Département de Géosciences

Changement Climatique

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Changement climatique et physique du climat (1)

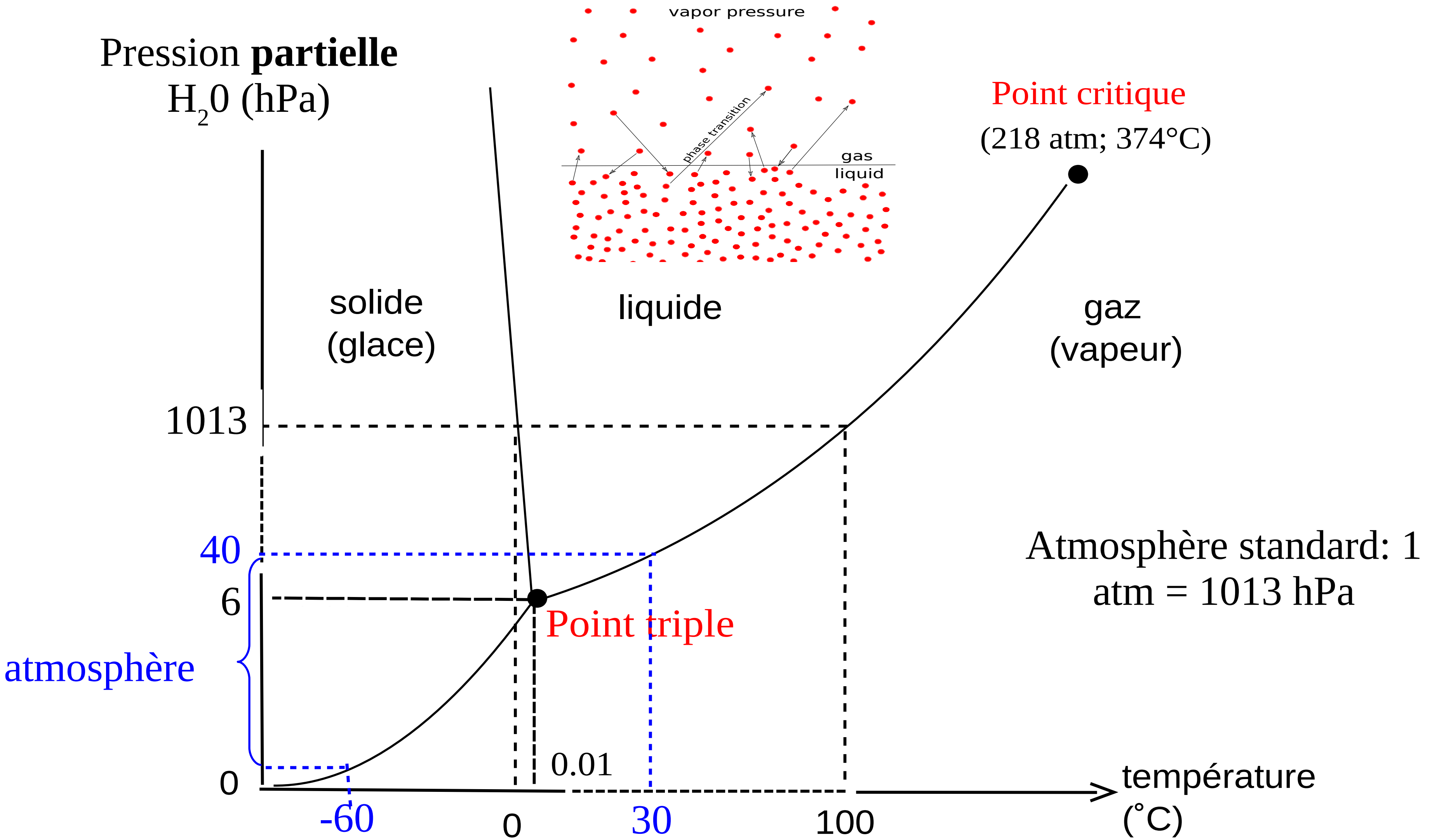
Changement climatique et cycle de l'eau

25 octobre 2018

Changement climatique et cycle de l'eau

- Formation des nuages et des précipitations
- Changement des précipitations moyennes
- Distribution géographique et intensité des changements de précipitations

Diagramme de phase de l'eau



Chaleur latente de changement d'état: **L* = Q/n ;** $\boxed{\mathbf{L = Q/m \approx 2{,}3\ 10^6\ J/kg}}$

Avec **Q** l'énergie thermique (chaleur) nécessaire pour faire passer **n** moles (ou une masse **m**) d'un état 1 à un état 2 à pression et température constantes

Relation de Clausius-Clapeyron

Variation avec la temp. de la pression partielle de changement d'état:

$$\boxed{\frac{dP}{dT}=\frac{L^*}{T\Delta V}}$$

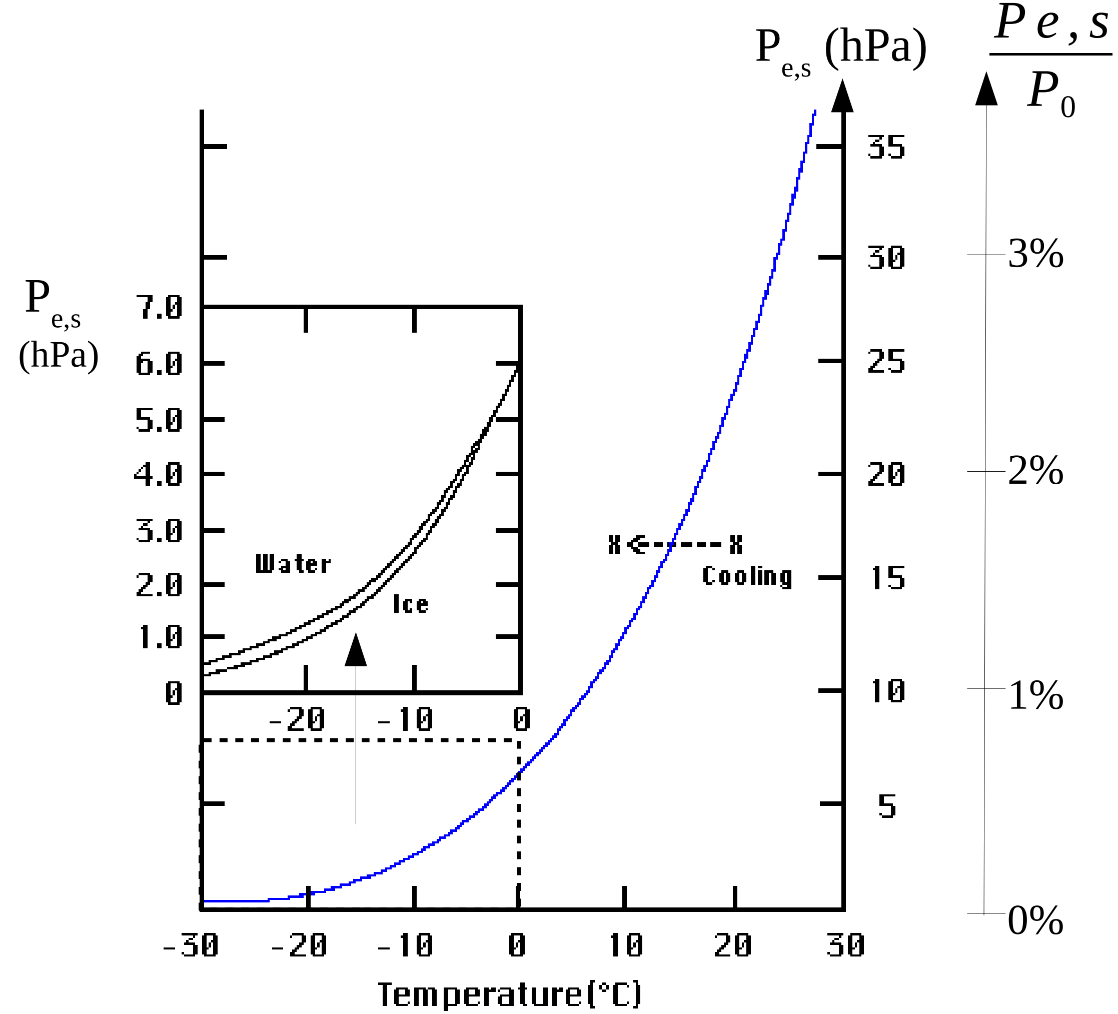
L^*: enthalpie de changement d'état
V: variation de volume entres les deux états à T et P constantes

Pour la vaporisation ou la sublimation de l'eau (si $L^*=c^{te}$ et gaz parfait):

$$\frac{dP_{e,s}}{dT}\approx\frac{L^* P_{e,s}}{T^2 R^*}$$

$$\boxed{P_{e,s}=P_0 e^{\frac{L^*}{R^*}\left(\frac{1}{T_0}-\frac{1}{T}\right)}}$$

$$P_{e,s}=P_0 e^{\left(14.33-\frac{5350}{T}\right)}$$ pour $T_0 \approx 20°C$



Humidité

Humidité relative $\boxed{H=\frac{P_e}{P_{e,s}}}$

Avec $\boldsymbol{P_e}$ pression partielle de H_2O
$\boldsymbol{P_{e,s}}$ pression partielle de H_2O à **saturation**

Rapport de mélange (en kg de vapeur d'eau par kg d'air, kg/kg)

$$\boxed{q=\frac{m_{vapeur\,d'eau}}{m_{air}}}=\frac{M_e}{M_{air}}\frac{P_e}{P}$$

avec M_e et M_{air} masse molaire de H_2O et air

$$q\approx 0.622\,P_e/P$$

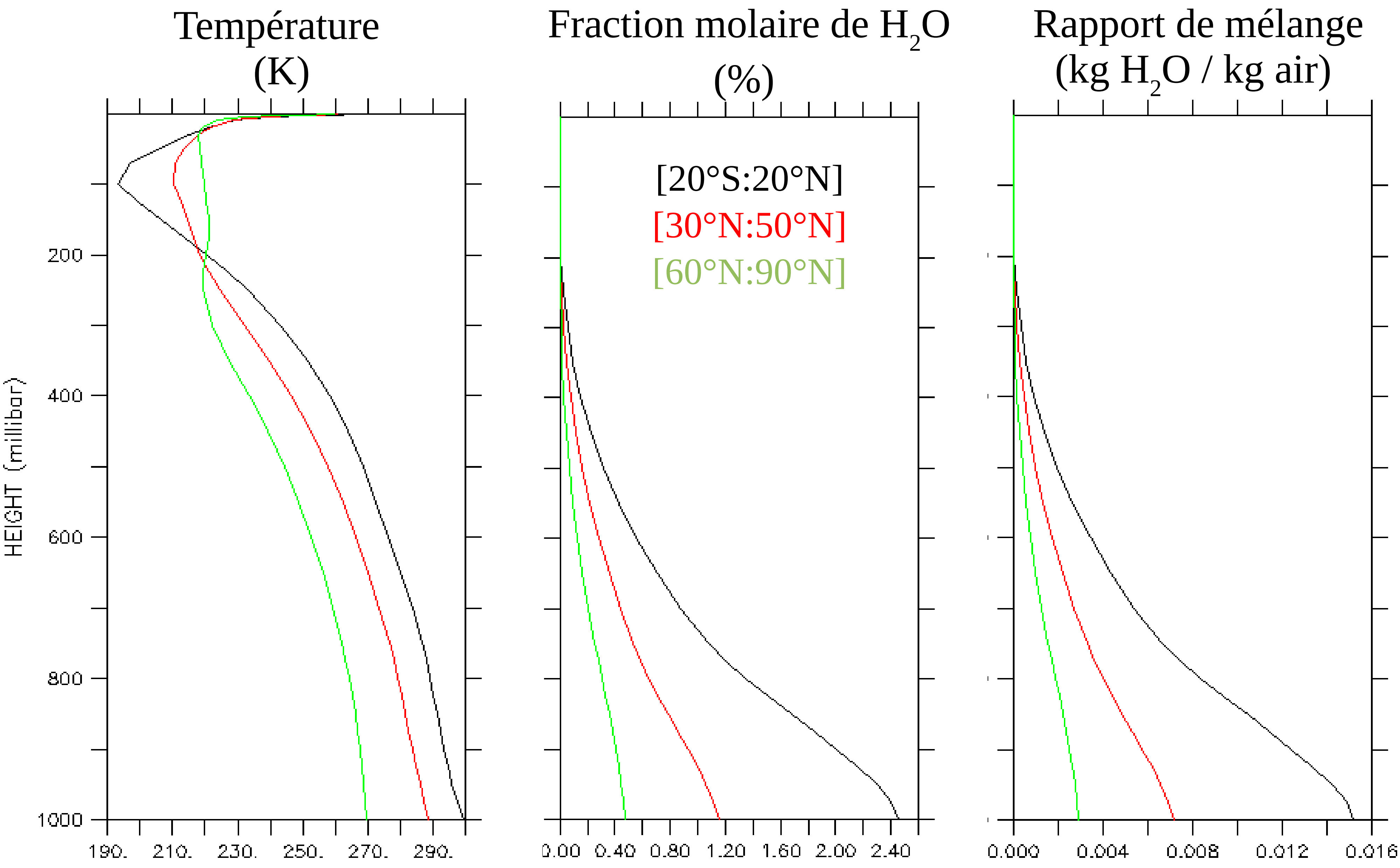
Rapport de mélange à la saturation : $q_s=\frac{M_e}{M_{air}}\frac{P_{e,s}}{P}$

Ordre de grandeur:

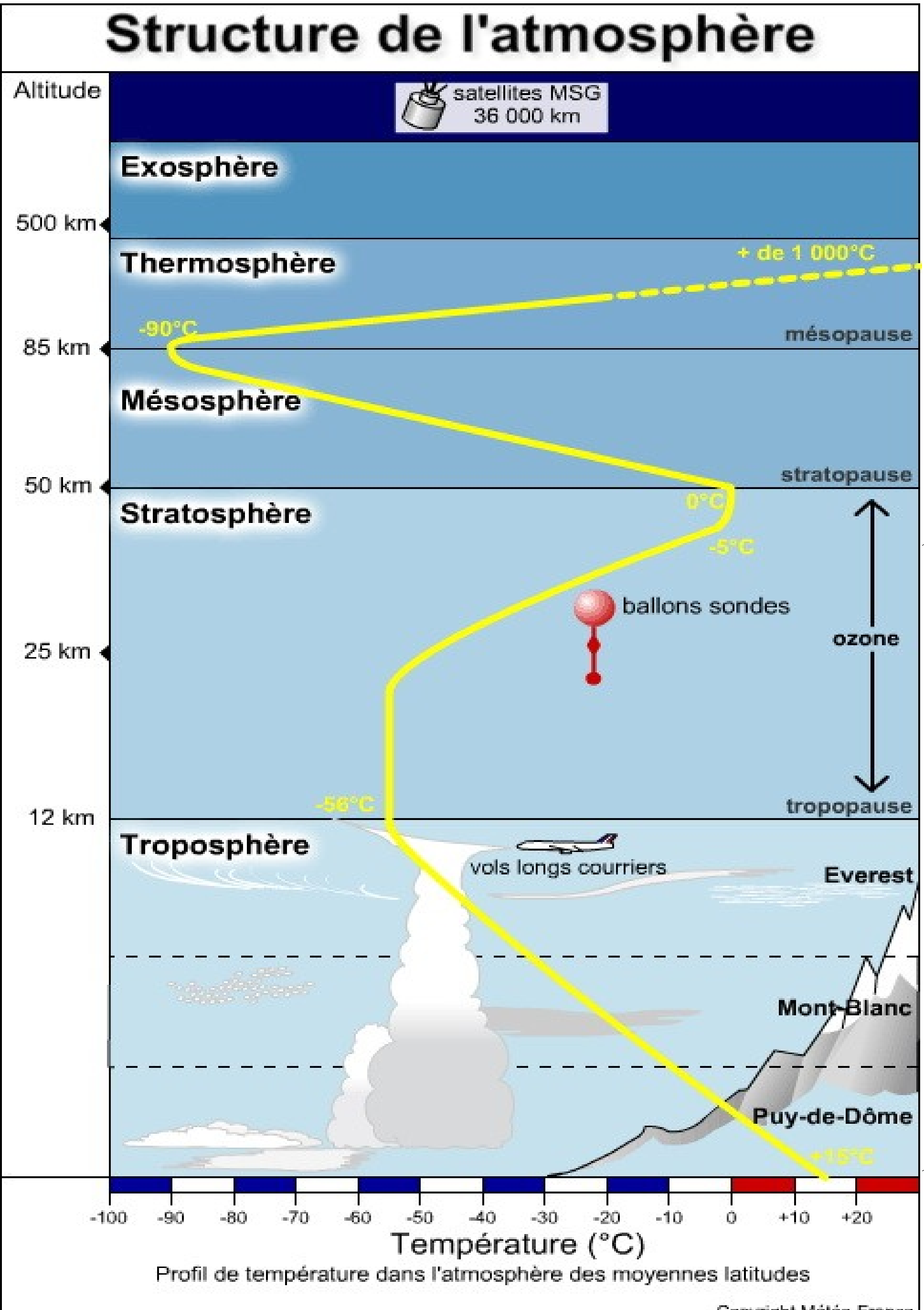
T	30°C	20°C	10°C	0°C	-20°C	-40°C
$\mathbf{P_{e,s}/P}$	4%	2.3%	1.2%	0.6%	0.1%	0.01%
$\mathbf{q_s}$ (kg/kg)	0.026	0.014	0.007	0.004	0.6‰	0.08‰

Profils verticaux

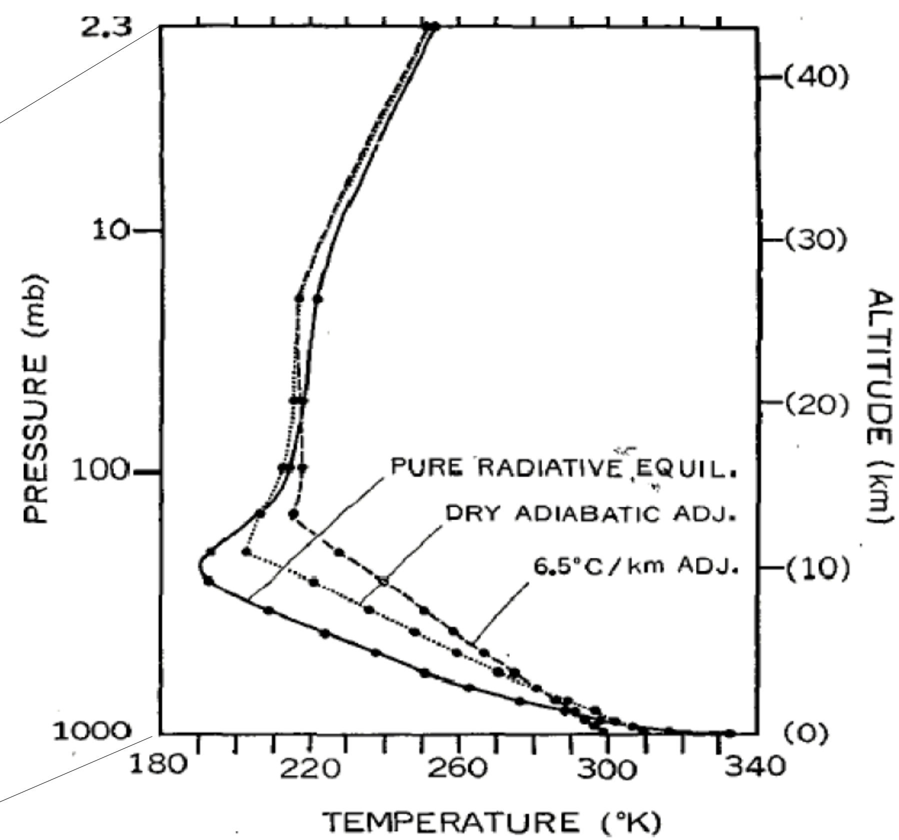
Analyses météorologiques ECMWF, moyenne annuelle



Variation de la température avec l'altitude



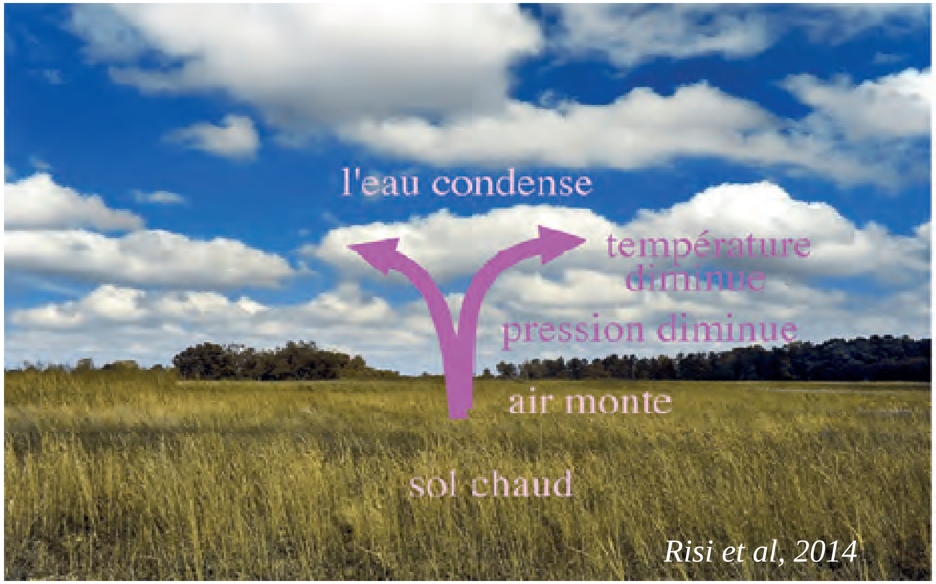
Profil de température avec un équilibre purement radiatif ou avec aussi de la convection
[Manabe and Strickler, 1964]

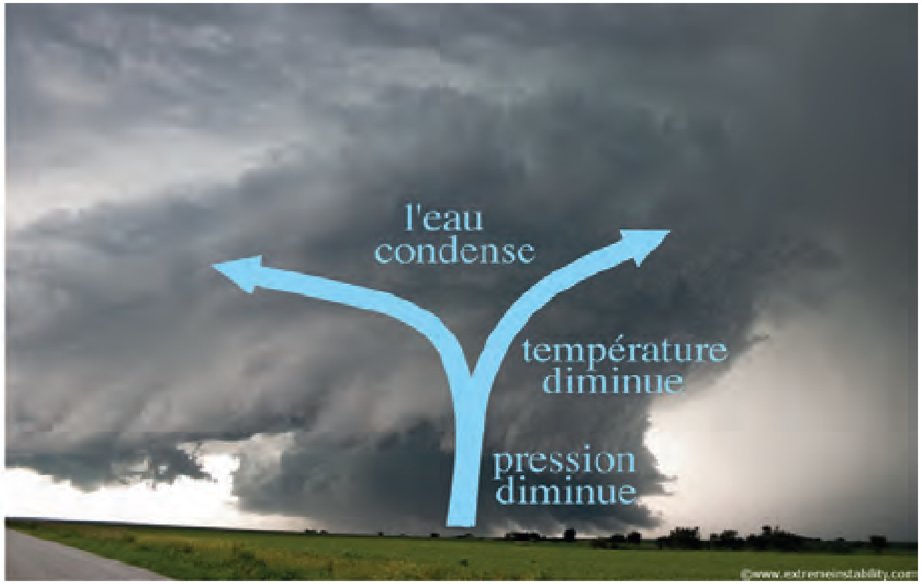


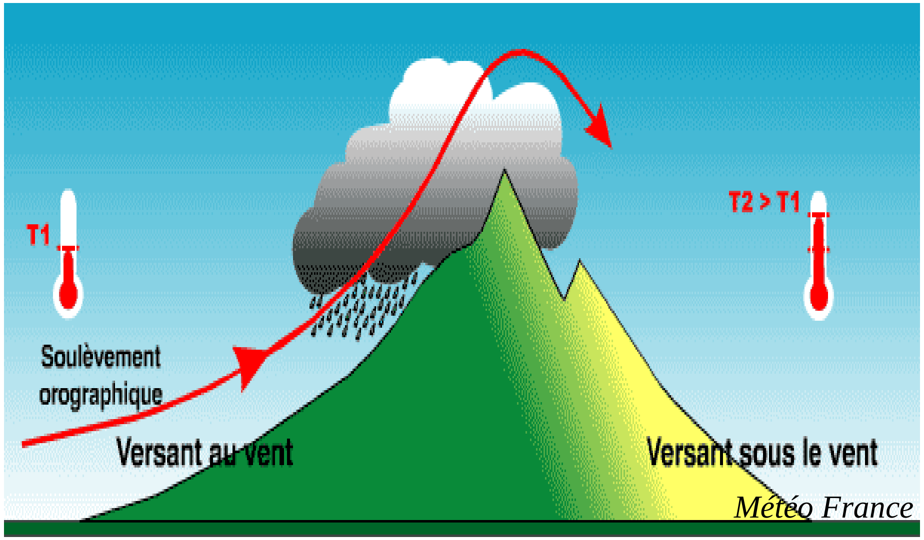
L'équilibre radiatif ne suffit pas pour expliquer le profil observé.

Formation des nuages

Presque tous les nuages se forment lors de l'ascension de l'air, qui se refroidit en montant. Nuages de couche limite, de convection (orage), orographiques...

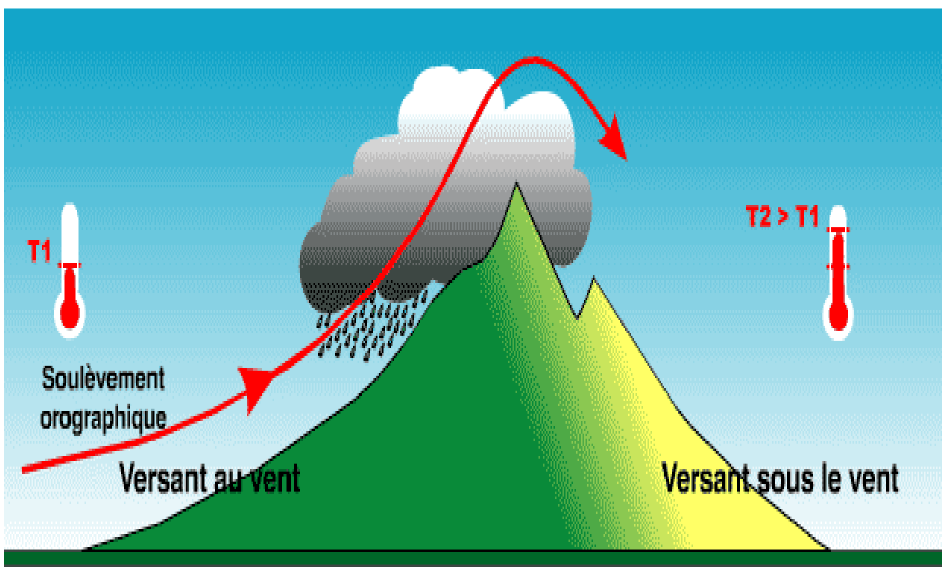


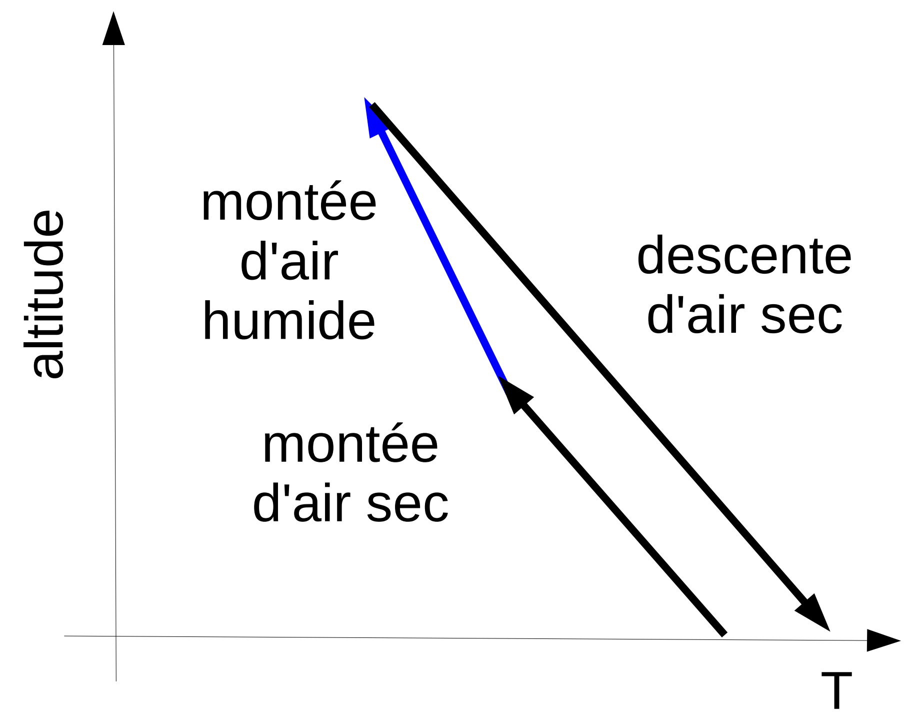




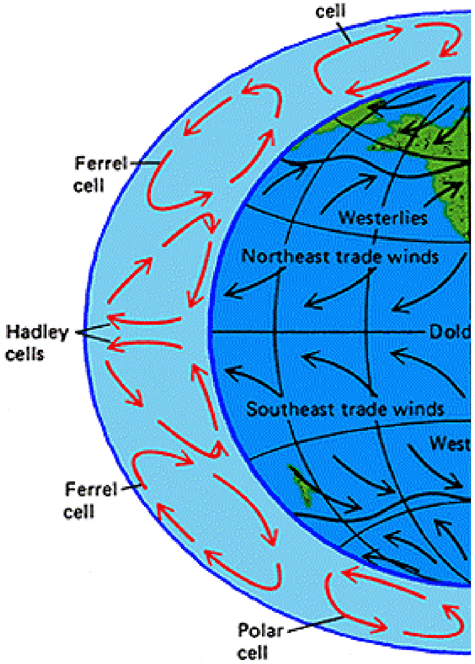
Effet de foehn

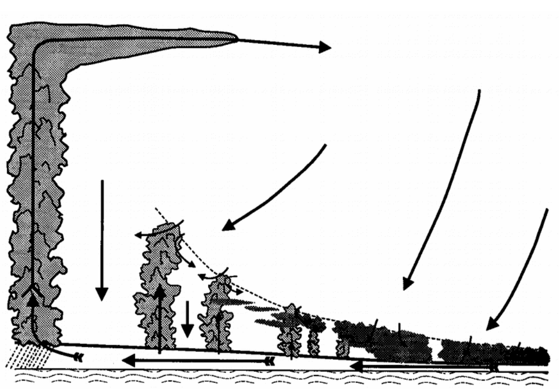
Du fait de la condensation de l'eau, qui libère de l'energie, l'air qui s'élève en formant un nuage se refroidit moins que l'air qui s'élève sans former de nuage.





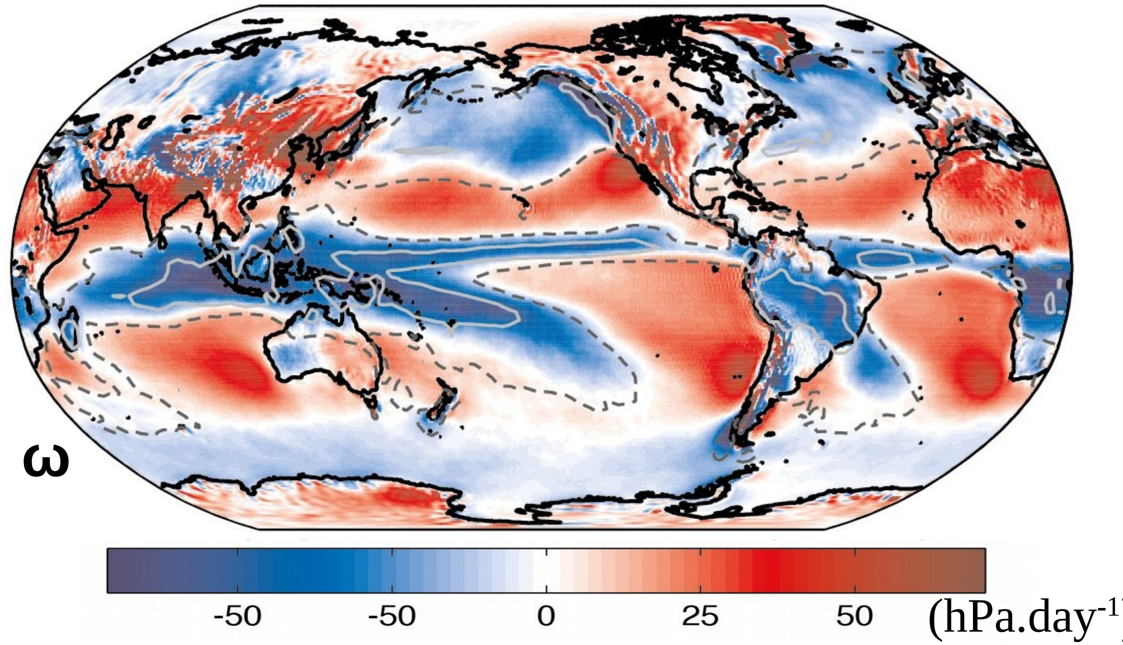
Circulation



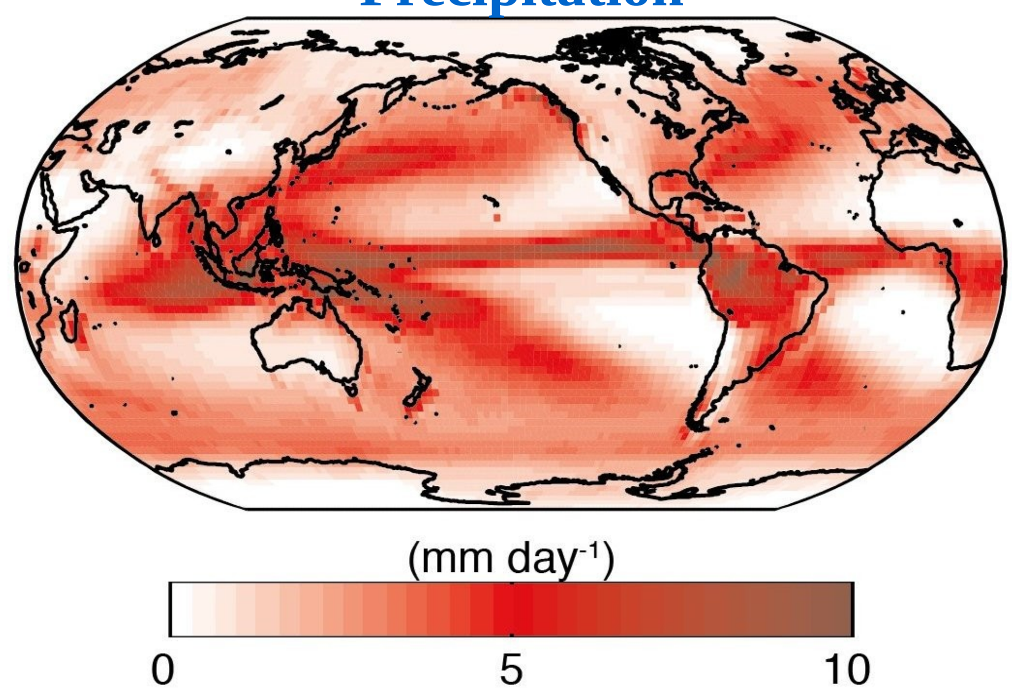


precip

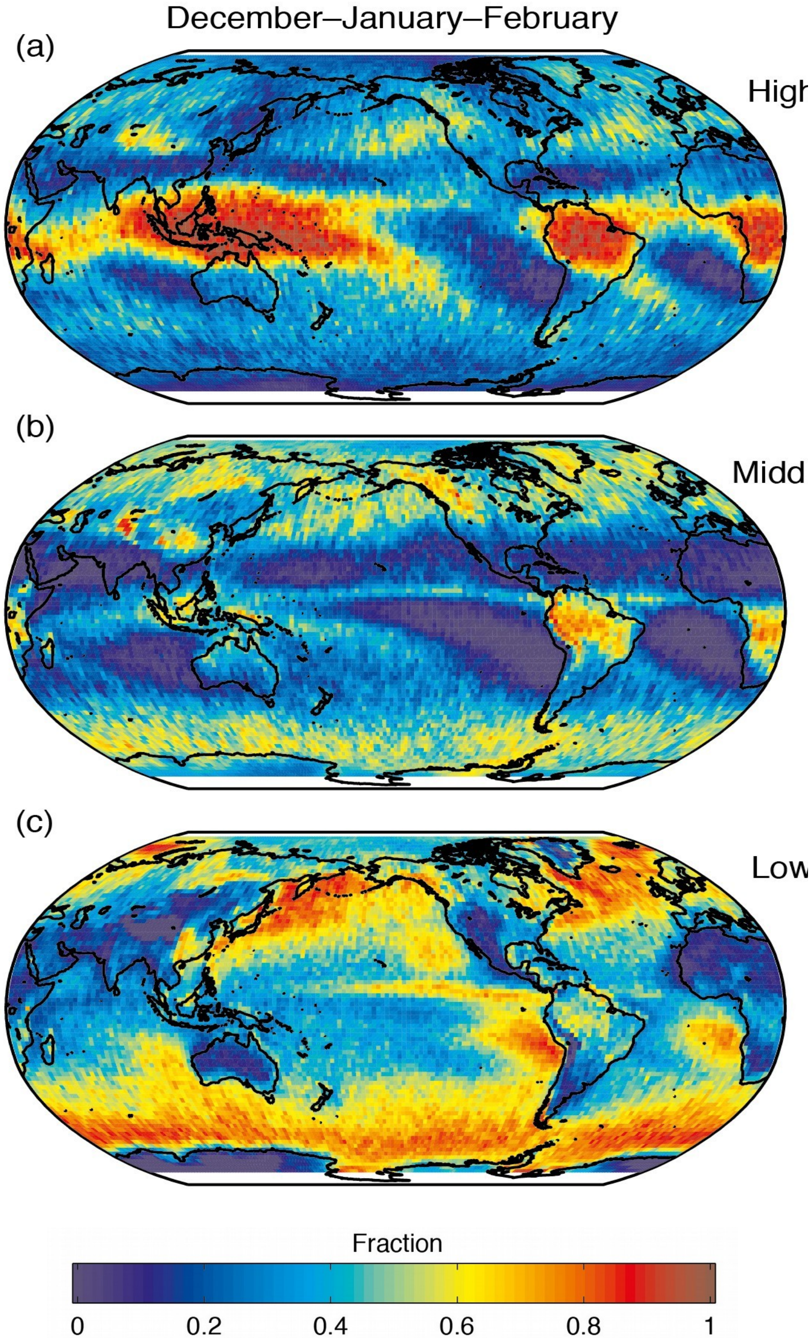
Mid-troposhere vertical pressure velocity ω



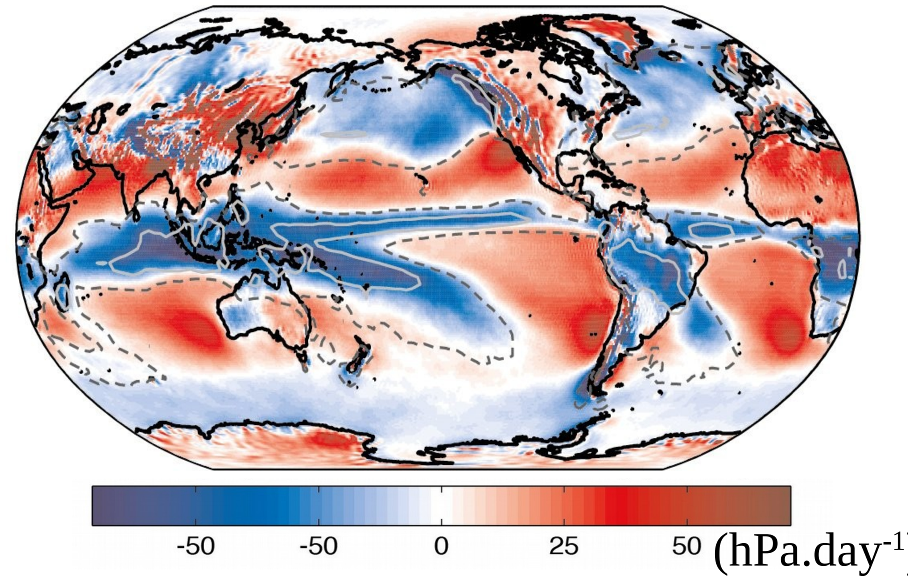
Precipitation



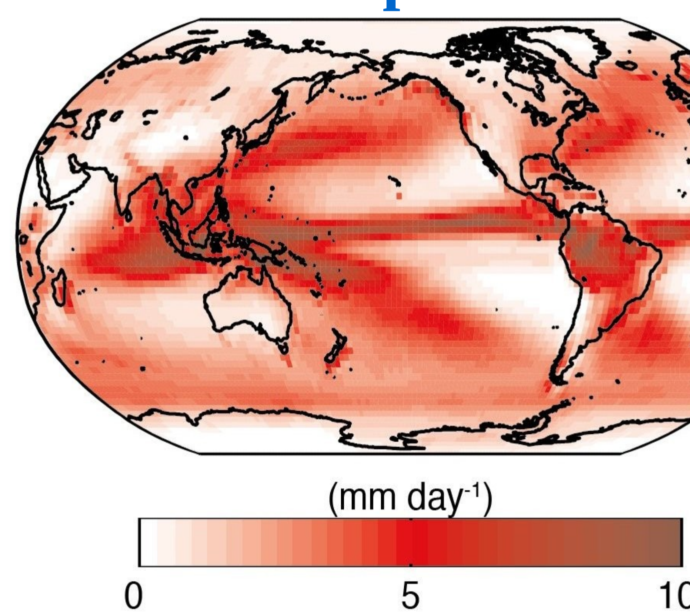
Cloud cover



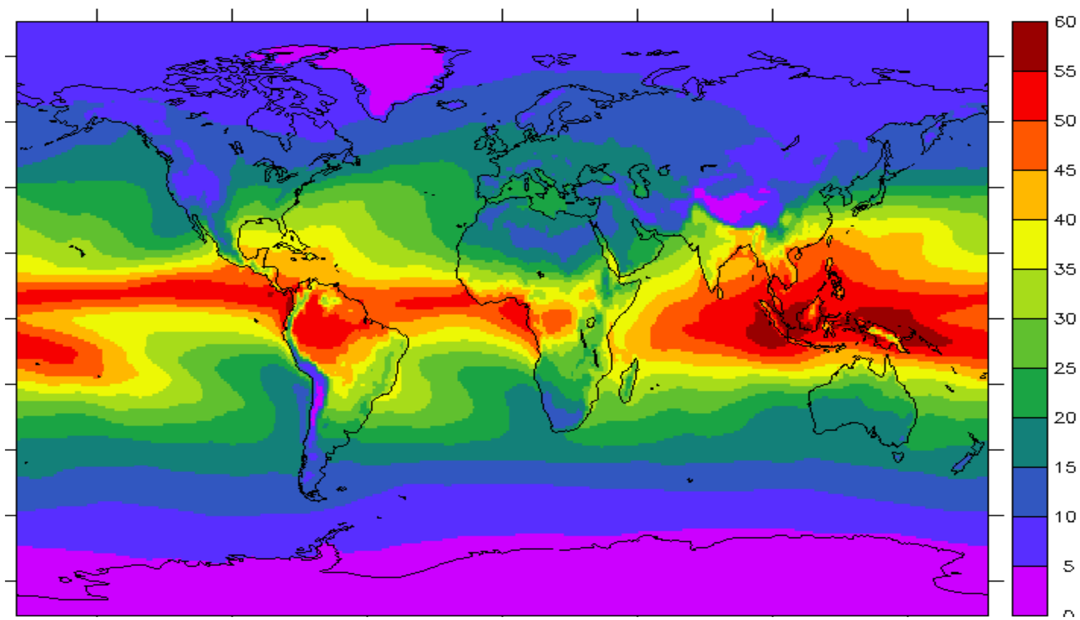
Mid-troposhere vertical pressure velocity ω



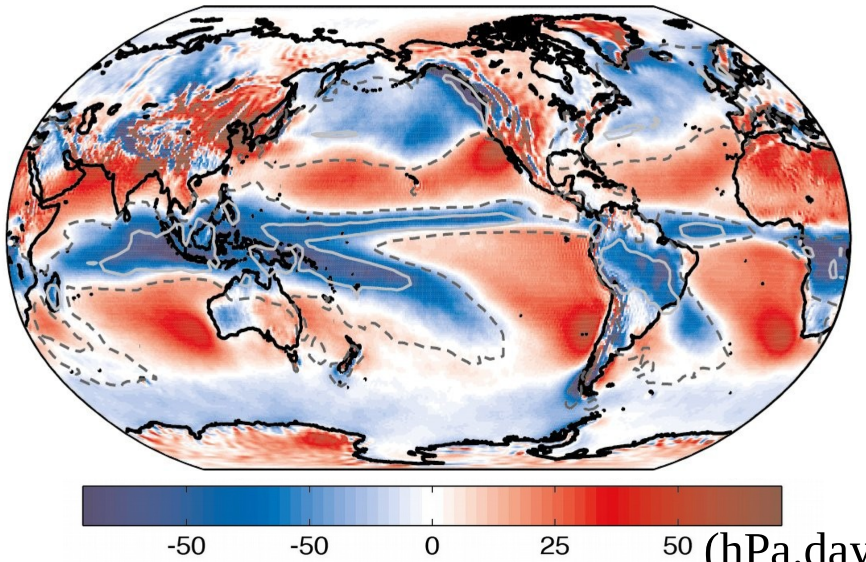
Precipitation



Total (vap, liq, sol) water amount (kg.m^{-2})

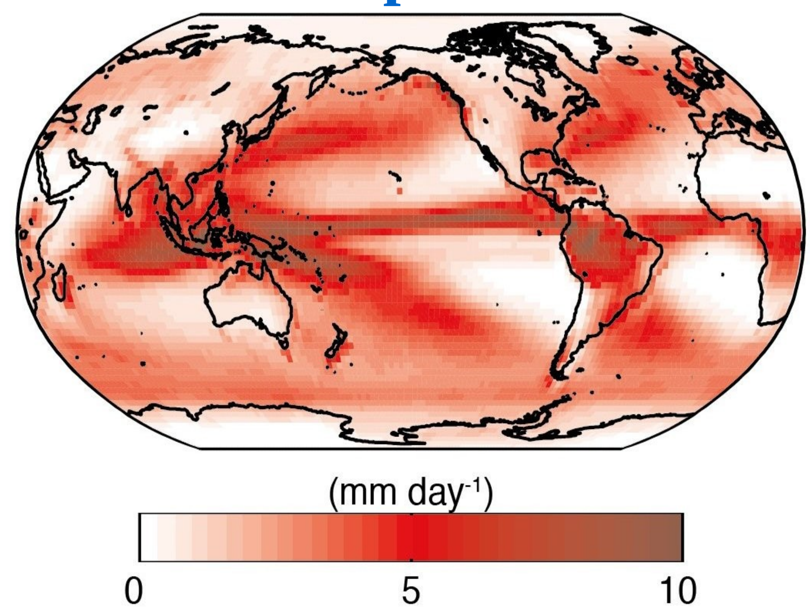


Mid-troposhere vertical pressure velocity ω



(hPa.day^{-1})

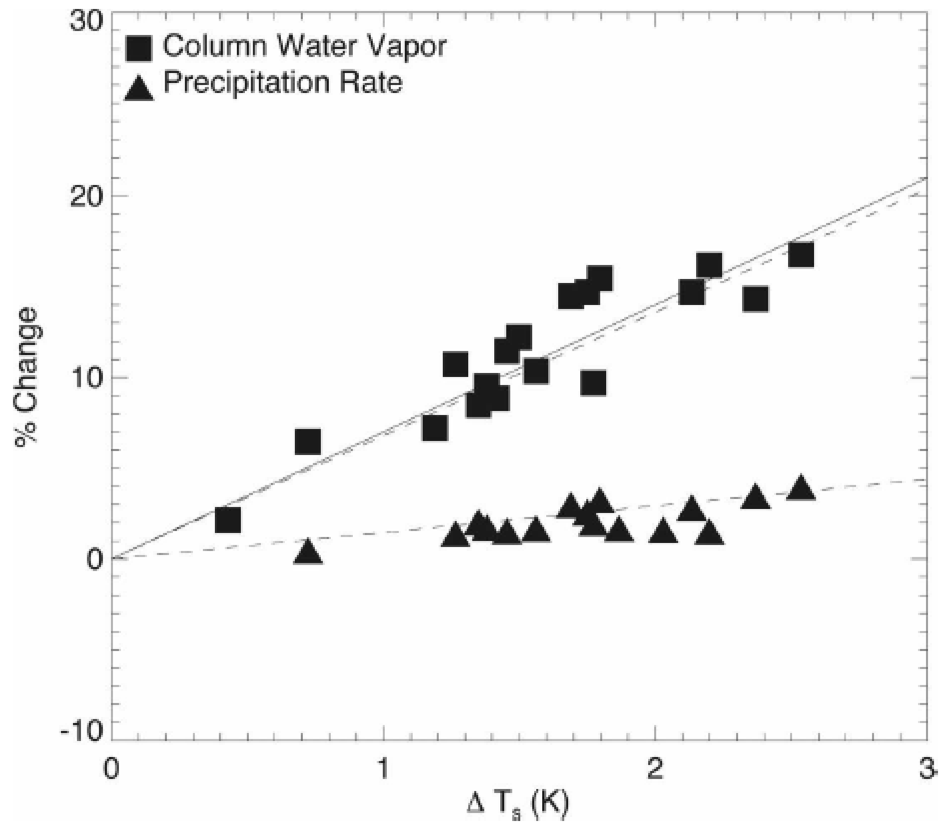
Precipitation



What control the change of **global precipitation?**

Global Hydrological Sensitivity

% Change of precipitation vs ΔTs
Multi-model results



Each symbol is
a model result

water vapor : +7.5 %/K

precipitation : +2 %/K

Stephens and Ellis, 2008

Energetic constraints

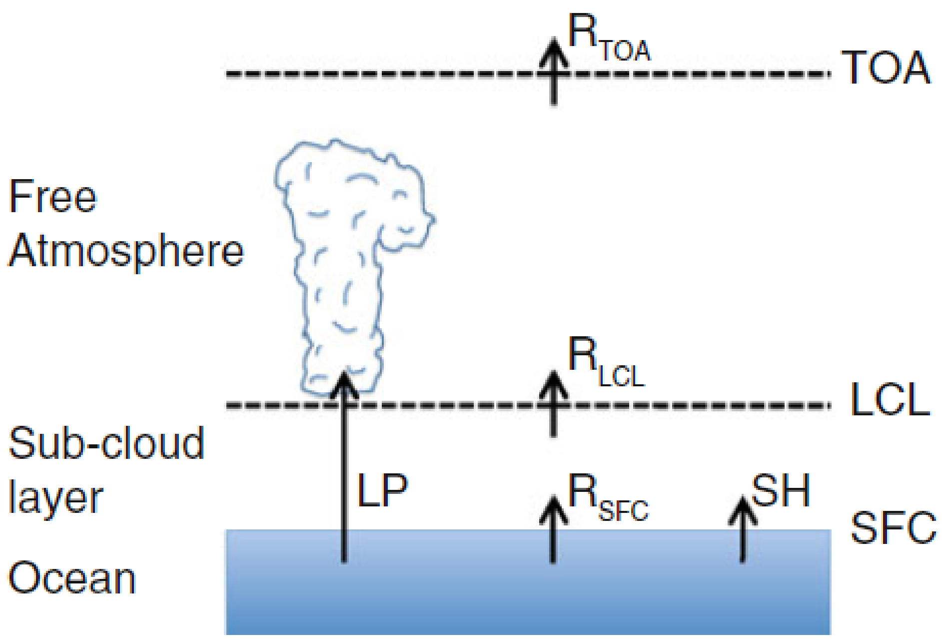
Vertically-integrated budget of dry static energy :

[latent heating **L.P**] + [radiative heating $\mathbf{R}_{\mathrm{ATM}}$] + [sfc sensible heat flux **SH**] = 0

P: precipitation
L: specific latent heat

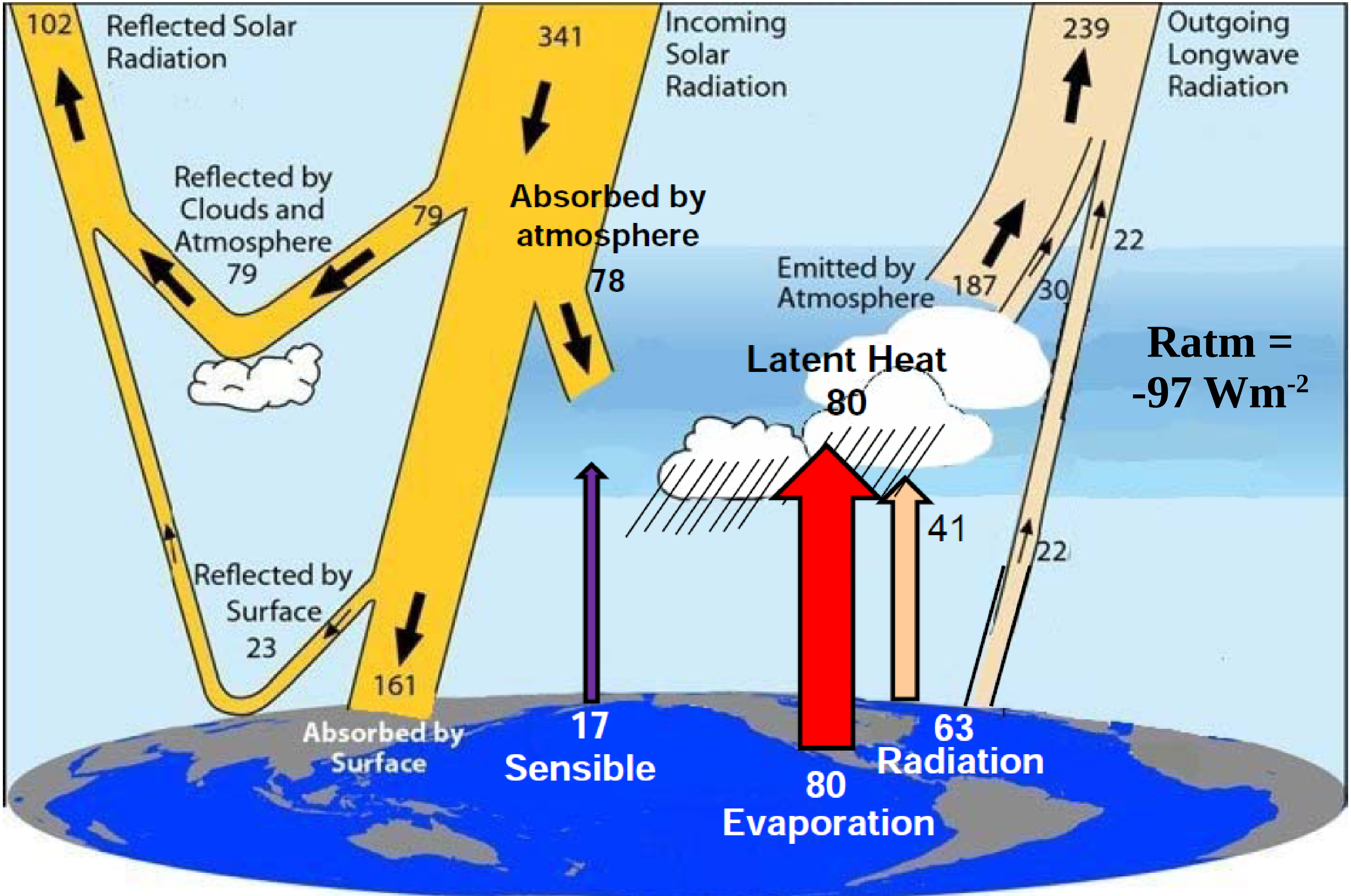
$$\boxed{L\,.\,P = -R_{ATM} - SH}$$

$$R_{ATM} = R_{\mathrm{SFC}} - R_{TOA}$$



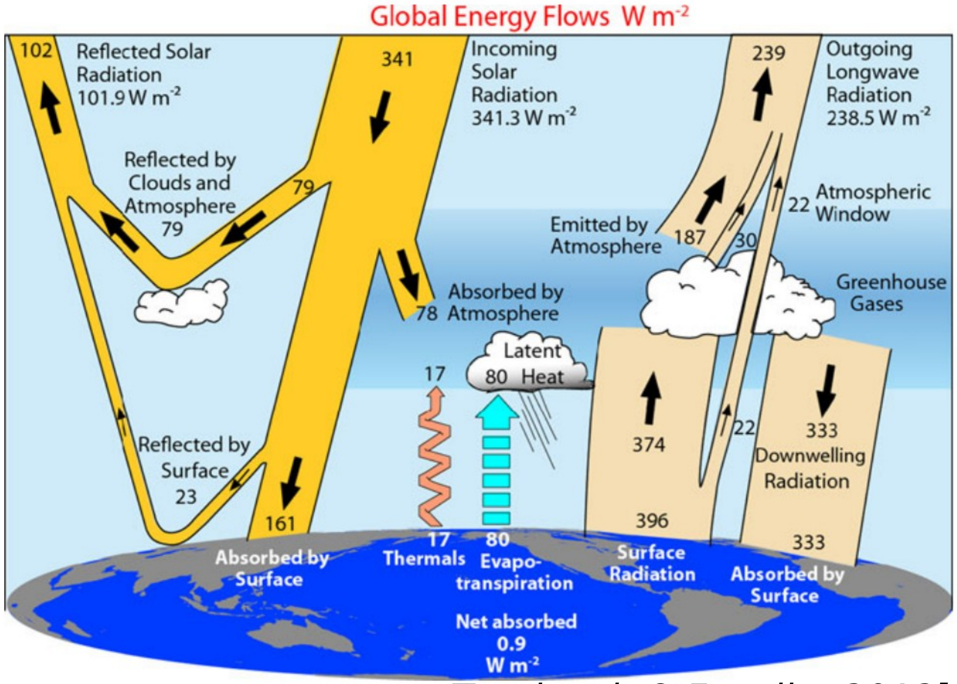
Mitchell, QJRMS, 1987
Soden and Held, J. Climate, 2006
Takahashi, JAS, 2009
O'Gorman et al., Surv. Geophys., 2012

Global Energy Flows (W.m^{-2})

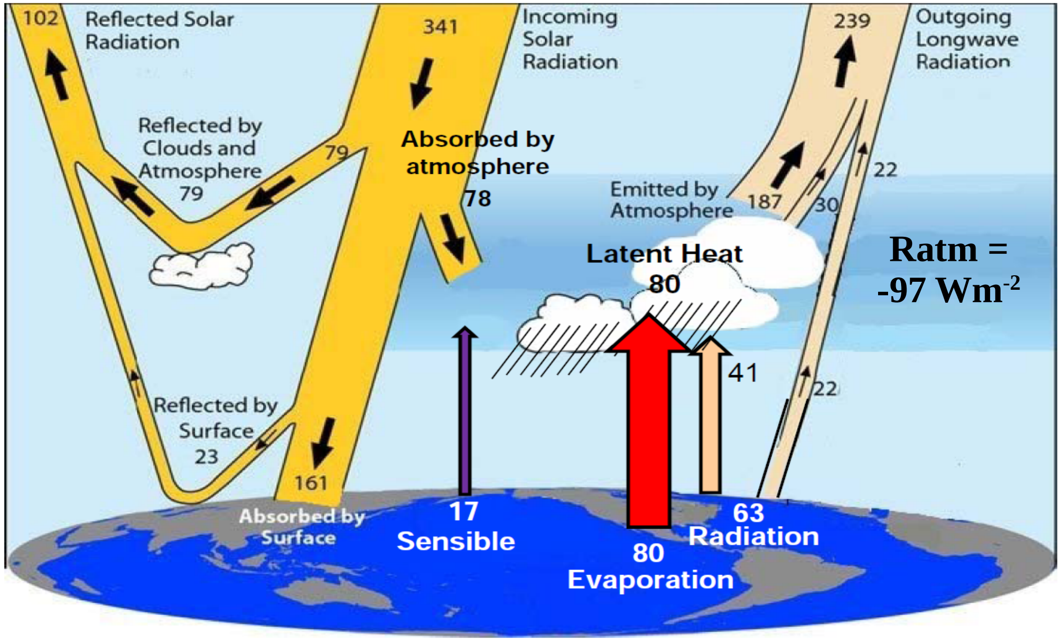


Adapted from [Trenberth & Fasullo, 2012]

Global Energy Flows (W.m^{-2})



Trenberth & Fasullo, 2012]



Adapted from [Trenberth & Fasullo, 2012]

Energetic constraints

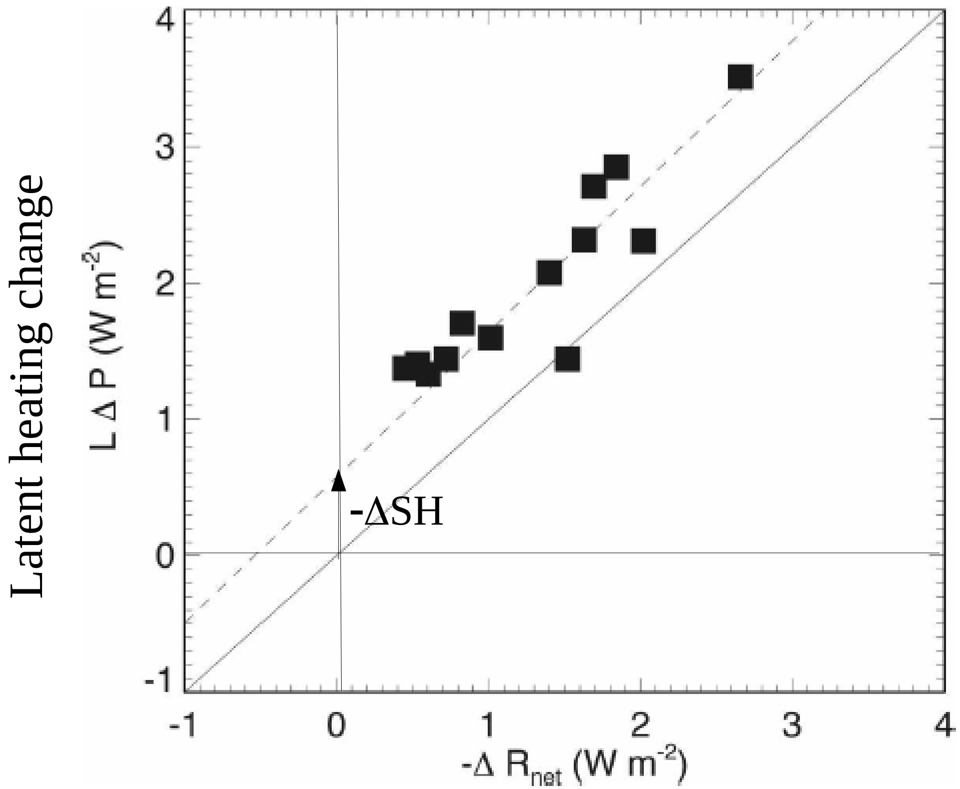
P: precipitation
L: specific latent heat

$$\boxed{L\Delta P = -\Delta R_{ATM} - \Delta SH}$$

- radiative **heating** change
= radiative **cooling** change

Each symbol is
a model result

Ensemble of models (CMIP3)



radiative cooling change

Stephens and Ellis, 2008

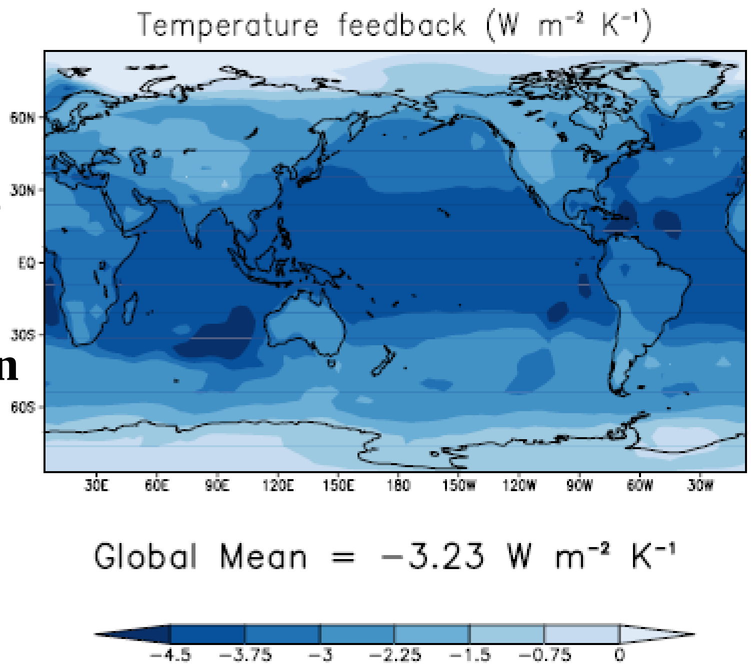
What controls the change in tropospheric radiative cooling in climate change ?

$$\frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x} \frac{\partial x}{\partial T_s}$$

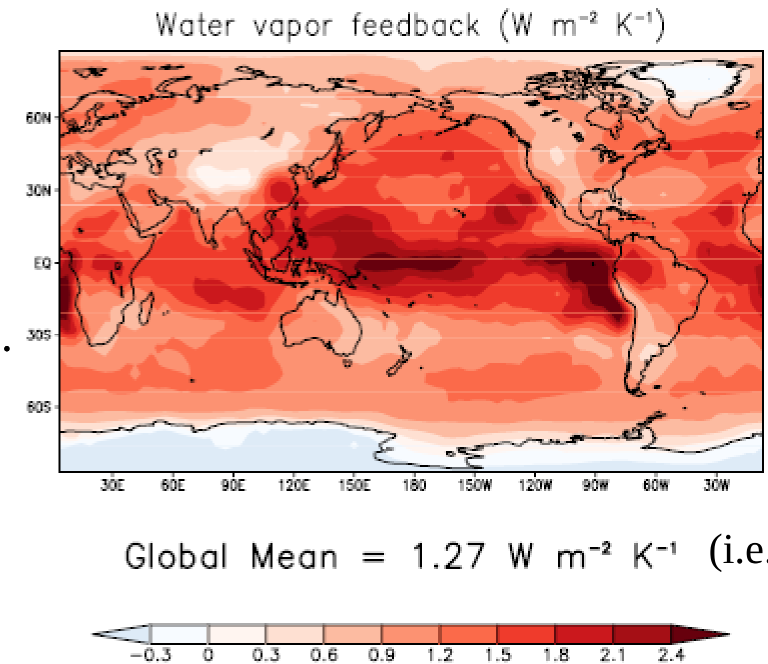
R : vertically integrated tropospheric radiative heating rate

Tropospheric radiative feedbacks

Increased temperature acts to **increasse precipitation**

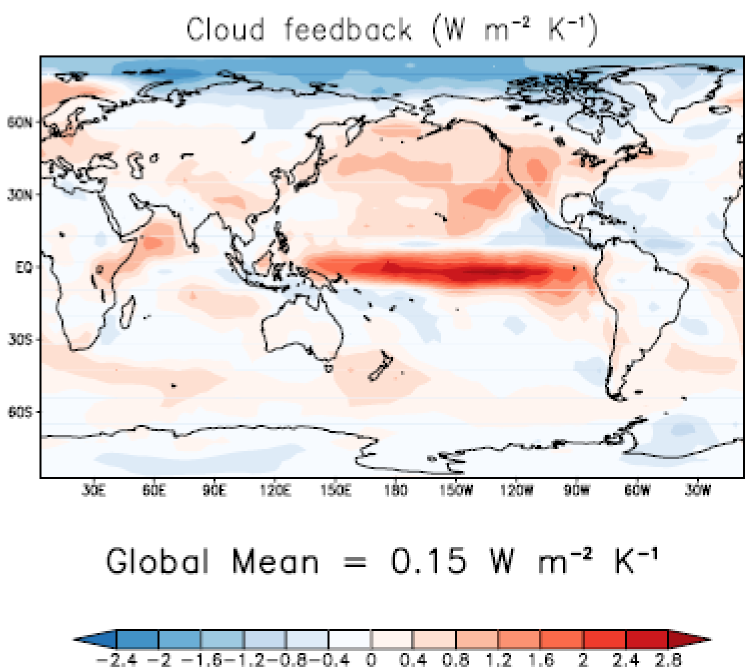


e.



(i.e. -40 %)

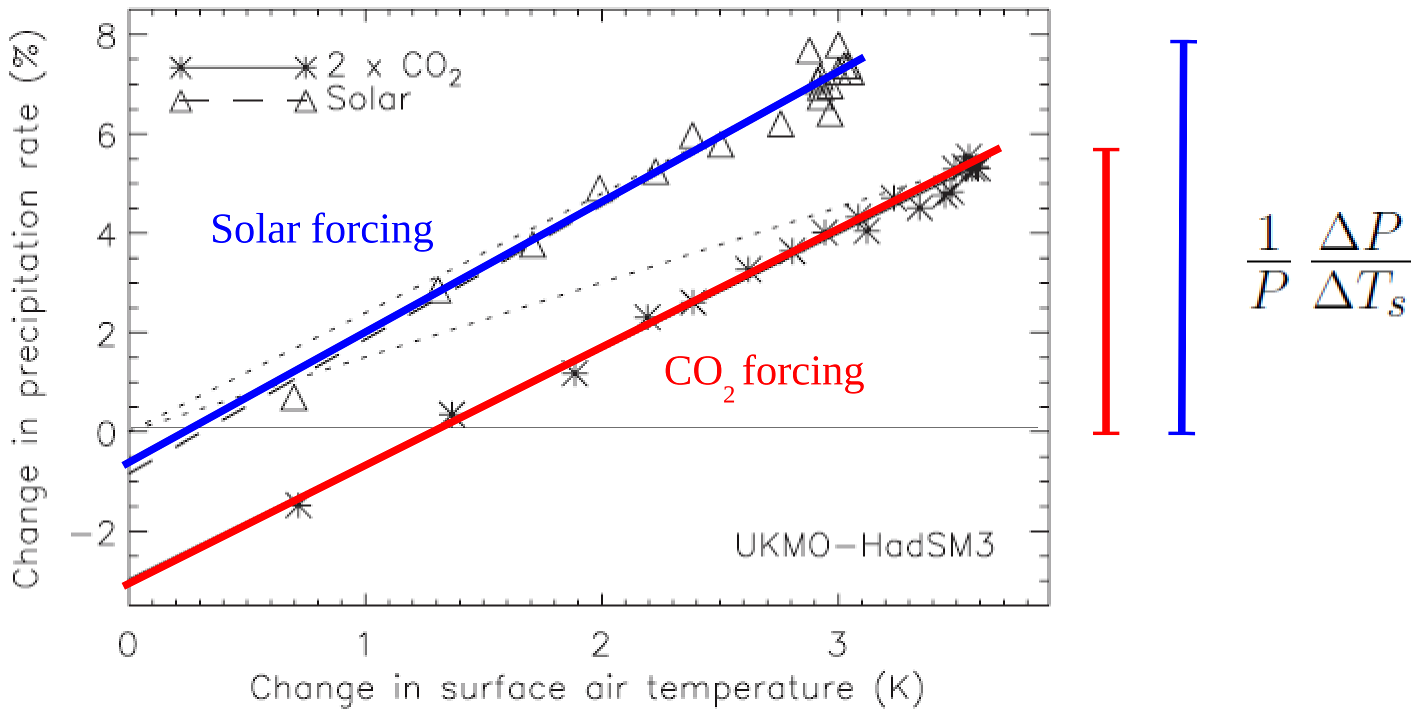
Increased water vapor acts to **reduce precipitation**!



$$\frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$$

Previdi, Env. Res. Lett., 2010

Dependence of hydrological sensitivity on forcing



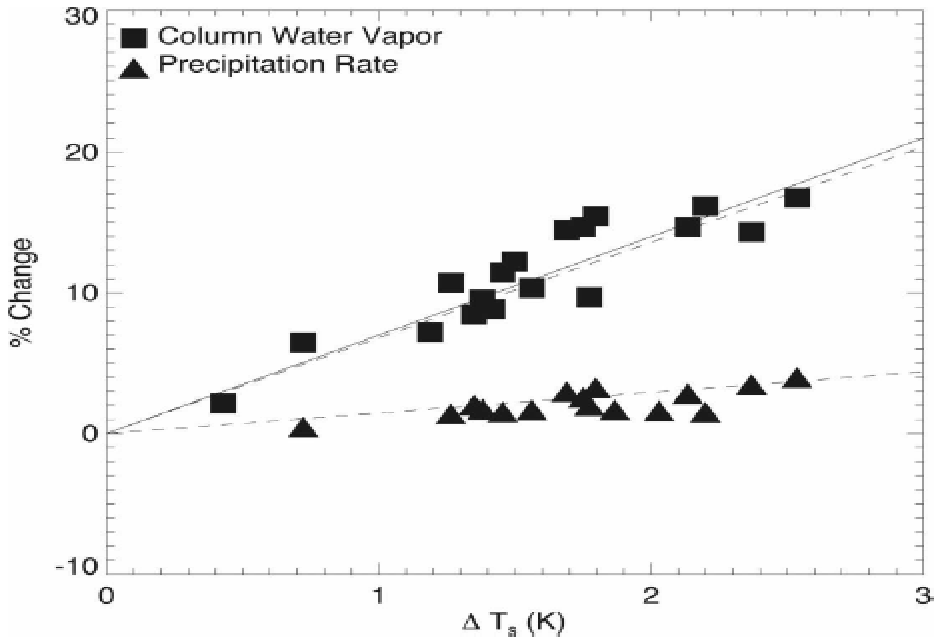
- Weaker hydrological sensitivity for CO_2 forcing than for solar forcing
- (Fast) precipitation adjustment to CO_2 forcing
- Precipitation response to ΔTs quite similar between the two forcing agents

Andrews et al., J. Climate, 2009

Global Hydrological Sensitivity

% Change of precipitation vs Δts

Multi-model results



water vapor : +7.5 %/K

precipitation : +2 %/K

Each symbol is a model result

Stephens and Ellis, 2008

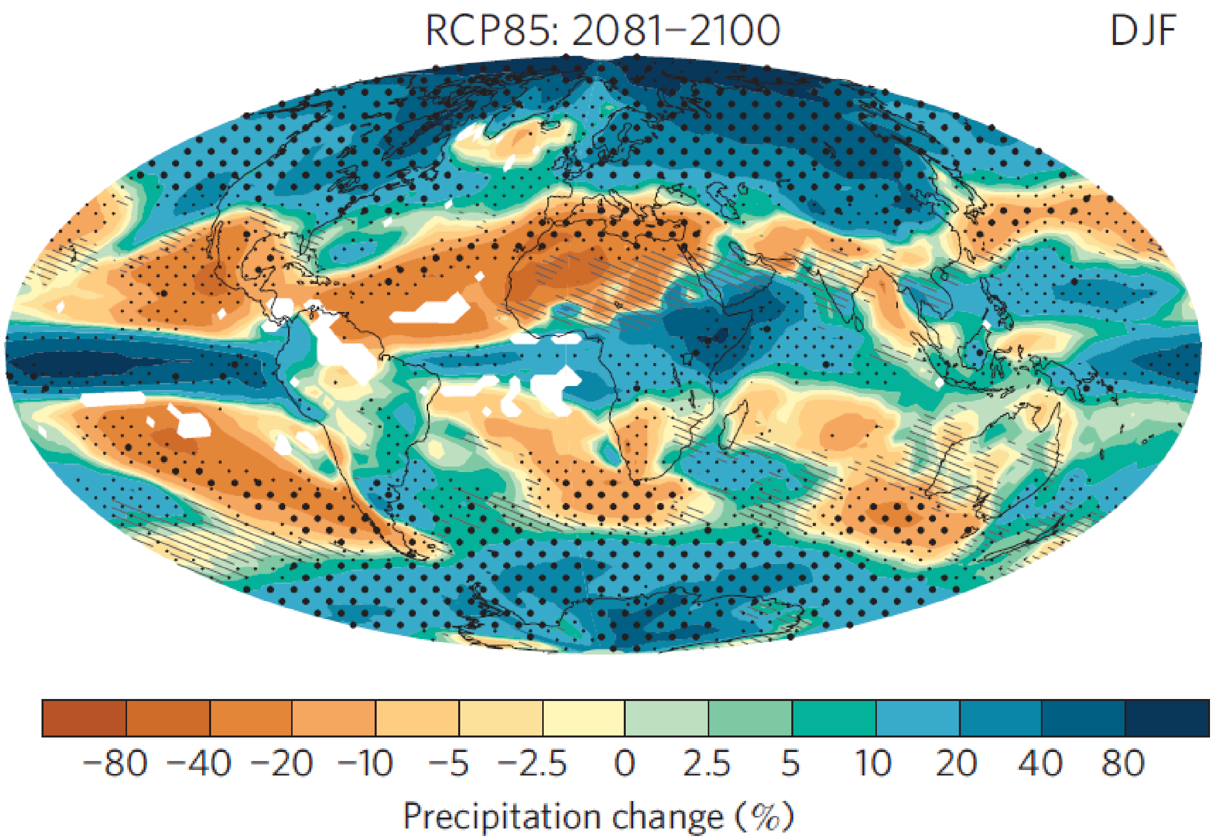
Precipitation is **sustained** by the availability of moisture and energy.

Global precipitation changes are limited by the availability of energy.

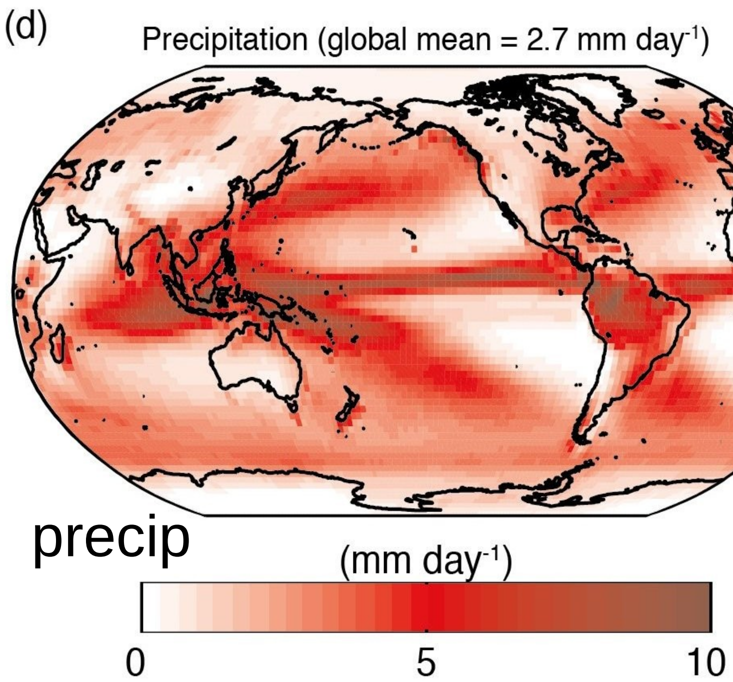
An increase of the atmospheric temperature *increases the radiative cooling and thefore inreases the global precipitation*

An increase of GHG (CO2, H20...) **or solar absorbent** (black carbon...) ***decreases the radiative cooling and therefore decreases the global precipitation***

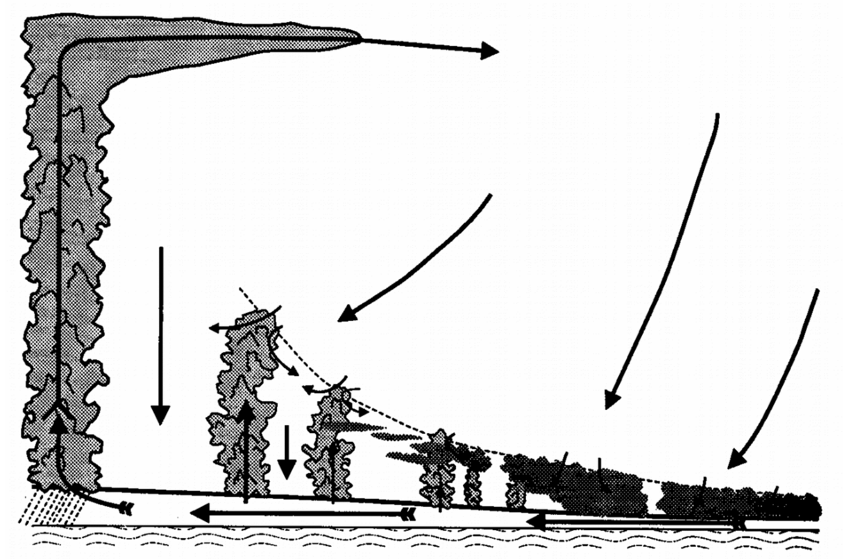
What controls regional precipitation changes ?

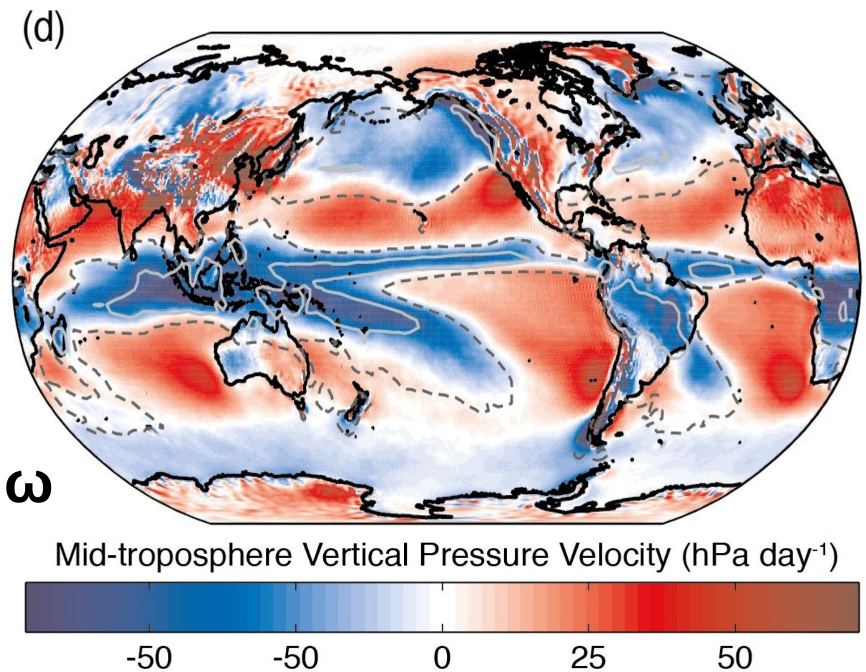


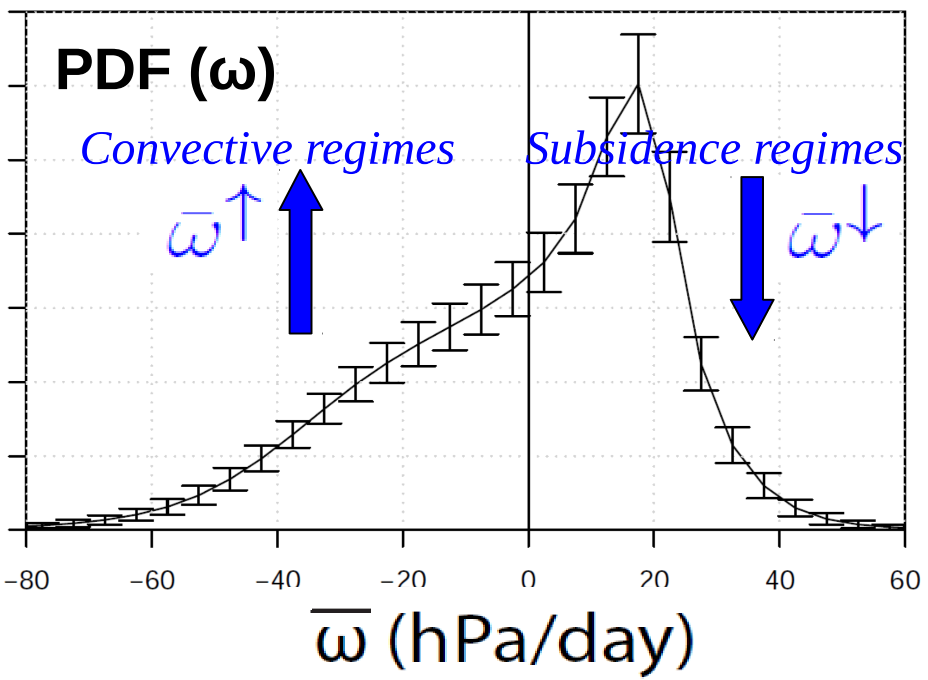
Present-Day Climate Variables



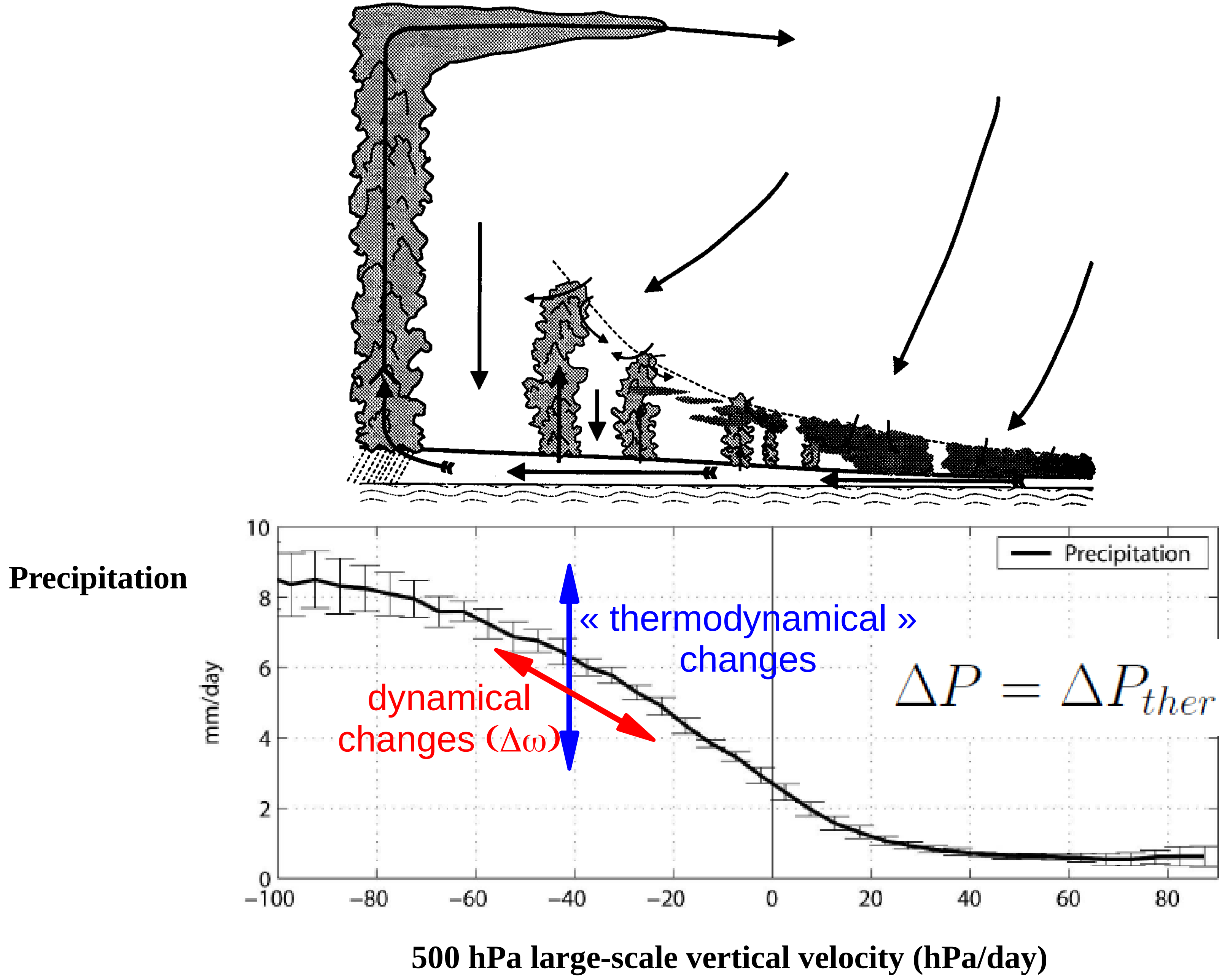
Tropical Overturning Circulation







Precipitation closely tied to large-scale atmospheric vertical motions



$$\Delta P = \Delta P_{ther} + \Delta P_{dyn}$$

Bony et al., J. Climate, 2006

What controls regional precipitation changes ?

Dynamical and thermodynamical components of precipitation changes

Analysis Method

- Water budget : $P = E - \left[\omega \frac{\partial q}{\partial P}\right] + H_q$
- Let $\overline{\omega}$ be mass-weighted vertical average of ω.
- Then : $P = E + \overline{\omega}\,\Gamma_q + H_q + V_q^\alpha$

surface evaporation

vertical advection

horizontal advection

shape of omega profile

$$\Delta P = \boxed{\left(\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^\alpha\right)} + \boxed{\Gamma_q\,\Delta\overline{\omega}}$$

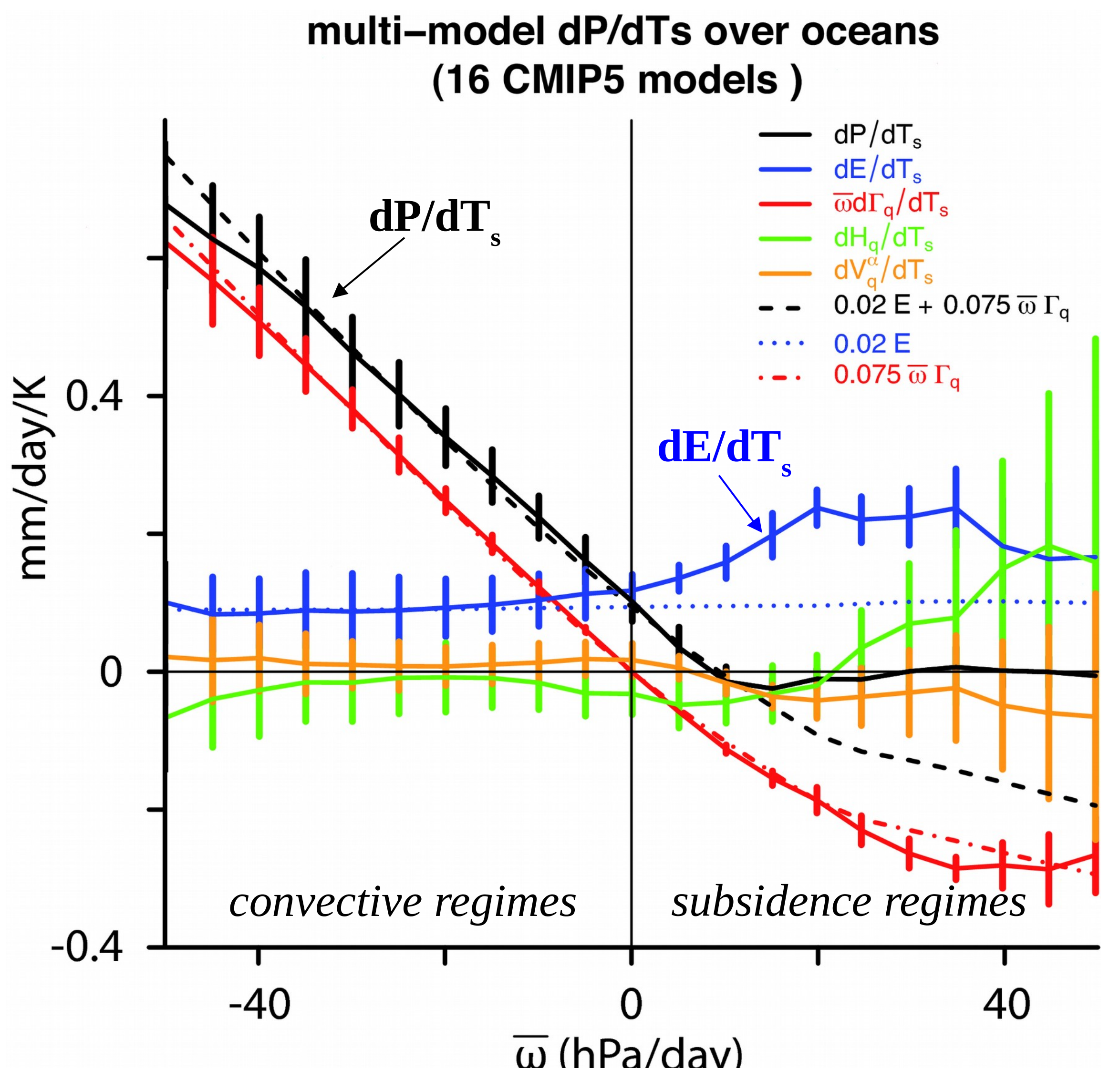
thermodynamical component

dynamical component

Bony et al., Nature Geosci., 2013

How would precipitation respond to global warming in the absence of change in vertical motion ?

- 16 CMIP5 models (mean and spread)
- *wet get wetter, dry get drier*
- *wet get wetter* more robust than *dry get drier*



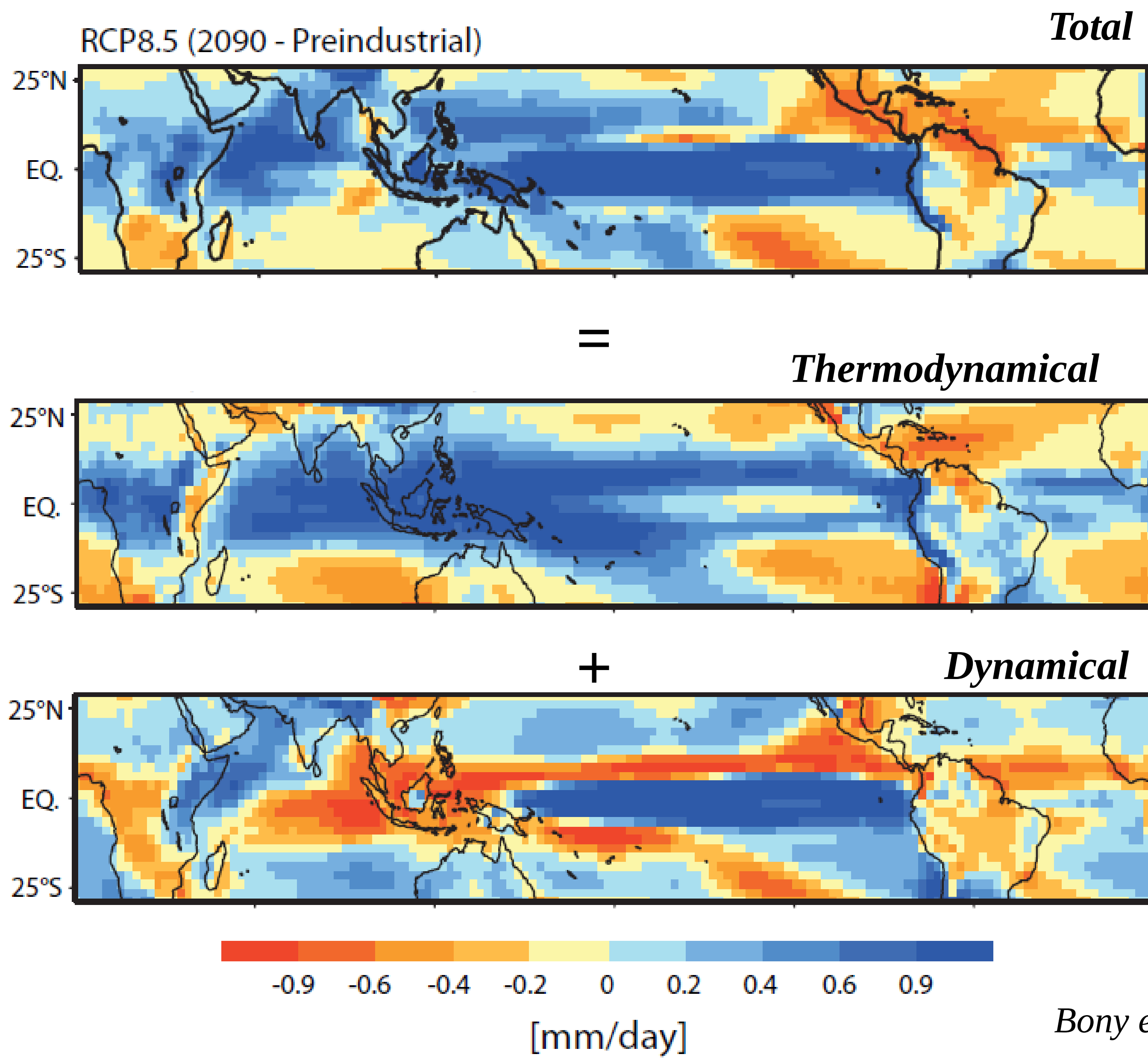
Clausius-Clapeyron

$$\Delta P = \boxed{(\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha})} + \cancel{\Gamma_q \Delta\overline{\omega}}$$

Bony et al., Nature Geosci., 2013

Tropical Precipitation Projections

RCP8.5 scenario at the end 21C



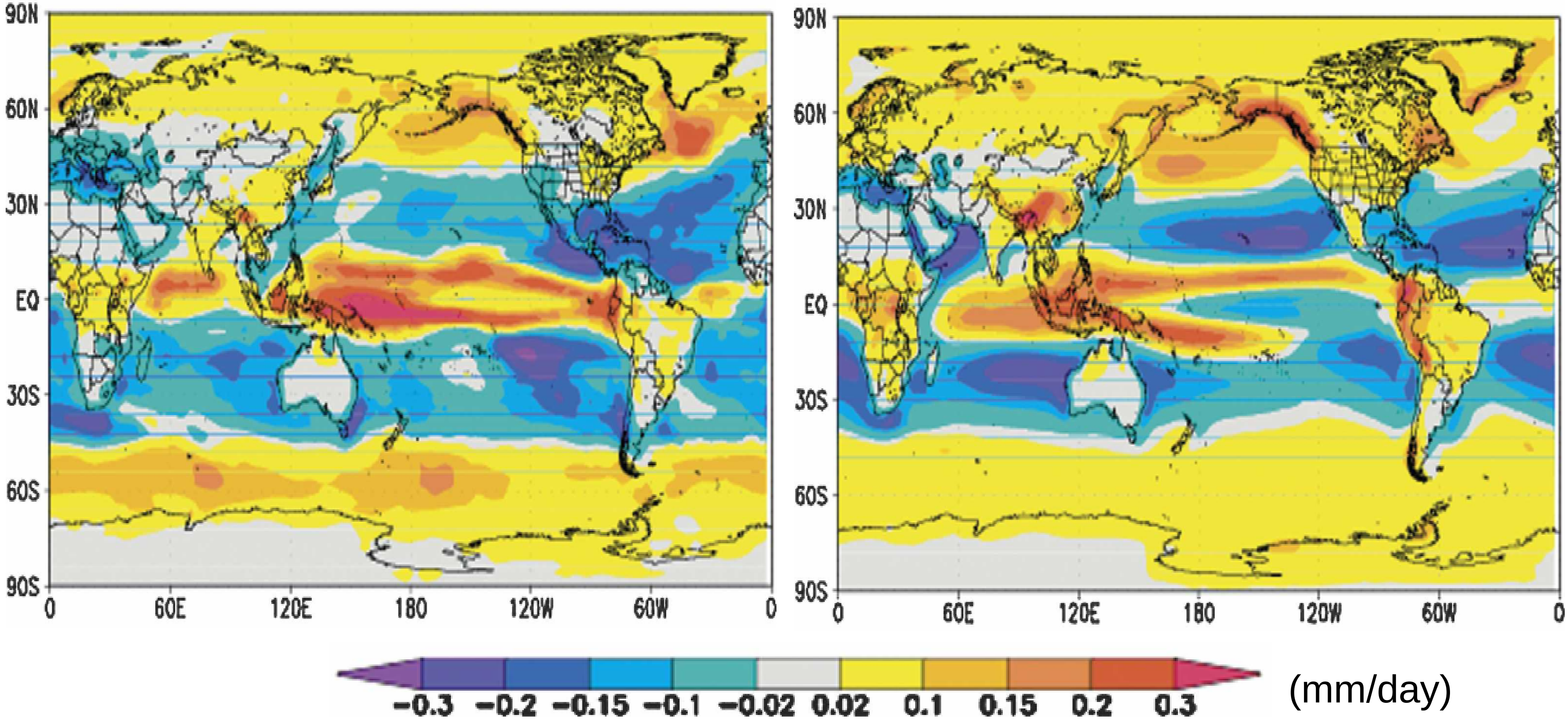
$$\Delta P_{ther} = \Delta P - \Delta P_{dyn}$$

$$\Delta P_{dyn} = \Gamma_q \Delta \overline{\omega}$$

Bony et al., Nature Geosci., 2013

The “wet-get-weter” and “dry get drier” paradigm

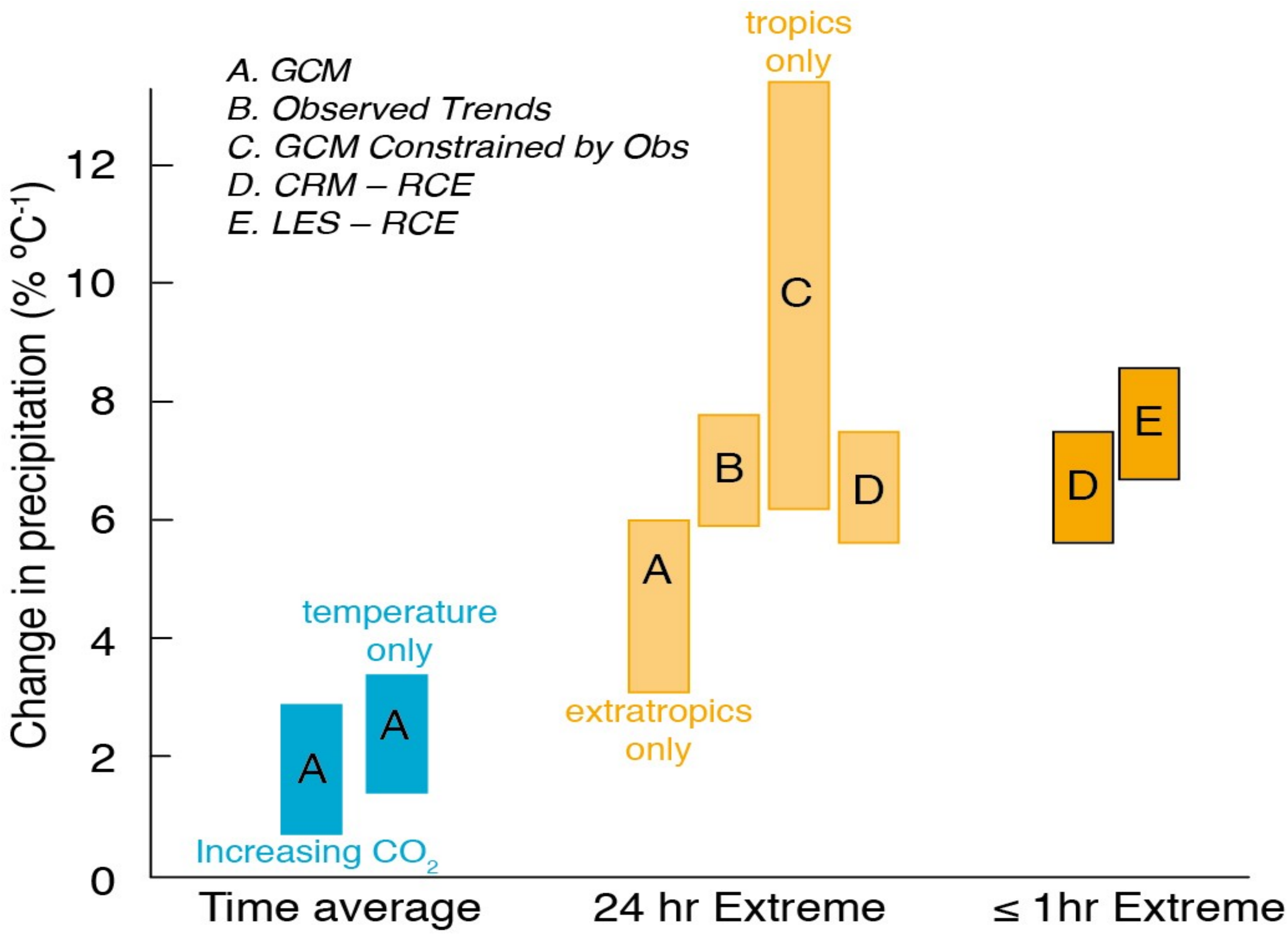
Precipitation - Evaporation



(a) The annual-mean distribution of Δ(P - E) and (b) the thermodynamic component (CPMIP3 models, SRES A1B scenario).

[Held & Soden, 2006]

The change in extreme precipitation



[IPCC AR5, 2013]

Pattern scaling

- For many models, as a first approximation :
  $\Delta X(\text{space,time}) = \text{global } \Delta T(\text{time}) \times \text{pattern(space)}$
- **Global ΔT : a scaling factor for many global and regional climate responses**