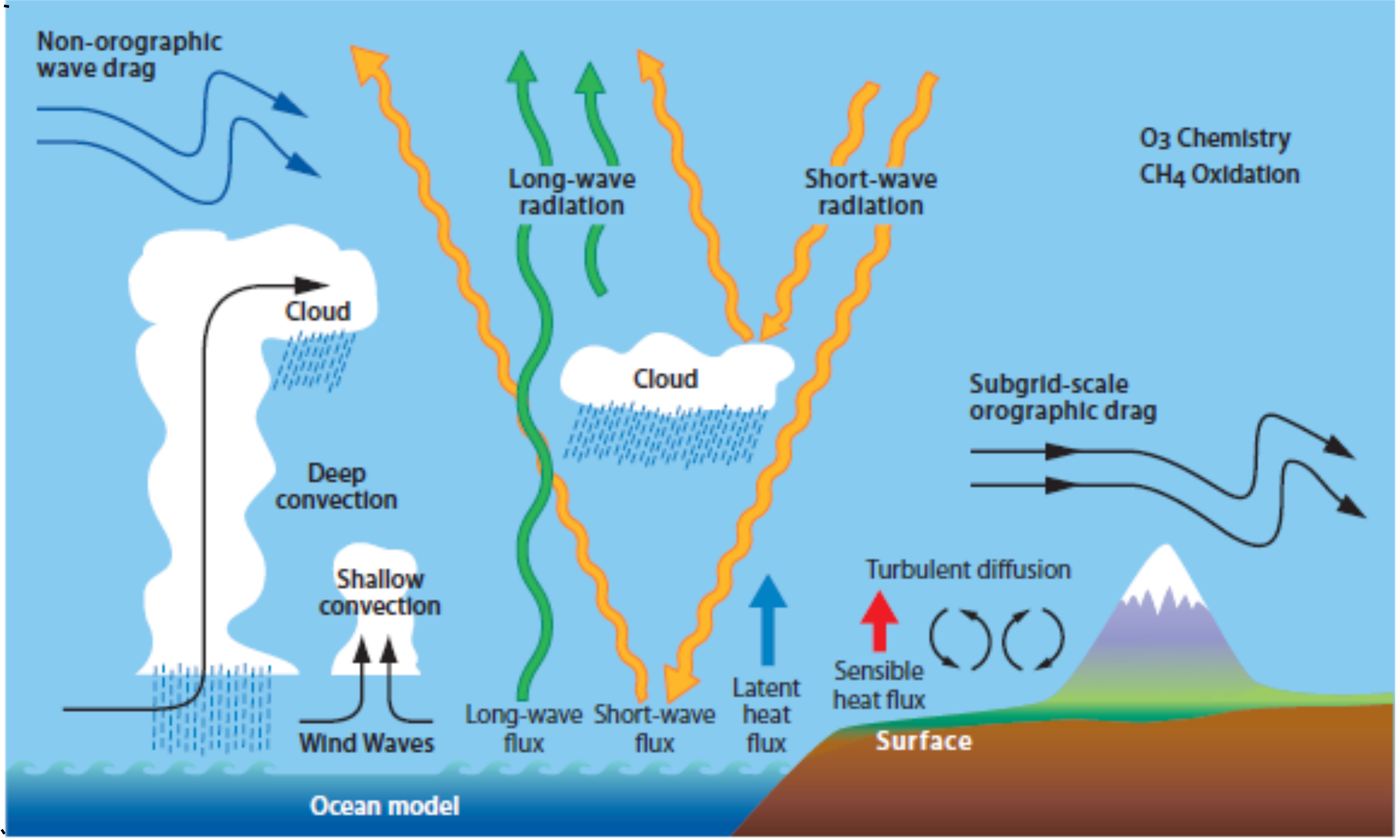
Radiations

Waves

Microphysics

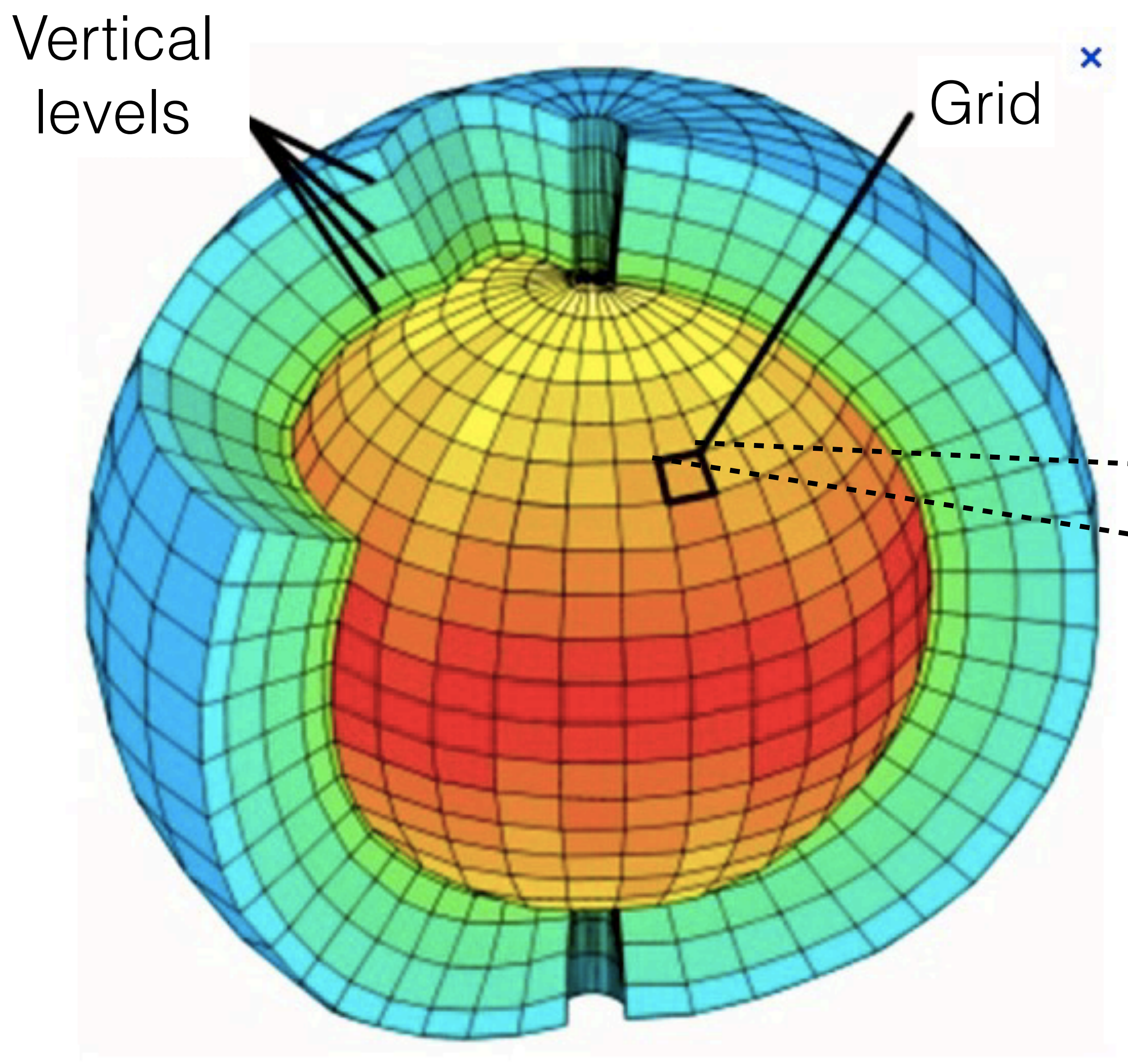
...

Subgrid scale processes in a typical climate model grid mesh



$25 \text{ km} < \Delta x < 200 \text{ km}$

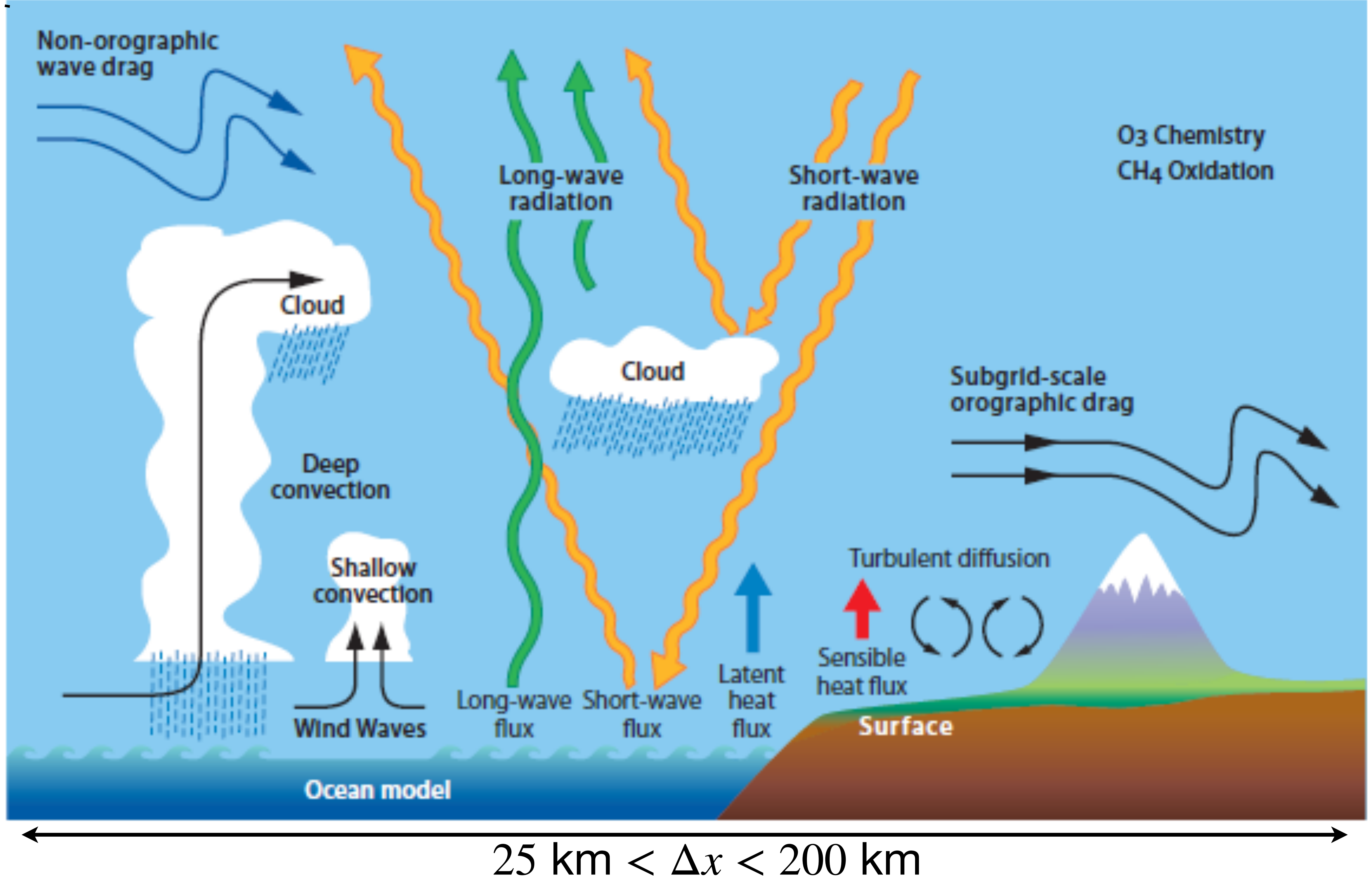
3.3 Between physics and numerics: parameterization of subgrid scale processes



Their mathematical formulation combines :

1. Theories
    - Radiation
    - Turbulence
    - Waves
2. ‘Partial models’
    - Convection
    - **Clouds**
    - Surface fluxes
    - Microphysics

Subgrid scale processes in a typical climate model grid mesh



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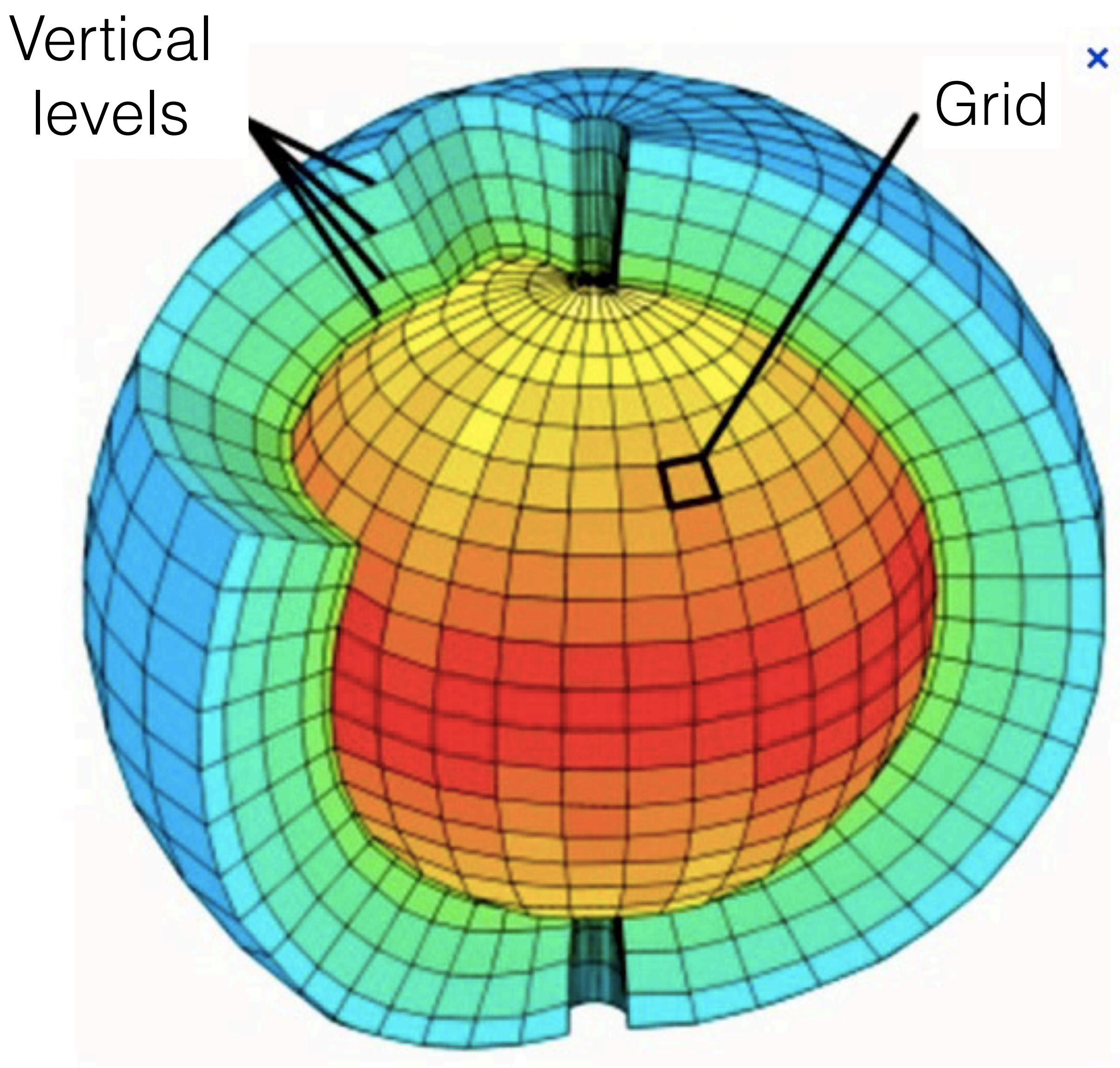

Their mathematical formulation combines :

1. **Theories**
    - Radiation
    - Turbulence
    - Waves
2. **‘Partial models’**
    - Convection
    - **Clouds**
    - Surface fluxes
    - Microphysics

Parameterizations

Mathematical formulations build from :

- Conceptual pictures (simplified and/or idealized)
- Physical considerations

… under the form of…

Equation set with tuning parameters :

- Geometry
- Population
- Dynamics
- Efficiency coefficients
- …

… and whose aim is to …

Estimate these processes on the large scale variables :

- Temperature
- Humidity
- Wind
- Pressure

Part 3 - Clouds in models

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3.4 What properties of clouds needs to be parameterized ?

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3.4 What aspects of clouds needs to be parameterized in currents GCM ?

… almost everything

Thermodynamics/Macrophysics

- Condensation heating rate
- Evaporation cooling rate
- Net vertical transport
- Mixing

Microphysics

- Precipitation
- Sedimentation
- Collection …

Radiation

- Cloud cover
- Cloud depth
- Transmission, scattering

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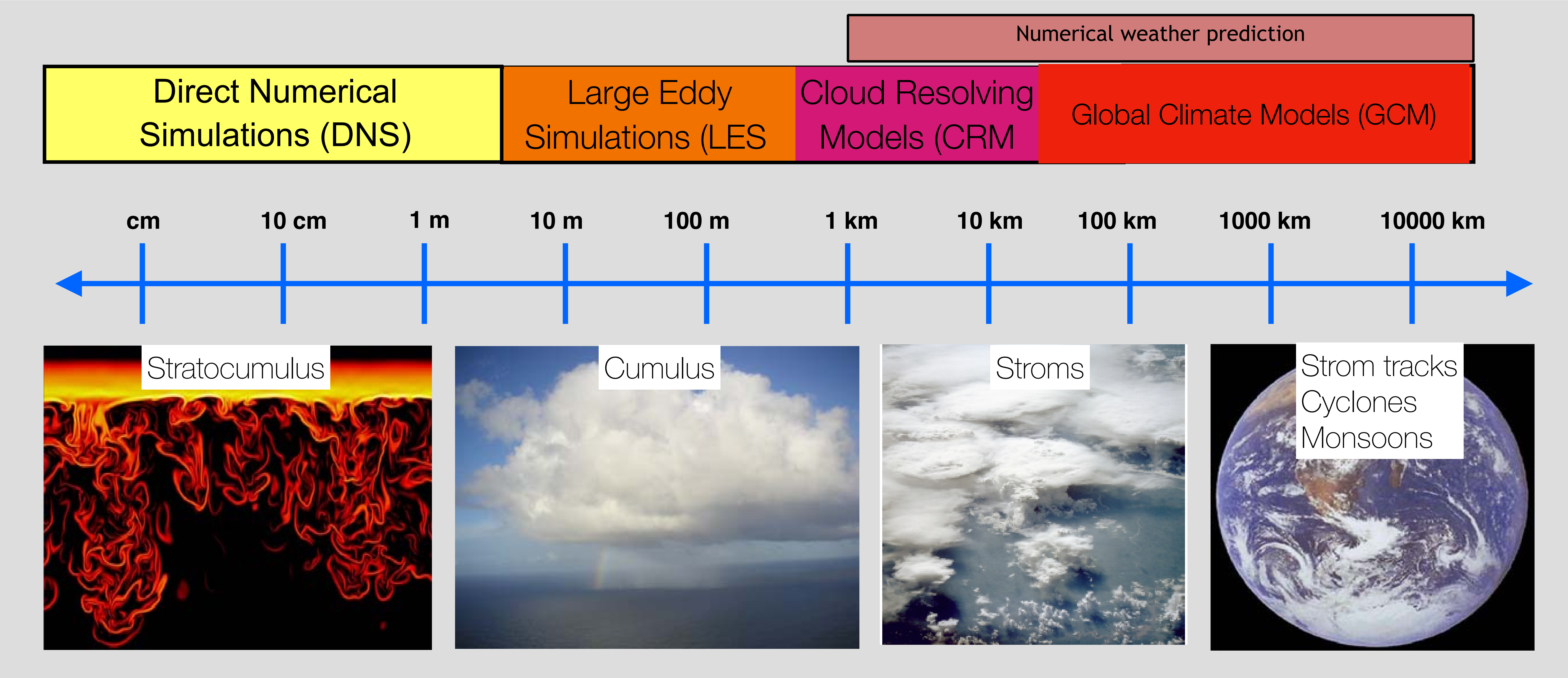
Radiation

- Cloud cover
- Cloud depth
- Transmission, scattering

When refining the resolution, less processes need to be parameterized



Numerical weather prediction

Direct Numerical Simulations (DNS)

Large Eddy Simulations (LES

Cloud Resolving Models (CRM

Global Climate Models (GCM)

Model hierarchy

cm | 10 cm | 1 m | 10 m | 100 m | 1 km | 10 km | 100 km | 1000 km | 10000 km

Grid spacing Δx

Microphysics

Radiation

Stratocumulus

Cumulus

Stroms

Strom tracks
Cyclones
Monsoons

Resolved cloud systems

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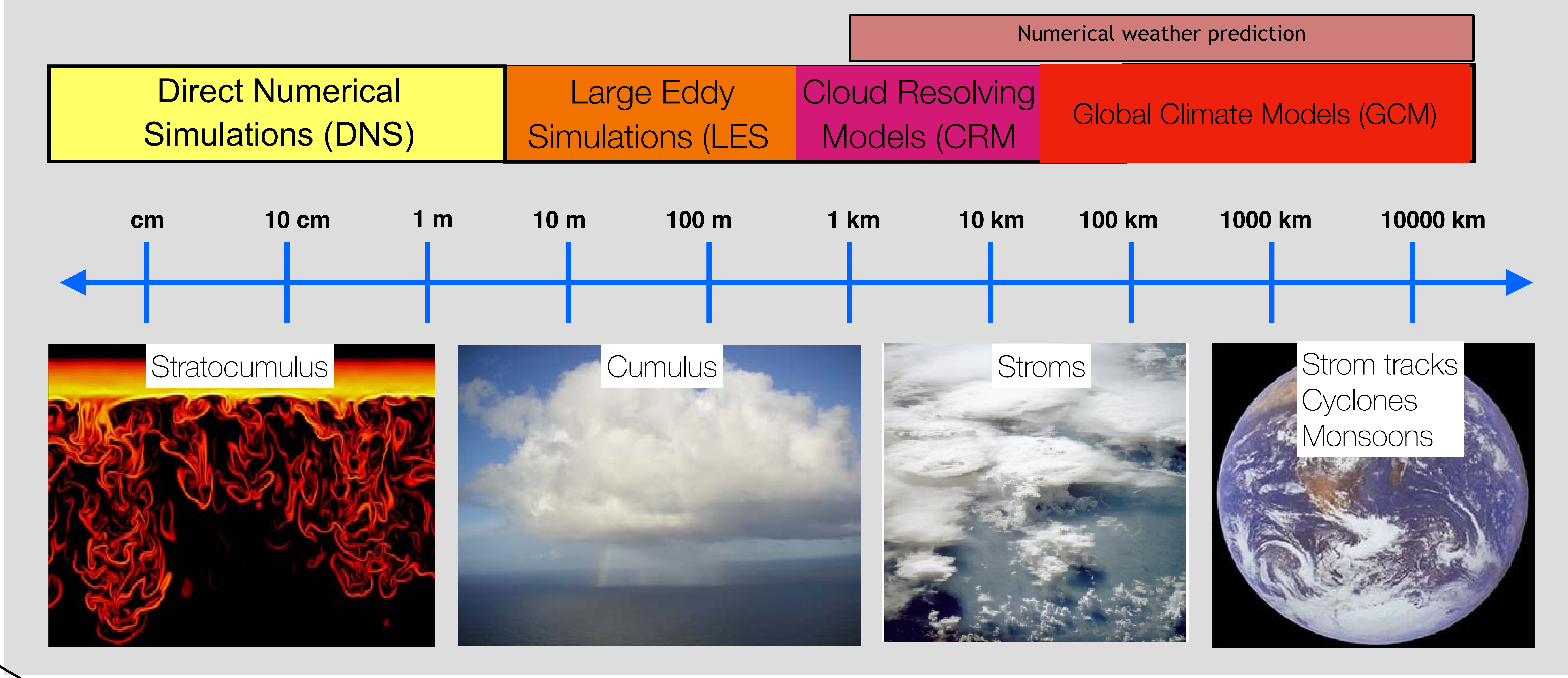

Model hierarchy

Grid spacing Δx

Resolved cloud systems

Microphysics

Radiation

Still need for parameterizations !

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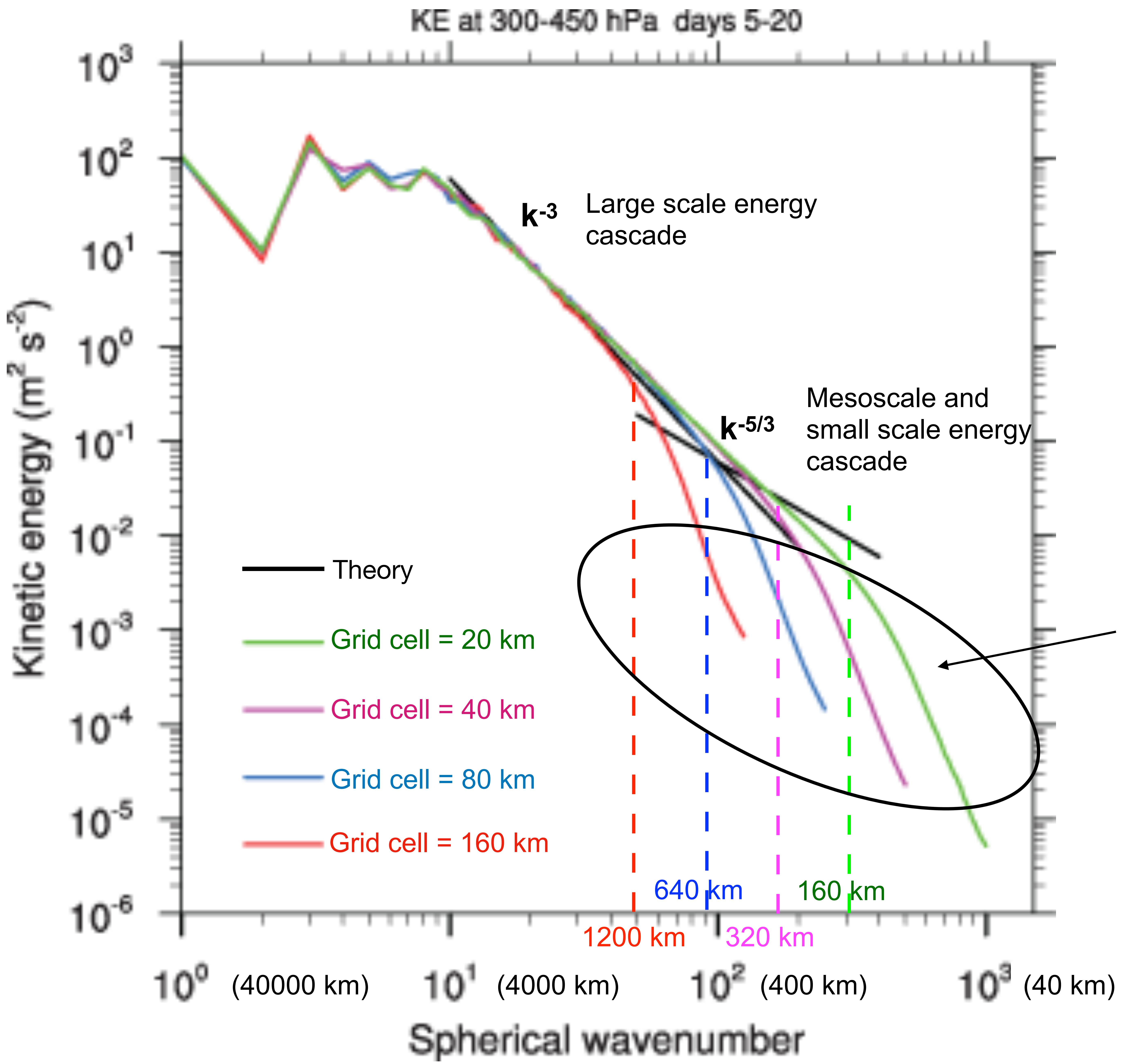
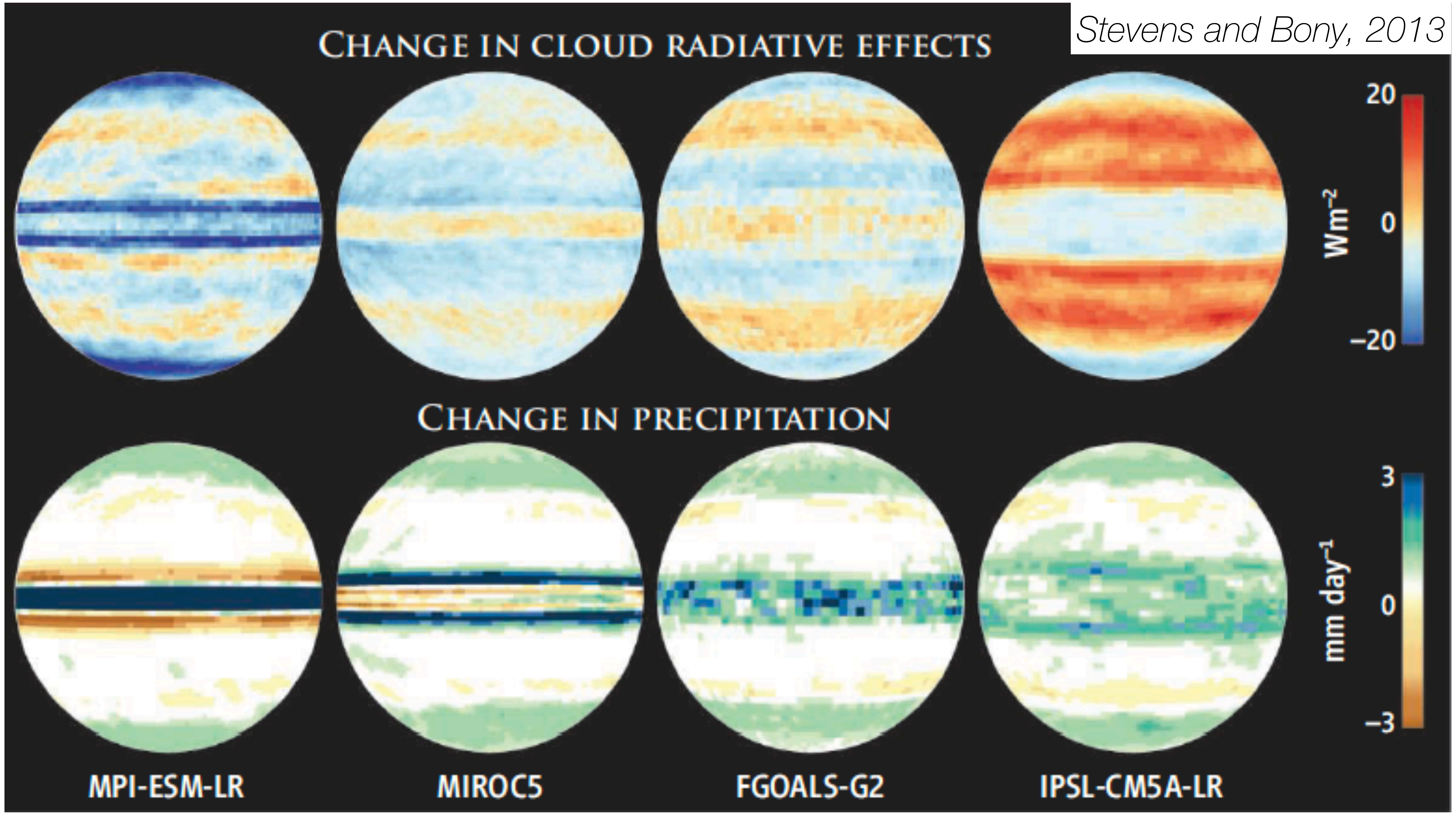


Models cannot capture the whole TKE spectra !

3.5 What are climate model missing ?

Response of 4 climate models to a +4K forcing run in aquaplanet mode



Stevens and Bony, 2013

Although run in very simple configuration, large discrepancies among models in response to warming

➡ Very basic physical processes are still misunderstood

3.5 What are climate model missing ? The cloud parameterization ‘deadlock’

Randall et al, 2003

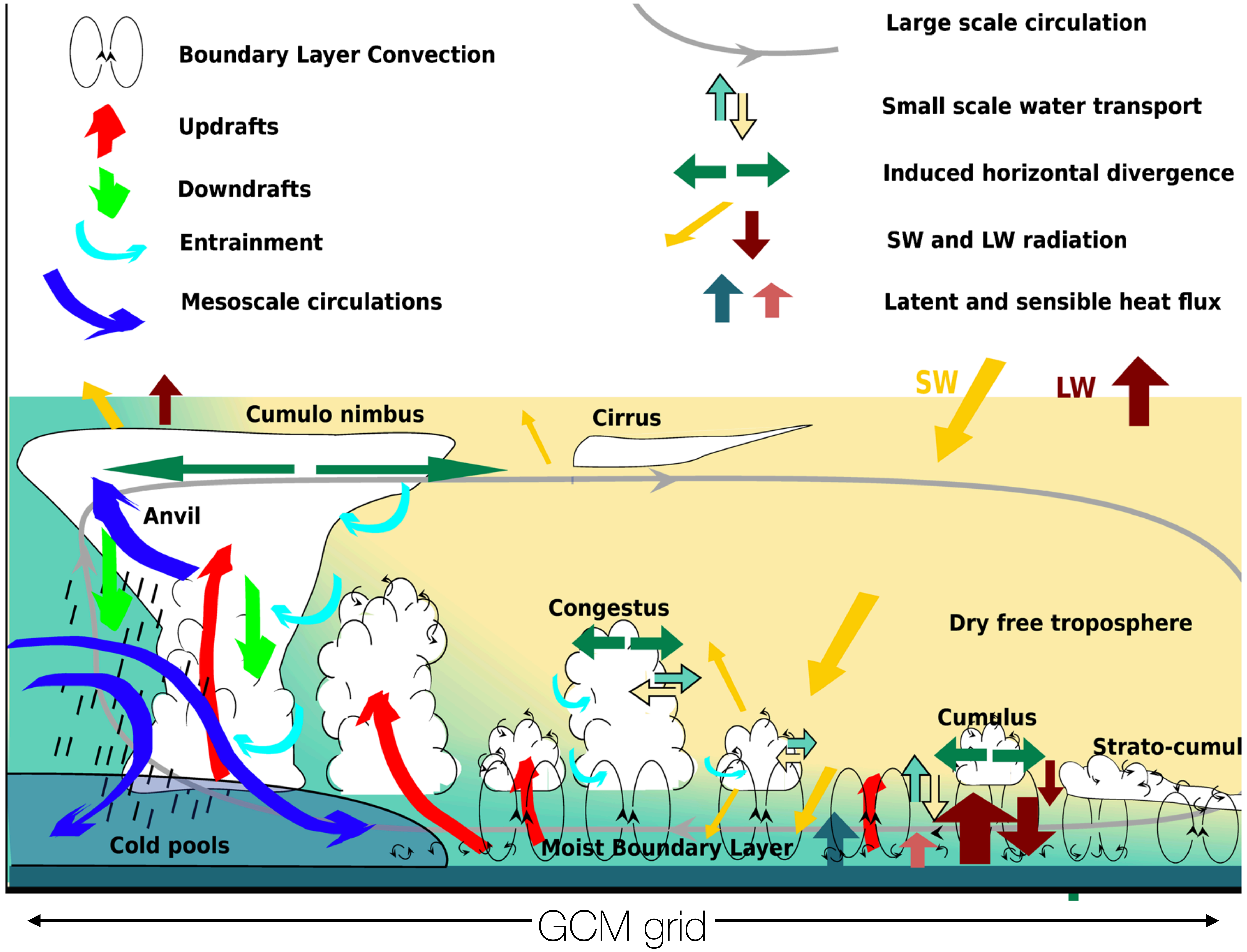
Fig. 8. Cloud parameterization research (blue line) began about 40 yr ago.

Randall et al, 2003: « The cloud parameterization problem is ‘deadlocked’ in the sense that our rate of progress is unacceptably low’

3.5 What are climate model missing ? The cloud parameterization ‘deadlock’

Sketch of the subgrid scale cloud processes (except microphysics)

Rio et al, 2019

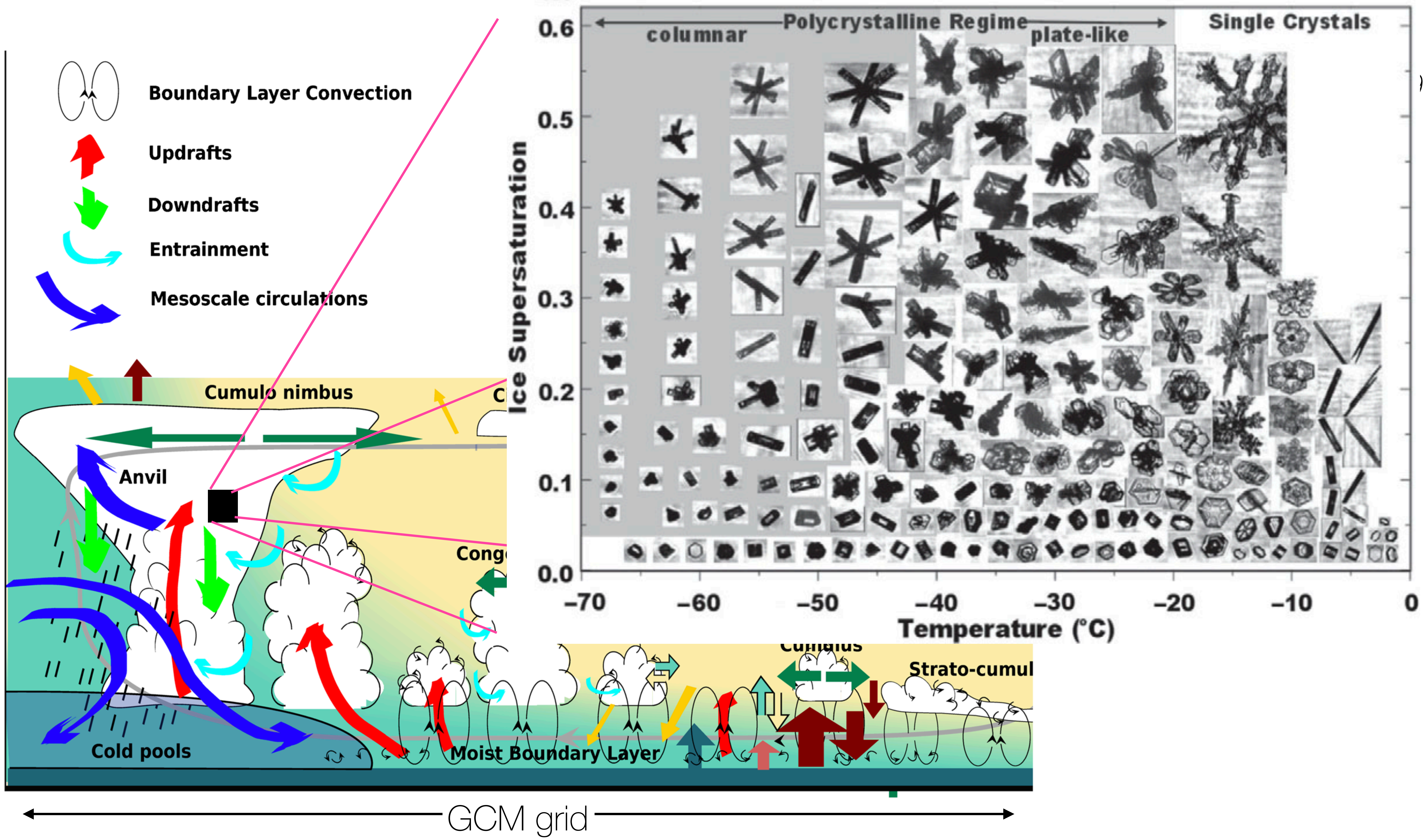


How to improve the represent of all these couplings ? (Should we continue trying ?)

- Numerical improvements: finer resolution BUT increasing computing cost
- Physical improvements: more subtle couplings represented BUT more parameters

3.5 What are climate model missing ? The cloud parameterization ‘deadlock’

Sketch of the subgrid scale cloud microphysical processes



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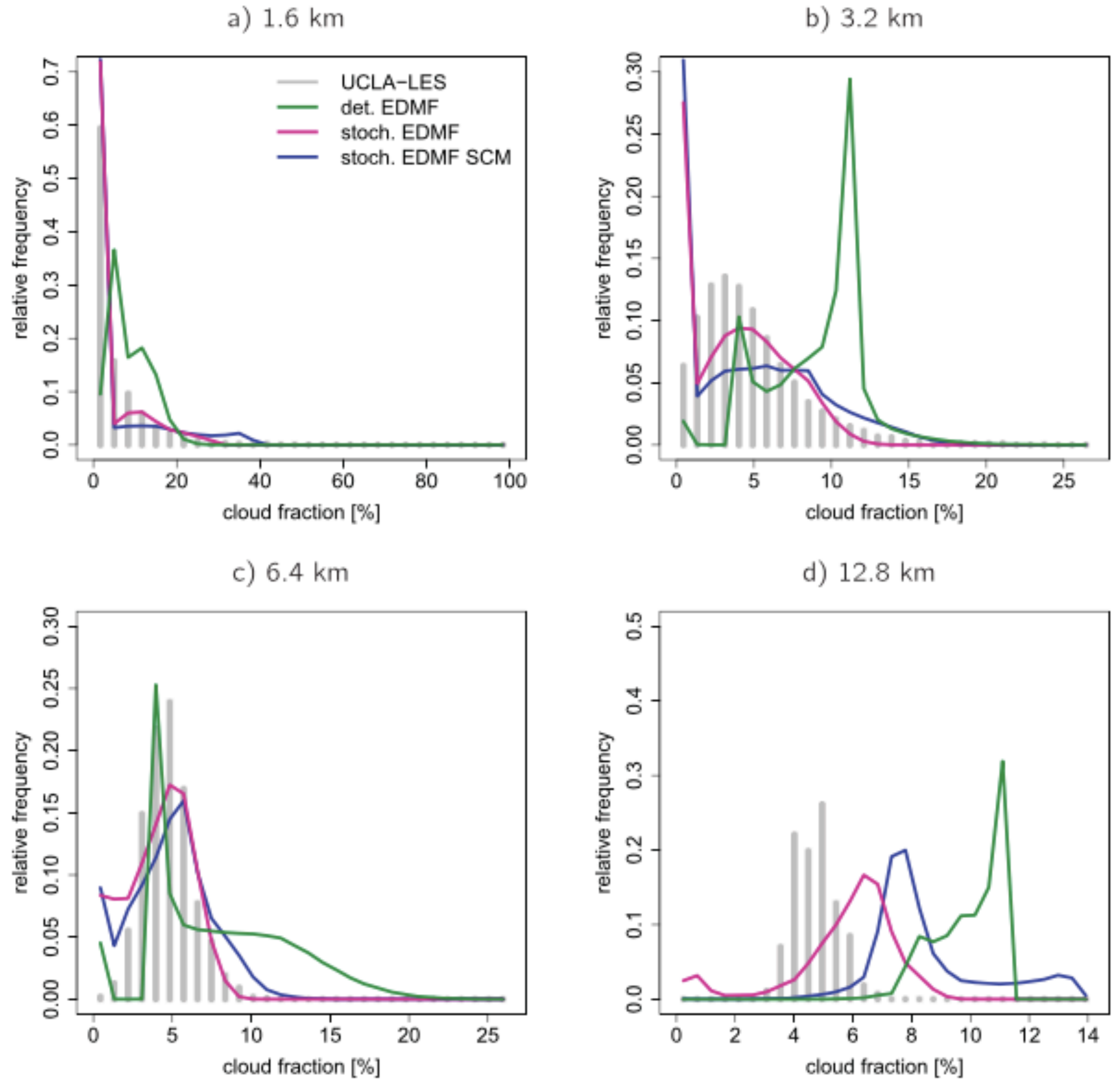
3.6 Upcoming models and parameterizations: Scale aware parameterization in GCMs

Cloud fraction PDF at different spatial resolutions

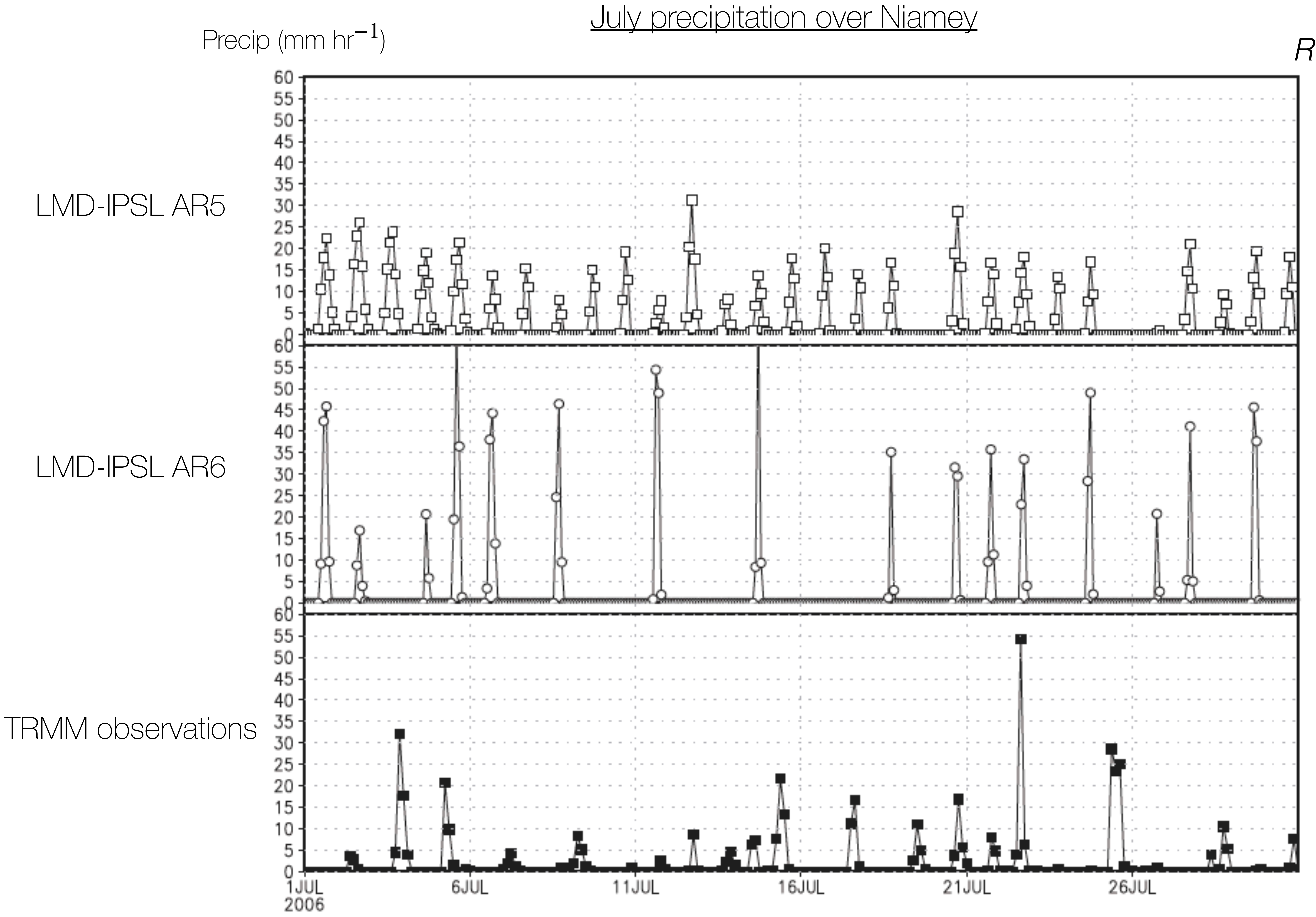
Sakradzija et al., 2016



Scale aware parameterization = whose behaviour is not, or loosely, sensitive to the numerical resolution

-> Robustness across spatial scales

3.6 Upcoming models and parameterizations: Stochastic parameterization in GCMs



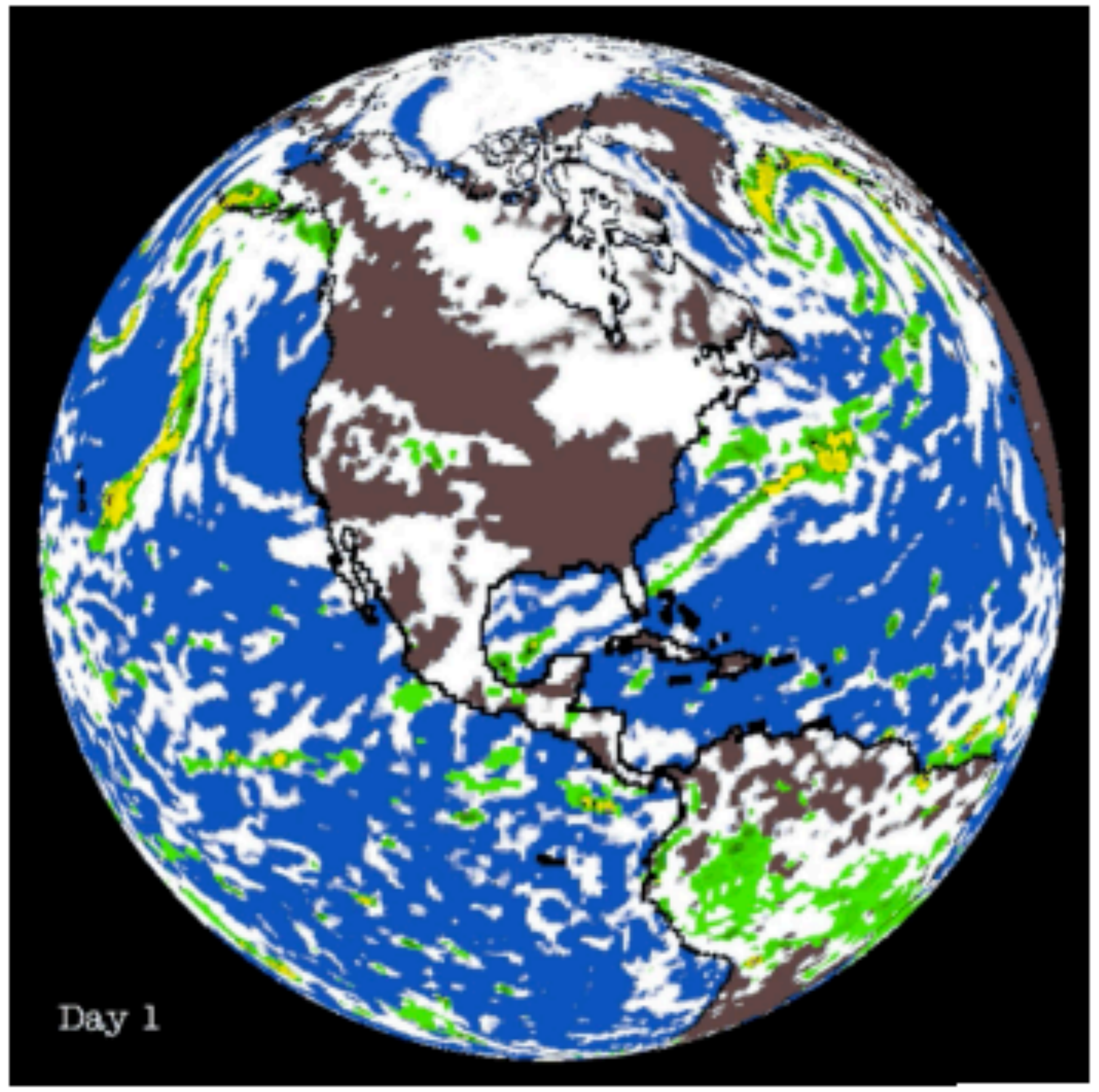
Rochetin et al., 2016

Stochasticity helps representing intermittency of rainfalls in (some) models

3.6 Upcoming models and parameterizations: Global Strom Resolving Models

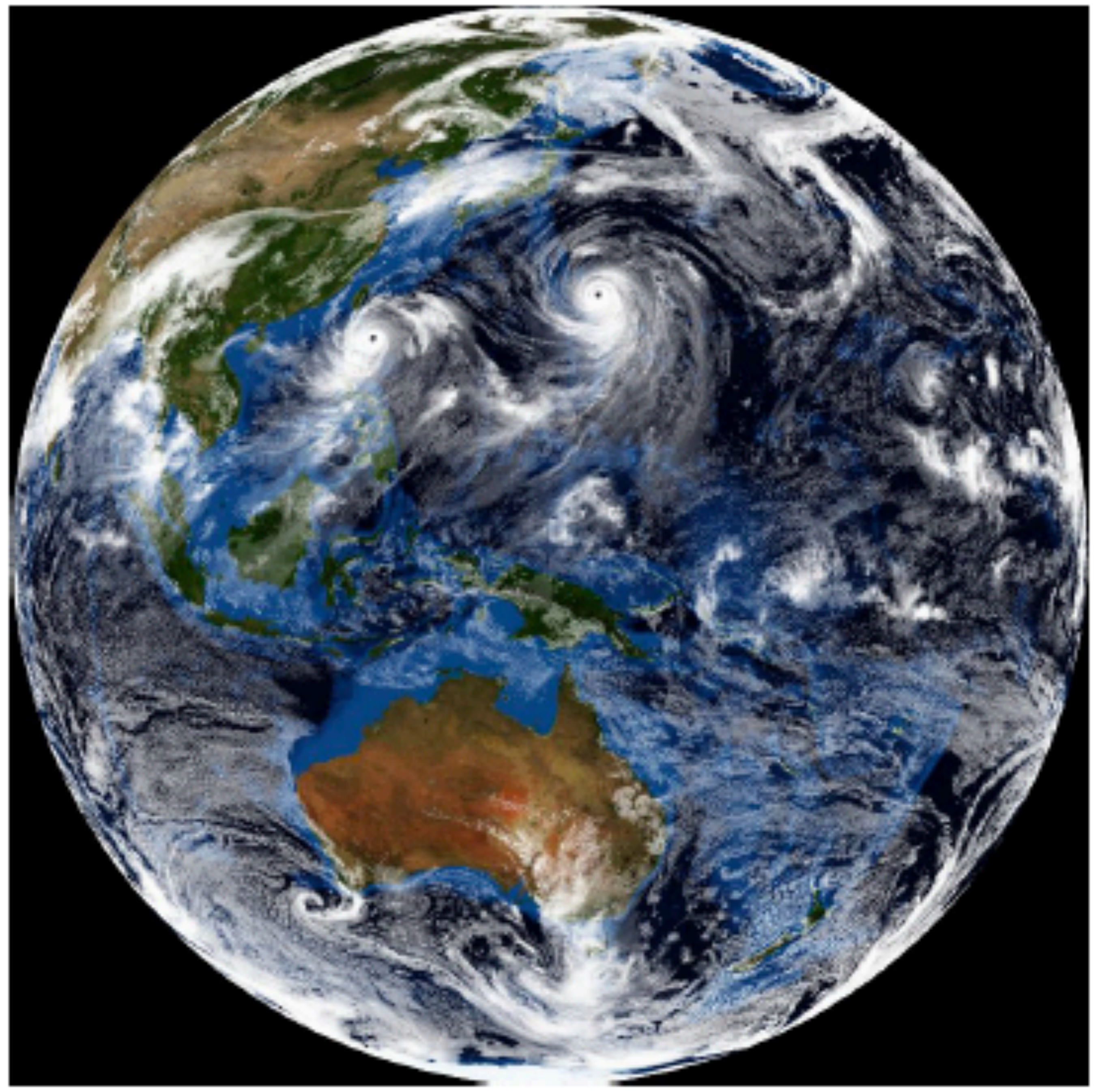
DYAMOND2 NICAM 3.5 km performed by Tamaki Suematsu on Fugaku (RIKEN), visualized by Tobias Koelling on Levante (DKRZ) during nextGEMs Hackathon@Vienna (Snapshot of surface wind speed, directly from original icosahedral data format)

ML Goal: Improve coarse-model simulations

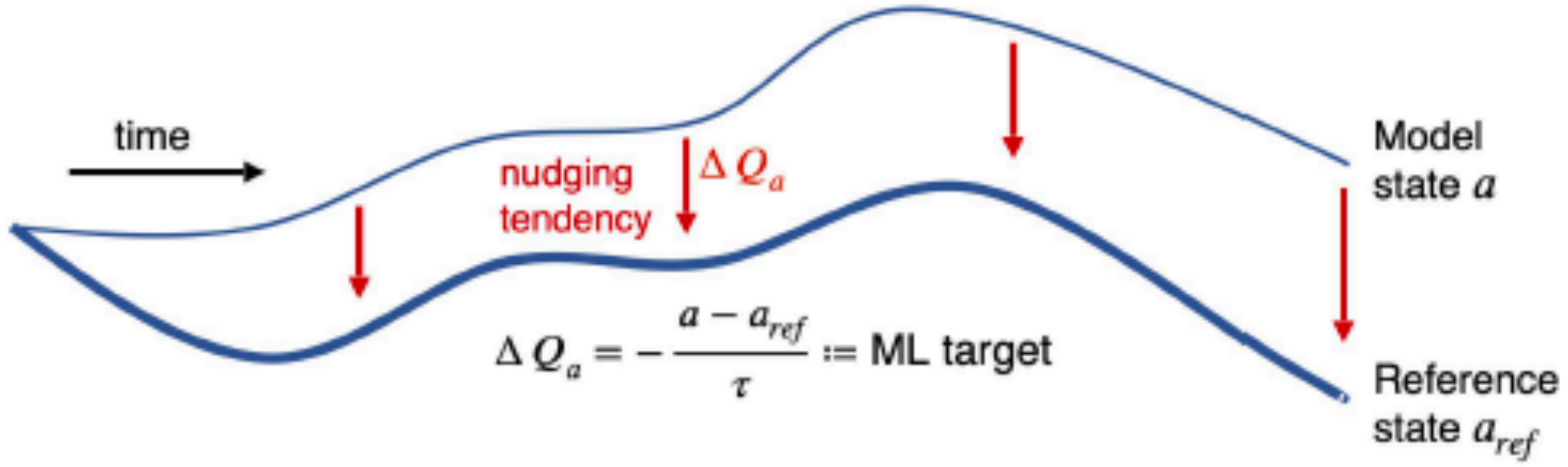


Climate model (25-200 km)

Train ML to correct parameterized column physics to make temperature and humidity of the coarse model track reference data.



High fidelity reference: observations or fine-grid (3 km) simulation



$$\Delta Q_a = -\frac{a - a_{ref}}{\tau} := \text{ML target}$$

3.6 Upcoming models and parameterizations

Although important progresses, climate models still miss some key features

1. Is it for physical reasons ?
    - Lack of understanding of key couplings ?
2. Is it for numerical reasons ('bad') reasons ?
    - Too much shortcomings in parameterizations ?
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New generation of models

1. Will they improve our confidence in future climate projections ?
    - Will they significantly reduce cloud uncertainties ?
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➡ Important controverses in the community !

➡ Need for new people/ideas to help building new paradigms from these controverses