Clouds in a Changing Climate

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Lecture #3 : Precipitation in a changing climate

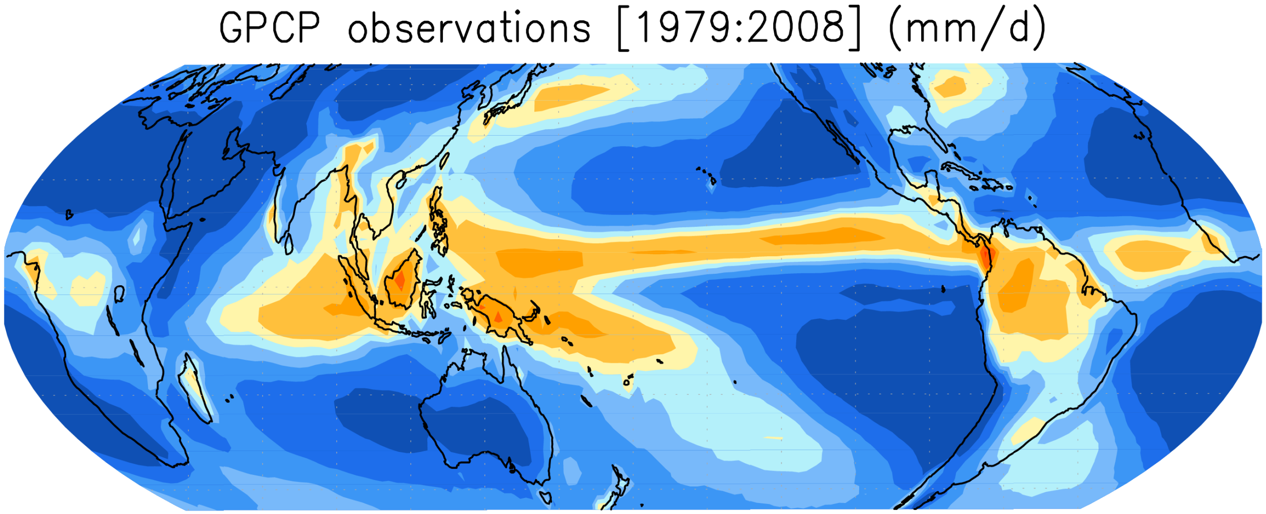
ÉCOLE DE PHYSIQUE
des HOUCHES

EUCLIPSE « Clouds in Climate » Summerschool
Les Houches, France, Jun 25 – Jul 5 2013

Clouds and Precipitation

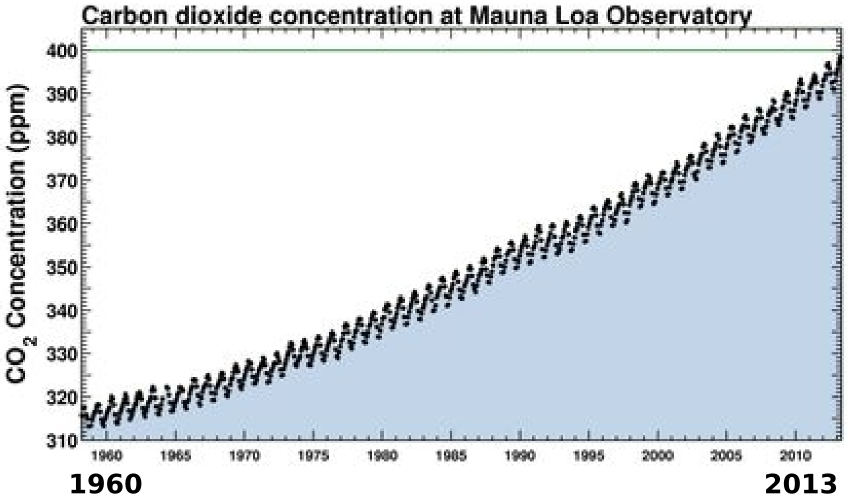
© Frédéric Batier

How and why will precipitation change in response to increased CO2 ?


GPCP observations [1979:2008] (mm/d)

ΔP ?

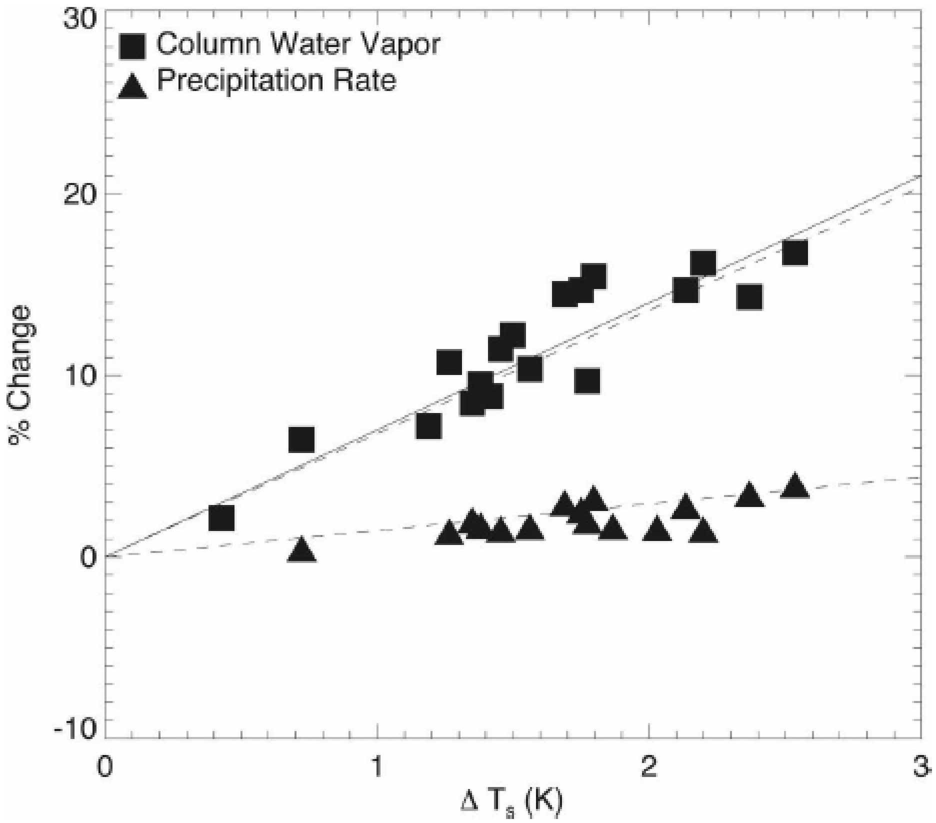
Mauna Loa



2013 : 400 ppm

Global Hydrological Sensitivity

% Change vs ΔTs



water vapor : +7.5 %/K

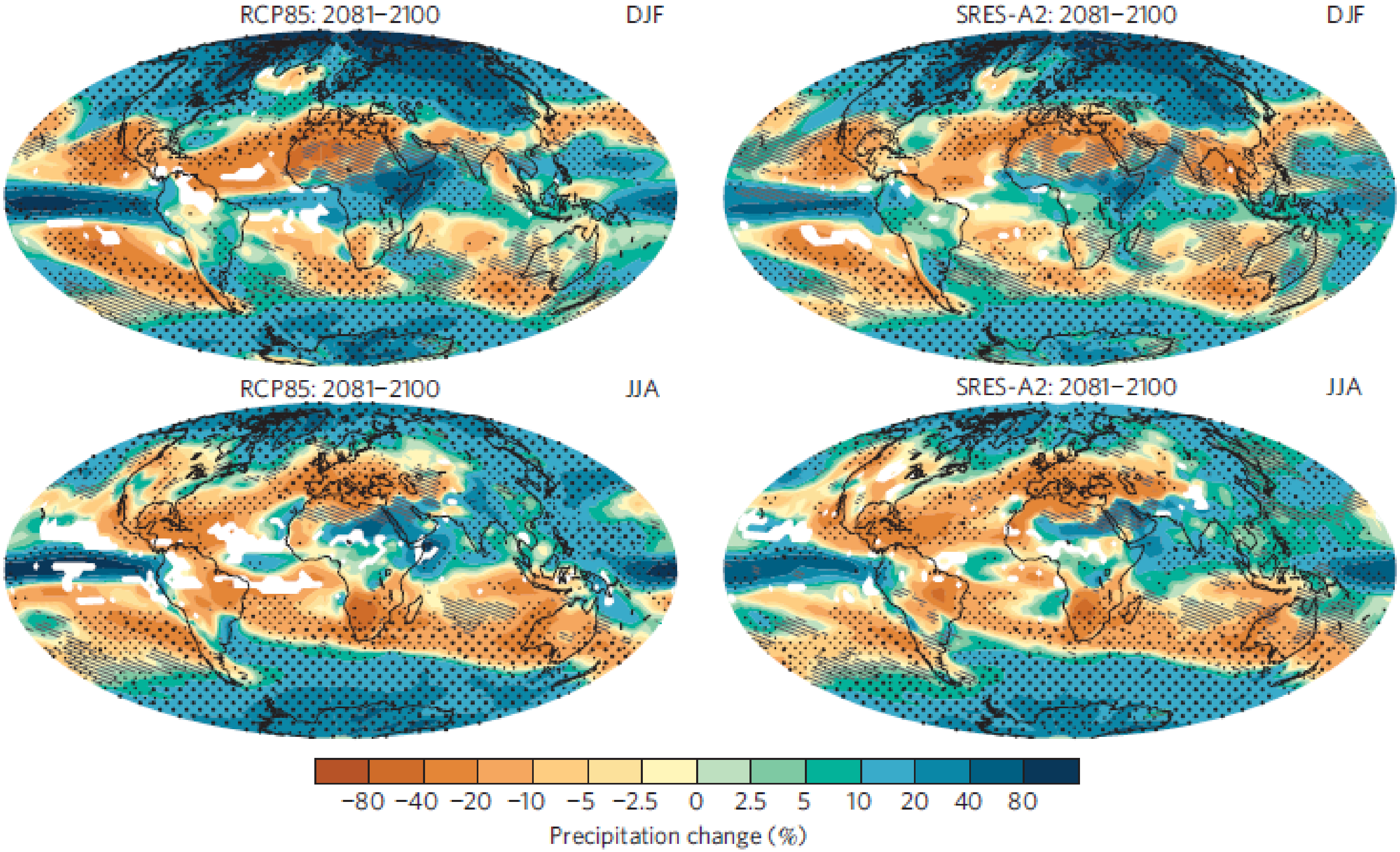
precipitation : +2 %/K

What controls the rate of global precipitation changes ?

Stephens and Ellis, J. Climate, 2008

Regional precipitation response

CMIP3 **CMIP5**



Interpretation of the pattern ? robustness ? uncertainties ?

Knutti and Sedlacek, Nat. Clim. Change, 2012

Questions

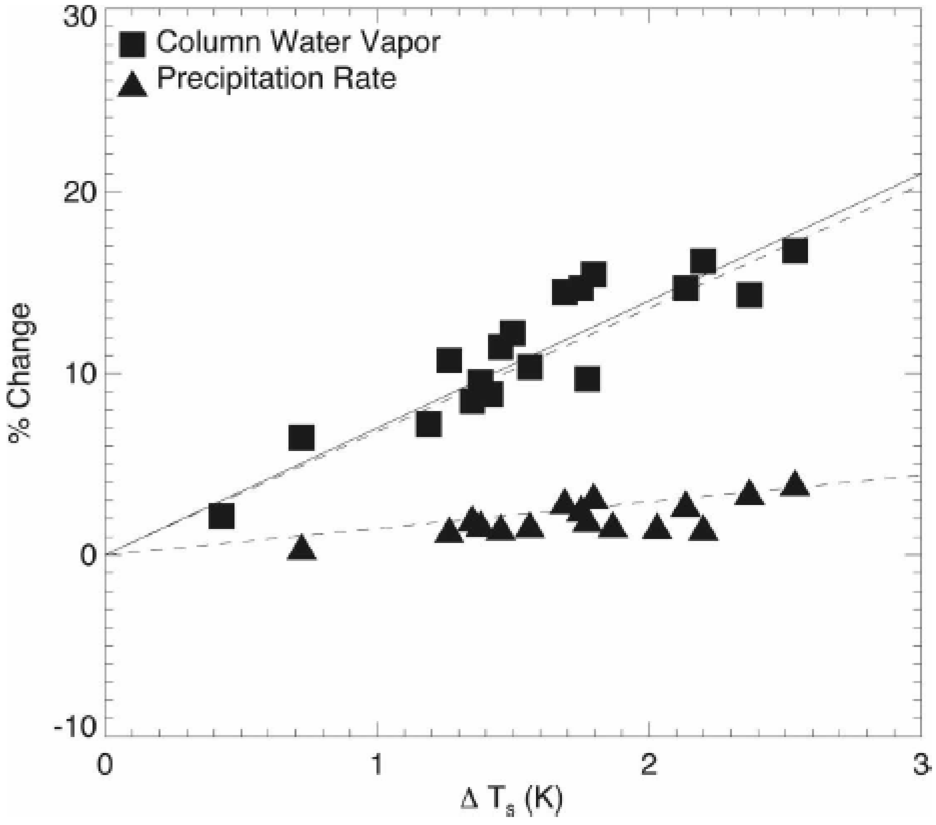
1. What controls the rate of global precipitation change ?

2. What controls the regional pattern of precipitation change ?
    - Understanding of the robust component ?
    - Where do uncertainties come from ?

3. How may cloud-radiative effects impact precipitation changes ?

Global Hydrological Sensitivity

% Change vs ΔTs



water vapor : +7.5 %/K

precipitation : +2 %/K

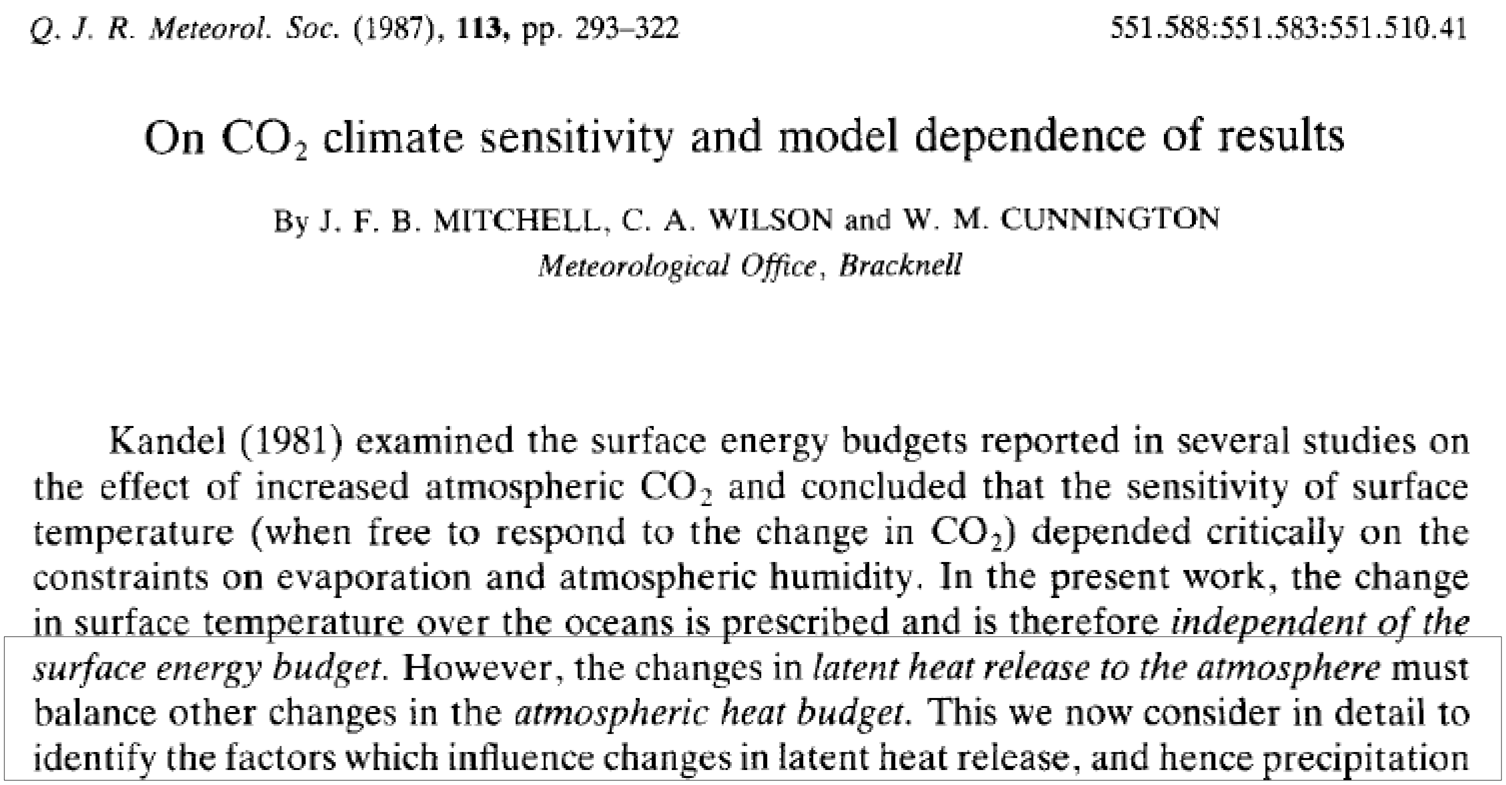
Precipitation is sustained by the availability of moisture and energy

.

Global precipitation changes are limited by the availability of energy.

Stephens and Ellis, J. Climate, 2008

Read this paper !



Q. J. R. Meteorol. Soc. (1987), **113,** pp. 293–322 551.588:551.583:551.510.41

On CO_2 climate sensitivity and model dependence of results

By J. F. B. MITCHELL, C. A. WILSON and W. M. CUNNINGTON

Meteorological Office, Bracknell

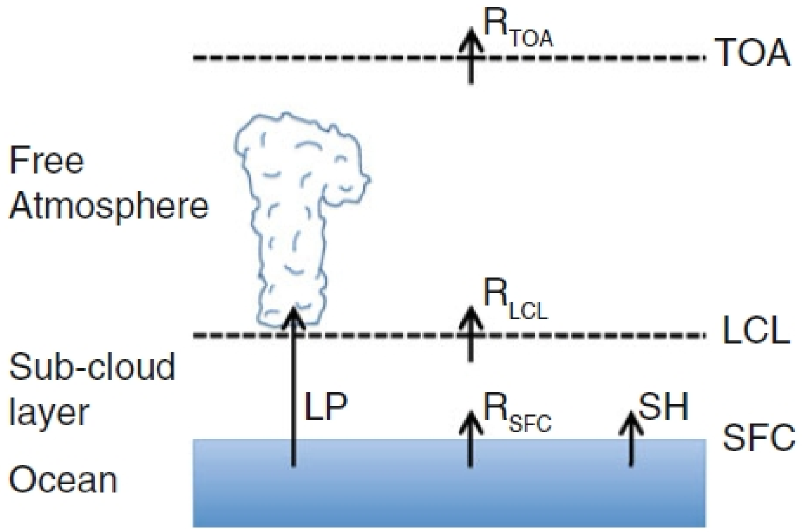
Kandel (1981) examined the surface energy budgets reported in several studies on the effect of increased atmospheric CO_2 and concluded that the sensitivity of surface temperature (when free to respond to the change in CO_2) depended critically on the constraints on evaporation and atmospheric humidity. In the present work, the change in surface temperature over the oceans is prescribed and is therefore *independent of the surface energy budget*. However, the changes in *latent heat release to the atmosphere* must balance other changes in the *atmospheric heat budget*. This we now consider in detail to identify the factors which influence changes in latent heat release, and hence precipitation

Energetic constraints

Vertically-integrated budget of dry static energy :

[latent heating] + [sfc sensible heat flux] + [radiative cooling] = 0

LP SH -R

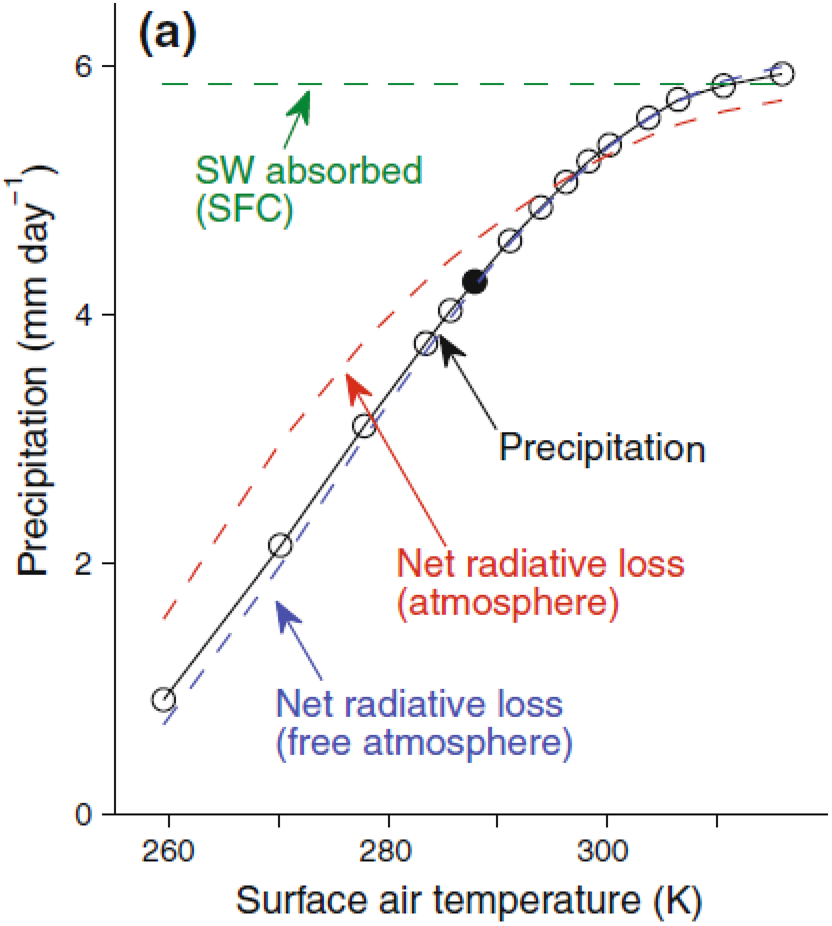


Δtropospheric radiative cooling

$$L\delta P = \boxed{\delta R_{\mathrm{TOA}} - \delta R_{\mathrm{SFC}}} - \delta SH$$

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

Energetic constraints



- Model simulations in which the optical depth of the LW absorber is varied

- More a radiative constraint than an energetic constraint

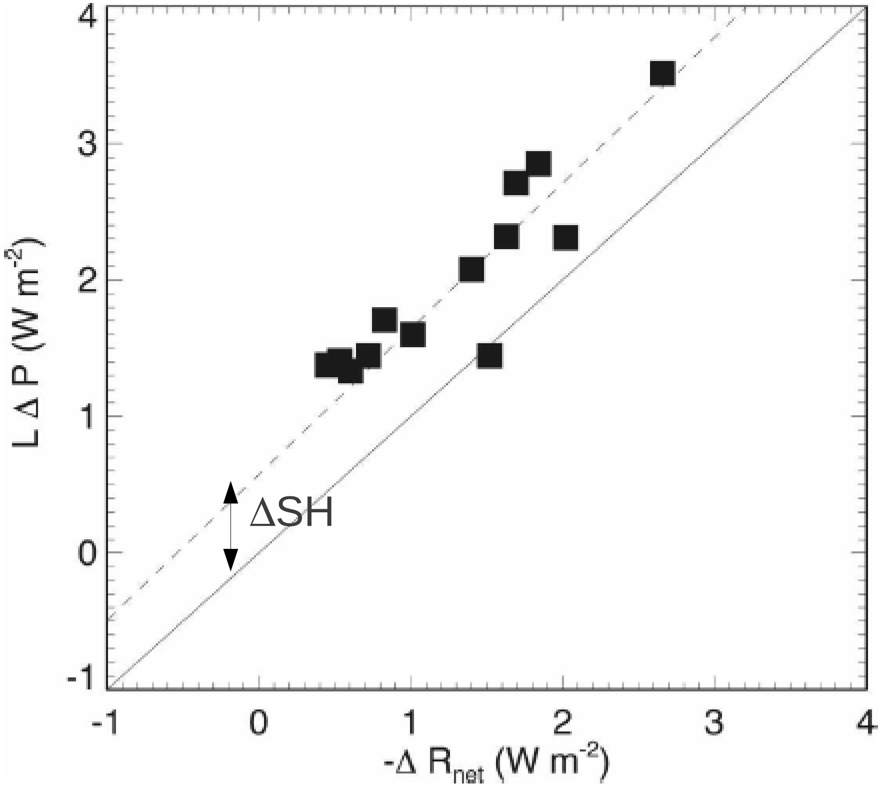
$$L\delta P \simeq \delta R_{\mathrm{TOA}} - \delta R_{\mathrm{LCL}}$$

- Upper bound on hydrological sensitivity

O'Gorman et al., Surv. Geophys., 2012

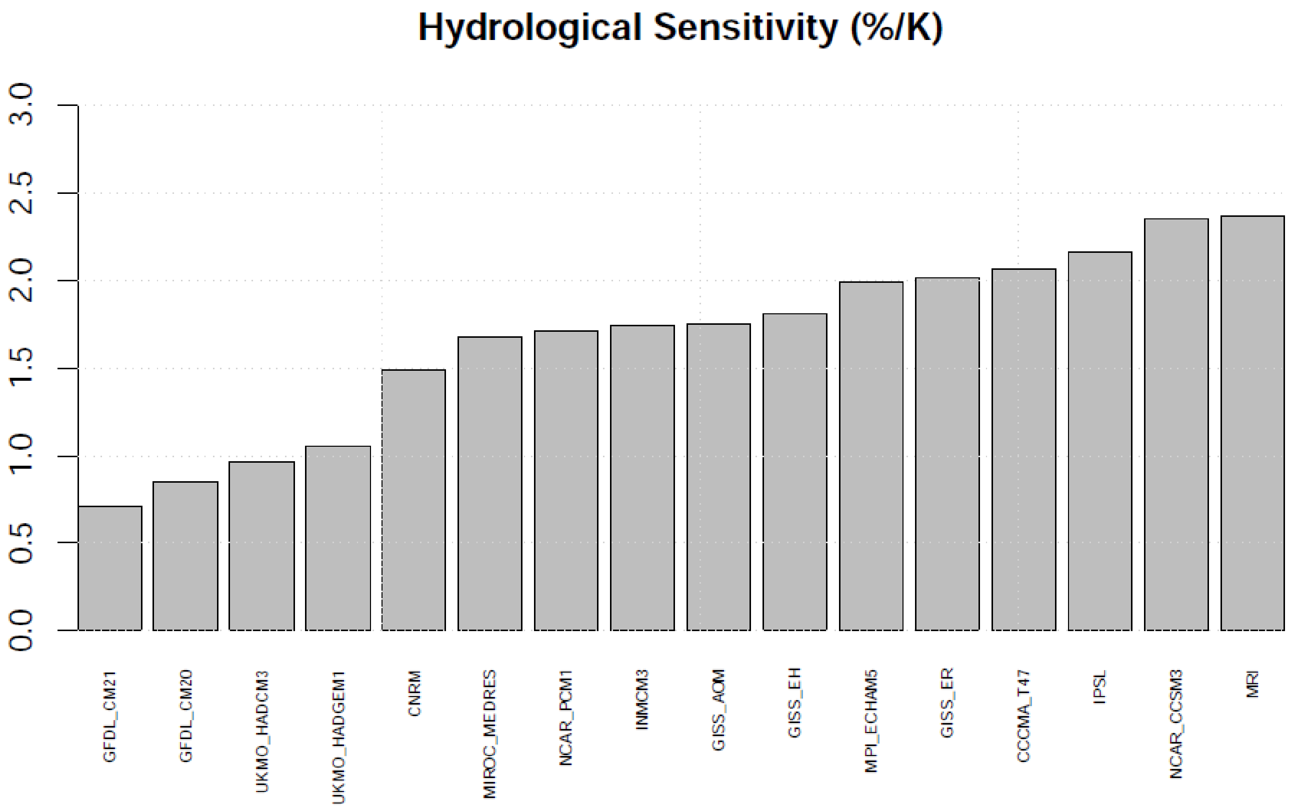
Energetic constraints

CMIP3



Stephens and Ellis, J. Climate, 2008

Hydrological Sensitivity



Range : 0.7 – 2.5 %/K (factor of about 3)

Why is there such a spread ?

after Previdi, Env. Res. Lett., 2010

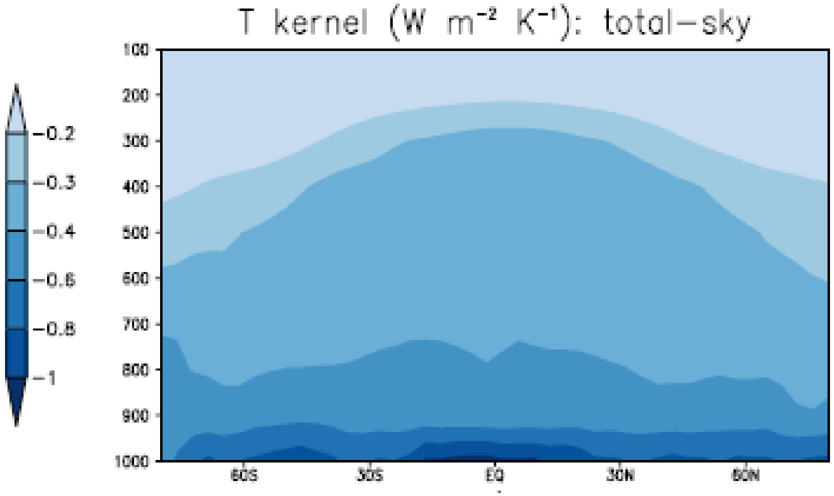
What controls the change in tropospheric radiative cooling in climate change ?

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

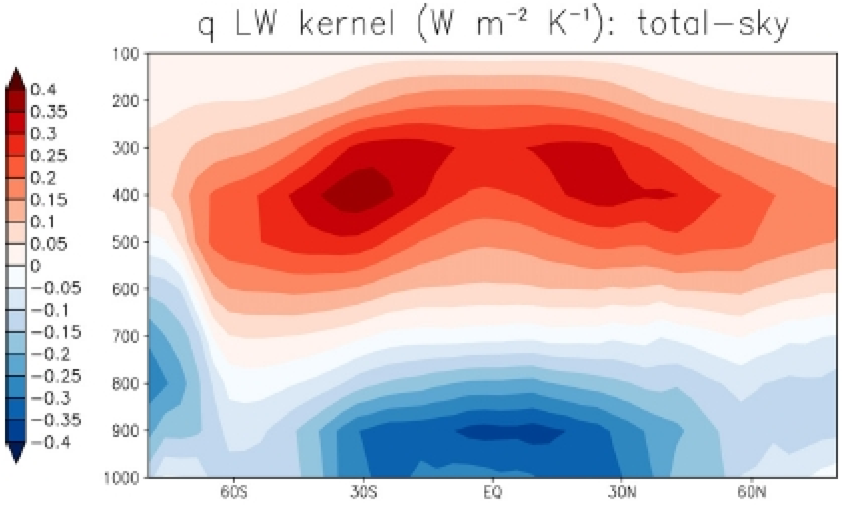
R : vertically integrated tropospheric radiative heating rate

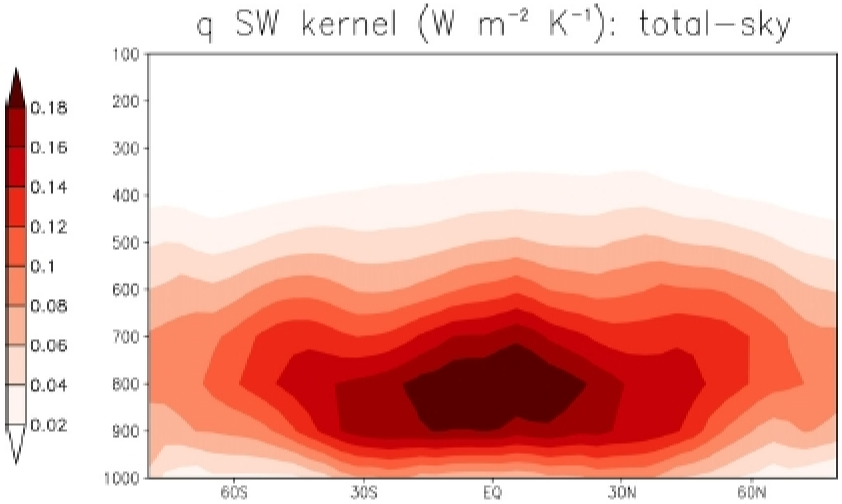
Tropospheric radiative cooling kernels

$$\frac{\partial R}{\partial x}$$


T kernel (W m^{-2} K^{-1}): total−sky

Increased temperature enhances the radiative cooling

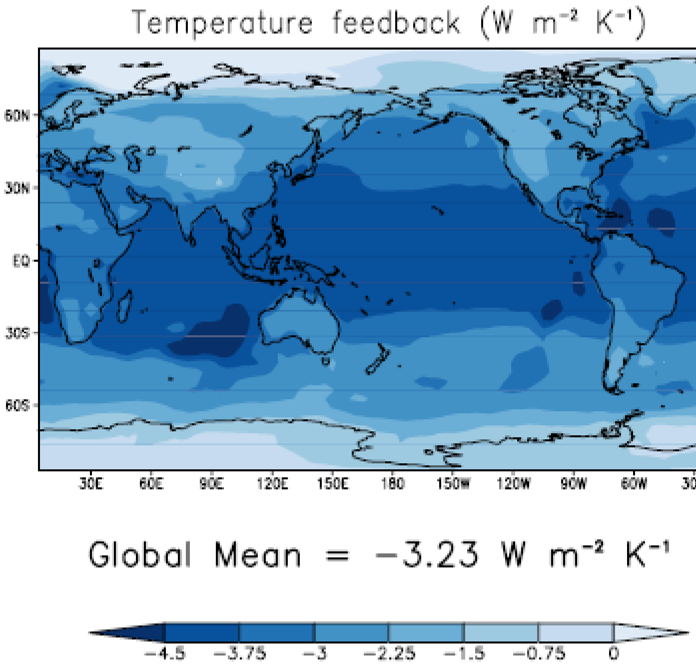

q LW kernel (W m^{-2} K^{-1}): total−sky


q SW kernel (W m^{-2} K^{-1}): total−sky

(q-kernels assume T increases by 1K while maintaining RH constant)

Previdi, Env. Res. Lett., 2010

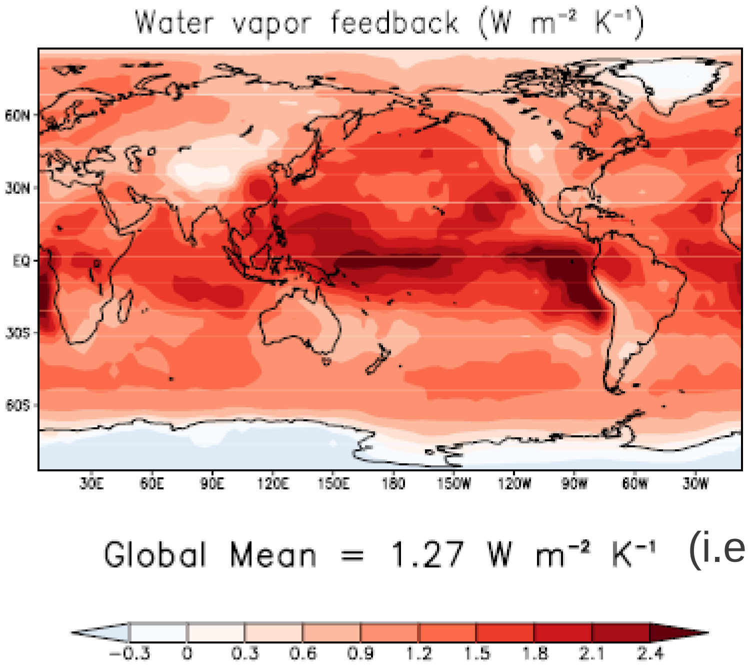
Tropospheric radiative feedbacks



Temperature feedback ($W\ m^{-2}\ K^{-1}$)

Global Mean = −3.23 $W\ m^{-2}\ K^{-1}$

e.

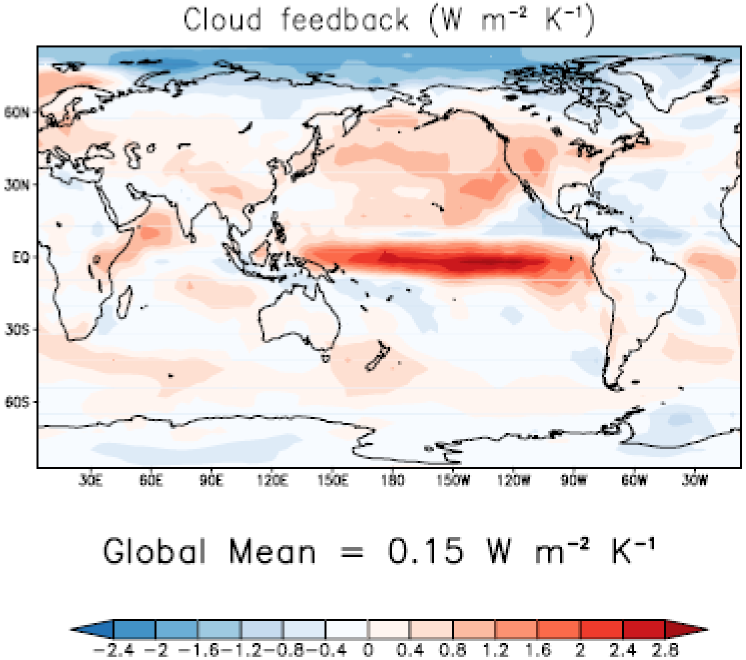


Water vapor feedback ($W\ m^{-2}\ K^{-1}$)

Global Mean = 1.27 $W\ m^{-2}\ K^{-1}$

Increased water vapor acts to reduce precipitation!

(i.e. -40 %)



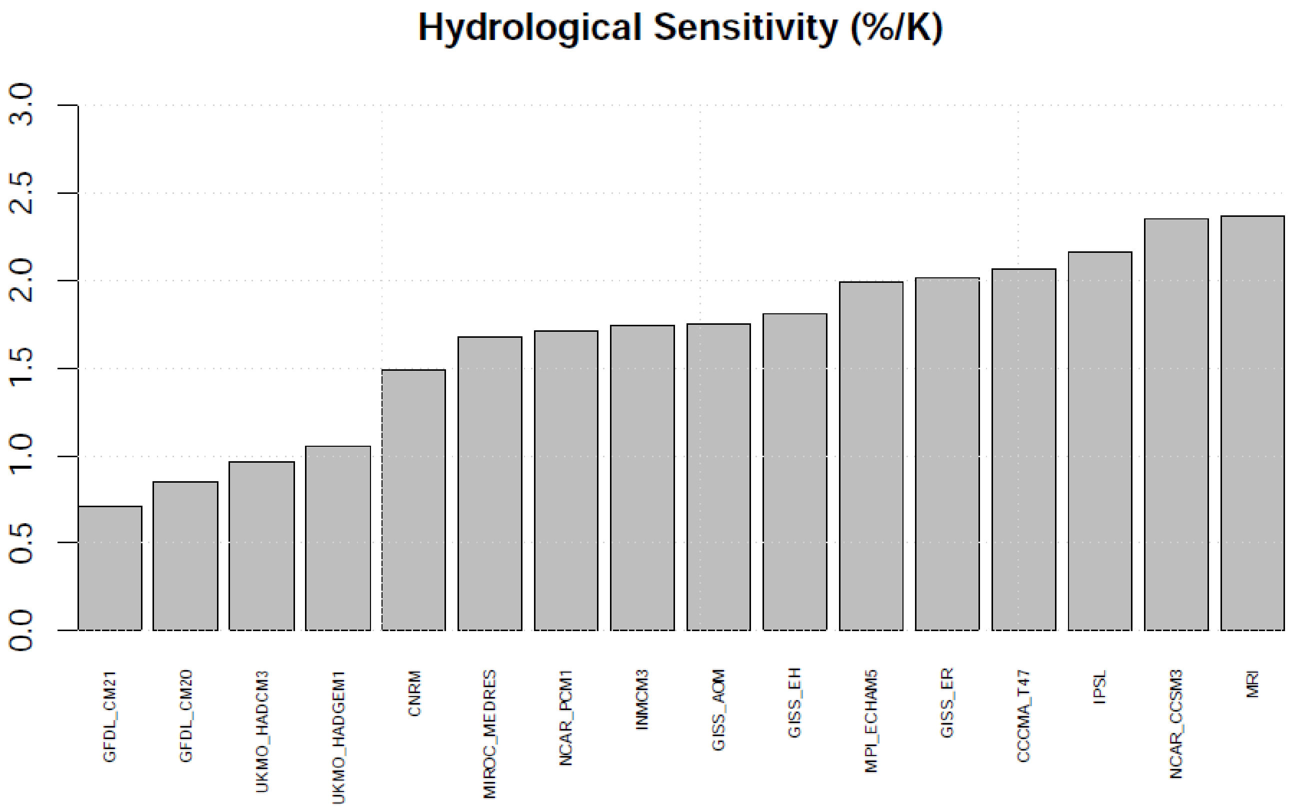
Cloud feedback ($W\ m^{-2}\ K^{-1}$)

Global Mean = 0.15 $W\ m^{-2}\ K^{-1}$

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

Previdi, Env. Res. Lett., 2010

Hydrological Sensitivity



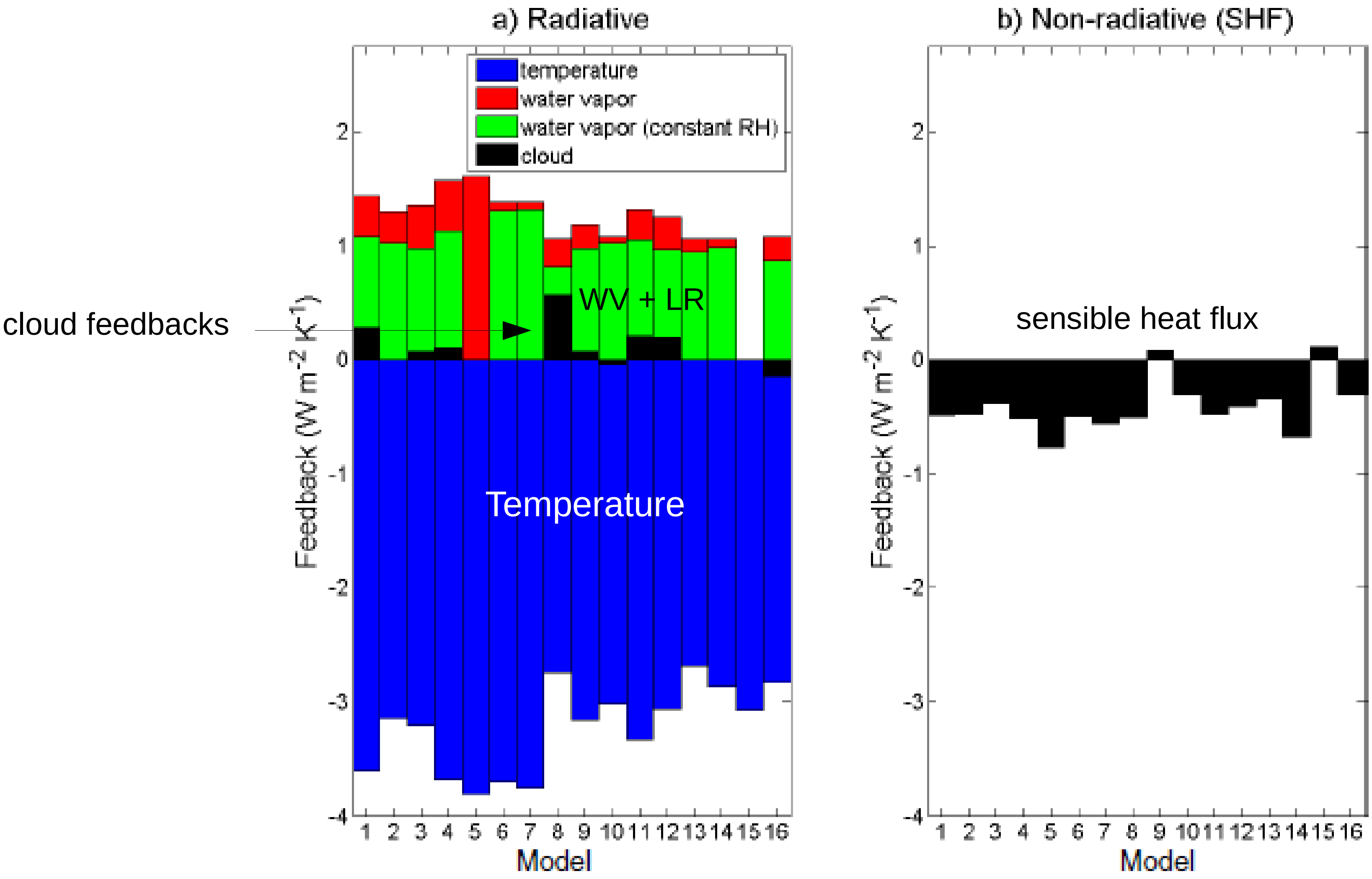
Hydrological Sensitivity (%/K)

Range : 0.7 – 2.5 %/K (factor of about 3)

Why is there such a spread ?

after Previdi, Env. Res. Lett., 2010

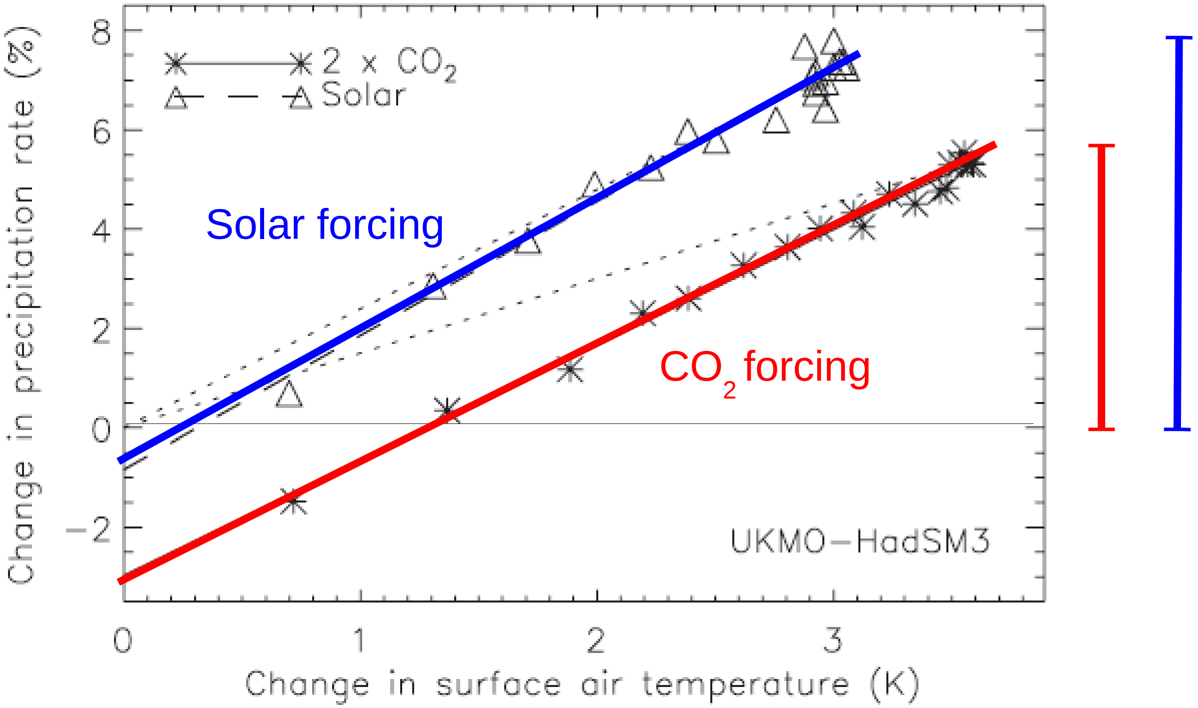
Interpretation of the spread



Roughly equal contributions from WV+LR feedback, cloud feedback, SH changes

Previdi, Env. Res. Lett., 2010

Dependence of hydrological sensitivity on forcing

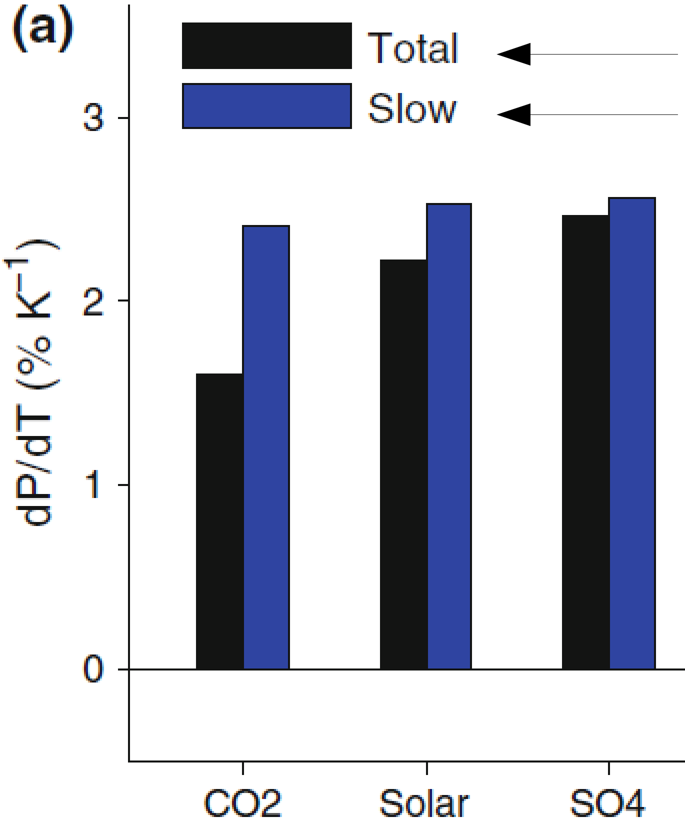


$$\frac{1}{P}\frac{\Delta P}{\Delta T_s}$$

- 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

Dependence of hydrological sensitivity on forcing



with adjustments

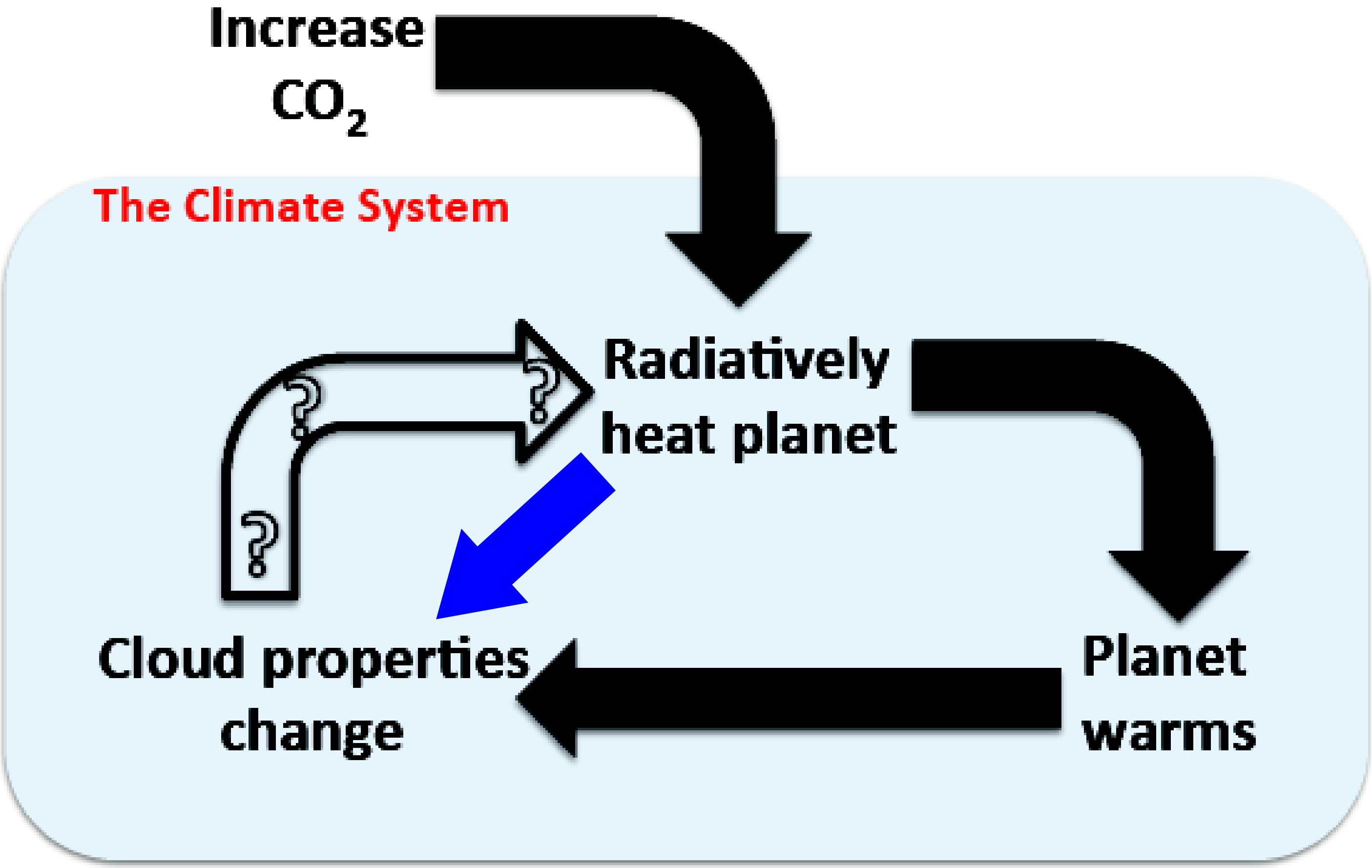
without adjustments

$$\frac{1}{P}\frac{\Delta P}{\Delta T_s}$$

Differences in hydrological sensitivities among different forcings primarily arise from differing adjustments

O'Gorman et al., Surv. Geophys., 2012 after Ming et al., GRL, 2010

How does CO2 affect clouds ?

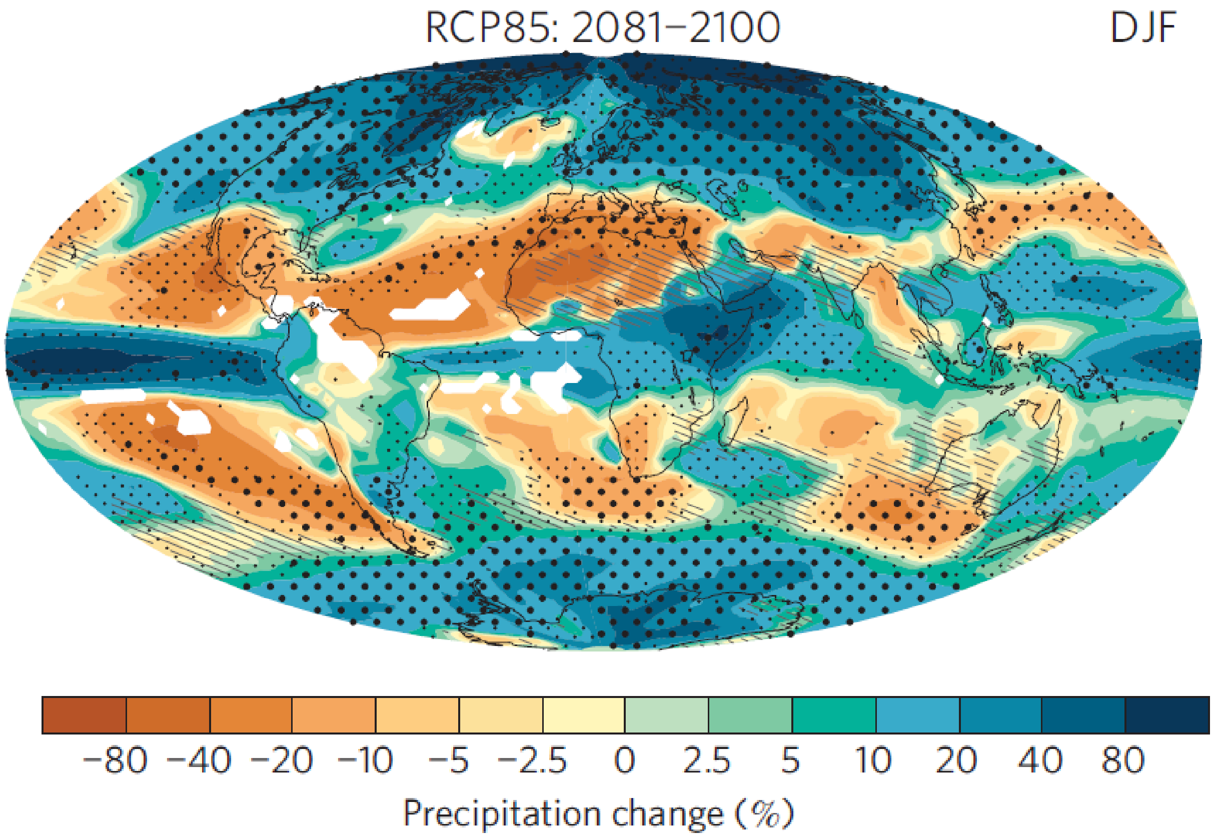


Also true for precipitation !

Temperature-mediated response + Fast adjustment

after Mark Zelinka (2013)

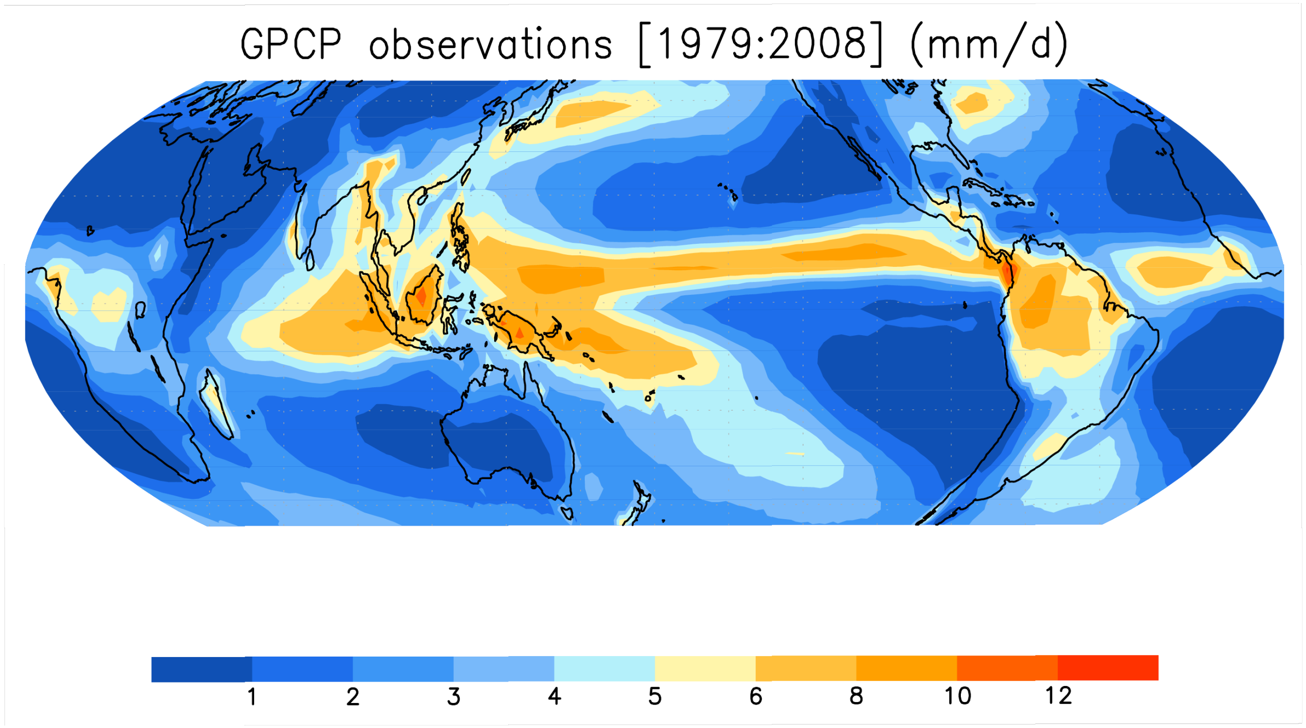
What controls regional precipitation changes ?



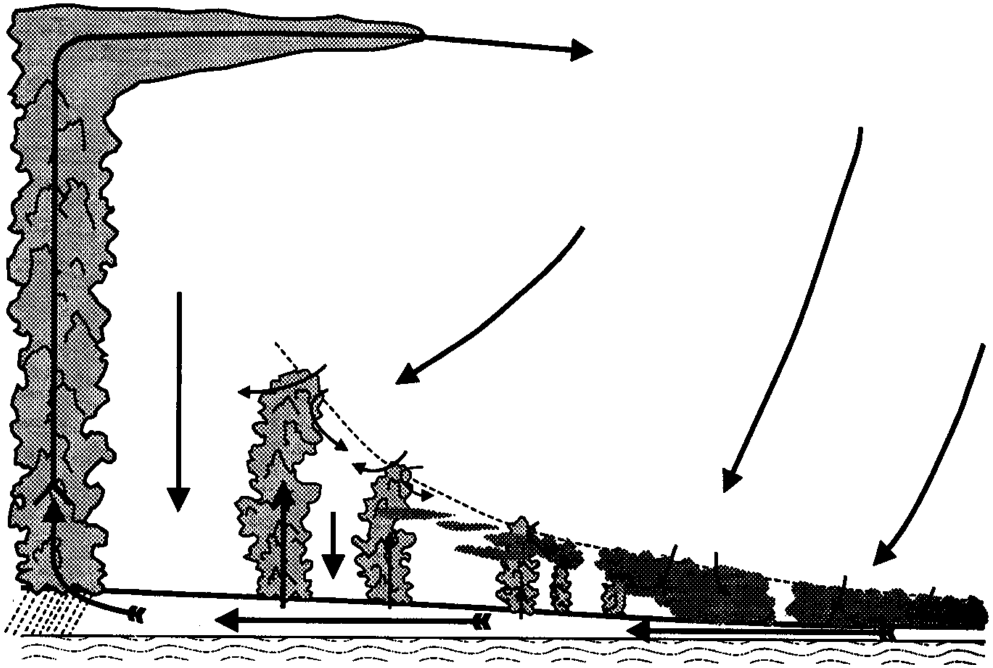
- How to interpret robustness and uncertainties ?

- How to decompose the problem into pieces ?

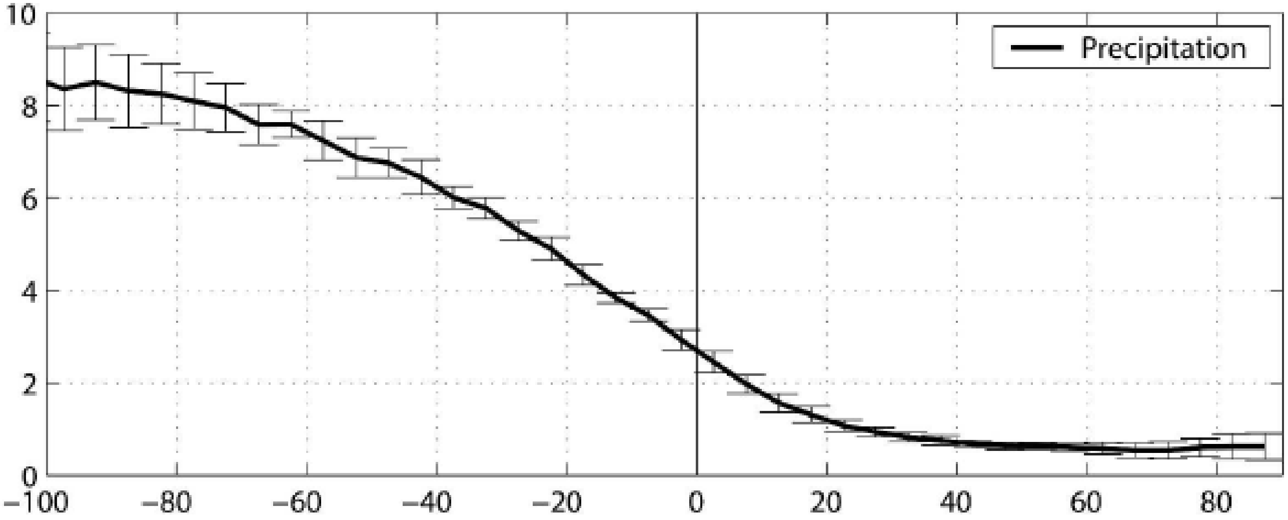
Present-Day Precipitation



Precipitation closely tied to large-scale atmospheric vertical motions



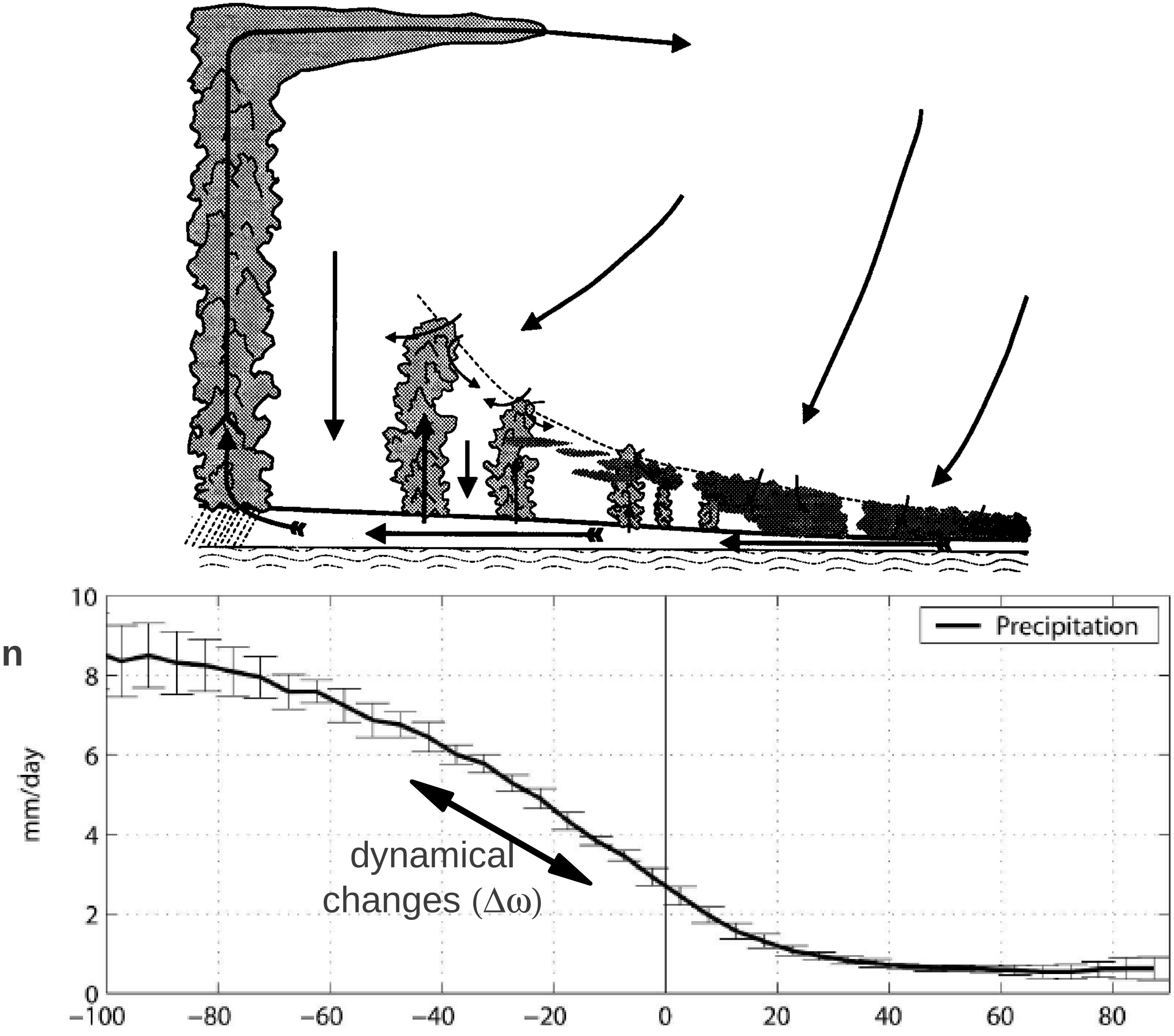
Precipitation



500 hPa large-scale vertical velocity (hPa/day)

Bony et al., J. Climate, 2006

Precipitation closely tied to large-scale atmospheric vertical motions



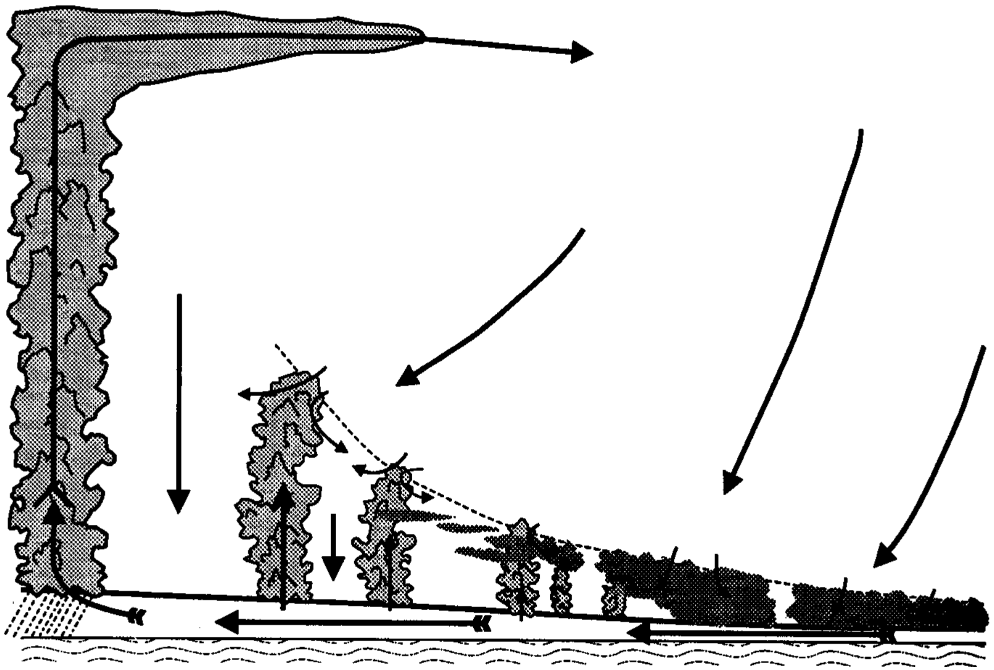
Precipitation

dynamical
changes (Δω)

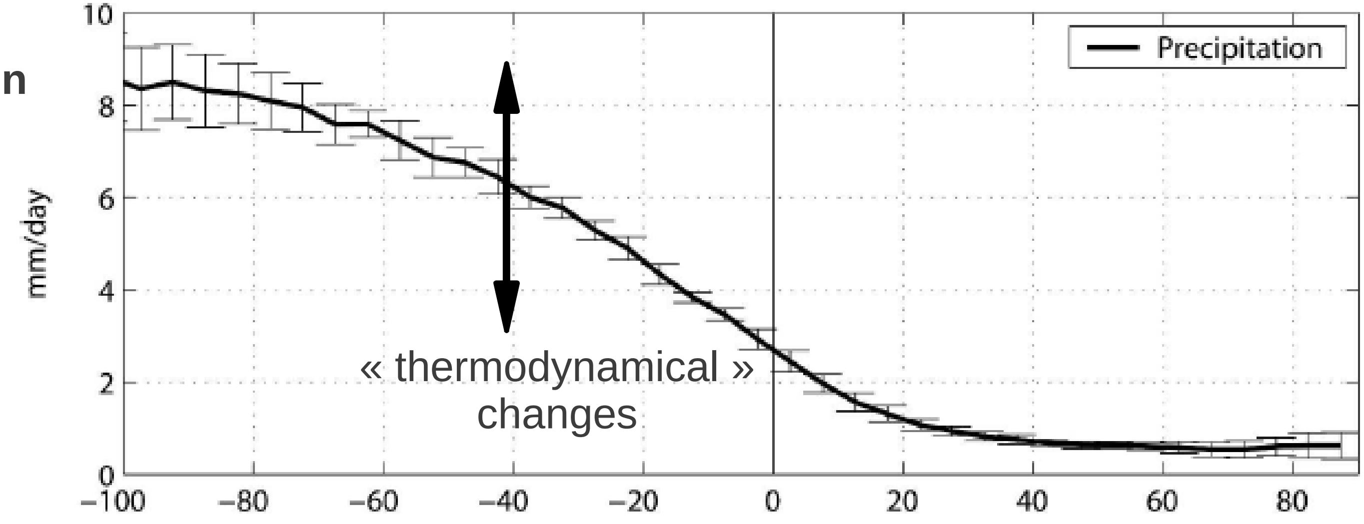
500 hPa large-scale vertical velocity (hPa/day)

Bony et al., J. Climate, 2006

Precipitation closely tied to large-scale atmospheric vertical motions



Precipitation

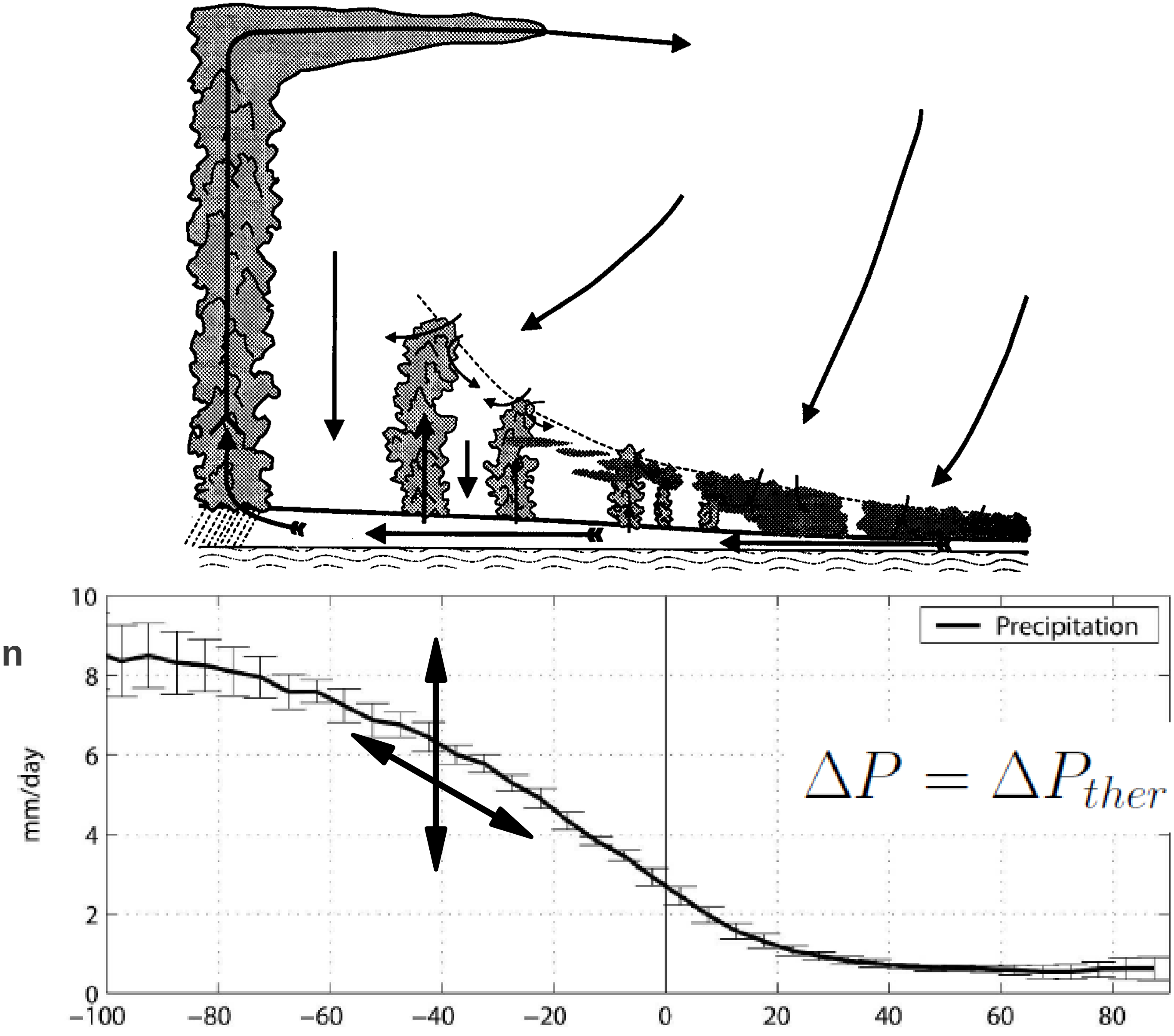


« thermodynamical »
changes

500 hPa large-scale vertical velocity (hPa/day)

Bony et al., J. Climate, 2006

Precipitation closely tied to large-scale atmospheric vertical motions



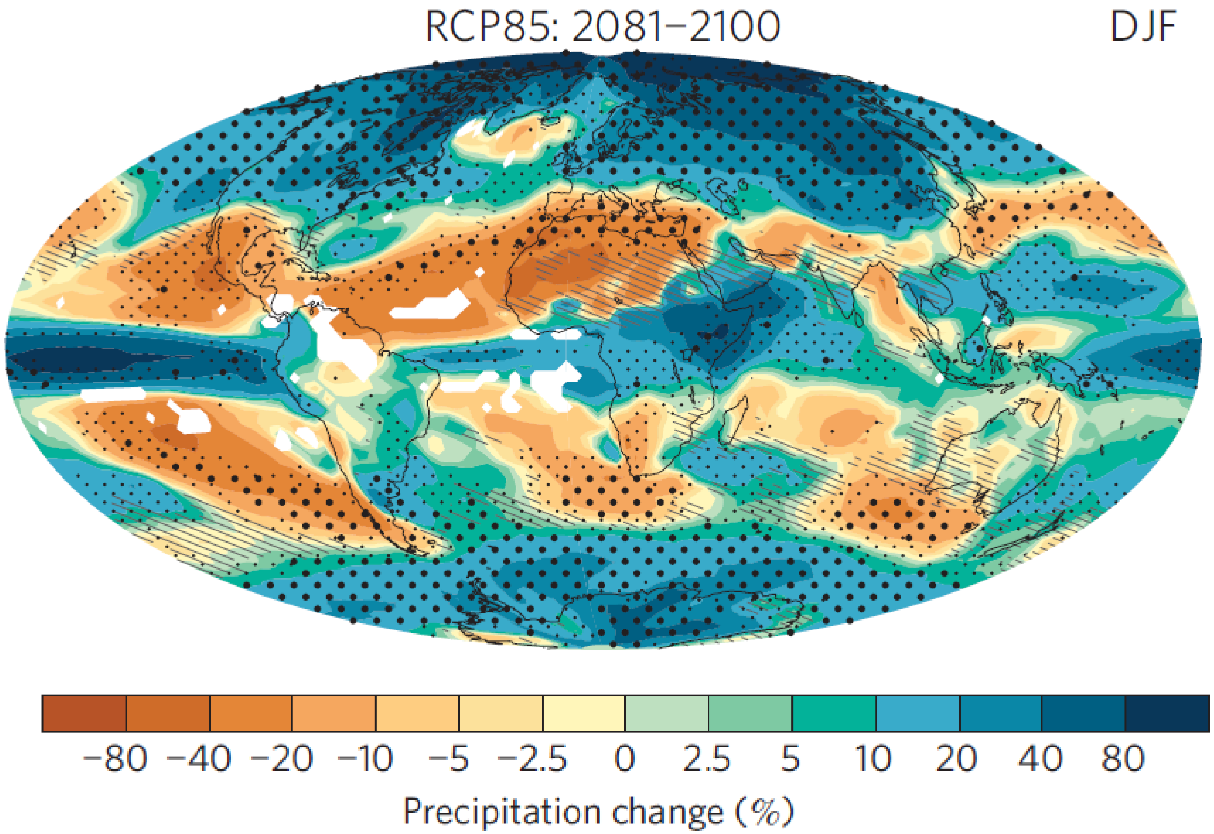
Precipitation

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

500 hPa large-scale vertical velocity (hPa/day)

Bony et al., J. Climate, 2006

What controls regional precipitation changes ?

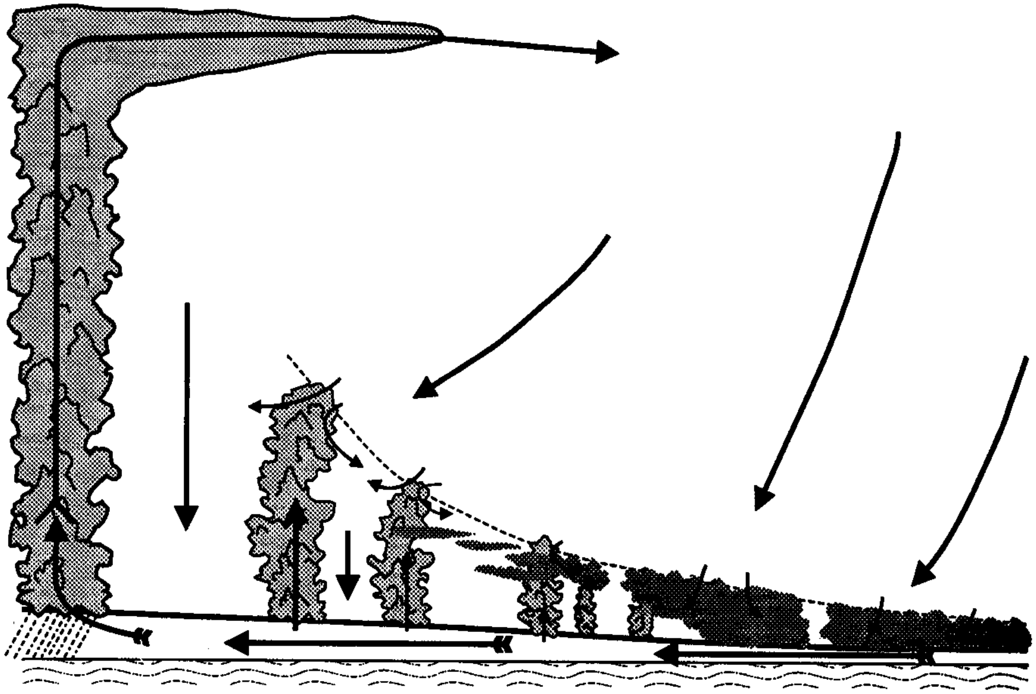


What controls regional precipitation changes ?

Radiative forcings can affect the atmosphere through :

- surface warming and water vapor changes
- tropospheric adjustments

Dynamical and thermodynamical components of precipitation changes



Let's focus on the tropics...

Analysis Method

- Water budget : $P = E - \left[\omega \frac{\partial q}{\partial P}\right] + H_q$

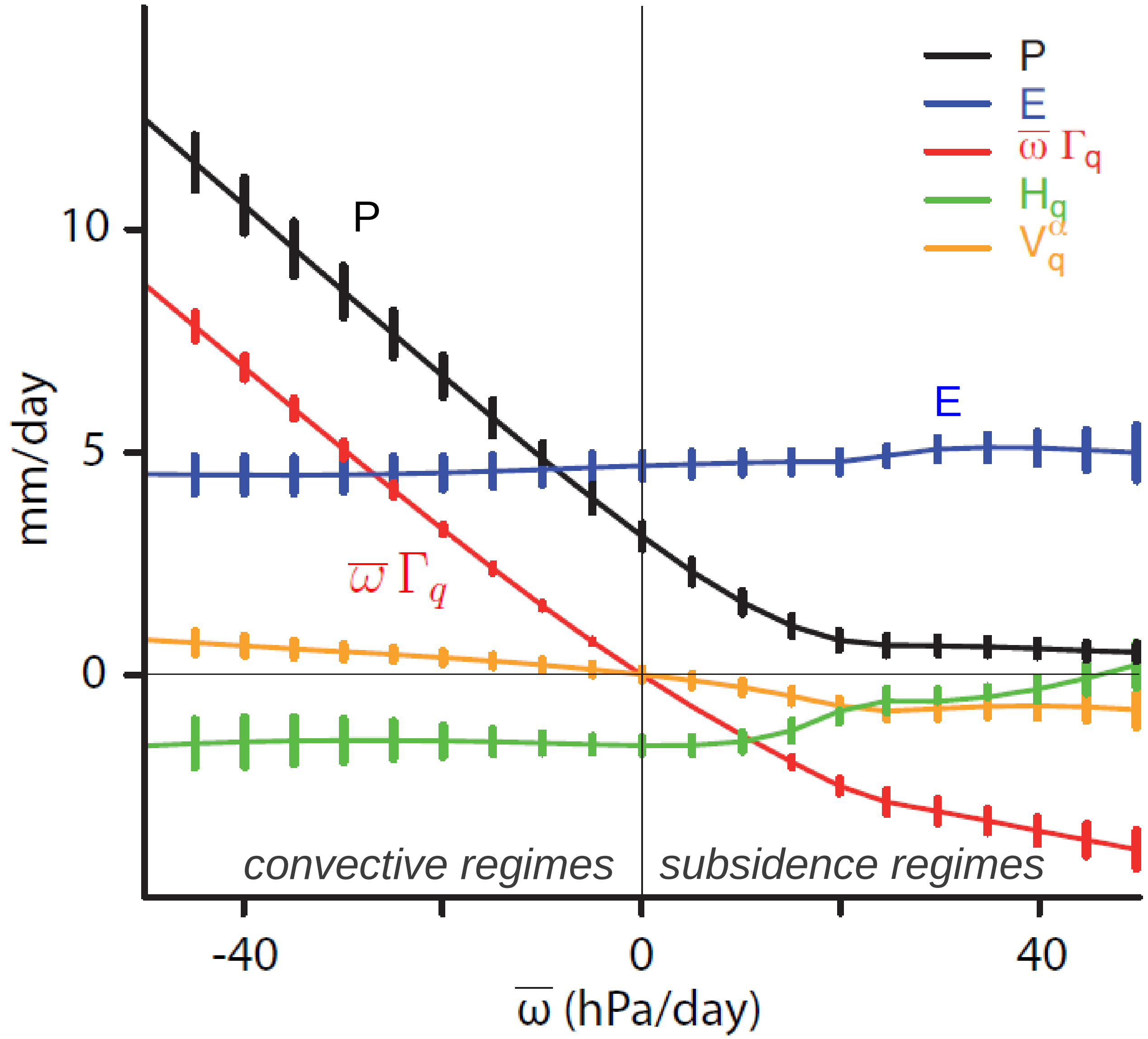
- Let $\overline{\omega}$ be mass-weighted vertical average of ω.

- Then : $$P = \underset{\substack{\nearrow \\ \text{surface} \\ \text{evaporation}}}{E} + \underset{\substack{\uparrow \\ \text{vertical} \\ \text{advection}}}{\overline{\omega}}\,\Gamma_q + \underset{\substack{\uparrow \\ \text{horizontal} \\ \text{advection}}}{H_q} + \underset{\substack{\nwarrow \\ \text{shape of} \\ \text{omega profile}}}{V_q^{\alpha}}$$

$$\text{with } \Gamma_q = -\left[\underset{\substack{\uparrow \\ \text{specified} \\ \text{first-baroclinic mode structure}}}{\psi(P)}\,\frac{\partial q}{\partial P}\right]$$

Bony et al., Nature Geosci., 2013

$$P = E + \overline{\omega}\,\Gamma_q + H_q + V_q^{\alpha}$$



multi–model mean precipitation over oceans
(16 CMIP5 models)

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

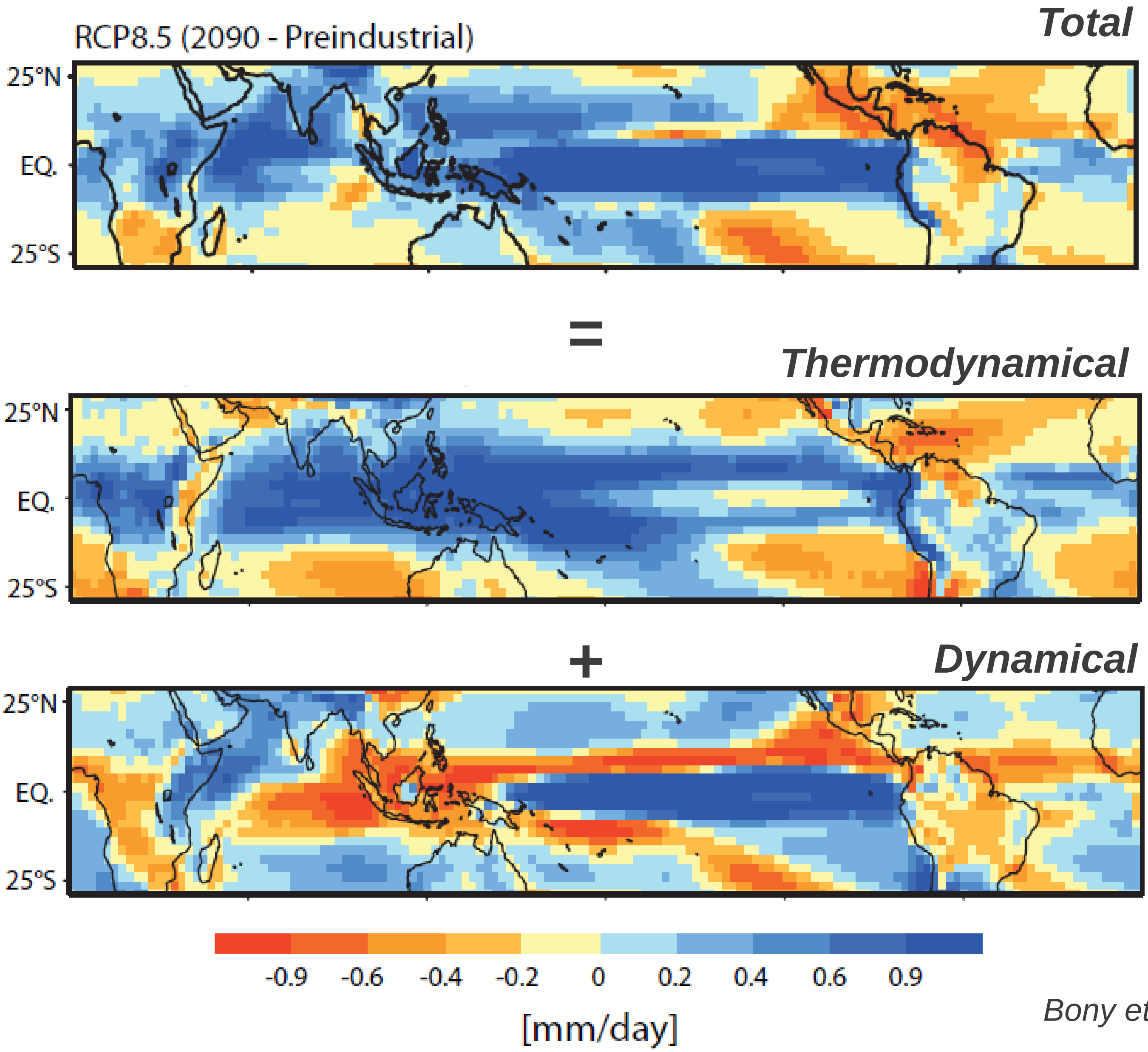
$$\Delta P = \boxed{\left(\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha}\right)} + \boxed{\Gamma_q\,\Delta\overline{\omega}}$$

thermodynamical component

dynamical component

Tropical Precipitation Projections

RCP8.5 scenario at the end 21C



Total

=

Thermodynamical

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

\+

Dynamical

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

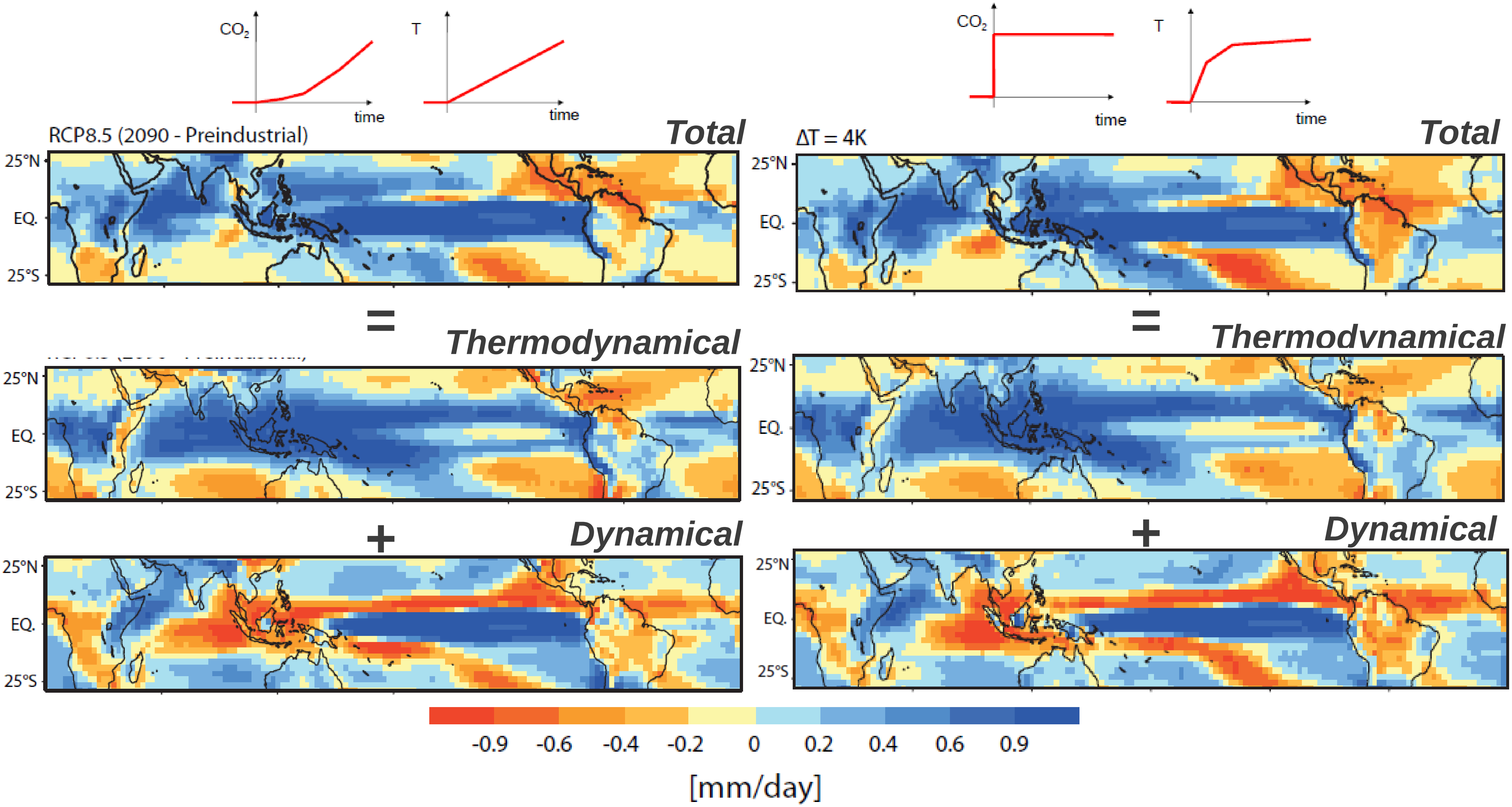
Bony et al., Nature Geosci., 2013

Tropical Precipitation Projections

RCP8.5 scenario vs idealized abrupt 4xCO2 expt

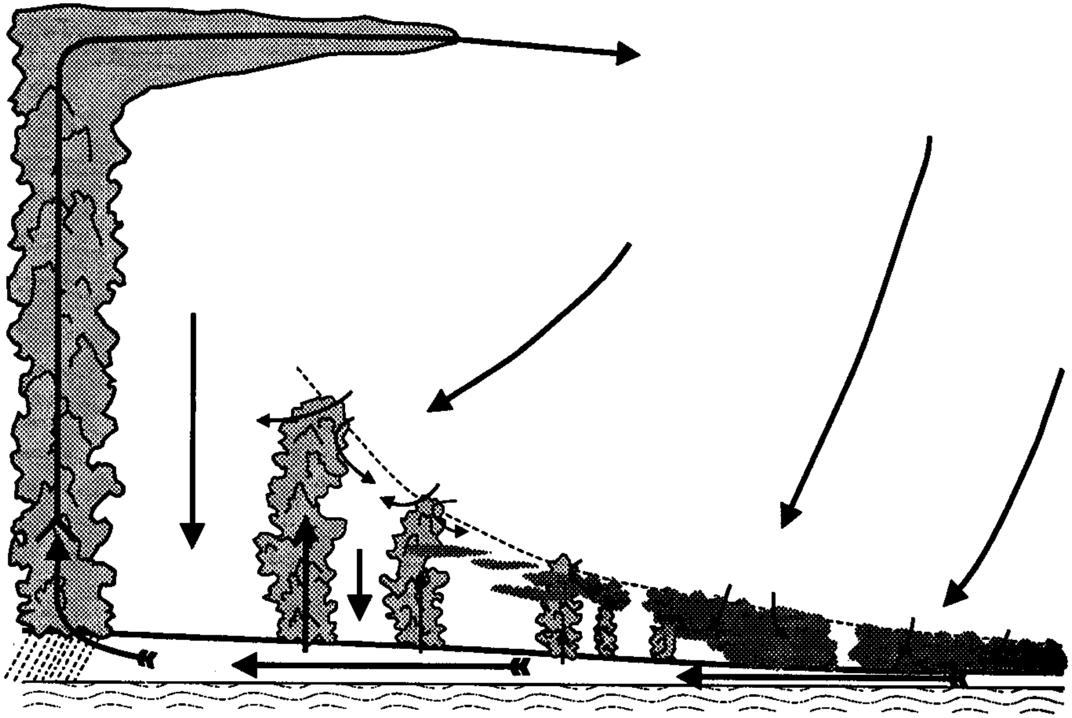
RCP 8.5, end 21C

Abrupt 4xCO2, ΔT = 4K



→ an opportunity to understand precipitation changes in climate change (RCP) scenarios

Interpretation of regional precipitation changes

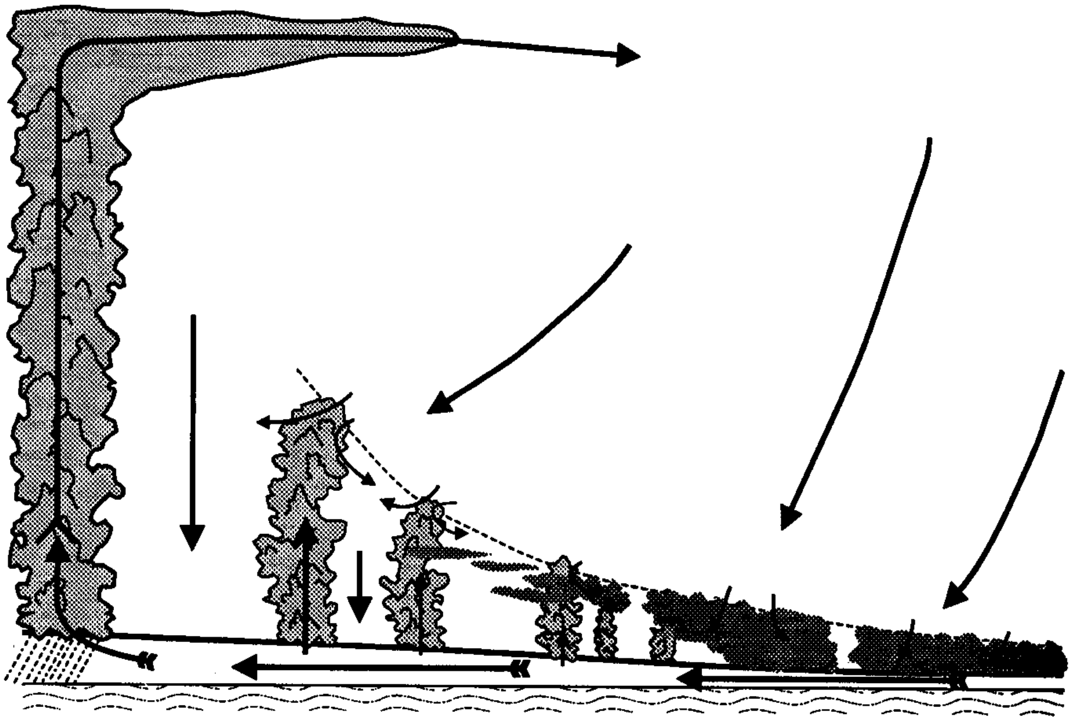


$$\Delta P = \boxed{\left(\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha}\right)} + \boxed{\Gamma_q\,\Delta\overline{\omega}}$$

thermodynamical component

dynamical component

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



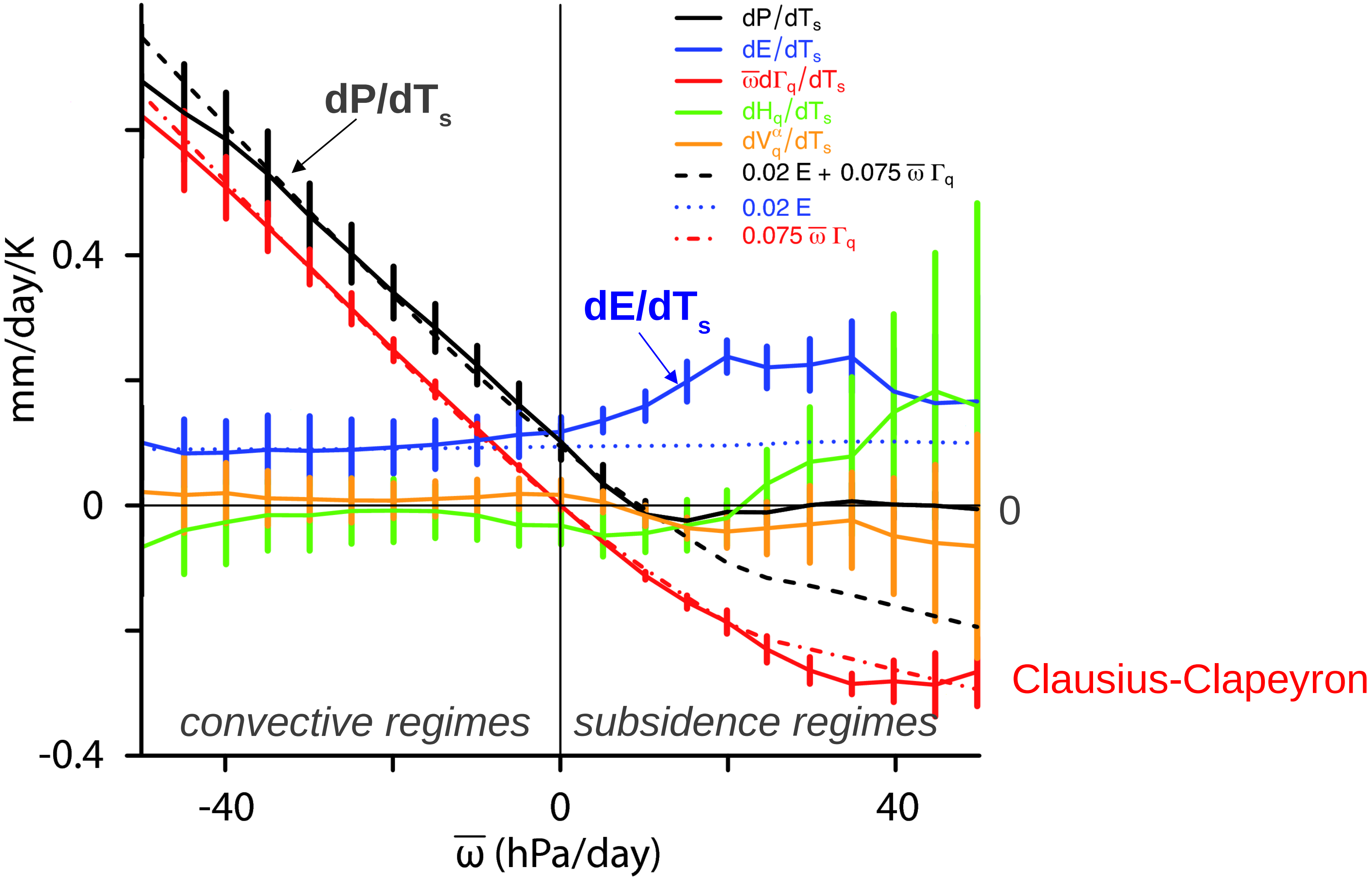
$$\Delta P = \boxed{(\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha})} + \boxed{\Gamma_q \xcancel{\Delta\overline{\omega}}}$$

thermodynamical component

dynamical component

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

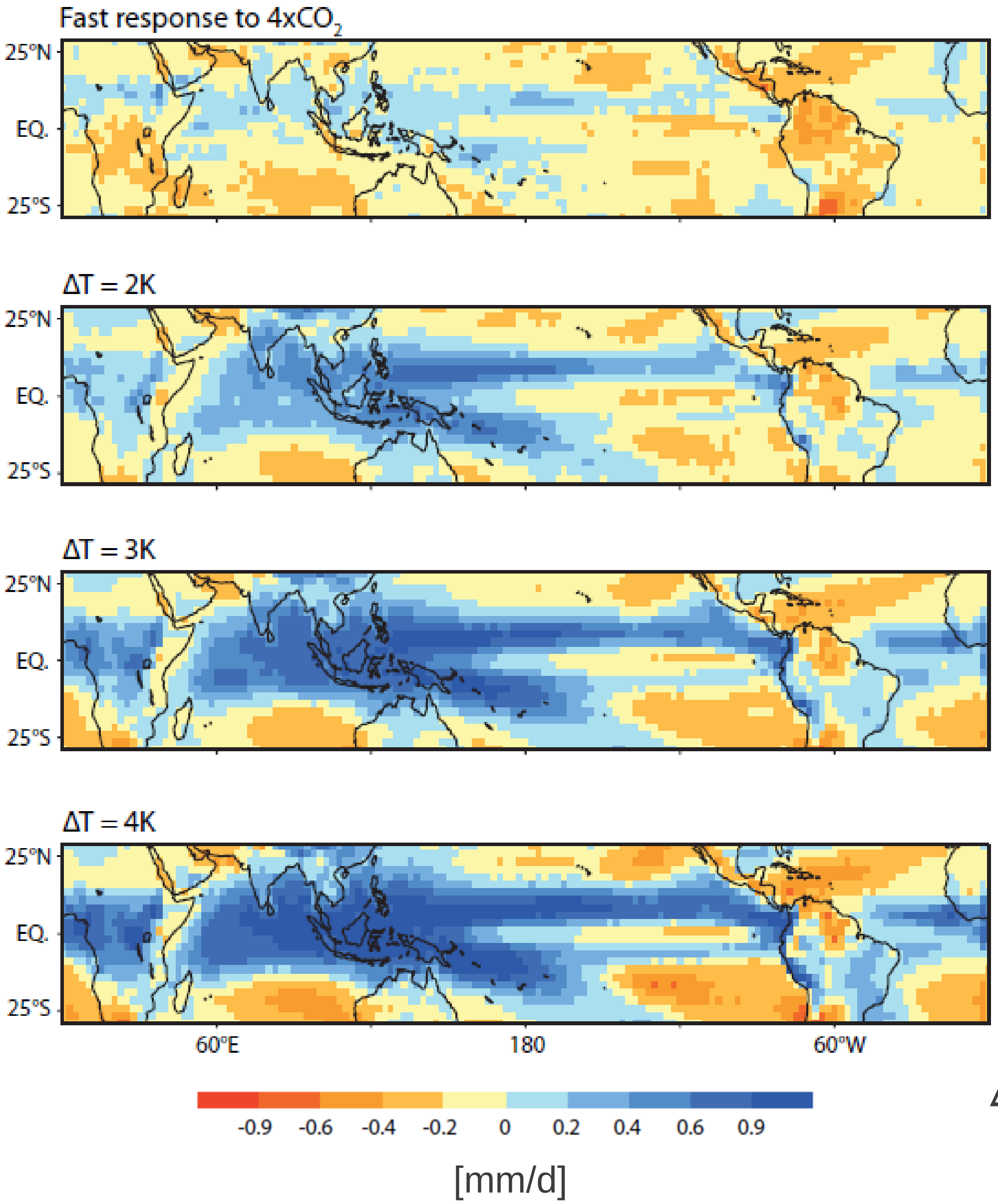
- 16 CMIP5 models (mean and spread)
- *wet get wetter, dry get drier*
- *wet get getter* more robust than *dry get drier*



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

Evolution of regional precipitation changes in abrupt 4xCO2 experiments

Thermodynamical component



ΔT < 1K (1st year)

ΔT = 2K

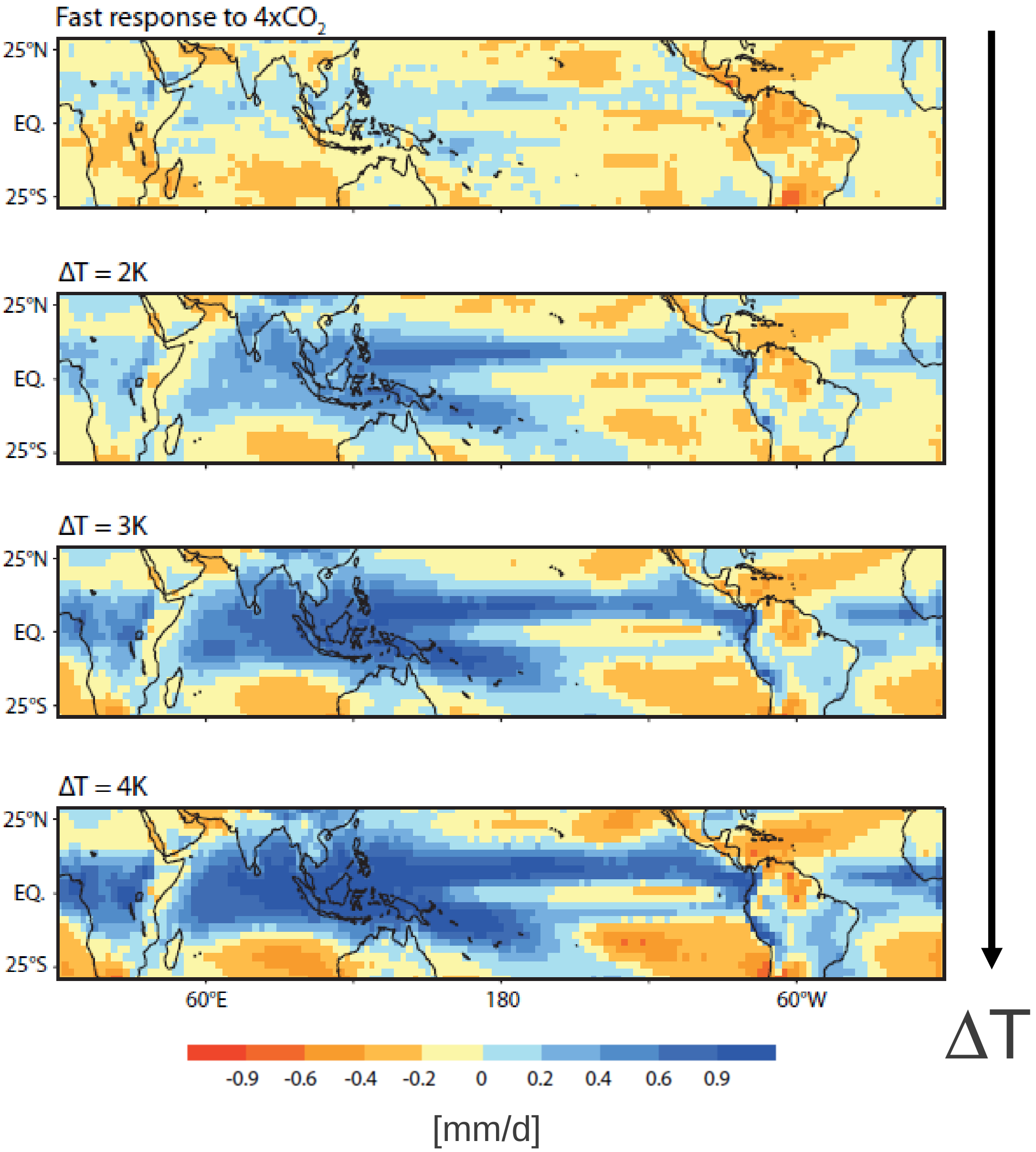
ΔT = 3K

ΔT = 4K

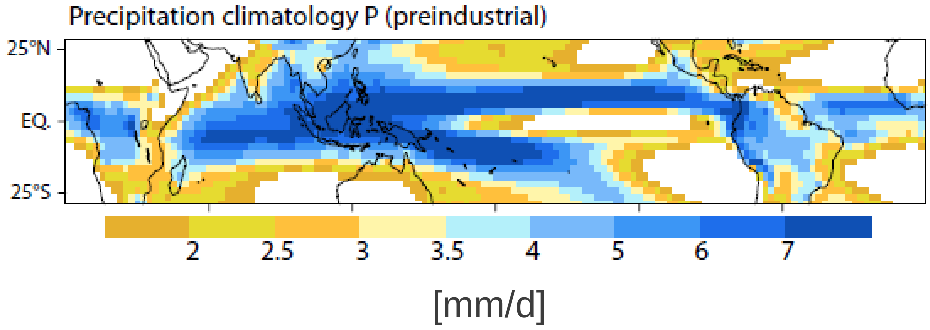
ΔT

Evolution of regional precipitation changes in abrupt 4xCO2 experiments

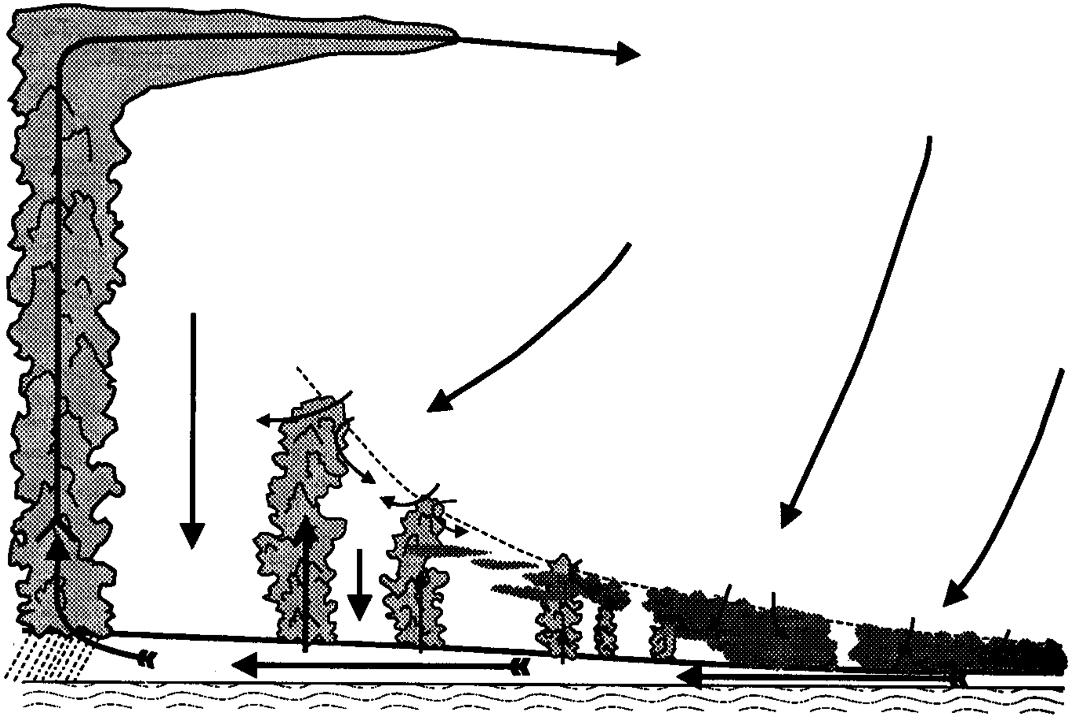
Thermodynamical component



Climatology



How do changes in the tropical overturning circulation affect regional precipitation changes ?



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

thermodynamical component

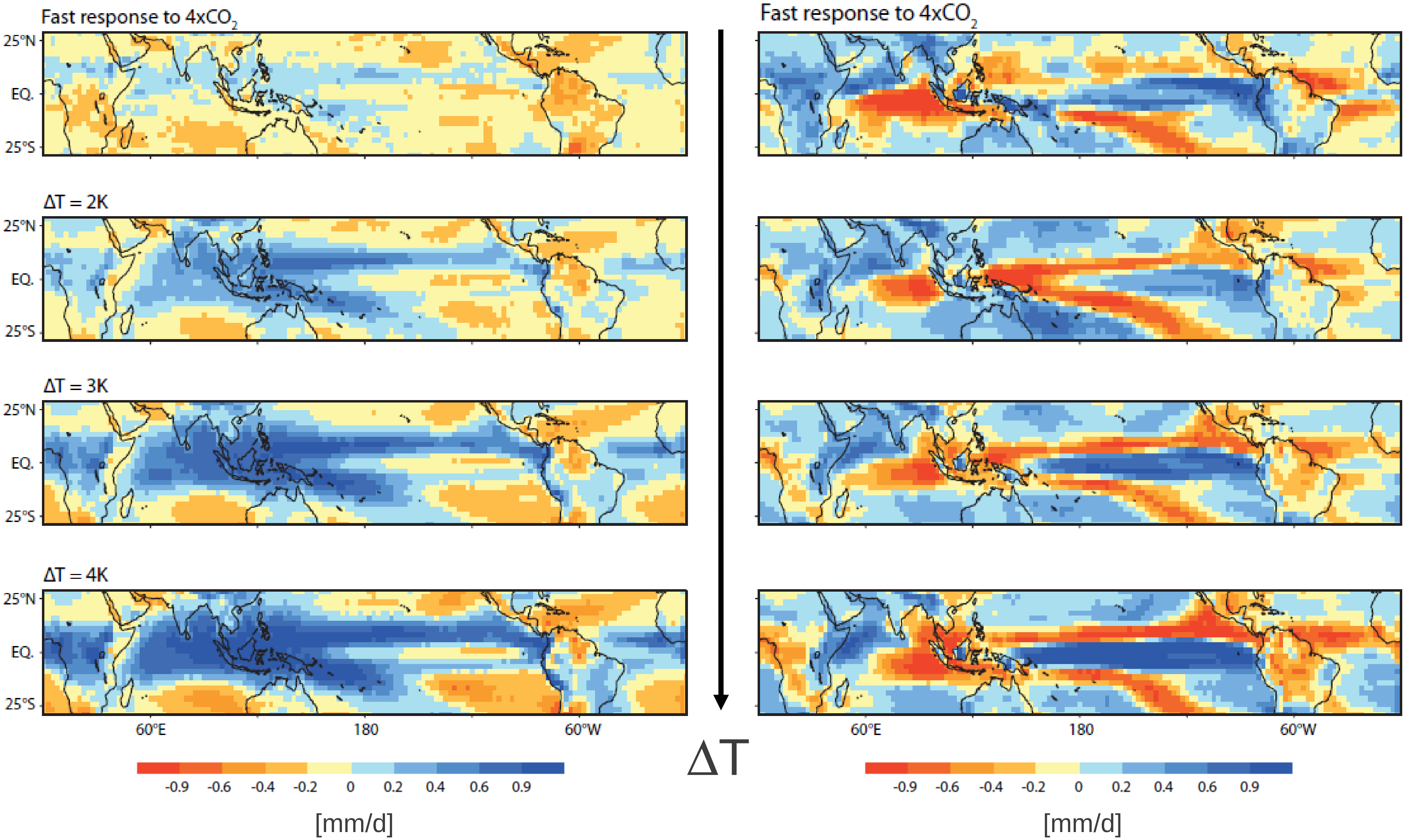
dynamical component

Evolution of regional precipitation changes in abrupt 4xCO2 experiments

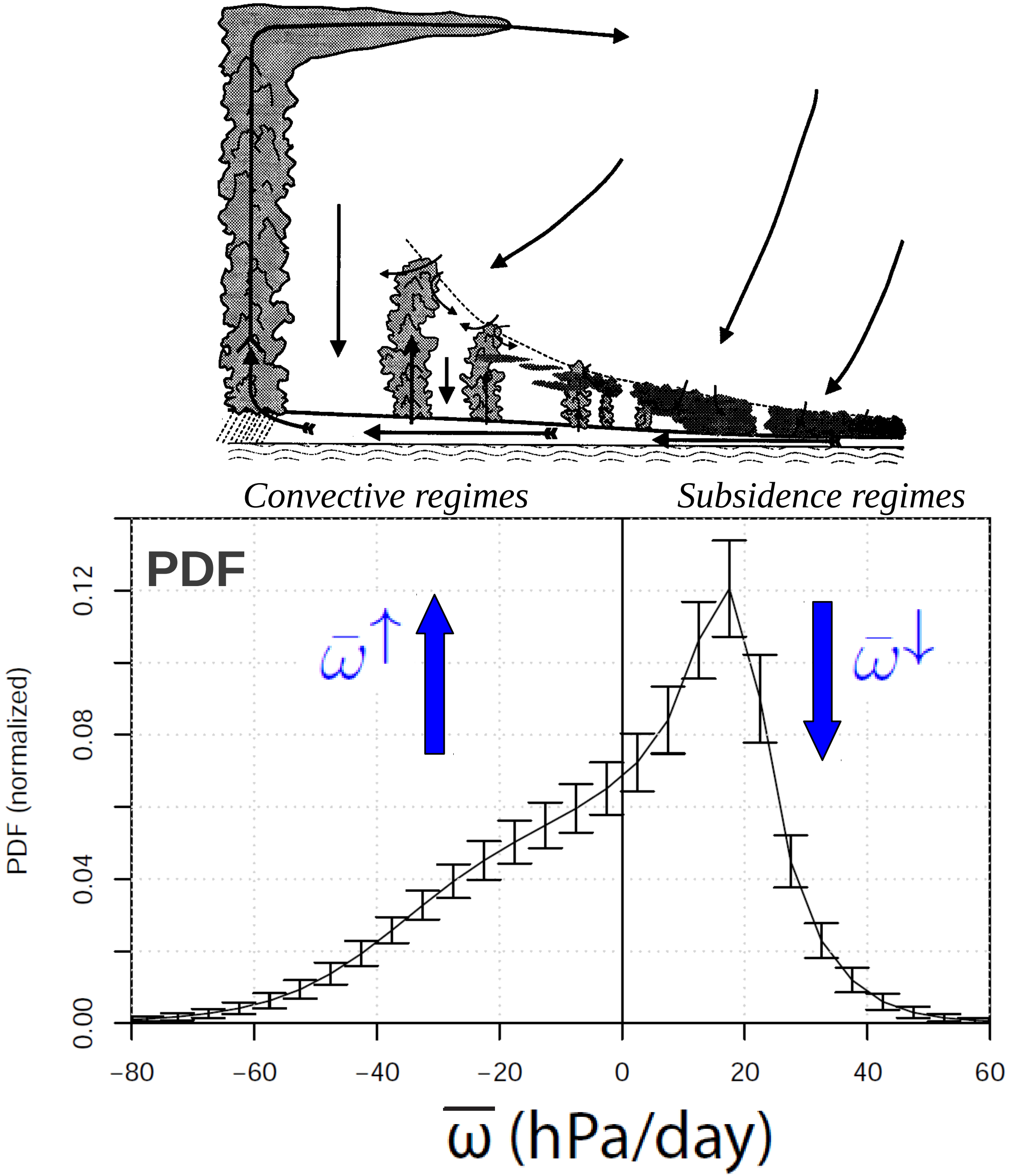
Thermodynamical component

Dynamical component

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



Tropical Overturning Circulation

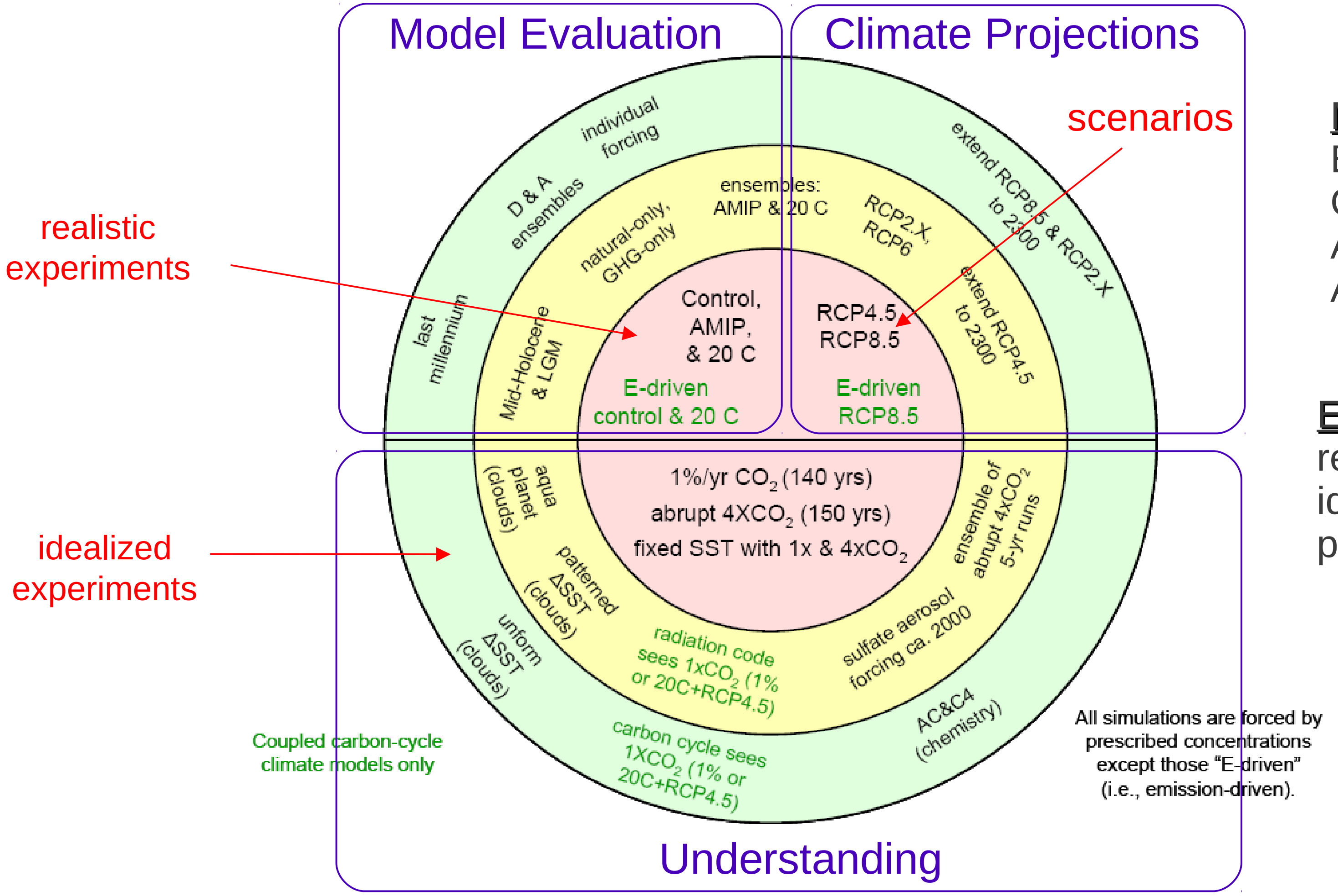


Index of Circulation Strength :

$\bar{\omega}^{\downarrow} - \bar{\omega}^{\uparrow}$

CMIP5

A hierarchy of models, experiments, configurations
(coupled ocean-atmosphere, atmosphere-only, aqua-planet..)



Model Evaluation

Climate Projections

Understanding

realistic experiments

idealized experiments

scenarios

Control, AMIP, & 20 C

E-driven control & 20 C

RCP4.5 RCP8.5

E-driven RCP8.5

1%/yr CO_2 (140 yrs)

abrupt $4XCO_2$ (150 yrs)

fixed SST with 1x & $4xCO_2$

ensembles: AMIP & 20 C

natural-only, GHG-only

Mid-Holocene & LGM

RCP2.X, RCP6

extend RCP4.5 to 2300

aqua planet (clouds)

patterned ΔSST (clouds)

radiation code sees $1xCO_2$ (1% or 20C+RCP4.5)

sulfate aerosol forcing ca. 2000

ensemble of abrupt $4xCO_2$ 5-yr runs

individual forcing

D & A ensembles

last millennium

extend RCP8.5 & RCP2.X to 2300

unform ΔSST (clouds)

carbon cycle sees $1XCO_2$ (1% or 20C+RCP4.5)

AC&C4 (chemistry)

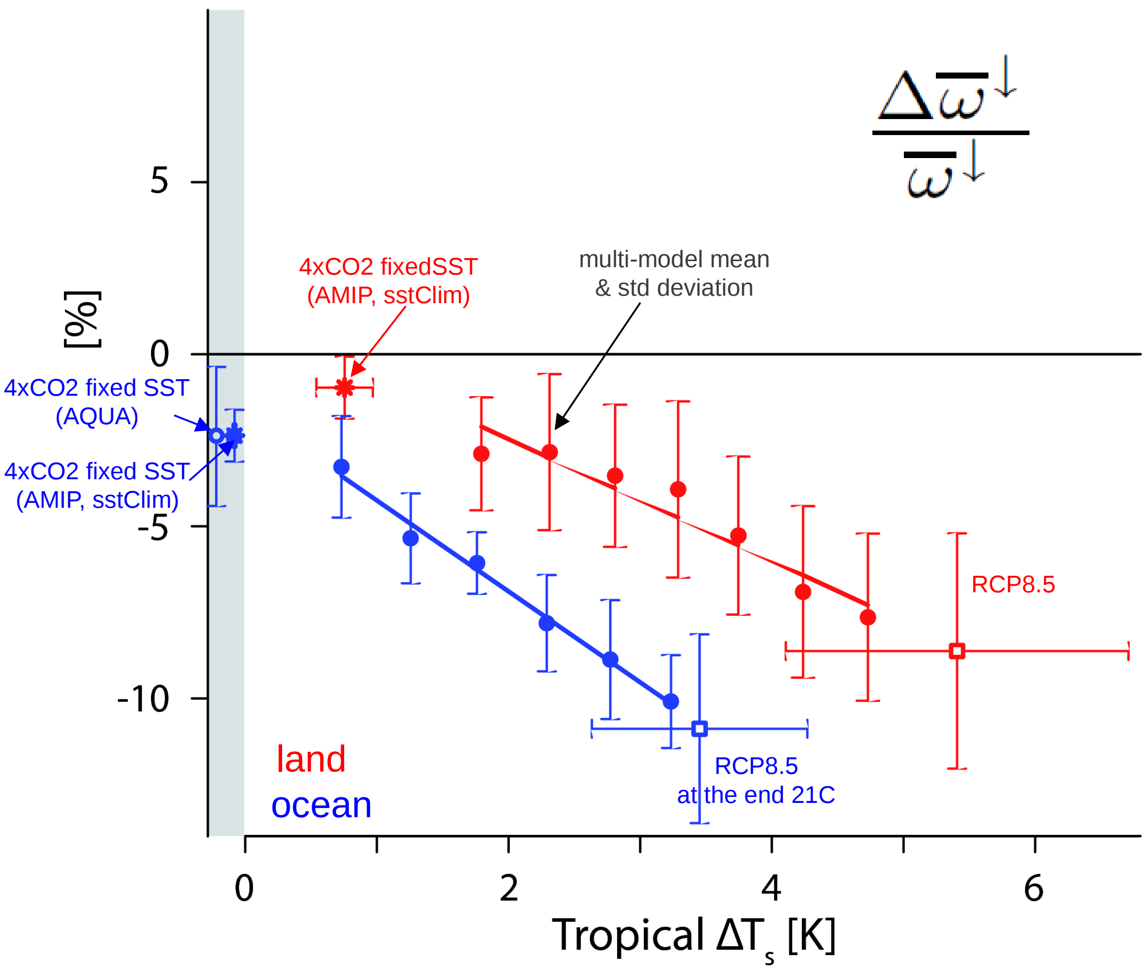
Coupled carbon-cycle climate models only

All simulations are forced by prescribed concentrations except those “E-driven” (i.e., emission-driven).

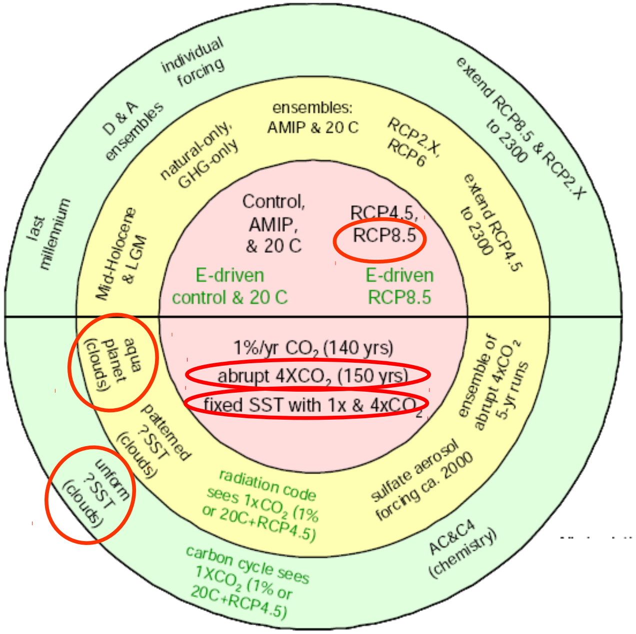
Models :
ESM
OAGCM
AGCM
Aqua-planet

Experiments :
realistic
idealized
partial forcings

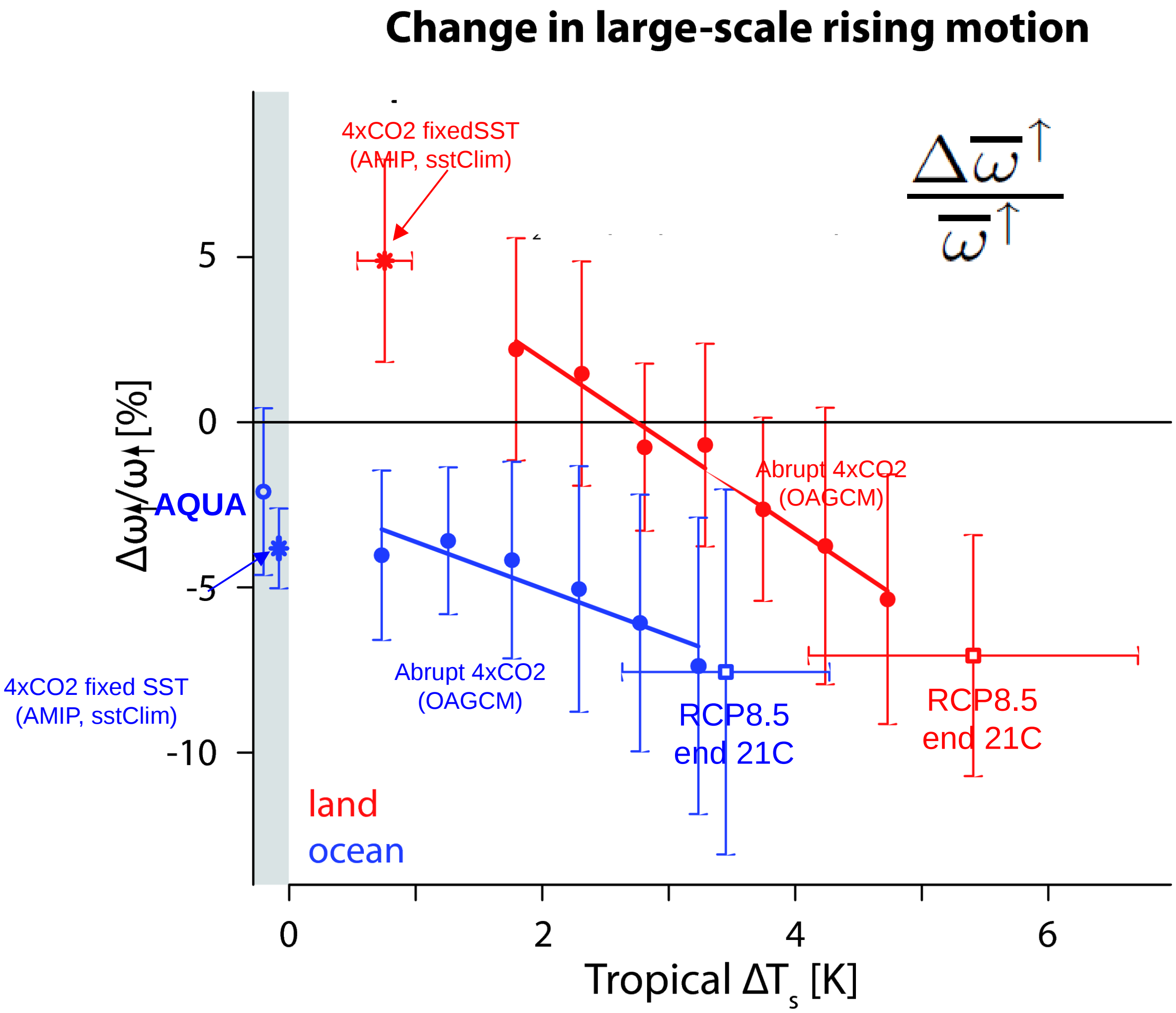
Change in circulation (%) predicted by CMIP5 models in response to increased CO2



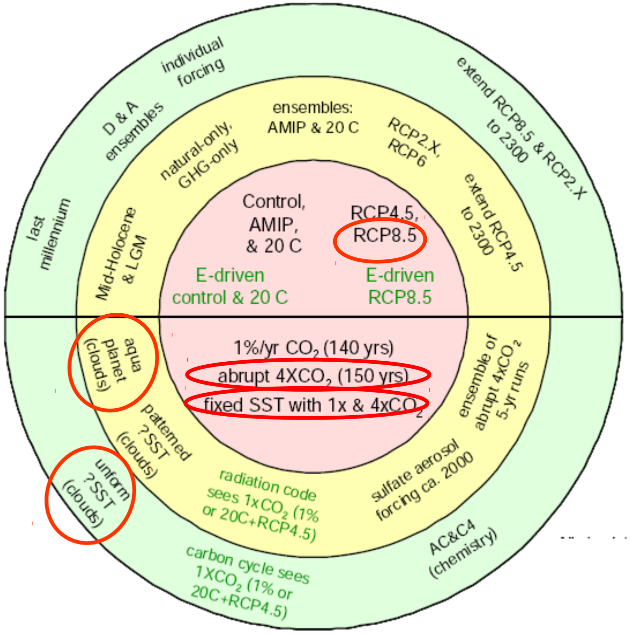
Change in large-scale subsidence



Change in circulation (%) predicted by CMIP5 models in response to increased CO2

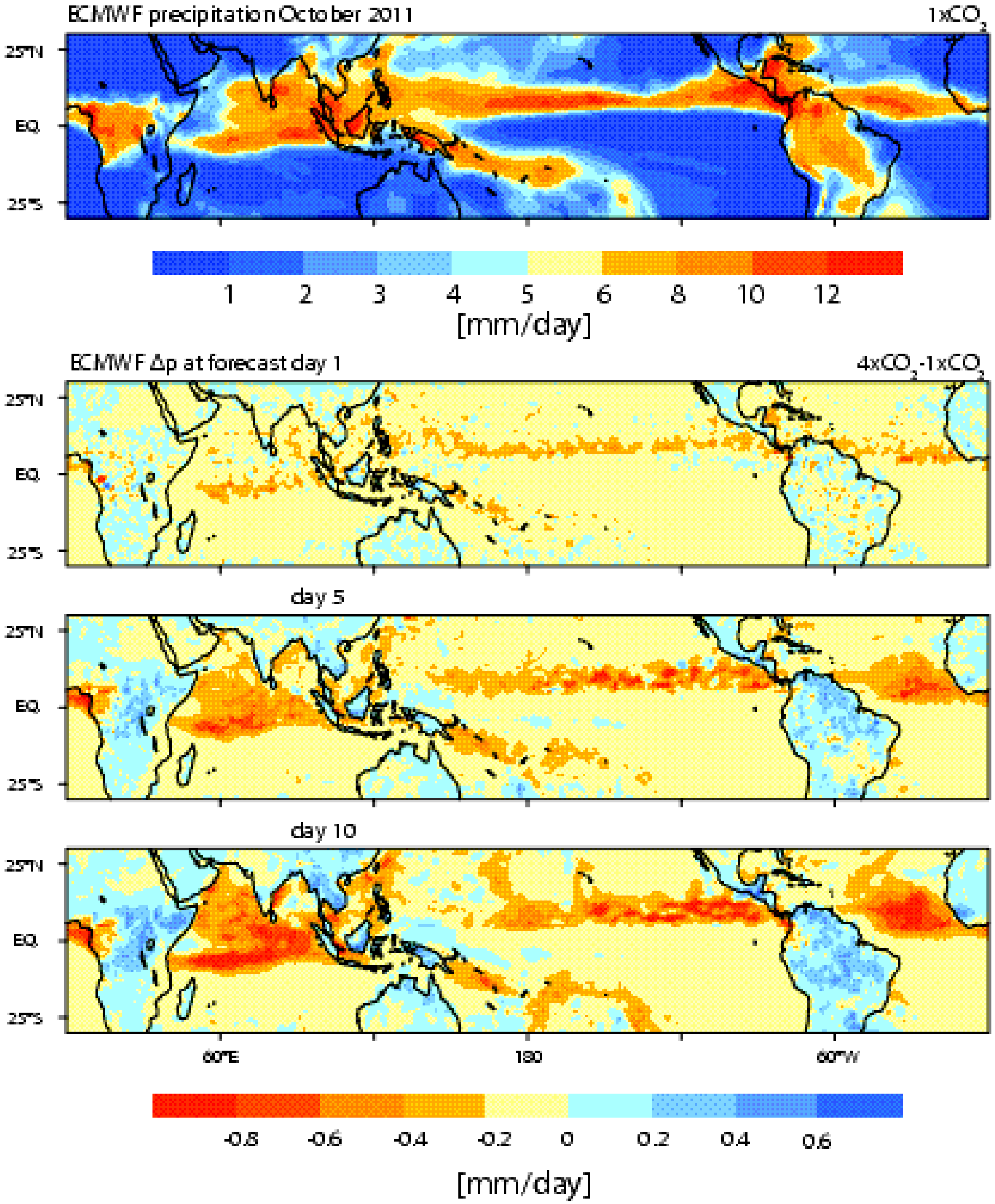


Change in large-scale rising motion



- Increased CO2 affects the strength of large-scale vertical motions in the atmosphere
- Even in the absence of surface temperature changes and land-sea contrasts
- Significant fraction of long-term changes, especially in convective regions

ECMWF-IFS monthly-mean Precipitation (October 2011)



1xCO2

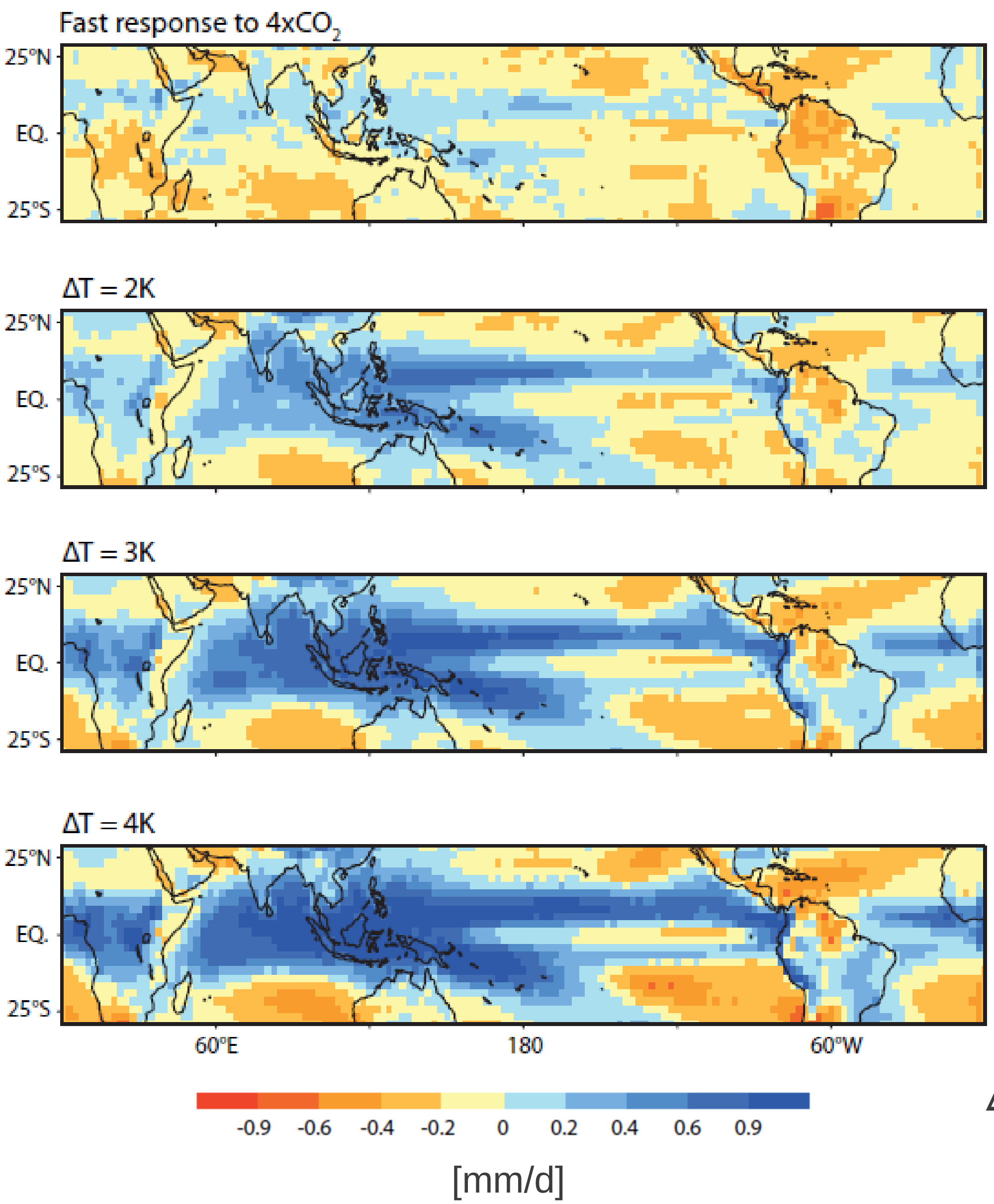
4XCO2–1xCO2
Day 1

4XCO2–1xCO2
Day 5

4XCO2–1xCO2
Day 10

Evolution of regional precipitation changes in abrupt 4xCO2 experiments

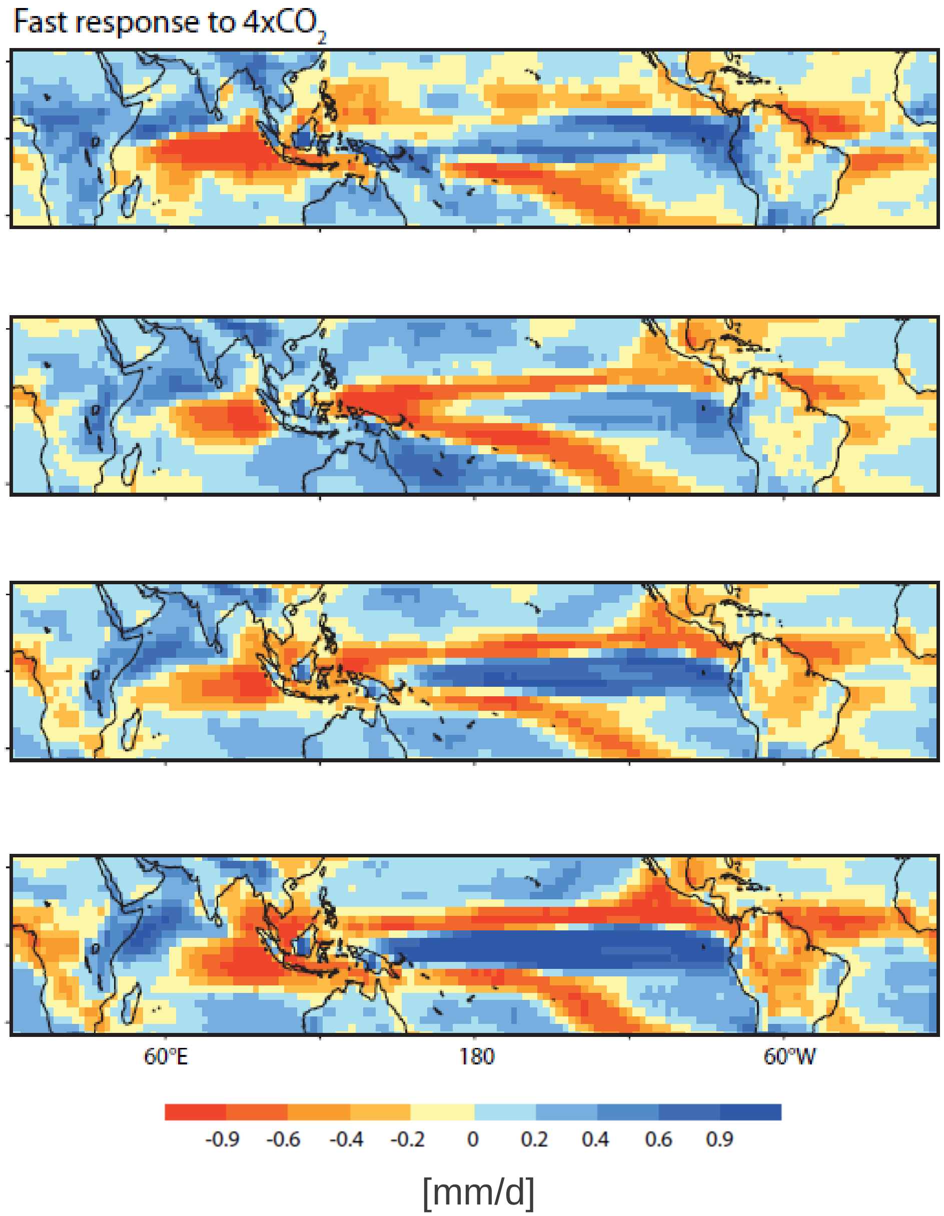
Thermodynamical component



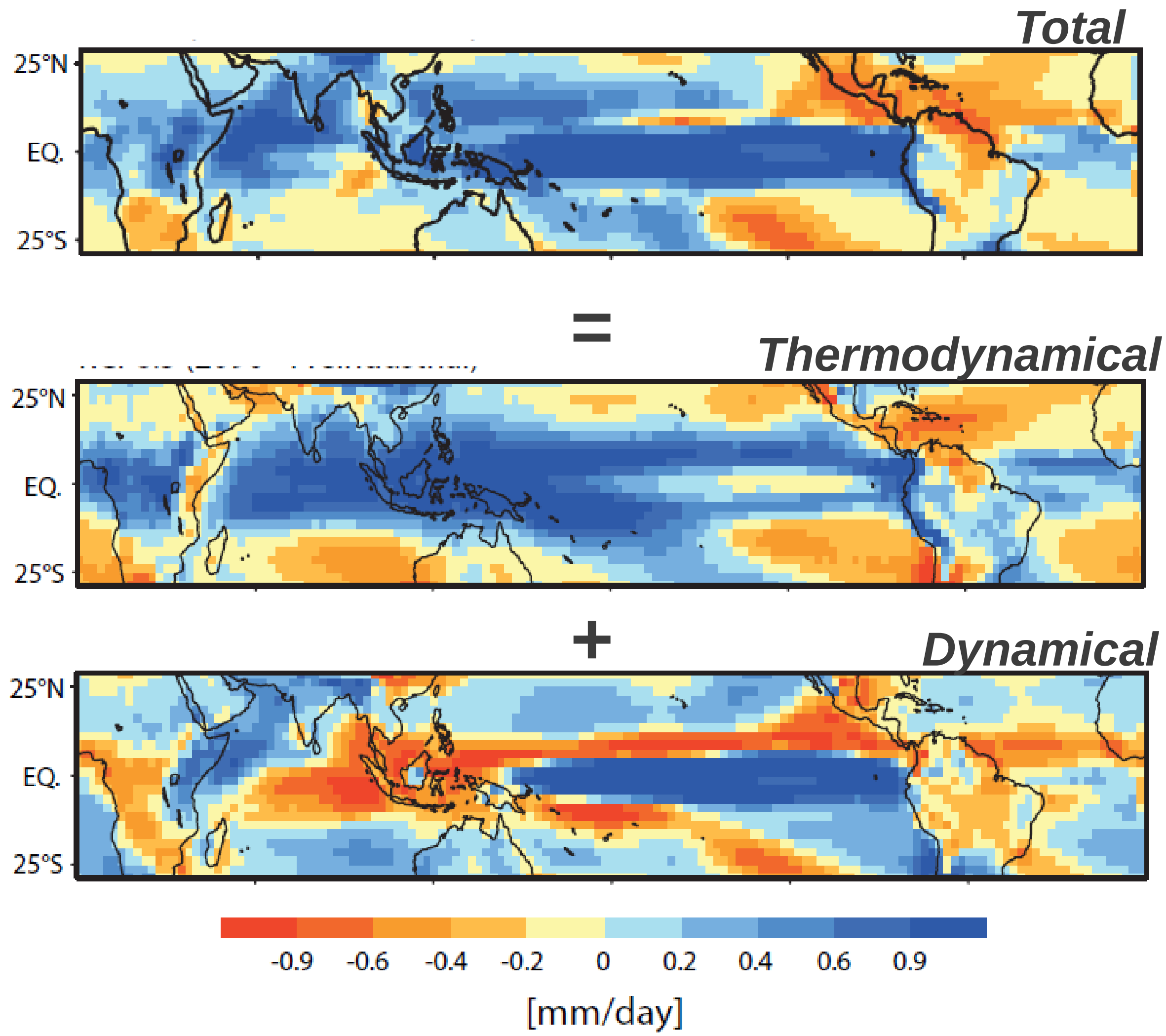
ΔT

Dynamical component

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



Regional pattern of precipitation projections



Decomposing precipitation changes into :

- thermodynamical and dynamical components,
- CO2 (fast) and temperature (slow) components

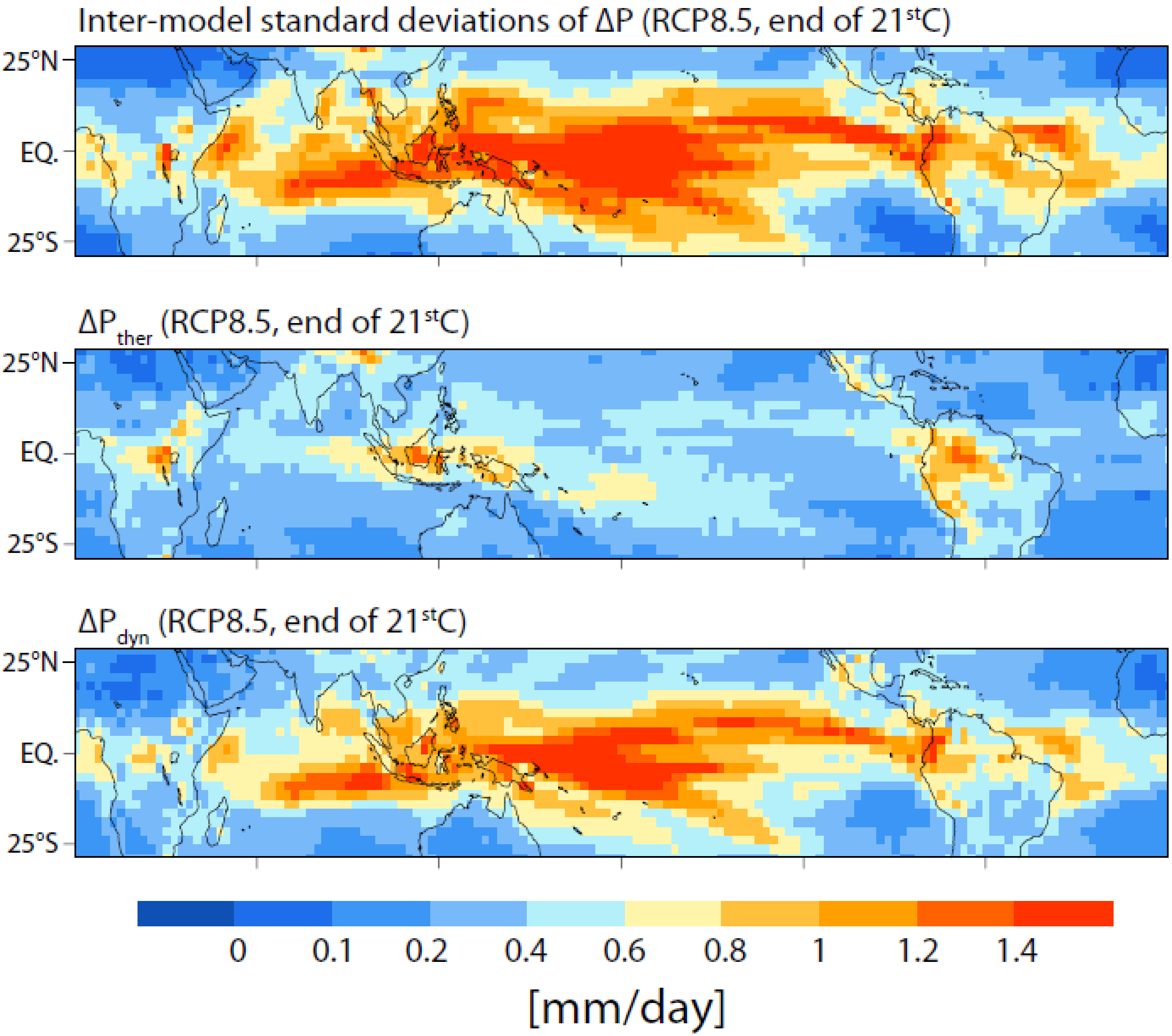
helps understand multi-model mean (robust) patterns

Pending Questions

- Given the robustness of the thermodynamical and dynamical mechanisms highlighted here, how to explain the large inter-model spread ?
- How to reduce uncertainties ?

Sources of inter-model spread at regional scale

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



ΔP

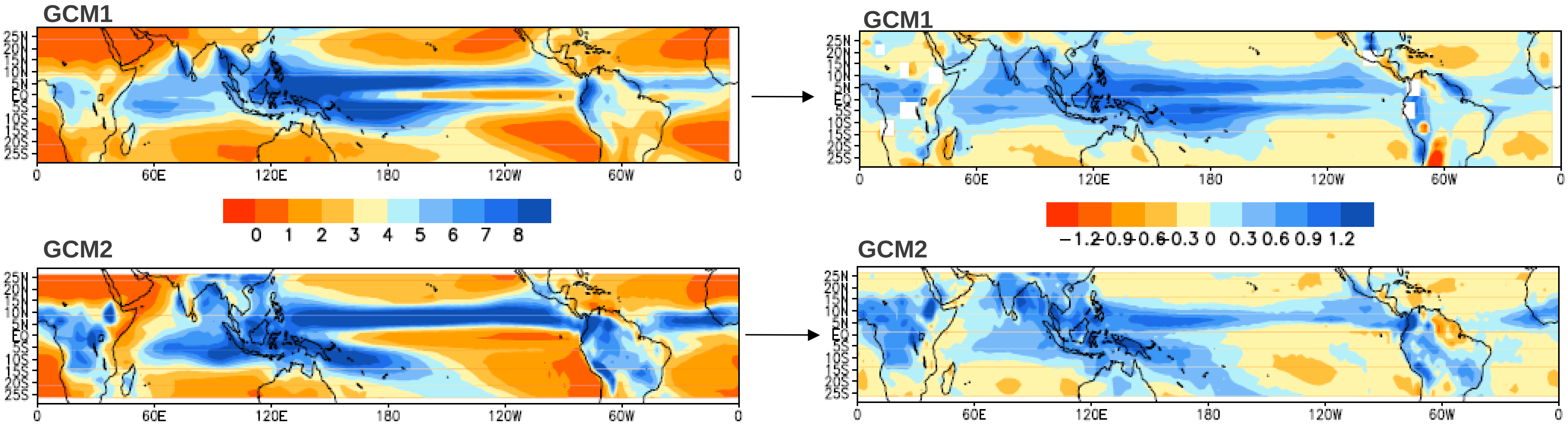
ΔP_{ther}

ΔP_{dyn}

Sources of inter-model spread at regional scale

1) $$\Delta P = \Delta P_{\text{dyn}} + \boxed{\Delta P_{\text{ther}}}$$

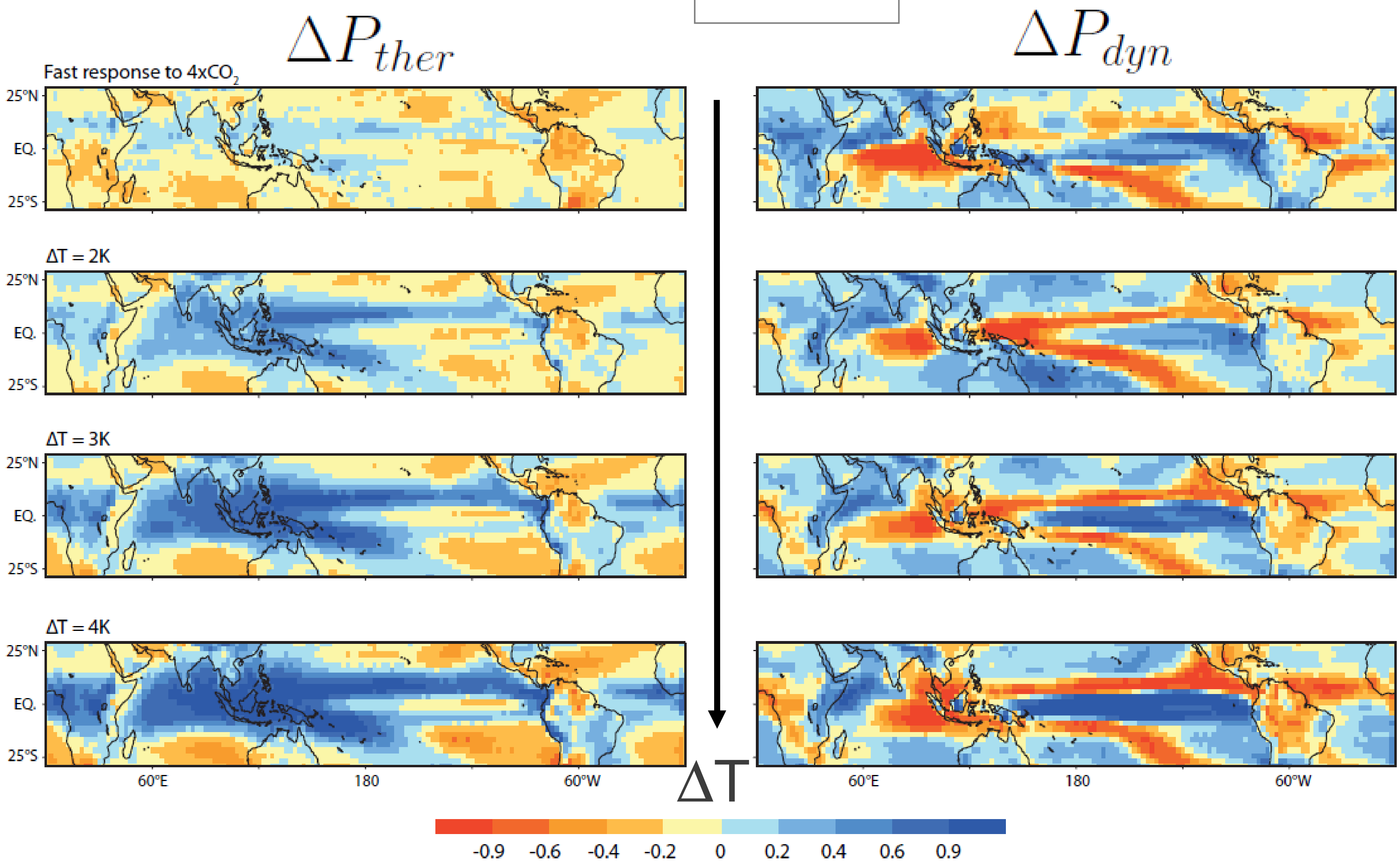
Precipitation climatology *Thermodynamical component (ΔT=3K)*



Observations of present-day precipitation and **better model climatologies** can help reduce this source of uncertainty

Sources of inter-model spread at regional scale

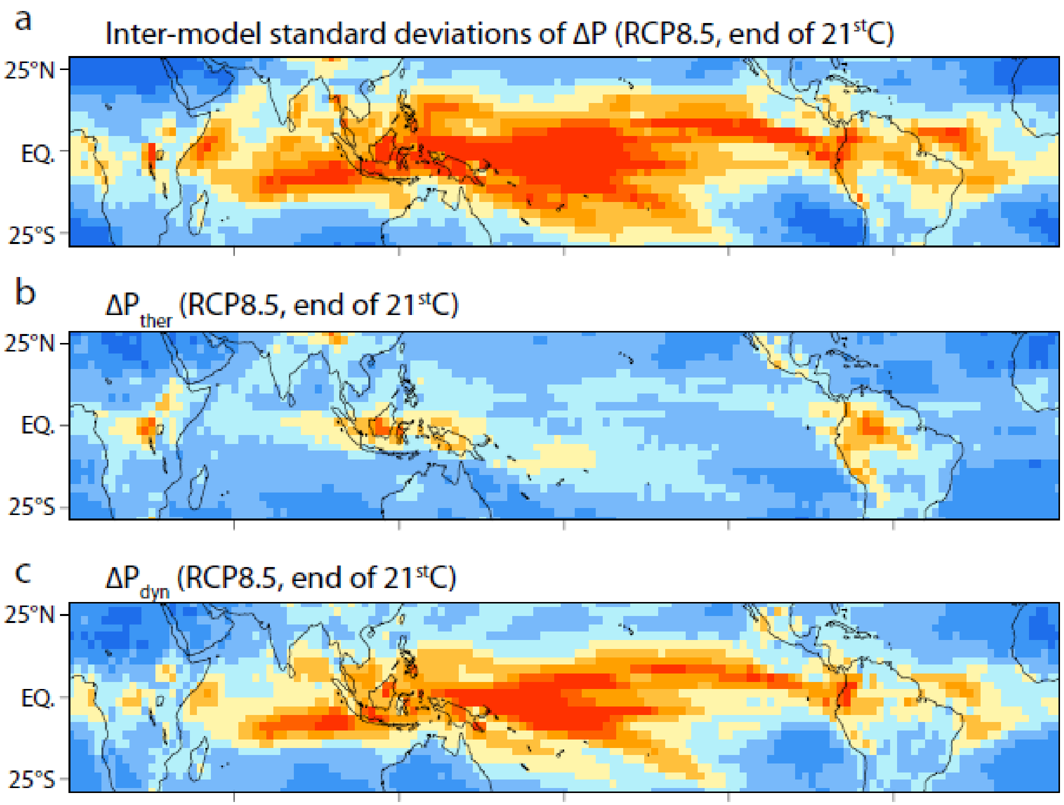
2) $\Delta P = \Delta P_{\mathrm{dyn}} + \Delta P_{\mathrm{ther}}$



Climate Sensitivity affects the relative magnitude of thermodynamic and dynamic components

Sources of inter-model spread at regional scale

2) $$\Delta P = \boxed{\Delta P_{\mathrm{dyn}}} + \Delta P_{\mathrm{ther}}$$

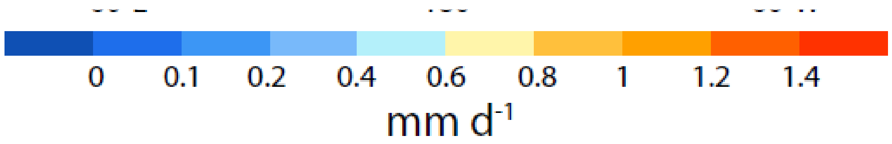


spread ΔP

spread ΔP_{ther}

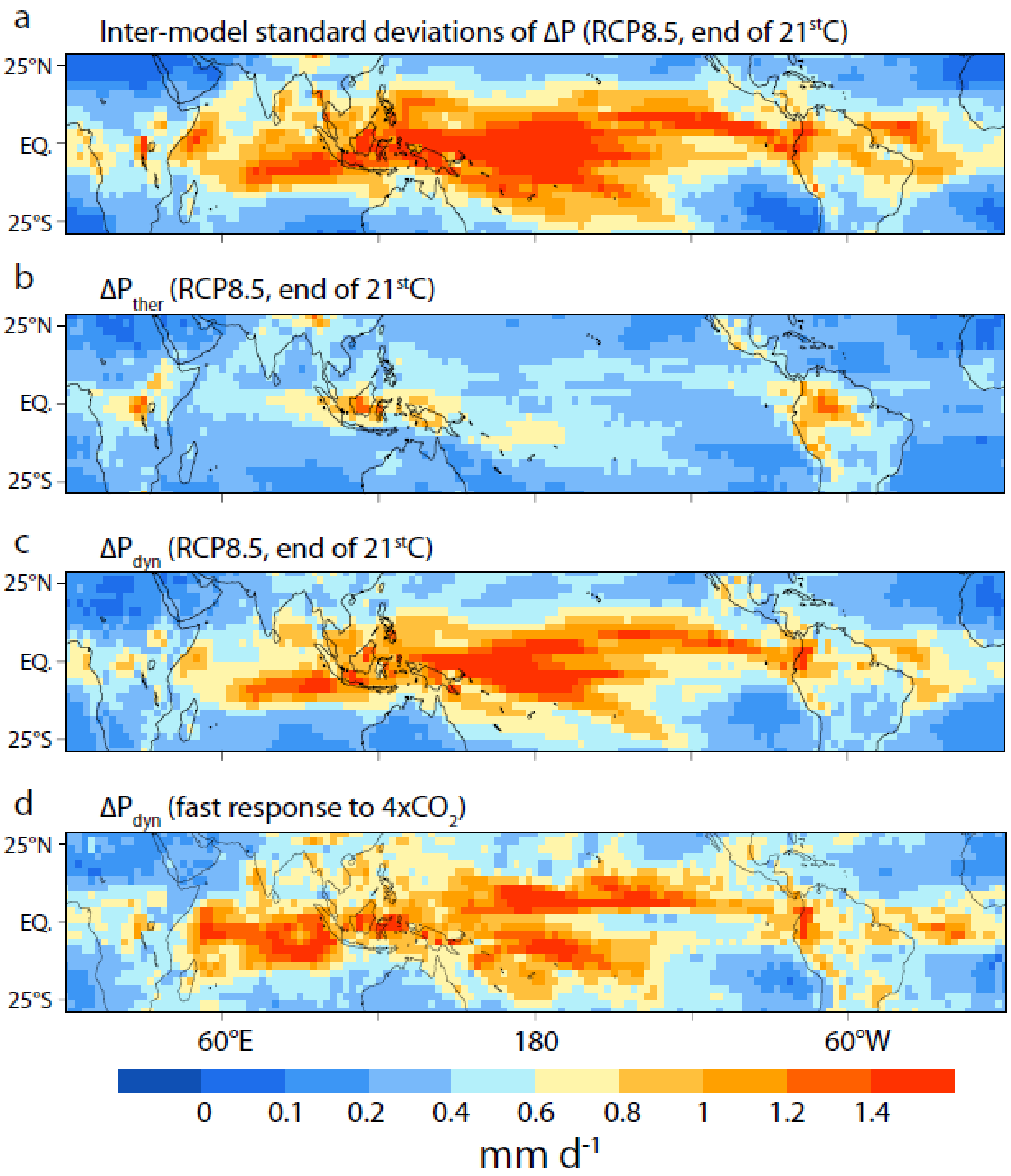
spread $\boxed{\Delta P_{dyn}}$

Where does the spread in the dynamical component come from ?



Sources of inter-model spread at regional scale

2) $\Delta P = \boxed{\Delta P_{\text{dyn}}} + \Delta P_{\text{ther}}$



ΔP

ΔP_{ther}

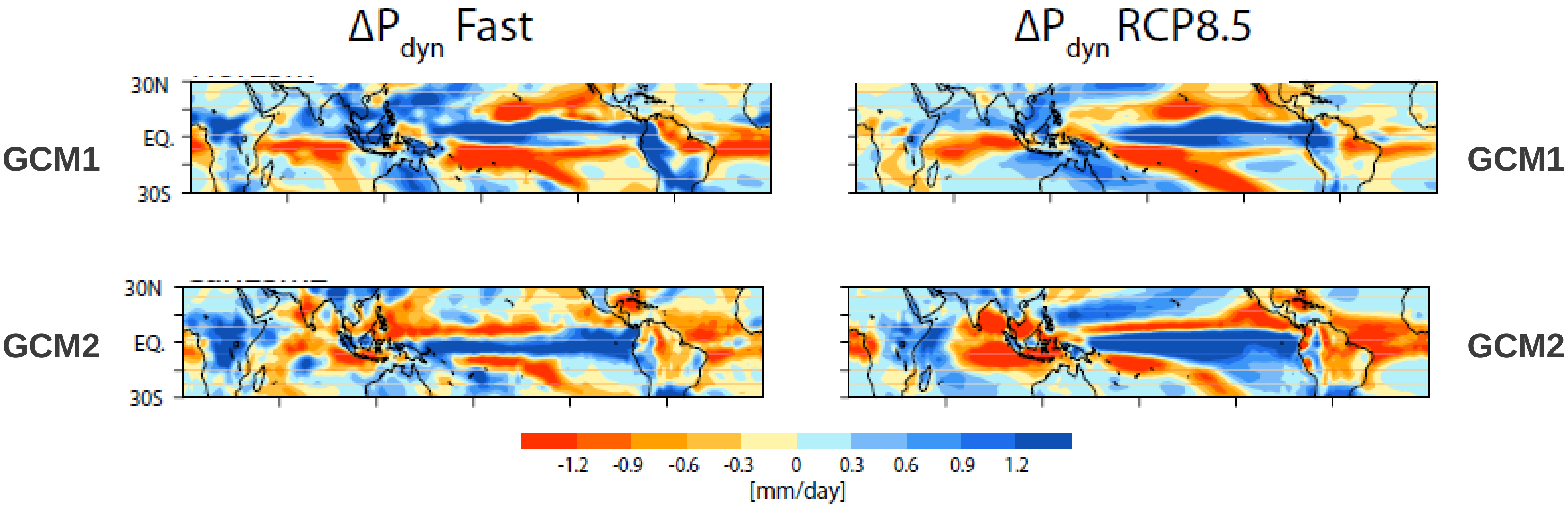
$\boxed{\Delta P_{dyn}}$

Fast dynamical adjustments to CO_2

Fast ΔP_{dyn}

Sources of inter-model spread at regional scale

2) $$\Delta P = \boxed{\Delta P_{\mathrm{dyn}}} + \Delta P_{\mathrm{ther}}$$



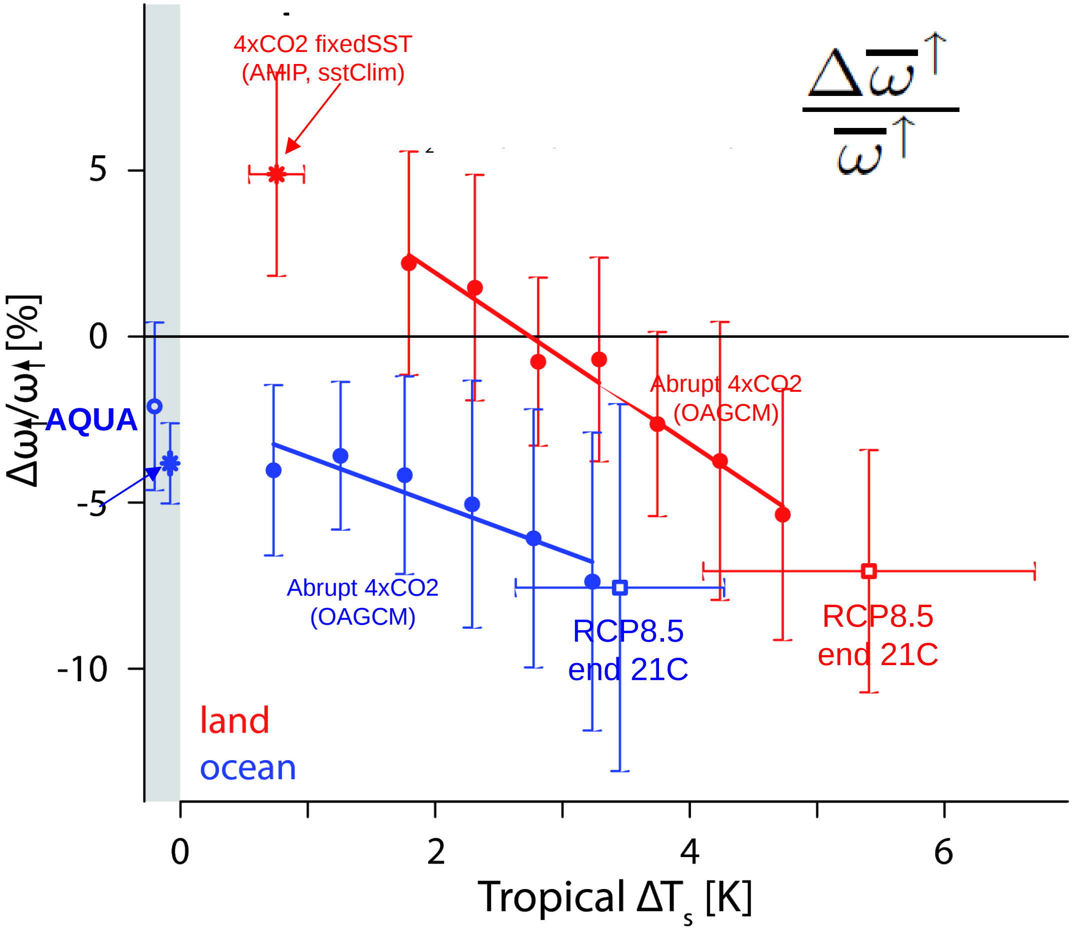
The direct effect of CO2 on circulation might explain part of inter-model differences in long-term dynamical changes, and thus in long-term precipitation projections.

However, the direct effect of CO2 explains only part of the spread of dynamical changes

Sources of inter-model spread at regional scale

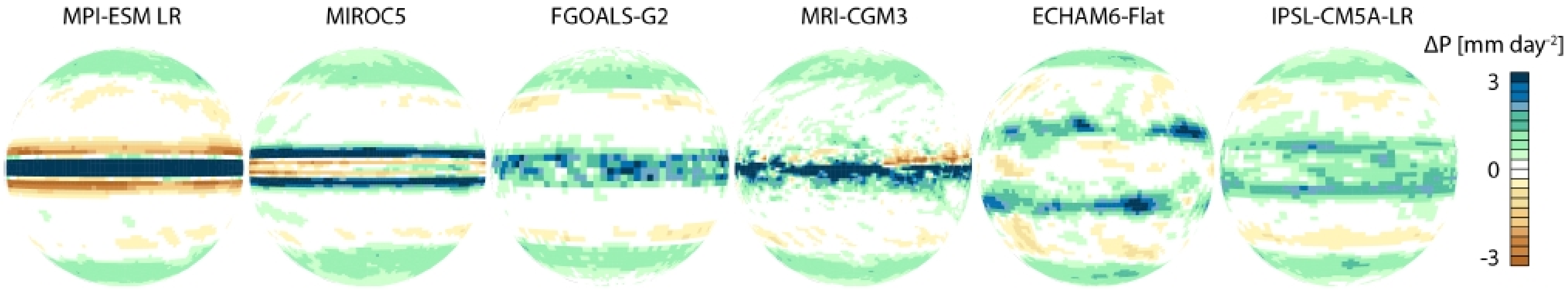
2) $$\Delta P = \boxed{\Delta P_{\mathrm{dyn}}} + \Delta P_{\mathrm{ther}}$$

Change in large-scale rising motion



However, the direct effect of CO2 explains only part of the spread of dynamical changes

Response of precipitation to a uniform SST+4K in CMIP5 aqua-planet models



- Uncertainties related to basic physical processes

- Critical limitation for mitigation and adaptation studies

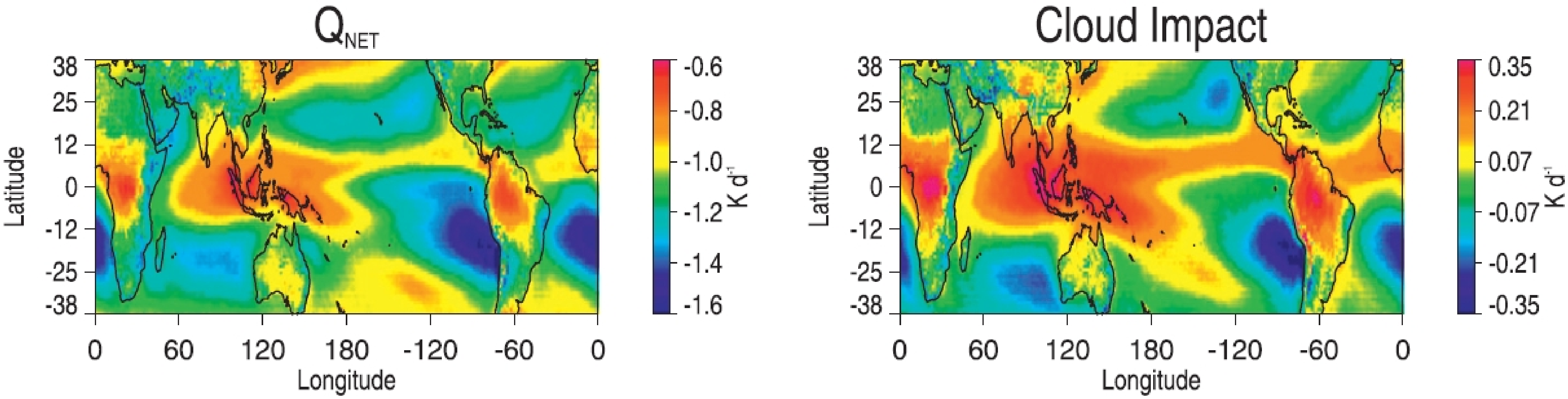
Our Challenge :
To understand these differences !

Stevens & Bony, Science, 2013

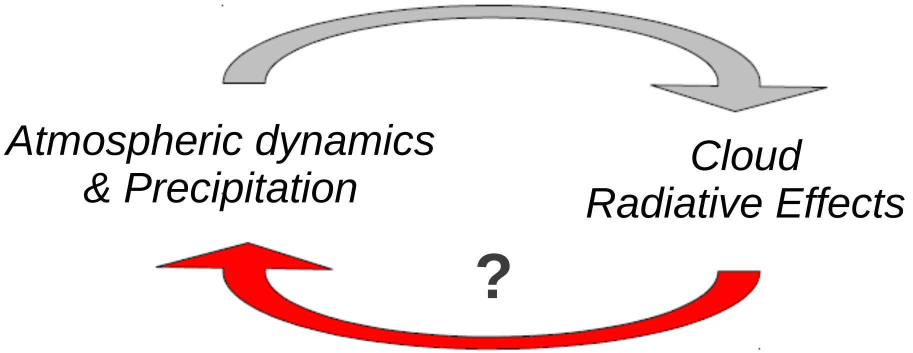
Coupling between clouds and large-scale dynamics

Clouds do not matter only for climate sensitivity

Tropospheric Radiative Heating and cloud-radiative effects *within* the troposphere
(as derived from TRMM observations)



(L'Ecuyer & McGarragh 2010)


Atmospheric dynamics
& Precipitation

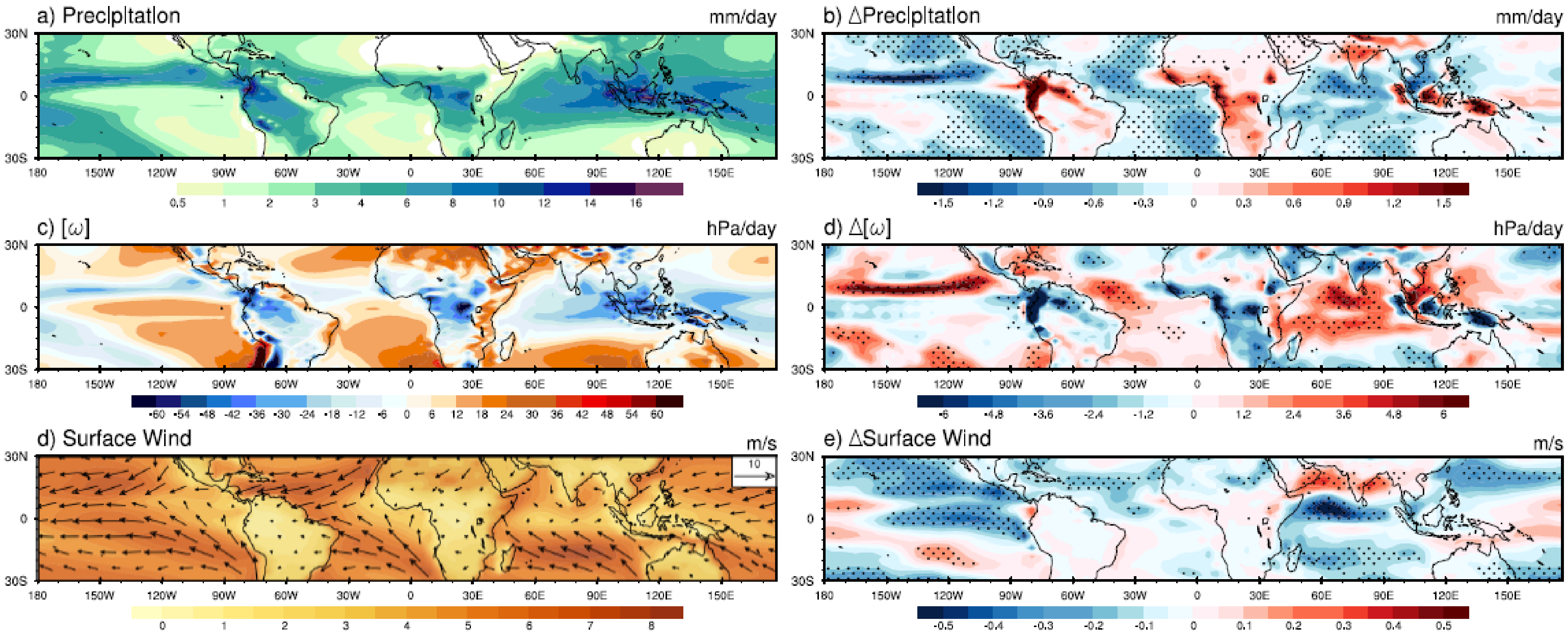
Cloud
Radiative Effects

?

Reponse of precipitation and circulation to PBL clouds radiative effects

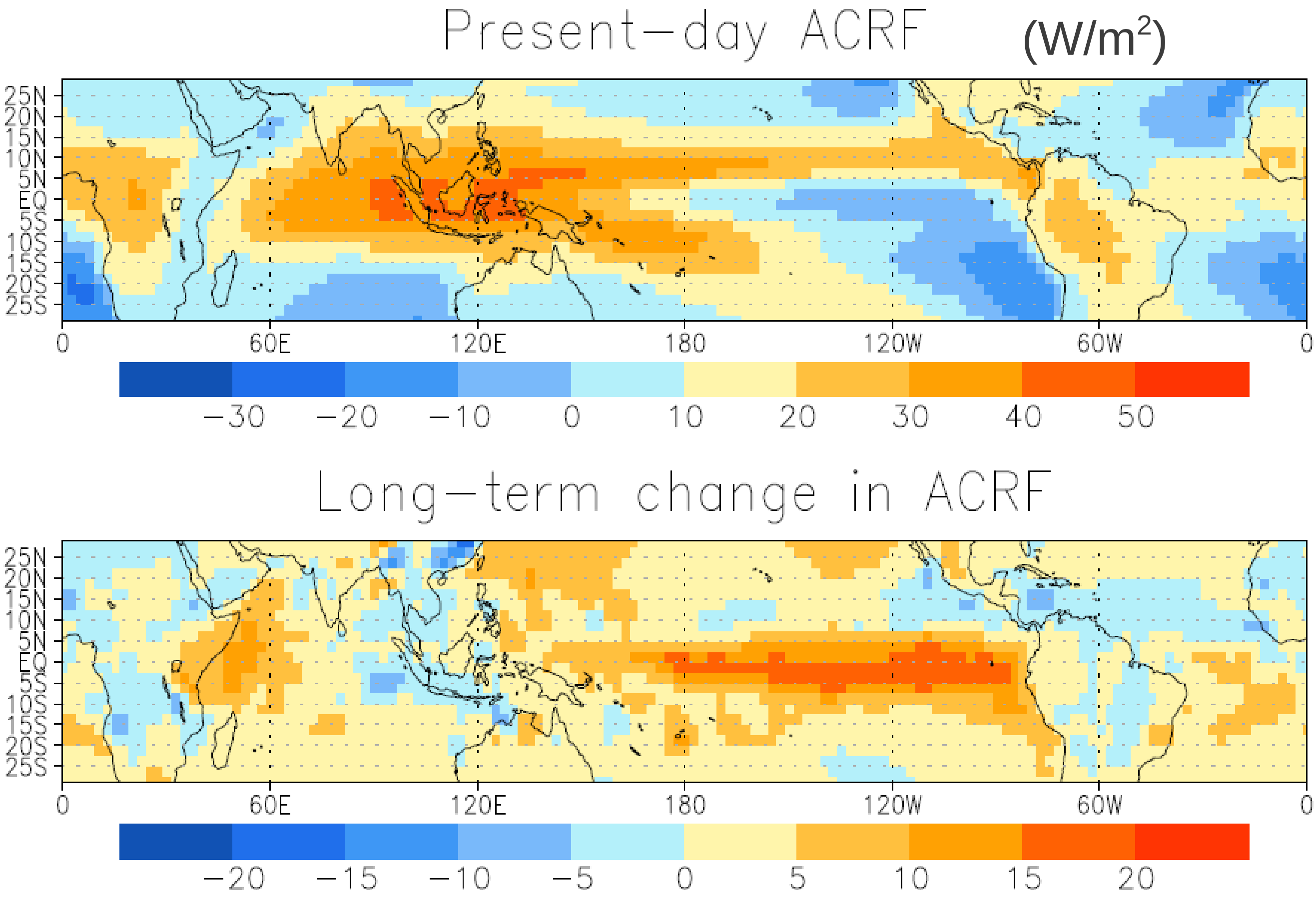
Climatology

Changes when PBL CRE = 0



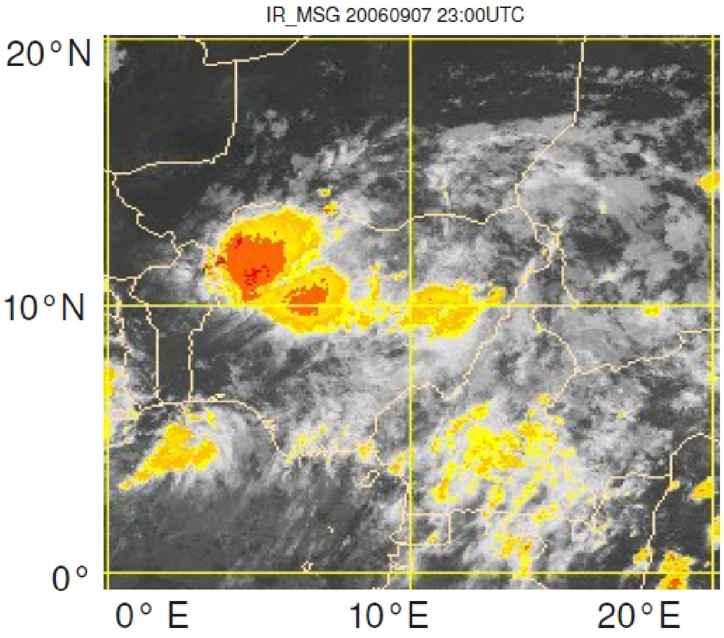
Fermepin & Bony, in prep

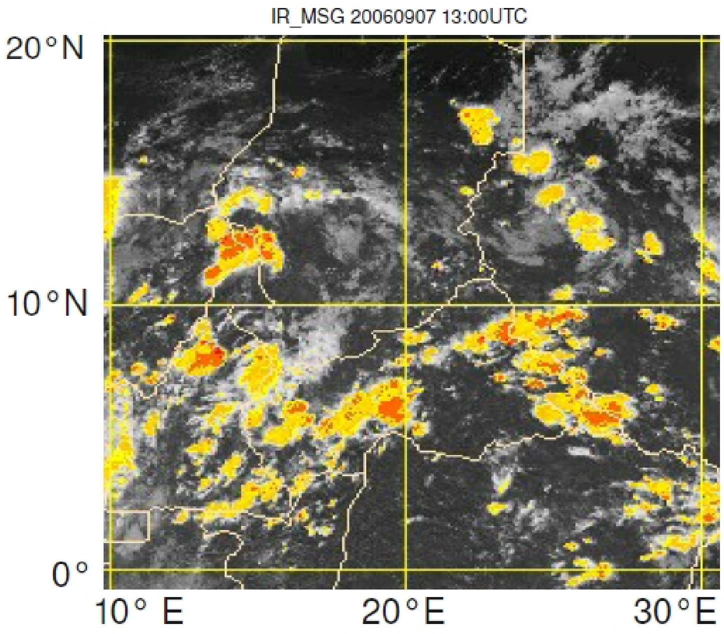
Response of tropospheric cloud-radiative effects to global warming predicted by CMIP5 OAGCMs



what role in large-scale circulation changes ?

Impact of convective aggregation ?





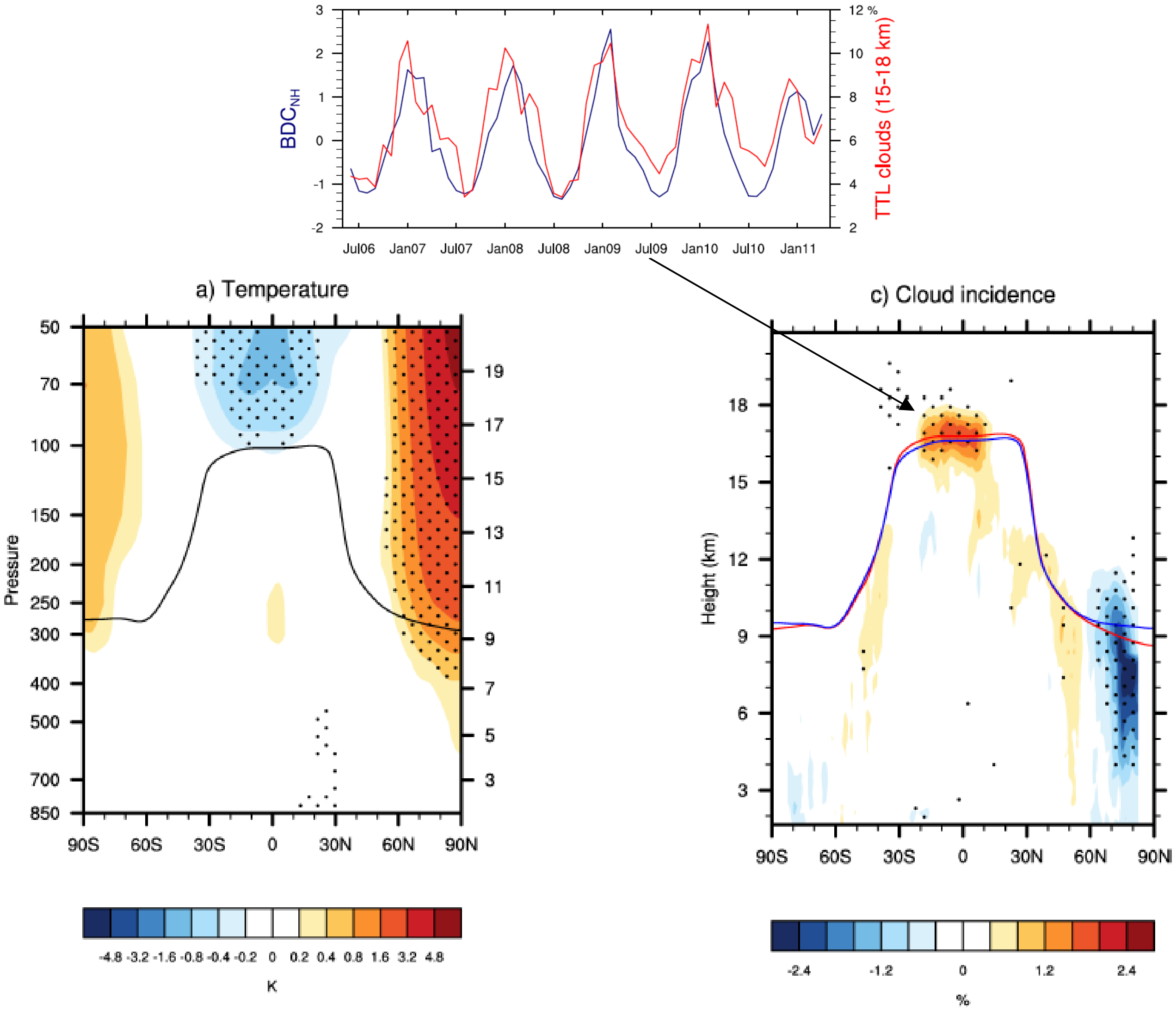
Observations and CRMs suggest that when tropical convection is in a more aggregated state :

- troposphere drier and less cloudy
- strong modulation of the column moist static energy

Impact on circulation and circulation changes ?

Bretherton et al., JAS, 2005
Tobin et al., J. Climate, 2012
Tobin et al., JAMES, 2013

Signature of the Brewer-Dobson circulation in tropospheric clouds



- Robust linkage between the BDC and clouds in the TTL and Arctic troposphere.
- Robust increase in the strength of the BDC in response to increased greenhouse gases
- What influence on long-term cloud changes and climate ?

Li & Thompson, JGR, 2013

Summary

- **Strong energetic constraints on the hydrological cycle**

- **Important direct effect of CO_2 on precipitation, both at global and regional scales**
    -> implications for geo-engineering options

- Thermodynamic and dynamic components of precipitation changes

- **Uncertainties in regional precipitation projections arise from different factors that we can start decomposing**

- **Interaction between cloud-radiative effects and the atmospheric circulation**

- **Better understanding of changes in large-scale circulation patterns needed**

- **Many exciting open questions**

Feedback welcome !