Lectures Outline :

Cloud fundamentals - global distribution, types, visualization and link with large scale circulation

Cloud Formation and Physics - thermodynamics, cloud formation, instability, life cycle of an individual cloud

Organization of deep convection at mesoscales - MCSs, MCCs, Squall lines, Tropical cyclones, Processes, Self-aggregation

Response of the hydrological cycle to climate change - mean precip, precip extremes

Clouds in a changing climate – climate sensitivity, cloud effect, cloud feedback, FAT

Clouds and turbulent moist convection

Caroline Muller

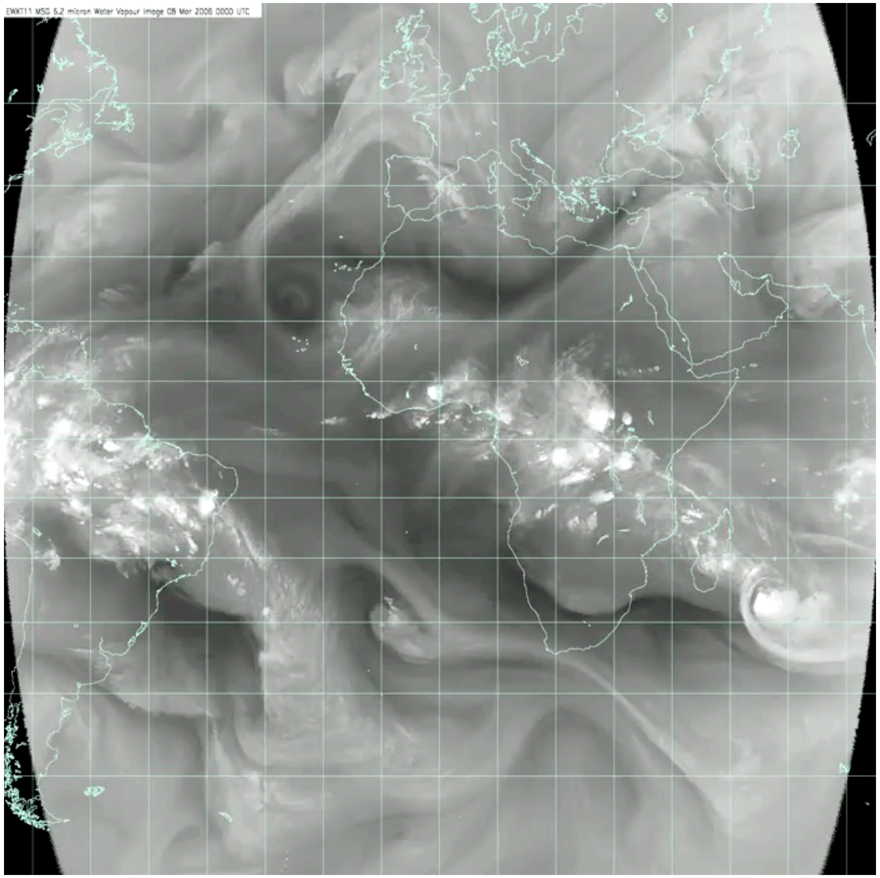
Lecture 4 : Response of the hydrological cycle to warming

&

Lecture 5 : Clouds in a changing climate

Tropical convection = “pop corn” convection

Water vapor from satellite



Small-scale tropical convection

Tropical convection parameterized in GCMs

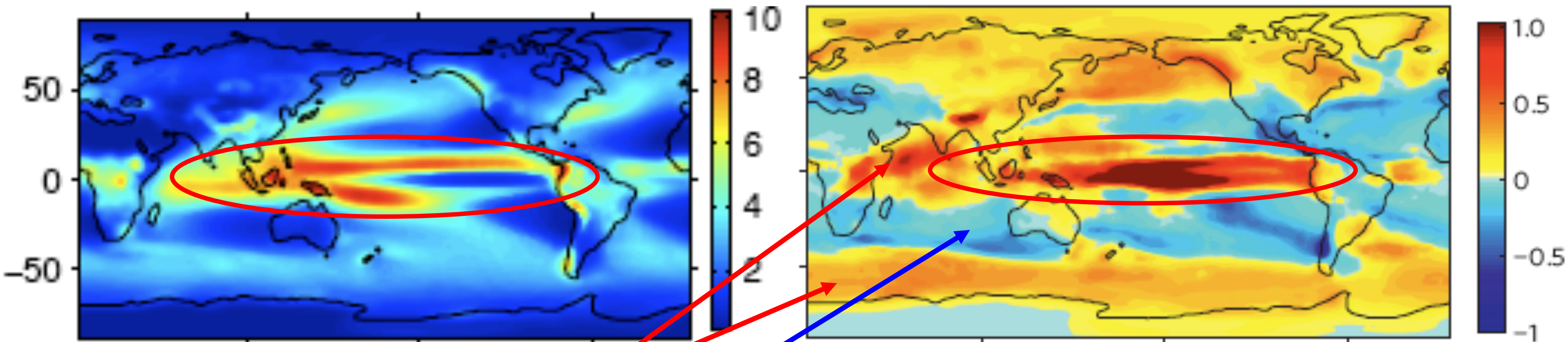
Mean precipitation : “rich get richer”

Robust responses between models for the spatial distribution of mean precipitation

[Held & Soden, J. Clim., 2006, 1200+ citations]

P (mm/day)
1981-1999 climatology

dP (mm/day)
(2081-2099) minus (1981-1999)



Increase in Tropics &
Extratropics
Decrease in Subtropics

Warming => “Rich get richer”

P ~ moisture convergence

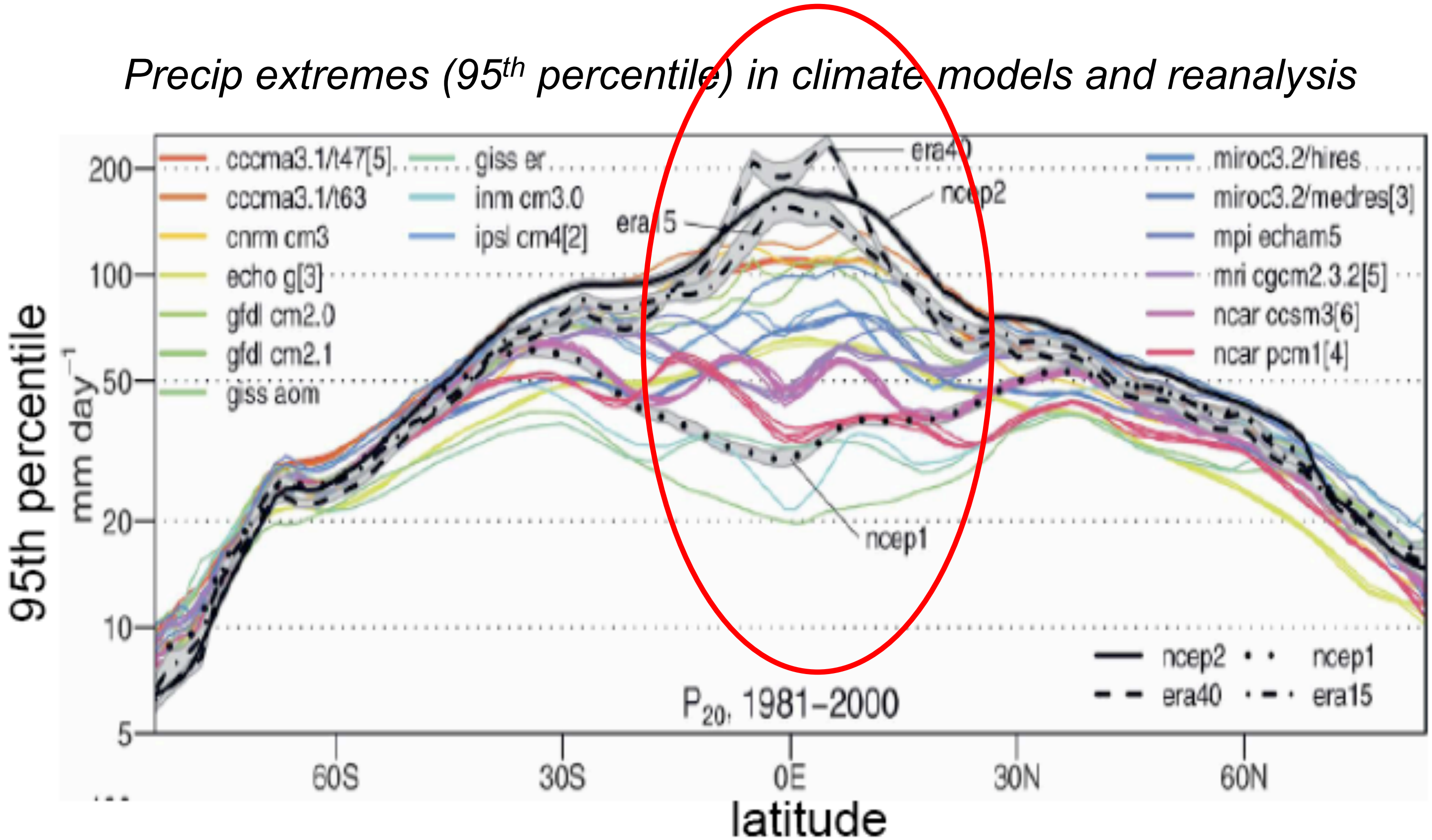
Moisture increases ~ CC rate. If to leading order the dynamics do not change:

- Anomalous P>0 ⇔ moisture convergence ⇔ dP ~ d(moisture convergence) > 0
- Anomalous P<0 ⇔ moisture divergence ⇔ dP ~ - d(moisture divergence) < 0

[Chou & Neelin, J. Clim., 2004
Muller & O’Gorman, Nat. Clim. Change, 2011]

Precipitation extremes

Precip extremes (95th percentile) in climate models and reanalysis

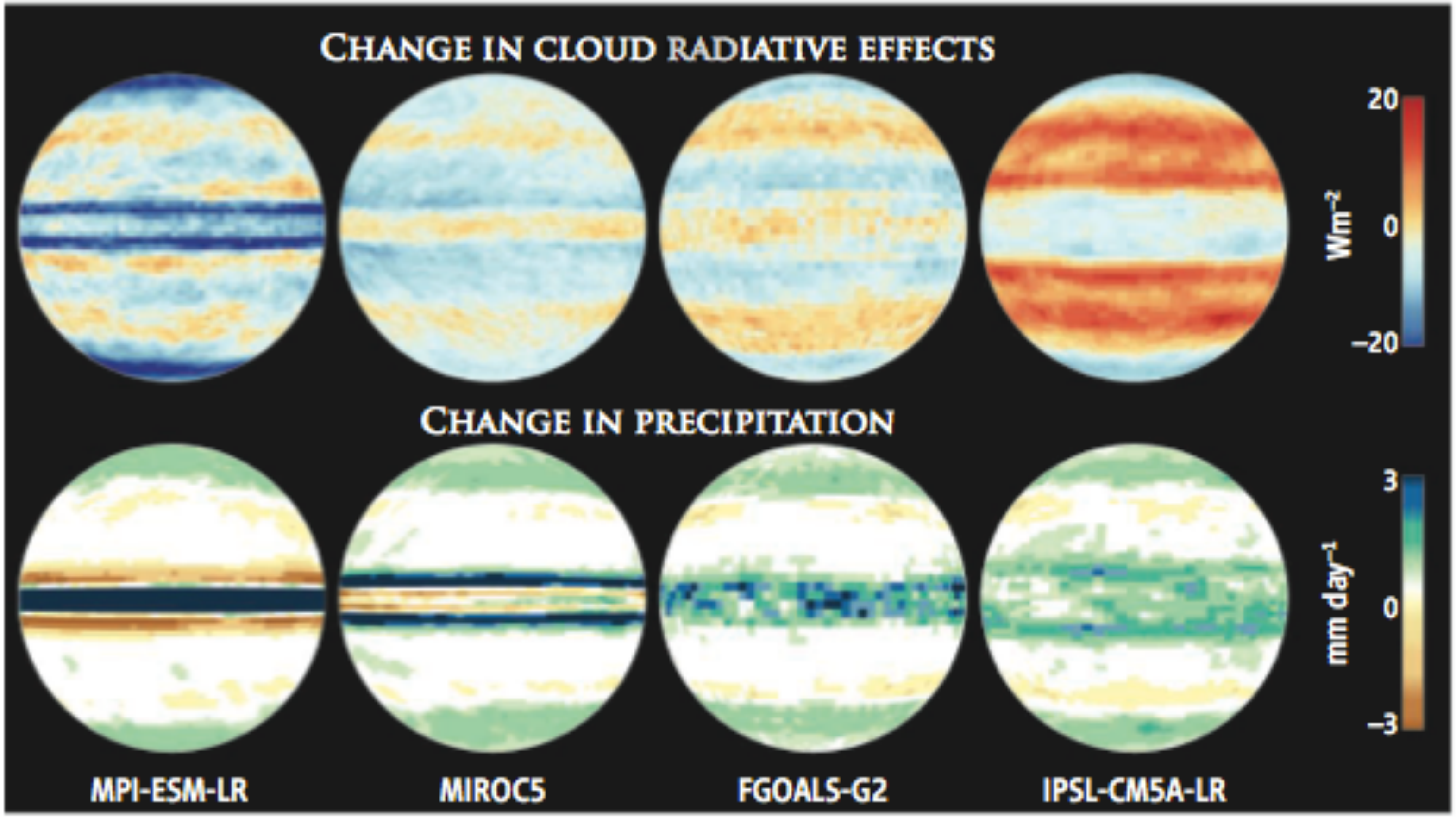


⇒Values NOT consistent in tropics and subtropics *[Kharin et al, 06]*

⇒Not correlated with resolution, hence convection param

⇒Models disagree *[O'Gorman&Schneider, 09; Sugiyama,Shiogama,Emori, 10]*

Tropical convection parameterized in GCMs



Wide variation. The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures.

[Stevens & Bony, Science 2013]

Tropical convection parameterized in GCMs

Hierarchy of models

- Because of numerous complex interactive processes, a sequence of models with increasing complexity were developed.

- Cloud-resolving models (CRMs) are simplified models.

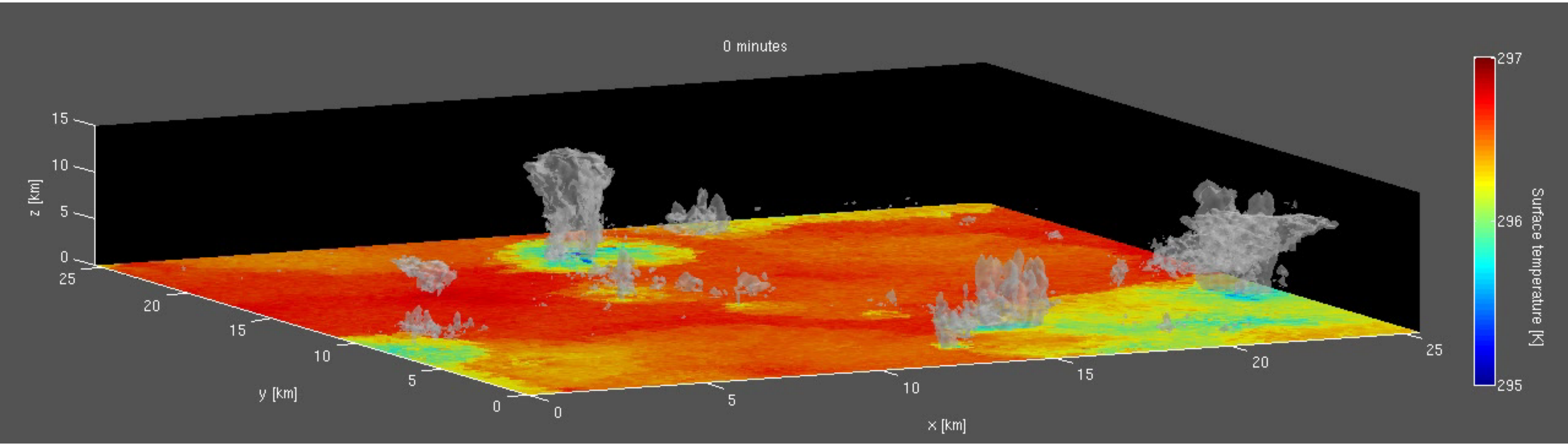
Isaac Held, 2014 (Science)

Cloud-resolving model SAM

- Anelastic momentum, continuity and scalar conservation equations
- Interactive radiative cooling (LW&SW radiation scheme NCAR CAM3)
- Fixed SST, square doubly-periodic domain, no rotation
- Run to statistical RCE (Radiative – Convective Equilibrium)
- (sponge layer in upper troposphere to absorb gravity waves)

[Khairoutdinov, M.F. and Randall, D.A., JAS 2003]

Clouds over near-surface temperature



Precip extremes: theory

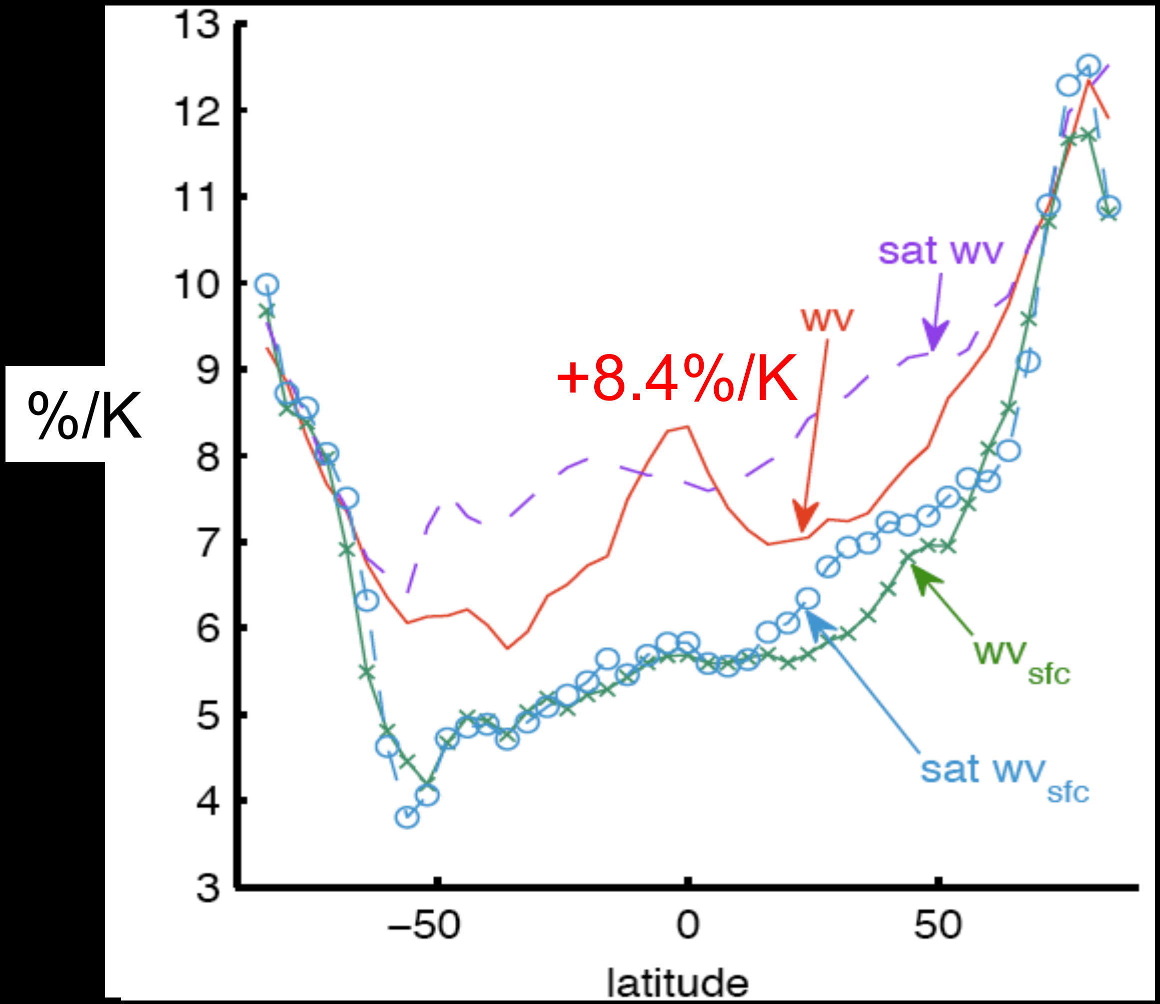
Precip extremes increase with temperature

Scale with atmospheric water vapor?

Clausius Clapeyron (CC)

$$\frac{\delta q_{sat}}{q_{sat}} \approx \frac{L_v \; \delta T}{R \; T^2}$$

GCM multi-model mean wv increase



[O'Gorman & Muller, Environmental Res. Lett., 2010]

Questions

- By how much do precip extremes increase with warming?
- How does it compare with change in wv?
- How do vertical velocities in updrafts change and how does it impact precip extremes?
- Can we derive a scaling that relates changes in precip extremes to mean quantities?

Part 1 : disorganized « pop corn » convection

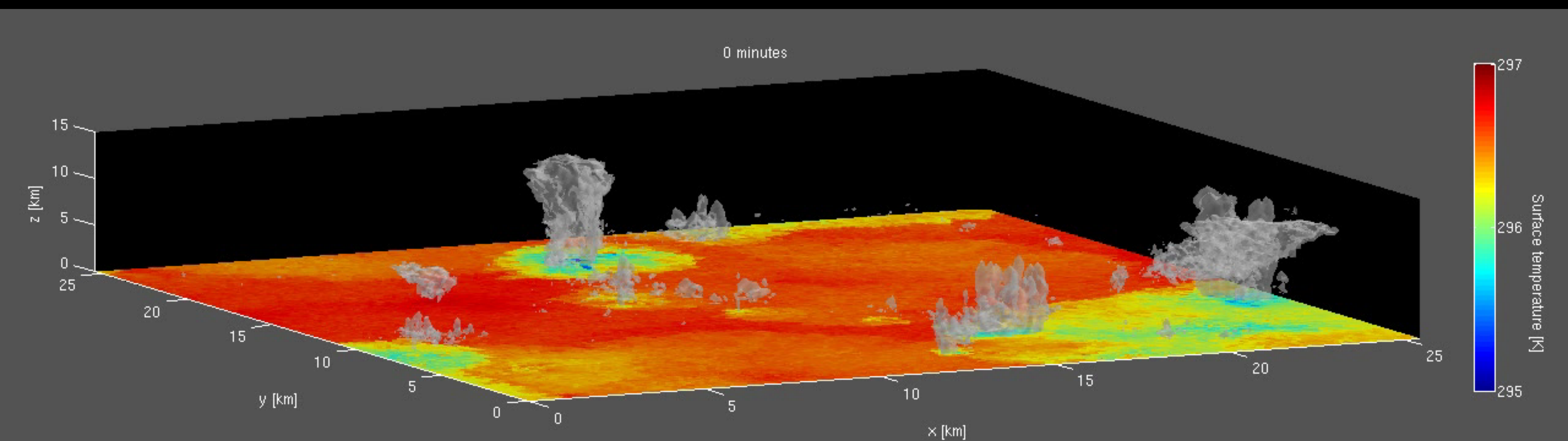
Part 2 : impact of convective organization

Tool: Cloud resolving model

- SAM *[Khairoutdinov, M.F. and Randall, D.A., JAS 2003]*
- Anelastic momentum, continuity and scalar conservation equations
- Fixed SST: 300K & 305K
- Specified radiative cooling $Q_{rad,300}$ & $Q_{rad,305}$
- Square, doubly-periodic domain, run to RCE

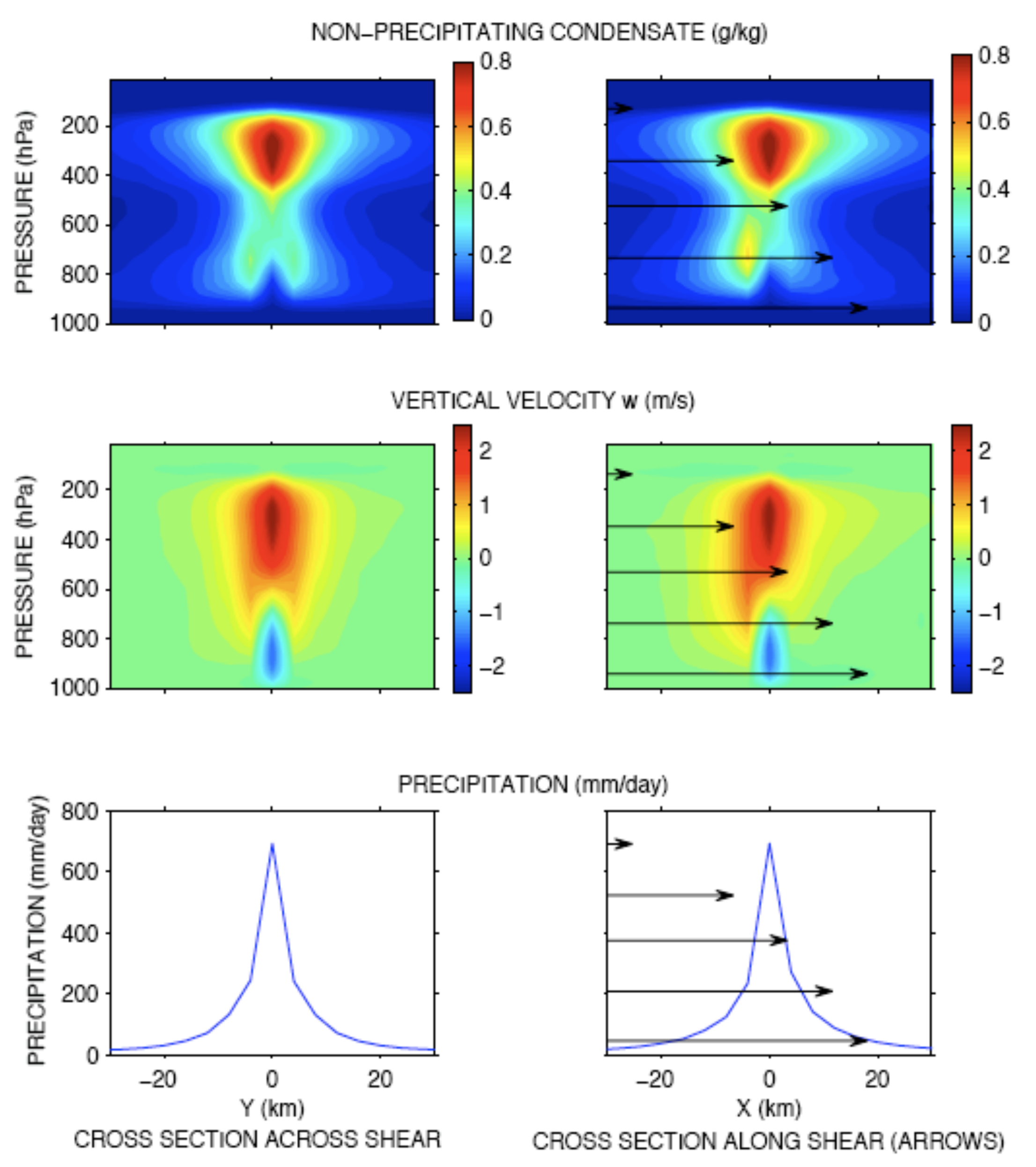
« cold » & « warm » runs

Clouds over near-surface temperature



- Want large domain -> 1024kmx1024km (dx=dy=4km)

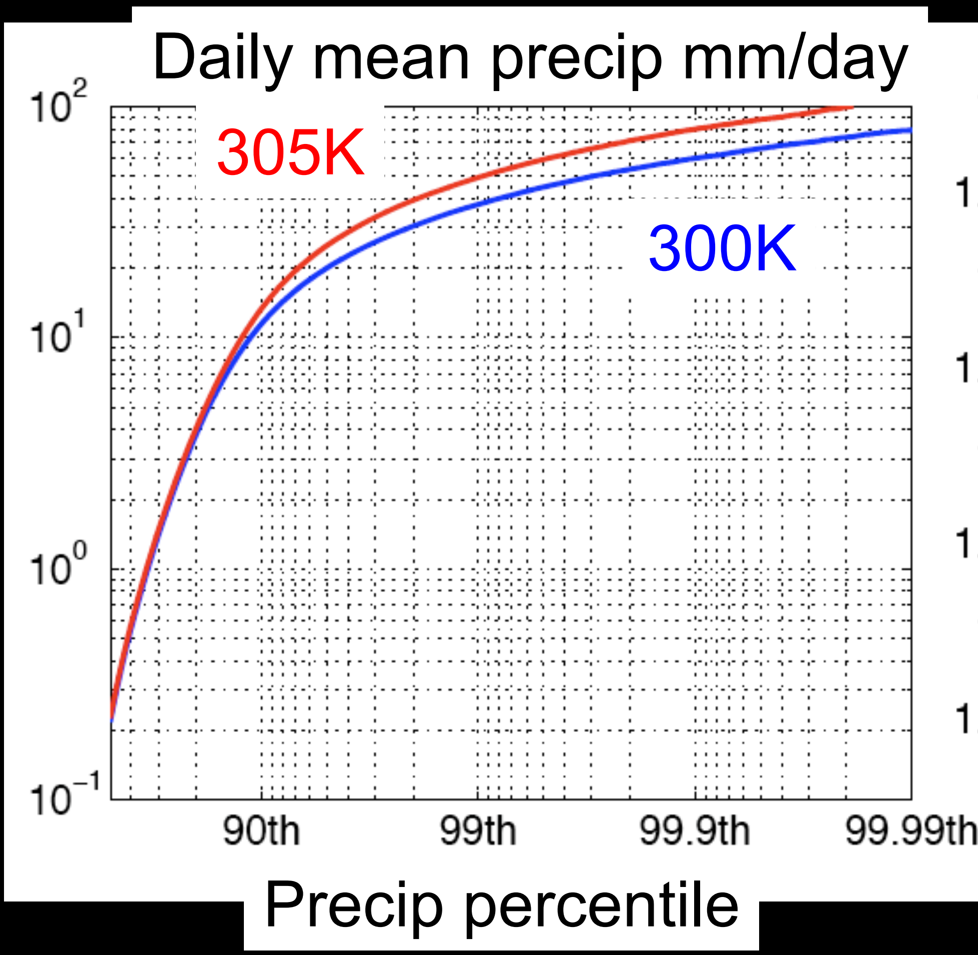
Composite P>99.9th percentile

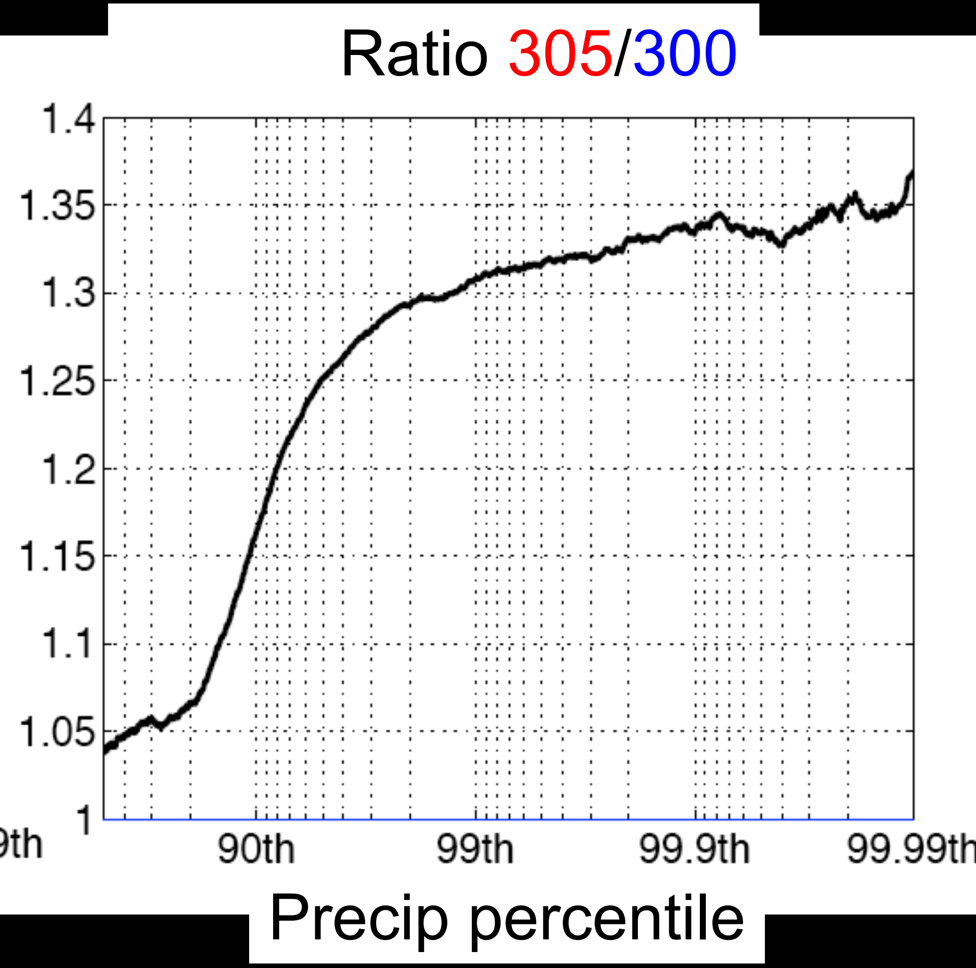


- Strong upward motion
- Downdrafts at low levels

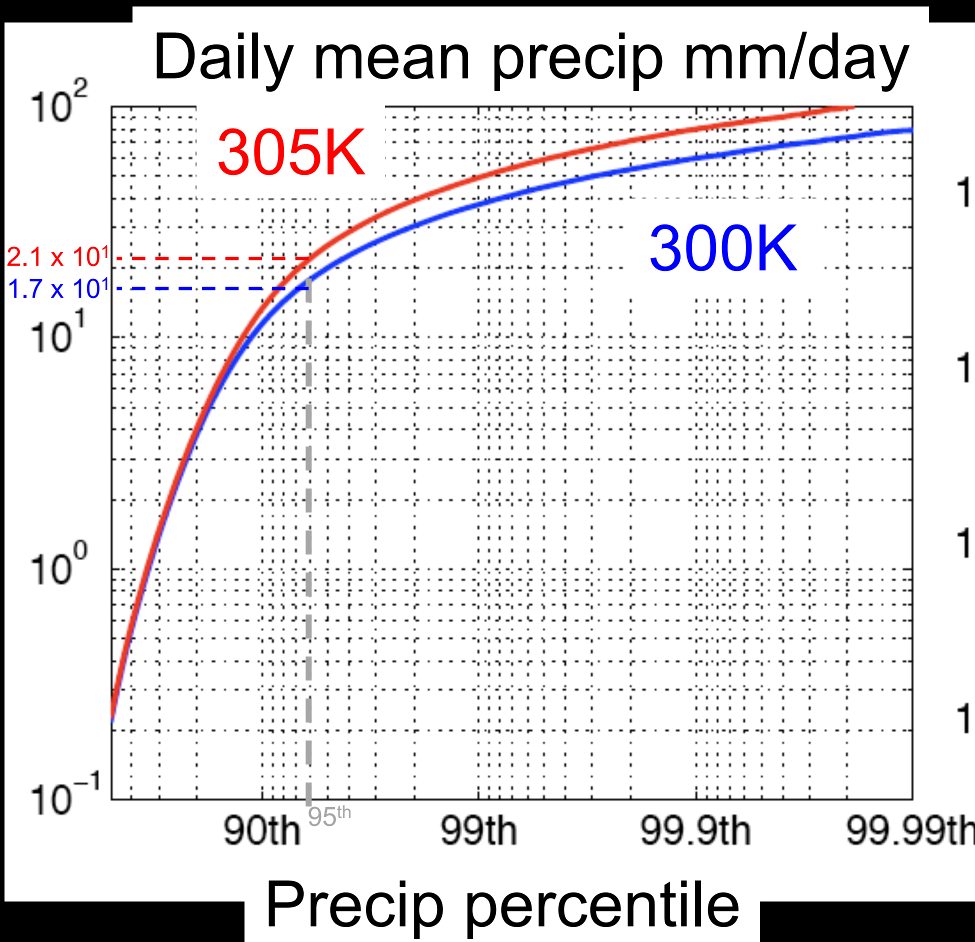
Asymmetry along shear: Preferred upward motion and cloudiness upwind

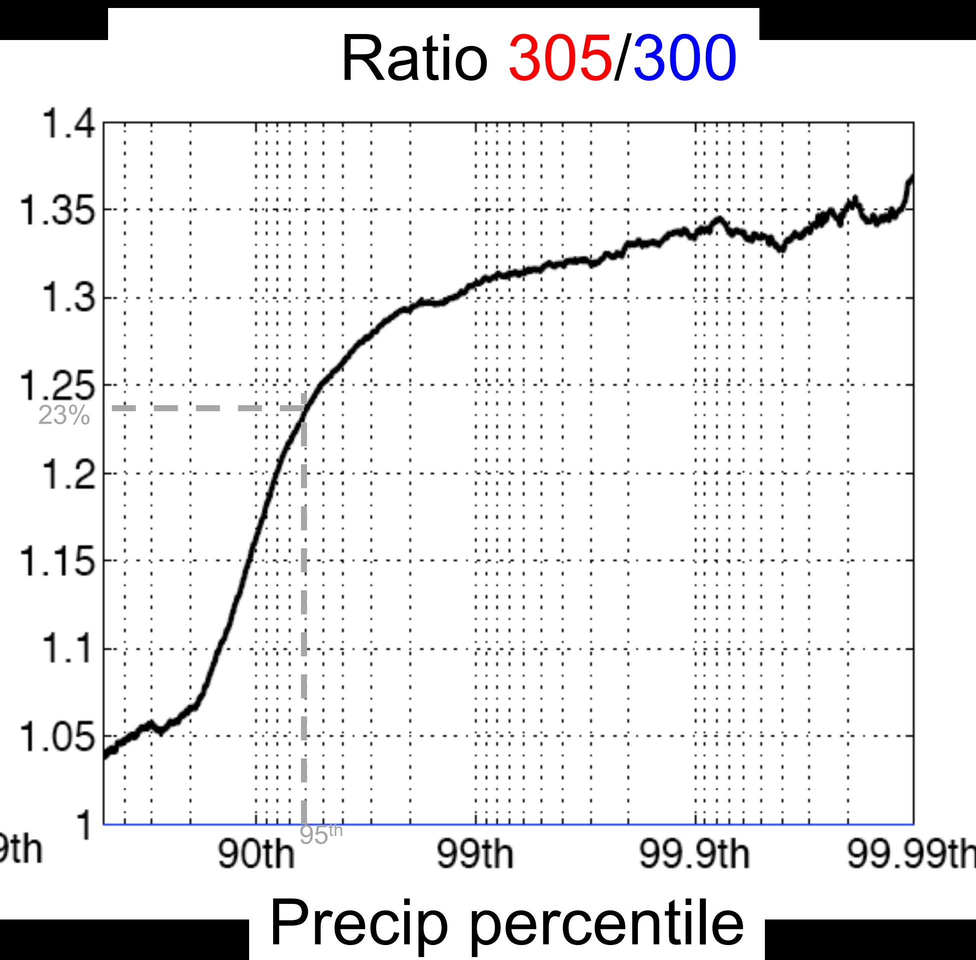
Extremes of precipitation





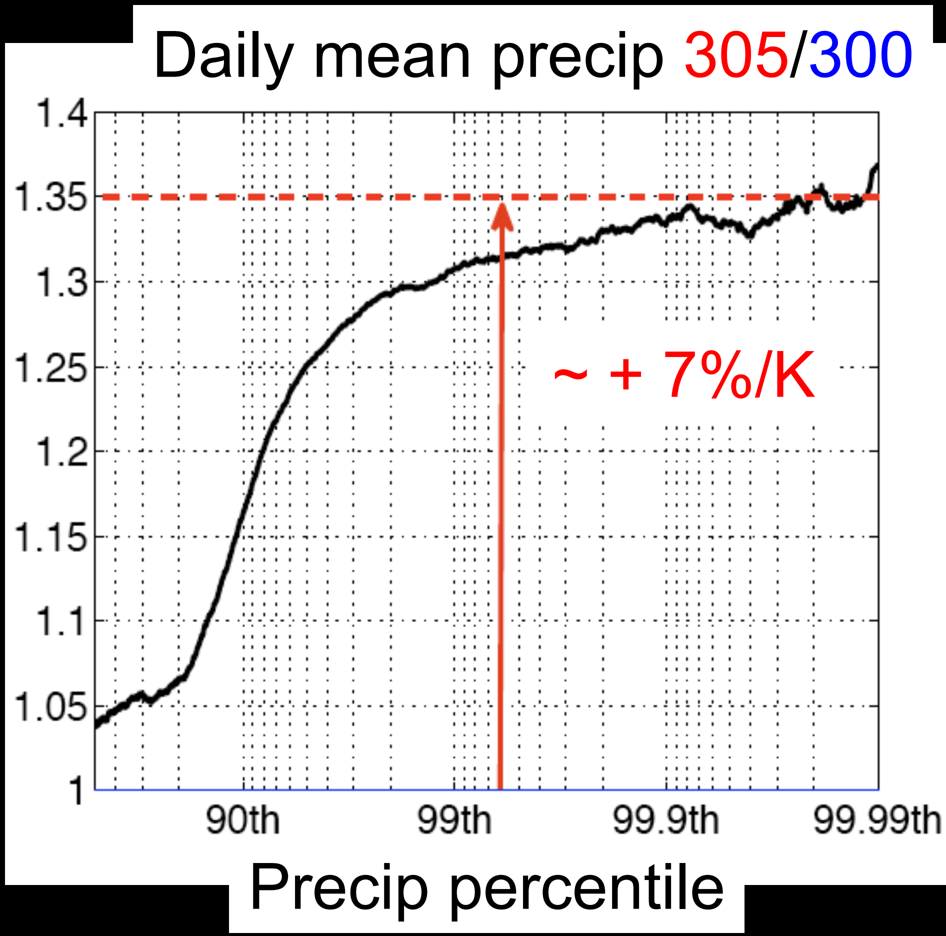
Extremes of precipitation

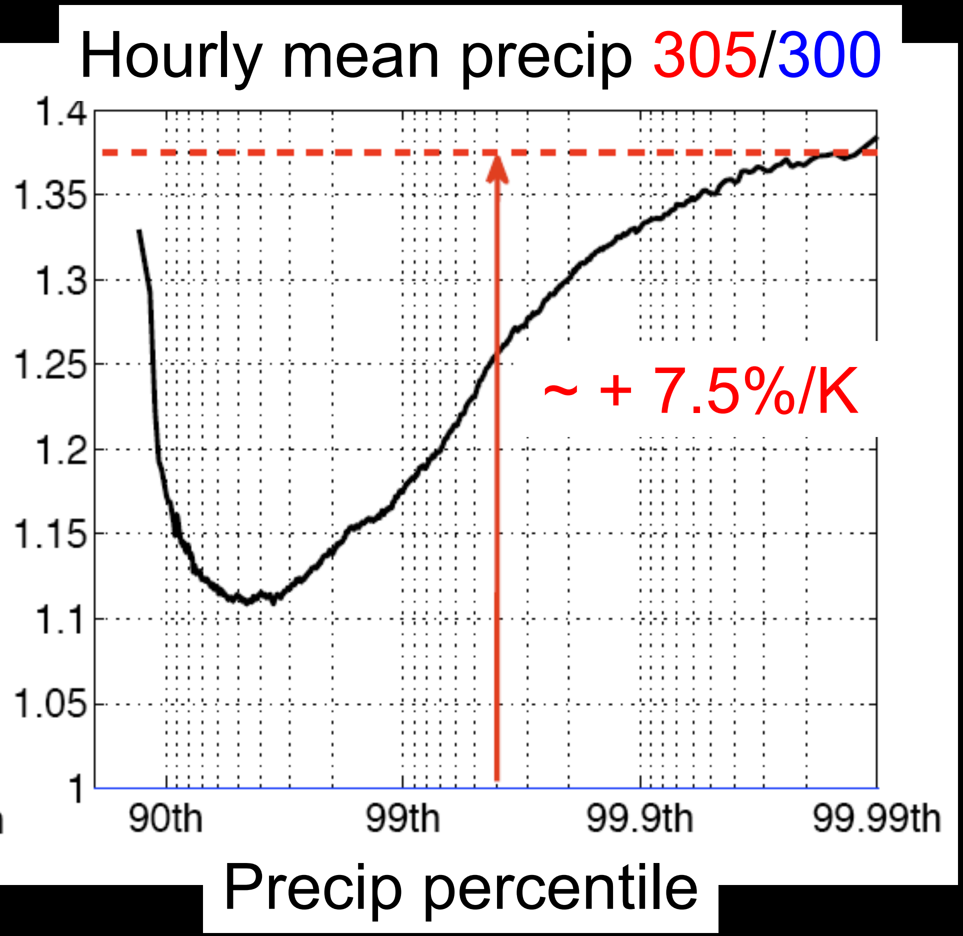




95th percentile = { 1.7×10^1 mm/day, 2.1×10^1 mm/day } ⇔ 23 % increase

Extremes of precipitation





Scaling for precipitation extremes

Dry static energy budget (neglect Qrad small compared to L_vP when precip strong)

$$\int \frac{Ds}{Dt}\bar{\rho}dz = L_v \int \frac{Dq_l}{Dt}\bar{\rho}dz + L_s \int \frac{Dq_s}{Dt}\bar{\rho}dz + L_v P$$

$$s = c_p T + gz, \quad q_l \text{ and } q_s = \text{condensates}$$

hydrostatic   moist adiabat

+ approx: $\frac{Ds}{Dt} \approx w\frac{\partial s}{\partial z}$ and $ds = \frac{c_p T}{\theta} d\theta = -L_v dq_{sat}$

=> Main balance:

$$P \approx \int w \frac{-\partial q_{sat}}{\partial z}\bar{\rho}dz - \int \frac{D(L_v q_l + L_s q_s)}{L_v Dt}\bar{\rho}dz$$

$$\approx \epsilon_p \int w \frac{-\partial q_{sat}}{\partial z}\bar{\rho}dz$$

Similar to earlier scalings *[Betts&Harshvardhan 87; O'Gorman&Schneider 09]*
with additional precip efficiency (net condensation lost as clouds)

Scaling for precipitation extremes

$$P \sim \epsilon_p \int w \frac{-\partial q_{sat}}{\partial z} \rho \, dz$$

Observed changes in precip efficiency are small =>

$$\delta P \sim \epsilon_p \, \delta \int w \frac{-\partial q_{sat}}{\partial z} \rho \, dz$$

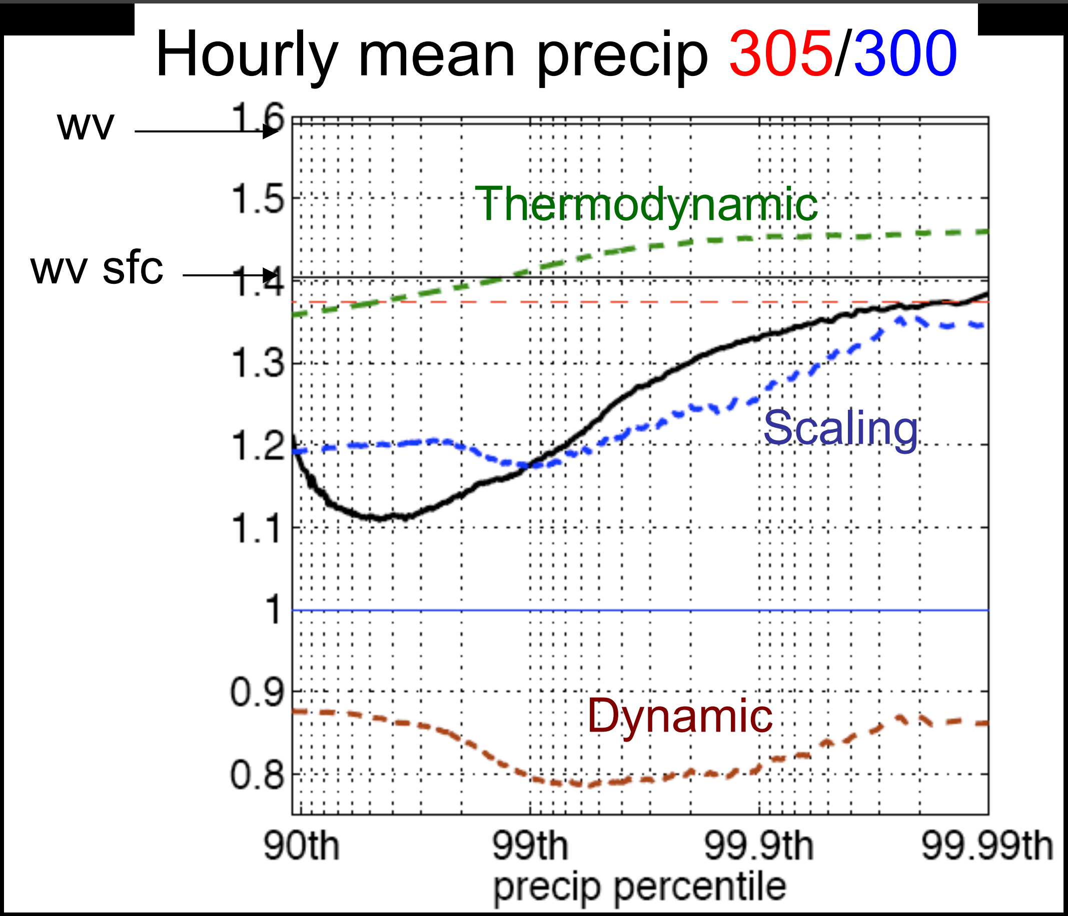
scaling

$$\sim \epsilon_p \int \delta(\rho w) \frac{-\partial q_{sat}}{\partial z} dz + \epsilon_p \int \rho w \, \delta\left(\frac{-\partial q_{sat}}{\partial z}\right) dz$$

Dynamic

Thermodynamic

Scaling for precipitation extremes



⇒Fairly good agreement of scaling, closer to wv sfc than wv

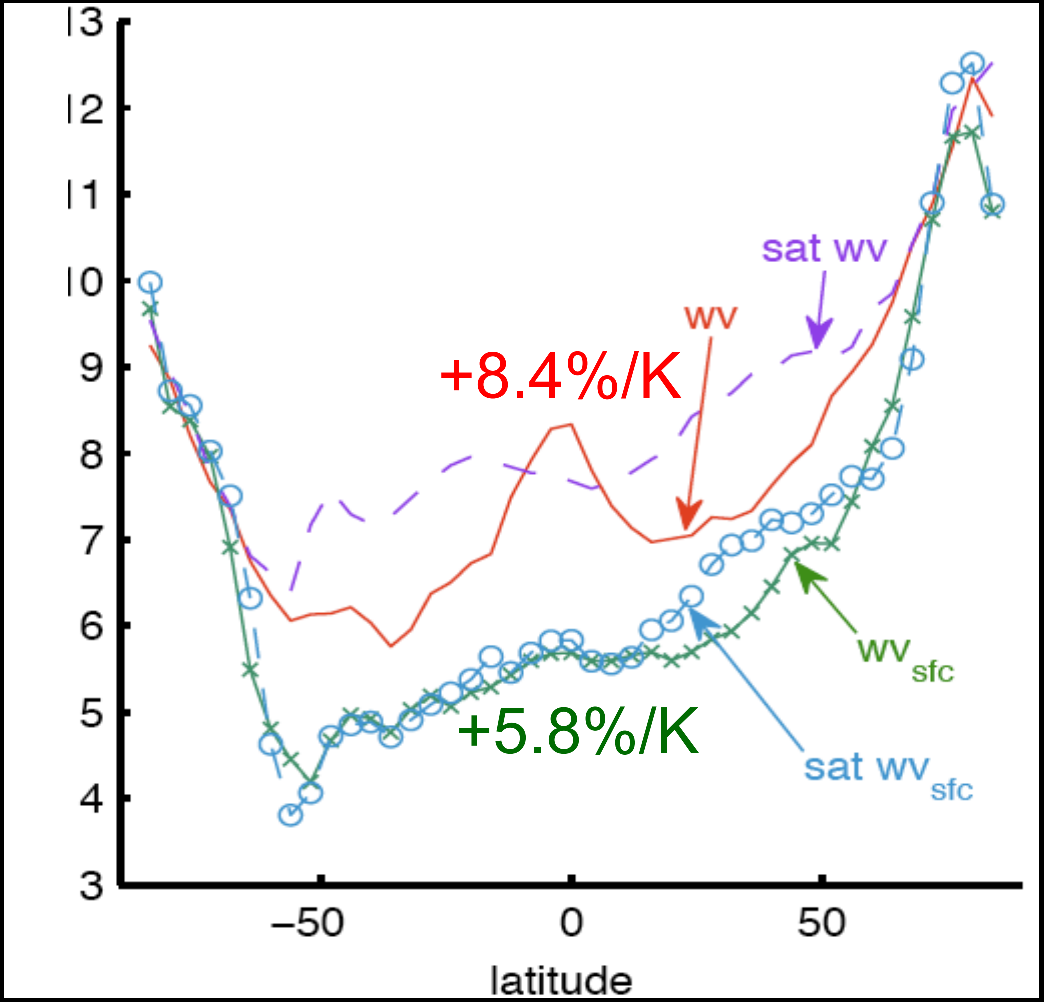
⇒To first order, thermodynamic

⇒Dynamics play 2ndary role, and tend to reduce P extremes

Scaling useful: relates changes in P extremes to mean fields

CC vs CCsfc

%/K



Precip extremes go up similar to sfc water vapor, less than column

Summary of results so far

- Shouldn't trust parameterized convection when looking at precip extremes

- We have looked at precip extremes in simulations with resolved convection

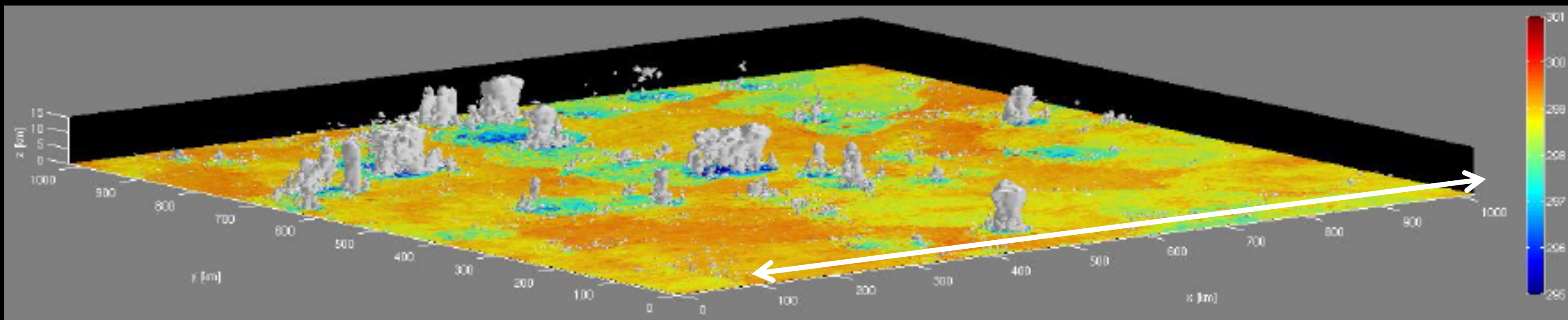
  Precip extremes go up similar to sfc water vapor, less than column

- To first order, captured by thermodynamics

- Dynamics play secondary role, and decrease precip rates

[Muller, O'Gorman, Back, J. Clim. 11]

Consistent with other study



SAM, L=1024km, dx=4km, square doubly-periodic

[Muller, O'Gorman, Back, J. Clim. 11]

◆ DAM, L=25km, dx=200m, square doubly-periodic *[Romps, JAS 11]*

⇒Despite very different settings, same result:

Precip extremes go up similar to sfc water vapor (CCsfc), substantially less than column water vapor (CC)

What happens when convection is organized?

Part 1 : disorganized « pop corn » convection

Part 2 : impact of convective organization

⇒ Convective organization could yield extremes amplification > CC because vertical velocities also increase with warming ?

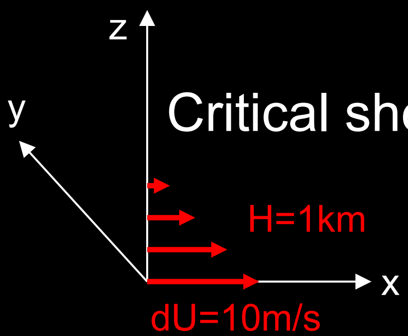
[Singleton&Toumi QJRMS 12]

Impact of convective organization on precip extremes amplification with warming?

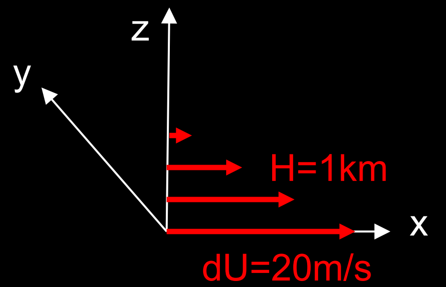
Squall lines (use vertical shear to organize the convection into arcs)

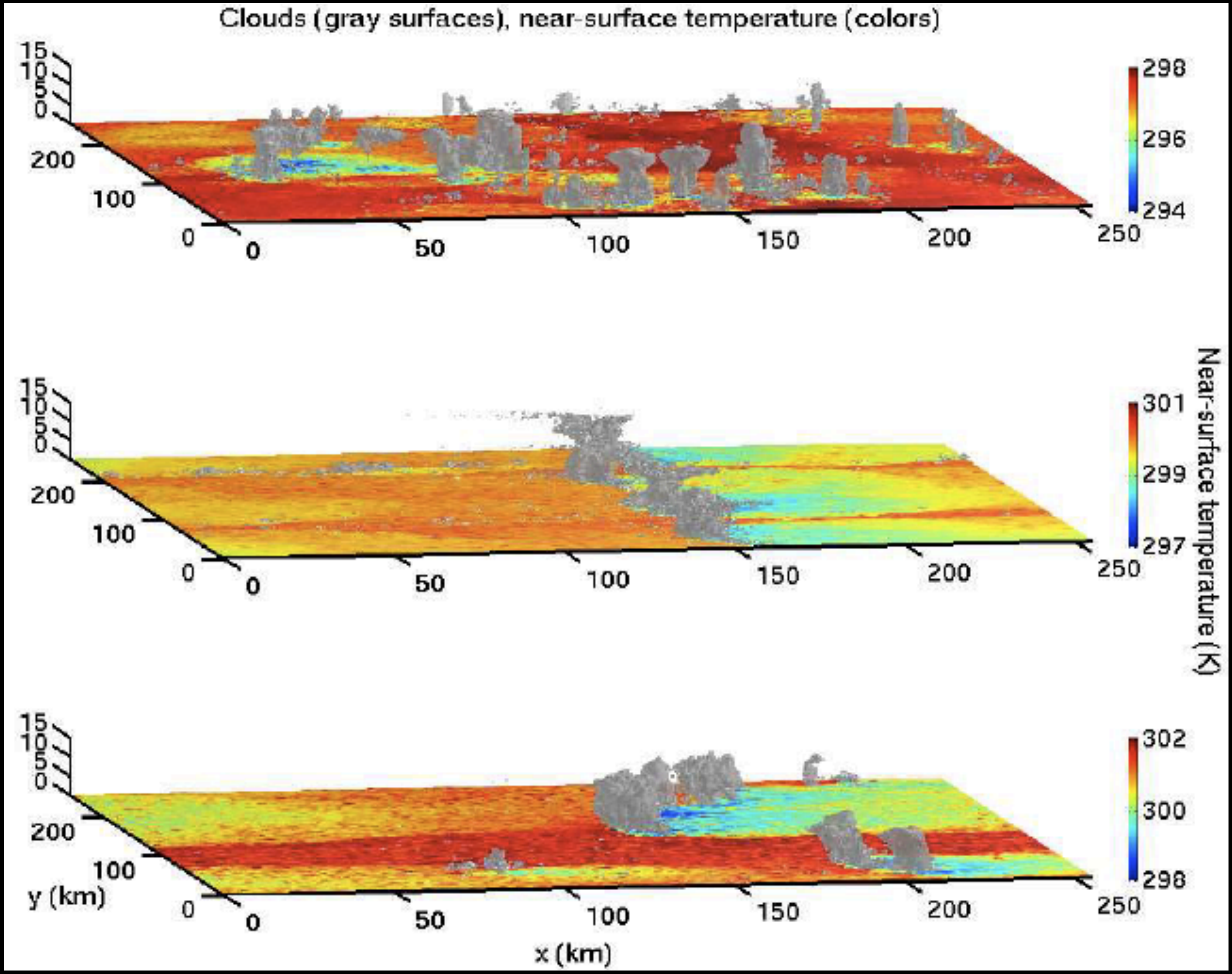
No shear:

Critical shear:



Supercritical shear:



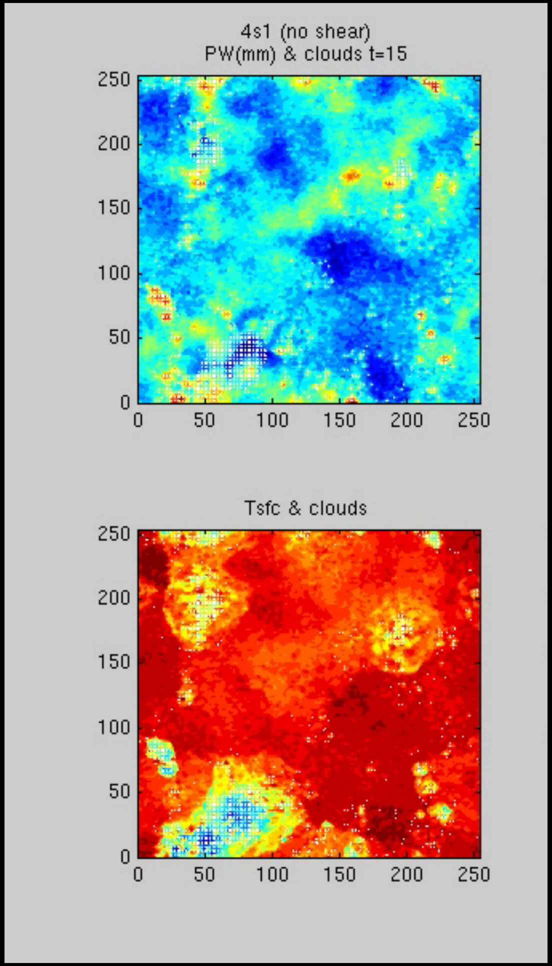


No shear

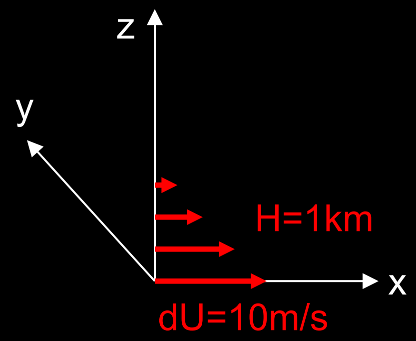
Top view

Color: PW

Color: Tsfc



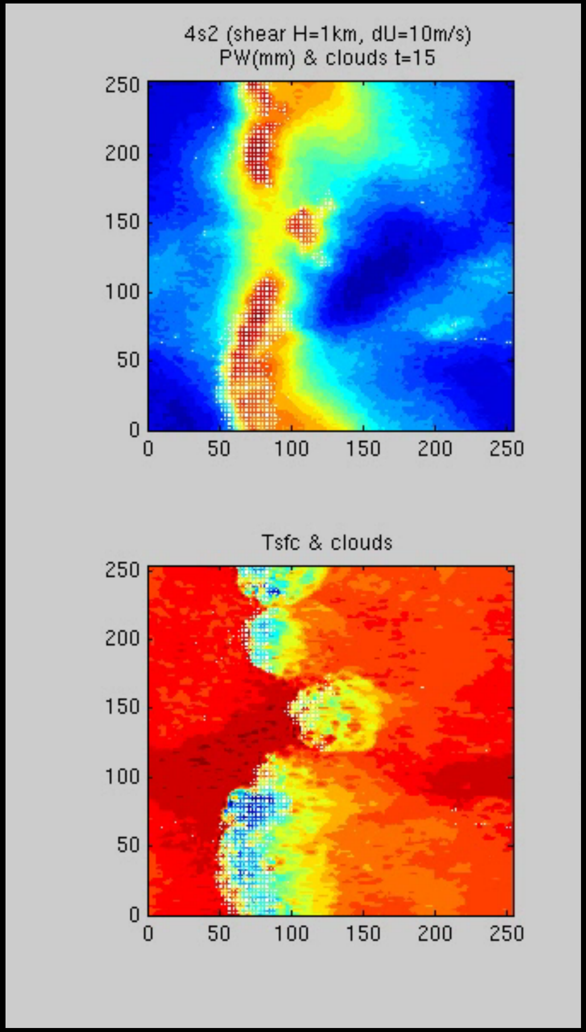
Critical shear



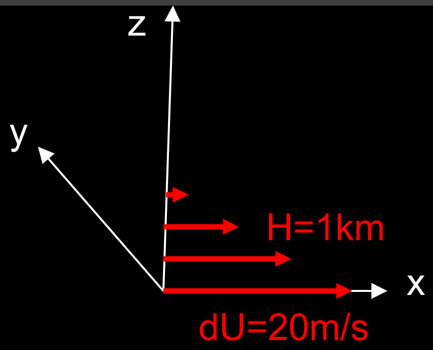
Top view

Color: PW

Color: Tsfc



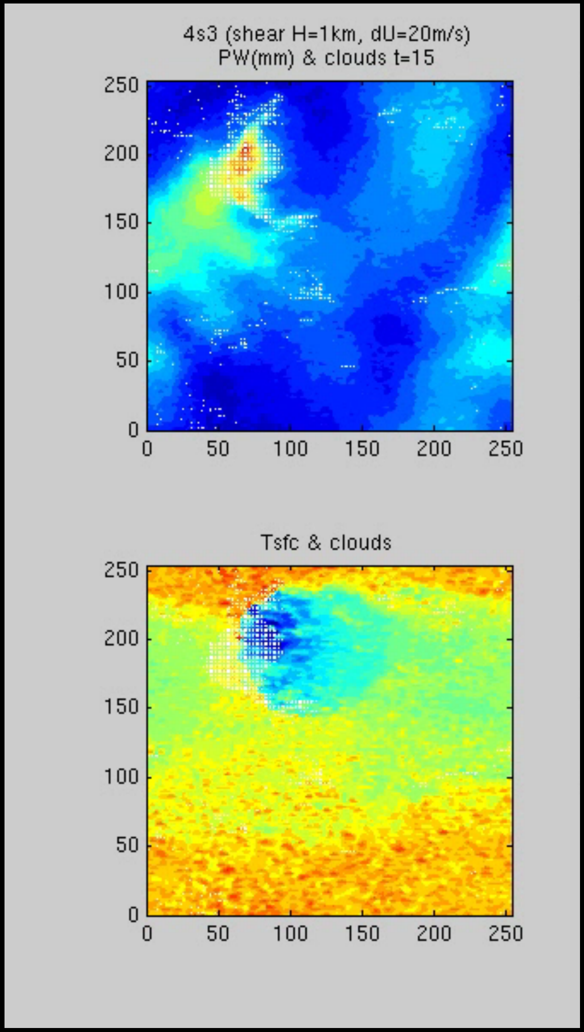
Supercritical shear



Top view

Color: PW

Color: Tsfc



Questions

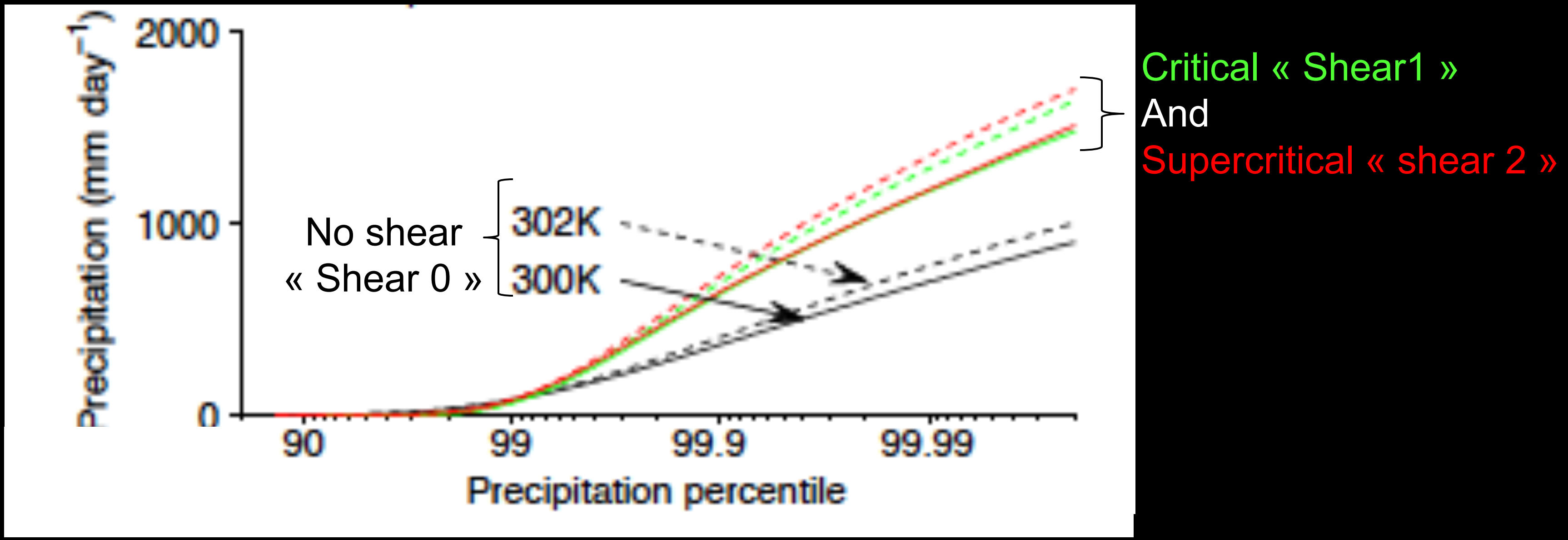
- Without convective organization, warming => amplification of precipitation extremes ~ CCsfc $<$ CC

  Still true in organized convection ?

- Is the response of precipitation extremes to warming monotonic in the strength of the background vertical shear?

- What are the thermodynamic and dynamic contributions to changes in precipitation extremes with warming? Can it help explain the sensitivity to shear?

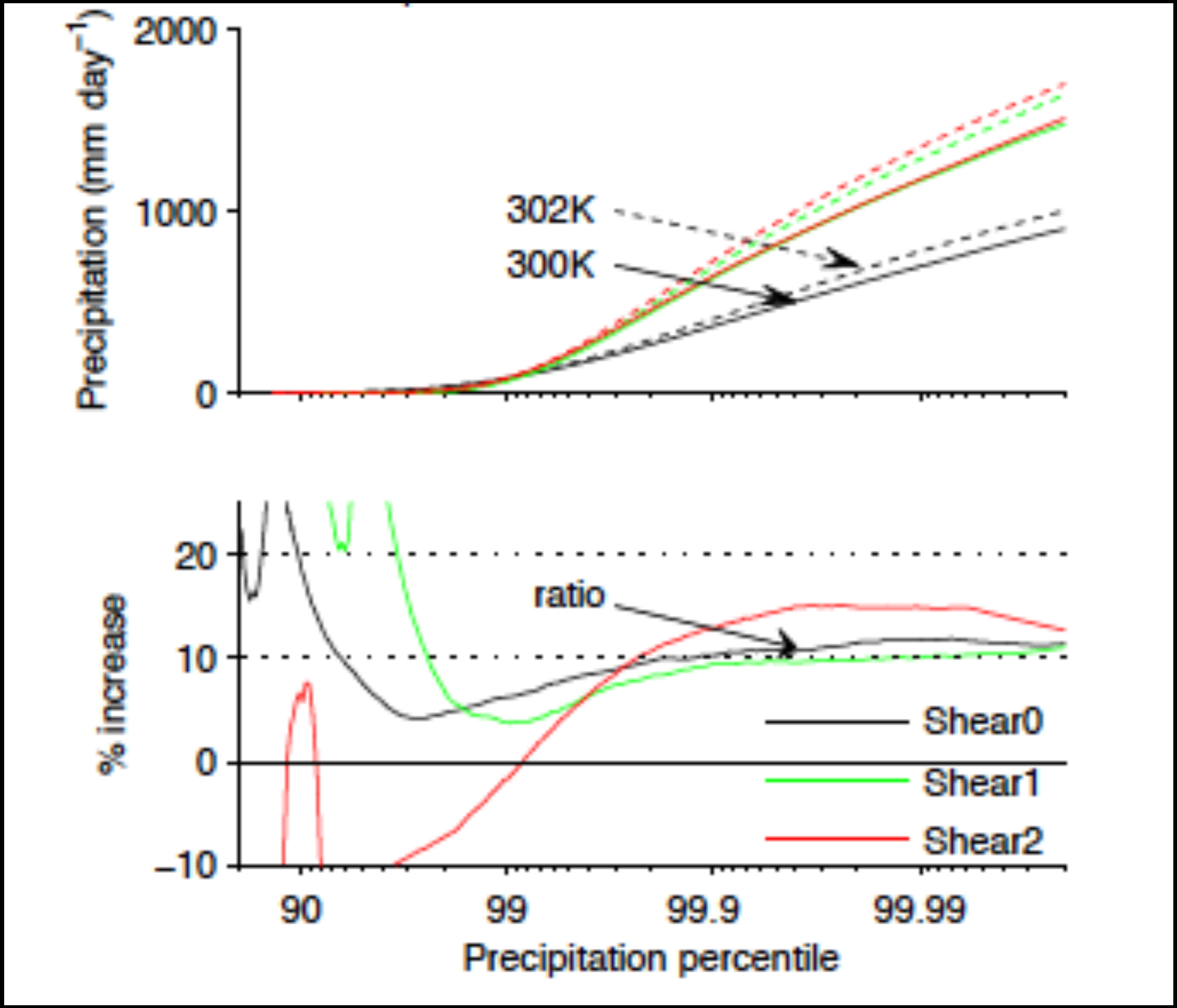
Extremes of precipitation



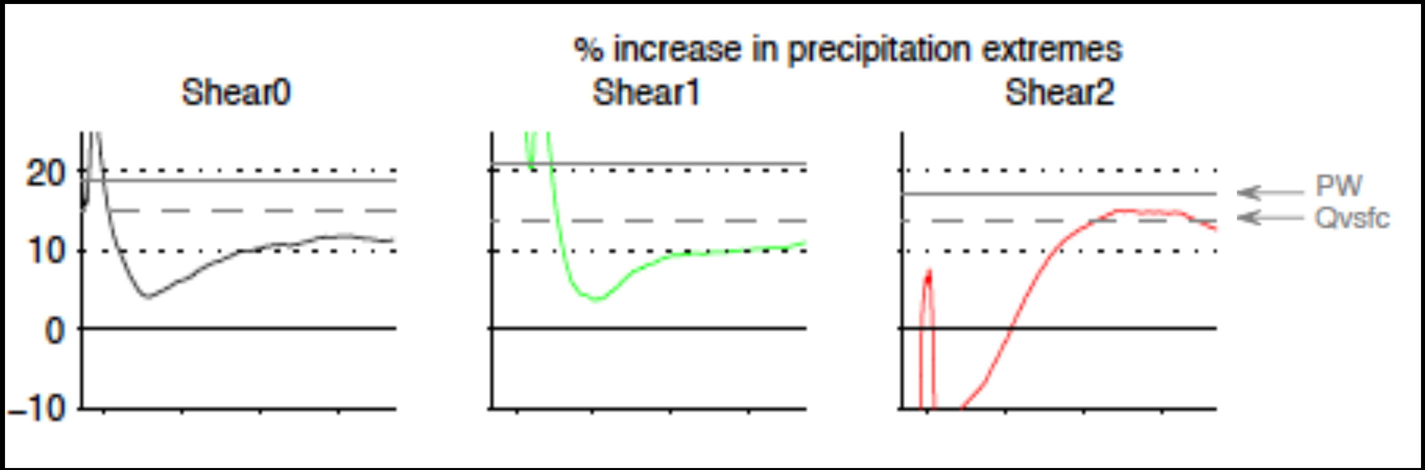
=> Precip extremes increase with warming

=> Stronger with shear but crit or supercrit has little impact

Extremes of precipitation



Extremes of precipitation vs CC and CCsfc

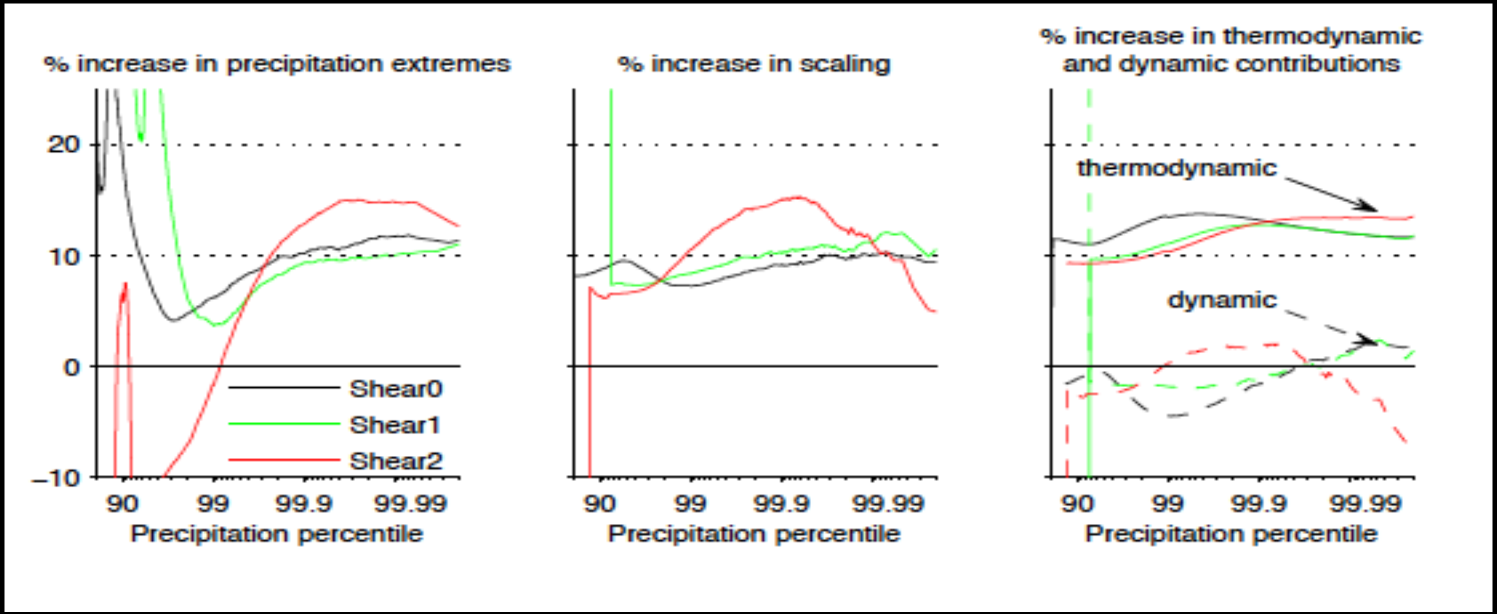


⇒ALL << CC, and closer to CCsfc in all cases

⇒Despite very different org, no shear or crit shear similar, with precip extremes increase smaller than CCsfc

⇒Supercrit shear yields stronger increase, similar to CCsfc

Extremes of precipitation vs scaling



⇒ good agreement

Magnitude of precip extremes changes same for all shears and is given by thermo ~ CCsfc

Difference between shears due to dynamics, which weaken precip extremes for no shear/critical shear, and strenghthen them for supercritical shear

=> How does that relate to CCsfc?

Approx scaling for precip extremes – relationship to water vapor

If changes in rel. hum. small ($dq_{sat} \sim dq_v$)
Then

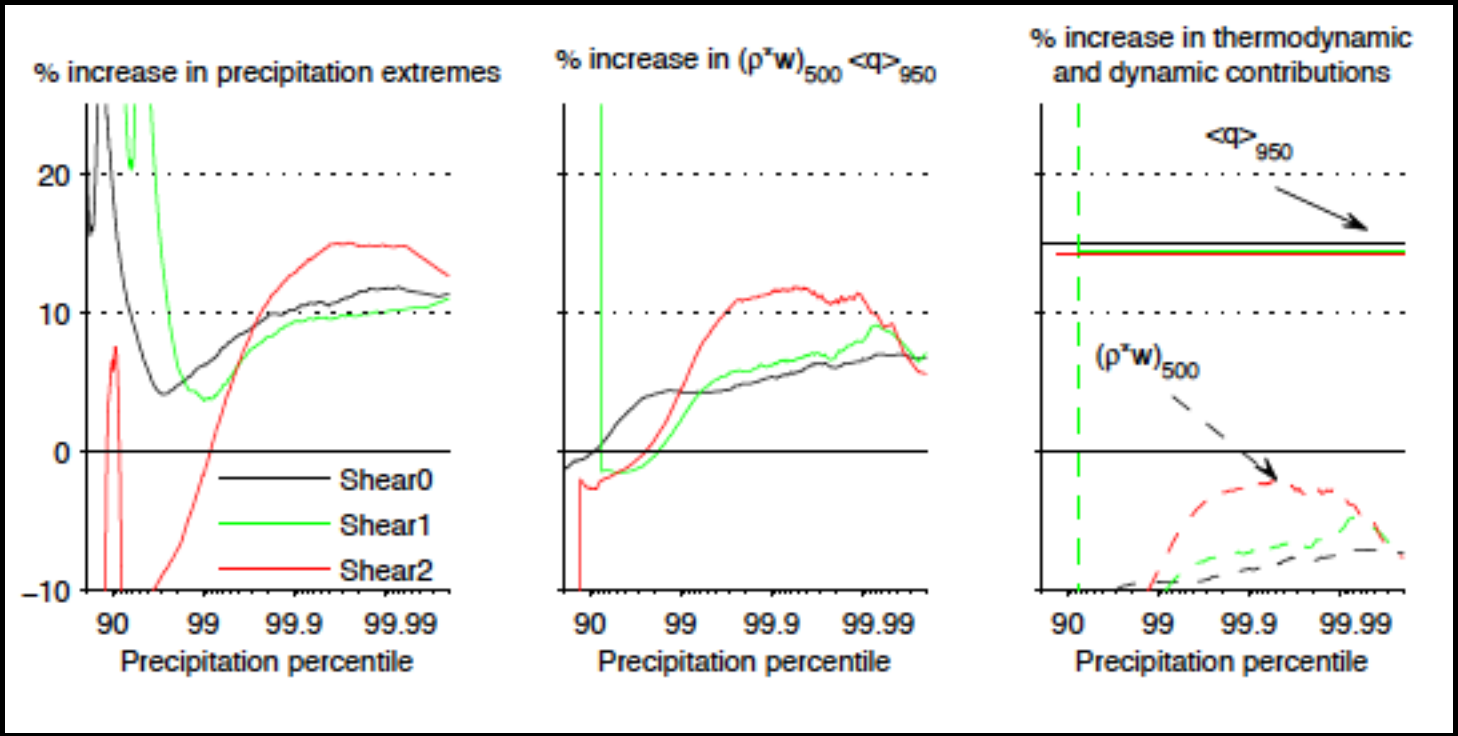
$$\delta P \sim \varepsilon_p \; \delta \int w \frac{-\partial q_v}{\partial z} \rho \, dz$$

If further assume that representative value of mass flux is its value at 500hPa, then

$$\int \bar{\rho} w \left(- \frac{\partial < q_v >}{\partial z} \right) \sim (\bar{\rho} w)_{500} \int - \frac{\partial < q_v >}{\partial z} = (\bar{\rho} w)_{500} < q_v >_{BL}$$

=> $$P_e \sim (\bar{\rho} w)_{500} < q_v >_{BL}$$

Extremes of precipitation vs approx scaling



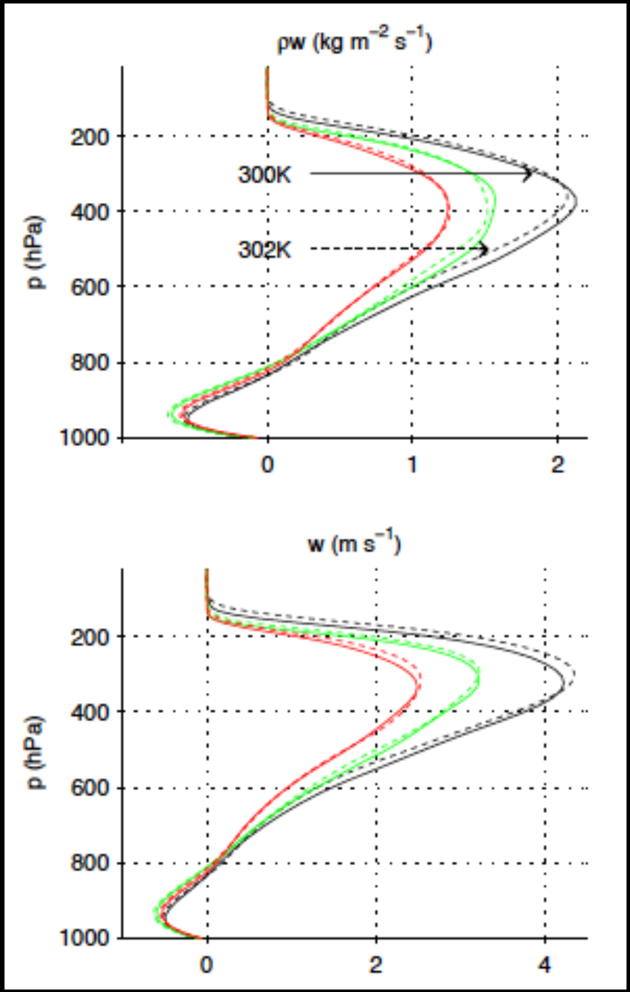
Agreement is not as good, but still captures the different behaviours for different shears.

To leading order, precip extremes increase follows BL water vapor

Dynamics play a secondary role and explain differences between shears

Note on dynamics

mass flux and w at 99.95th precip percentile



⇒Convective mass fluxes decrease DESPITE increase in vertical velocities. Former more relevant for precip extremes.

Results from cloud-resolving model

- Precip extremes go up similar to CCsfc, substantially less than CC, even in organized convection.

- Despite very different organizations, amplification of precip extremes without shear and with critical shear surprisingly similar, rate of increase slightly smaller than CCsfc.

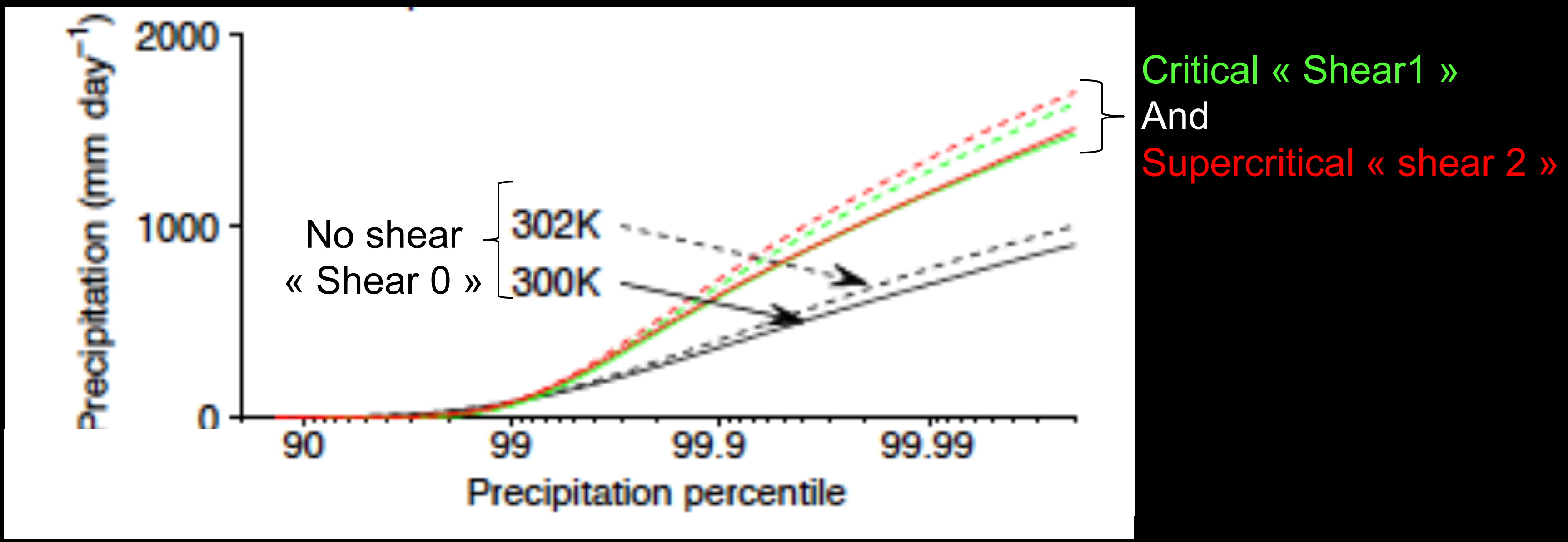
  The dependence on shear non-monotonic : extremes more sensitive to supercritical shear, rates slightly larger than CCsfc.

- For all shears, the magnitude of precip extremes changes related to thermodynamics, close to CCsfc

  dynamics play secondary role, differ for different shears. Caused by different responses of convective mass fluxes in individual updrafts.

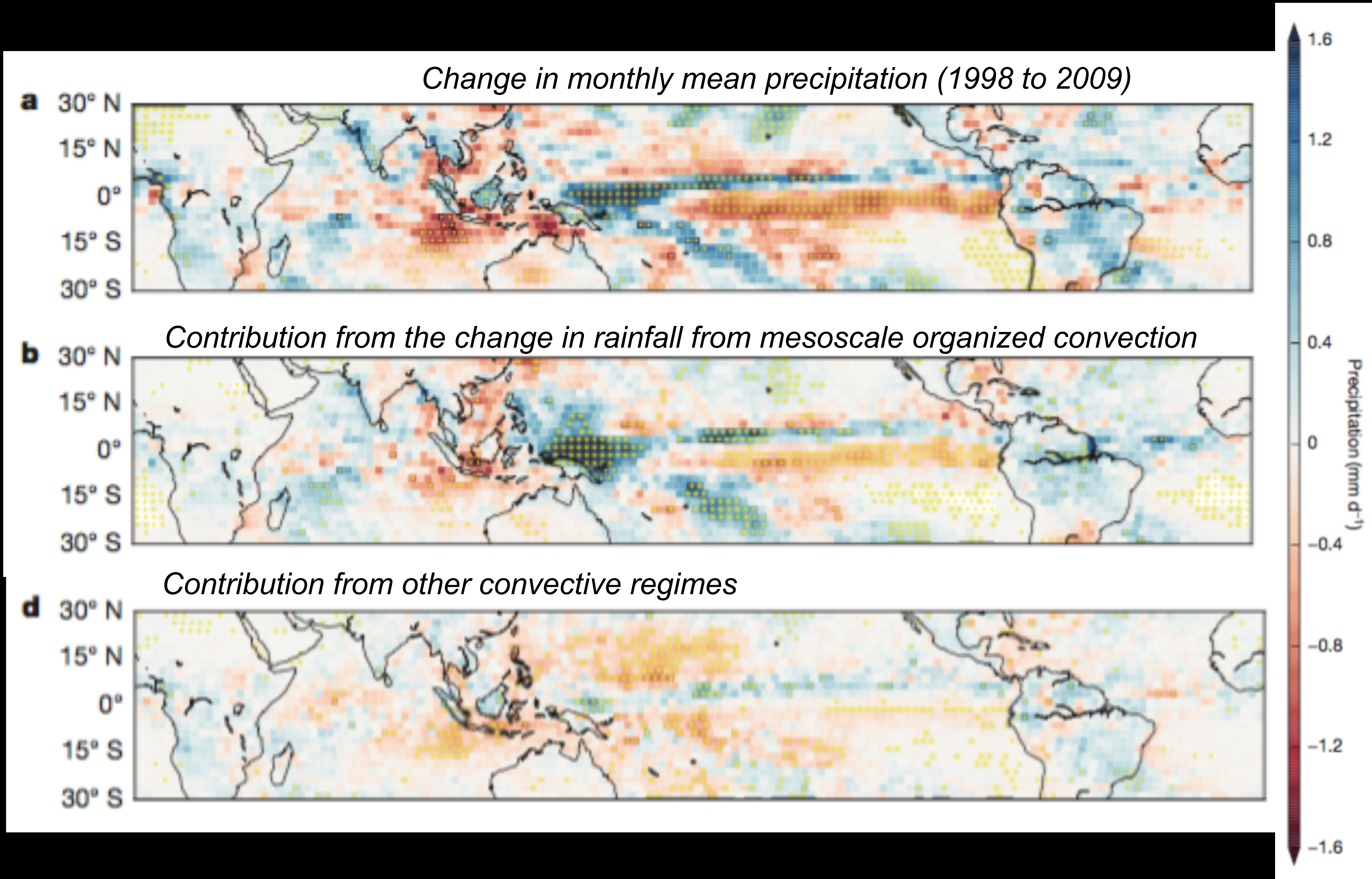
[Muller, J Clim 13]

Note: possible large uncertainty in tropical precipitation estimates from changes in organization…



If organization changes with warming, large change in precip extremes !

Recent trends in tropical precipitation linked to organization



Tan et al, Nature 2015

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Cloud fundamentals - global distribution, types, visualization and link with large scale circulation

Cloud Formation and Physics - thermodynamics, cloud formation, instability, life cycle of an individual cloud

Organization of deep convection at mesoscales - MCSs, MCCs, Squall lines, Tropical cyclones, Processes, Self-aggregation

Response of the hydrological cycle to climate change - mean precip, precip extremes

Clouds in a changing climate – climate sensitivity, cloud effect, cloud feedback, FAT

With thanks to Sandrine Bony

Clouds in a changing climate

OUTLINE

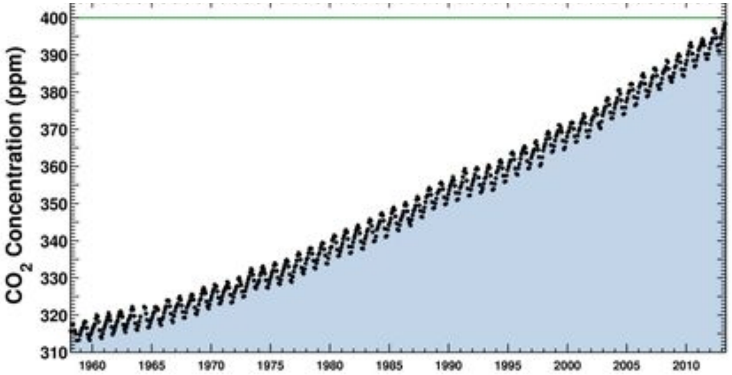
- Climate sensitivity
- Quantifying climate feedbacks
- Cloud feedback processes

Climate sensitivity

Clouds in a ***changing climate***

Mauna Loa Observatory

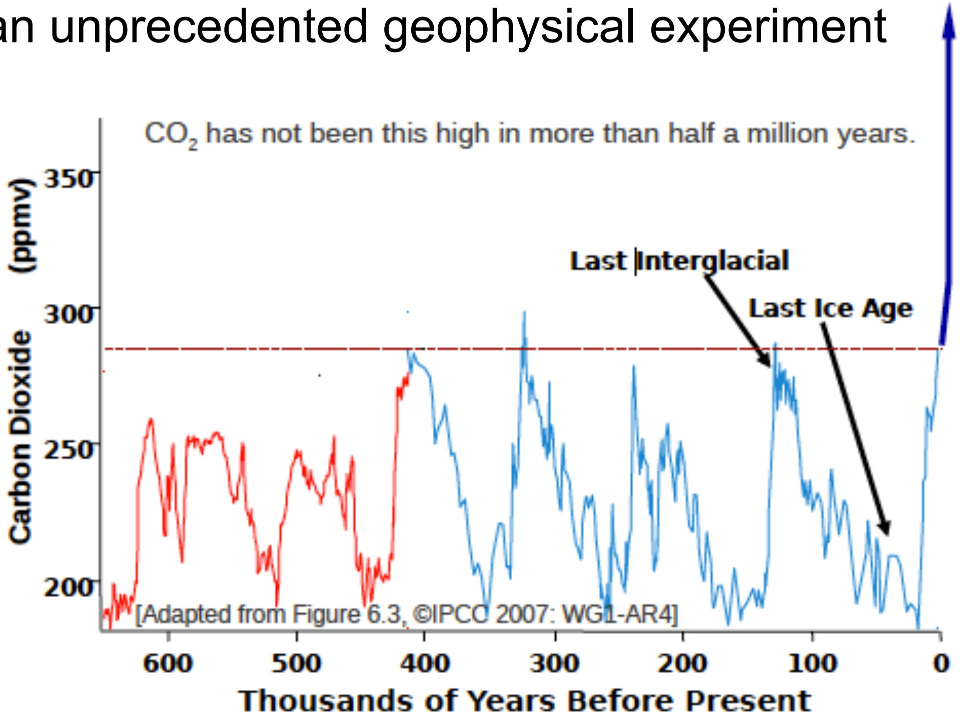
CO2 concentrations at Mauna Loa



1960 2013

2013:
400ppm

Humanity is running an unprecedented geophysical experiment



Climate sensitivity

Climate sensitivity: equilibrium change in global mean surface temperature ΔT_s when atmospheric CO_2 is doubled.

An Early Assessment of Long-Term Climate Change : The "Charney Report" (1979)

Carbon Dioxide and Climate:
A Scientific Assessment

Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23-27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

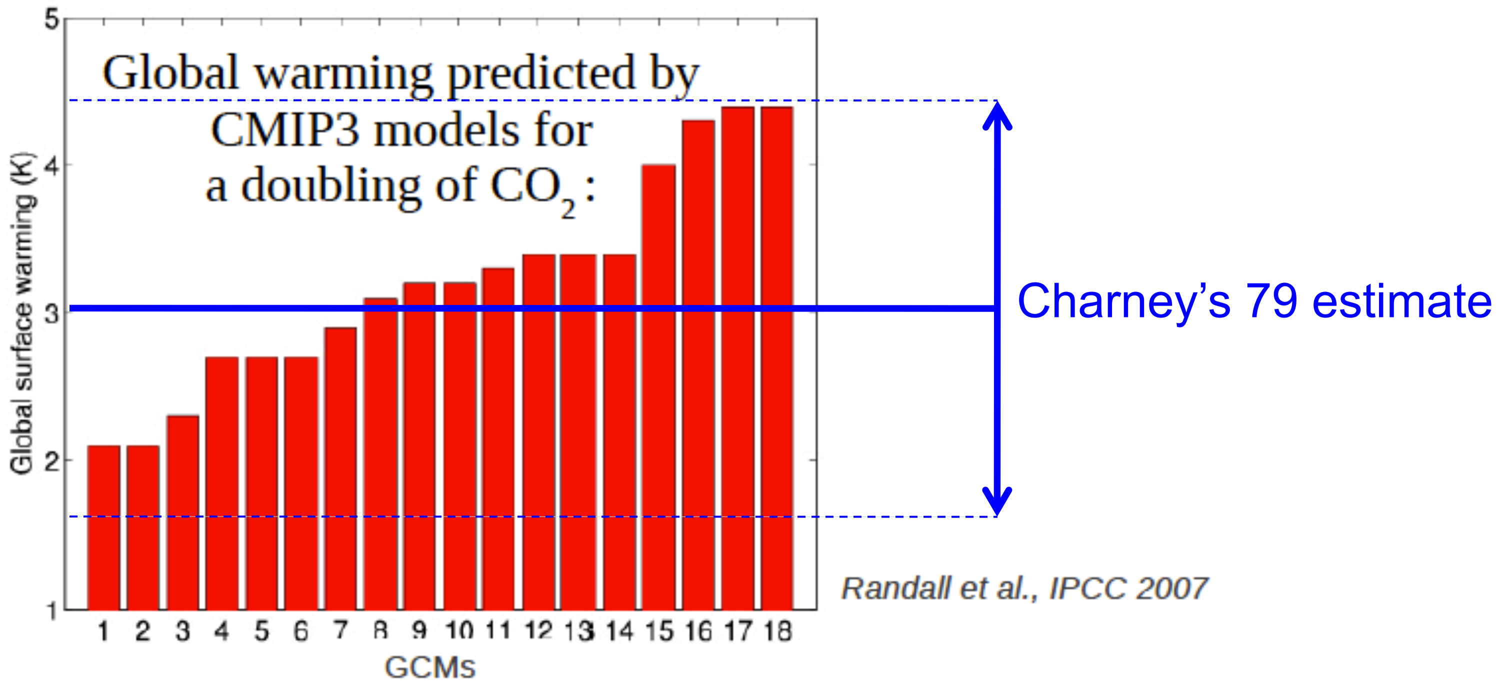
Jule Charney
(1917-1981)

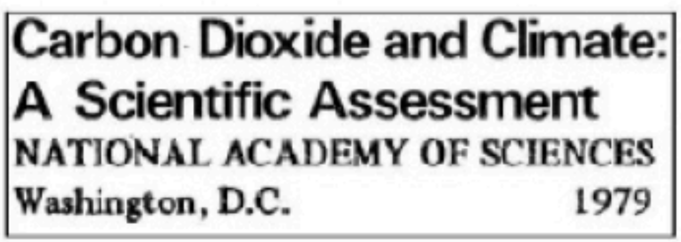
- climate sensitivity estimate :
  range 1.5 – 4.5 K ; likely value : 3 K

- key uncertainties include :
  cloud feedbacks
  role of the ocean in carbon and heat uptake
  regional precipitation changes

ECS estimate from Manabe & Wetherhald

Climate sensitivity





Carbon Dioxide and Climate:
A Scientific Assessment
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

AR5

1990 1995 2001 2007 2013

Climate sensitivity

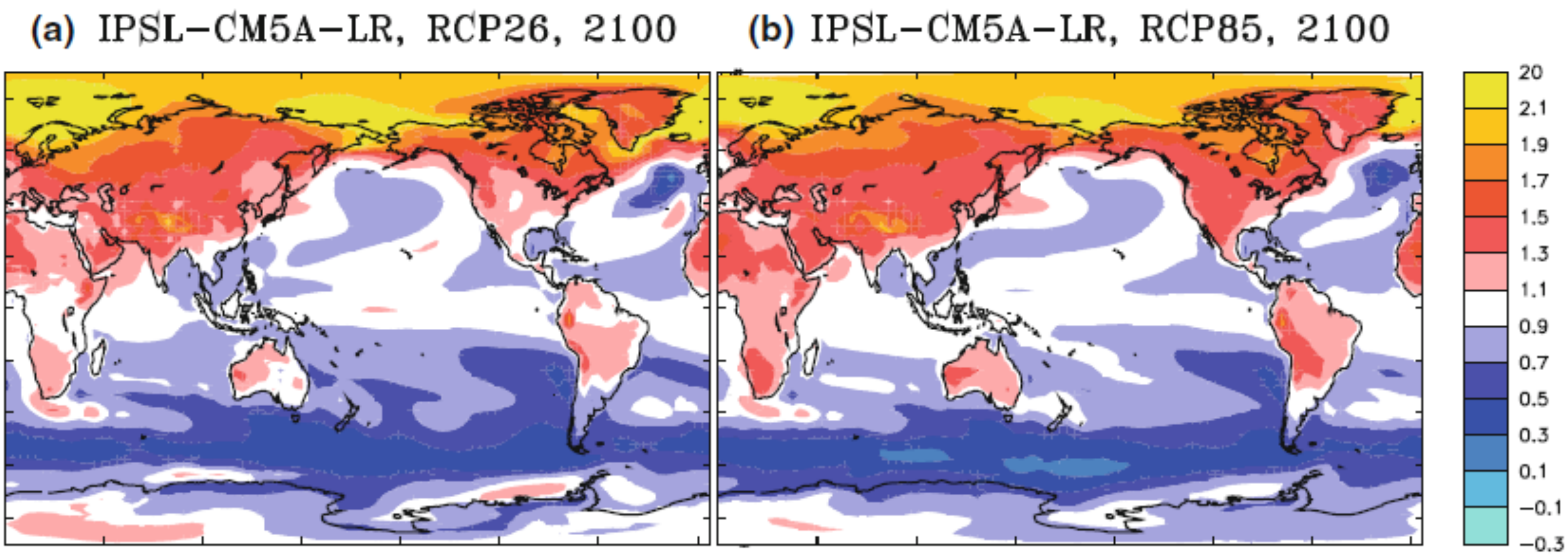
Why do we care so much about global ΔT_s ?

- For many models, as a first approximation :

  $$\Delta X(\text{space,time}) = \text{global } \Delta T_s(\text{time}) \text{ x pattern(space)}$$

- Global ΔT_s : a scaling factor for many global and regional climate responses
- Maybe it works in the real world too (at least to some extent)

Change in temperature normalized by global ΔT_s (K/K)

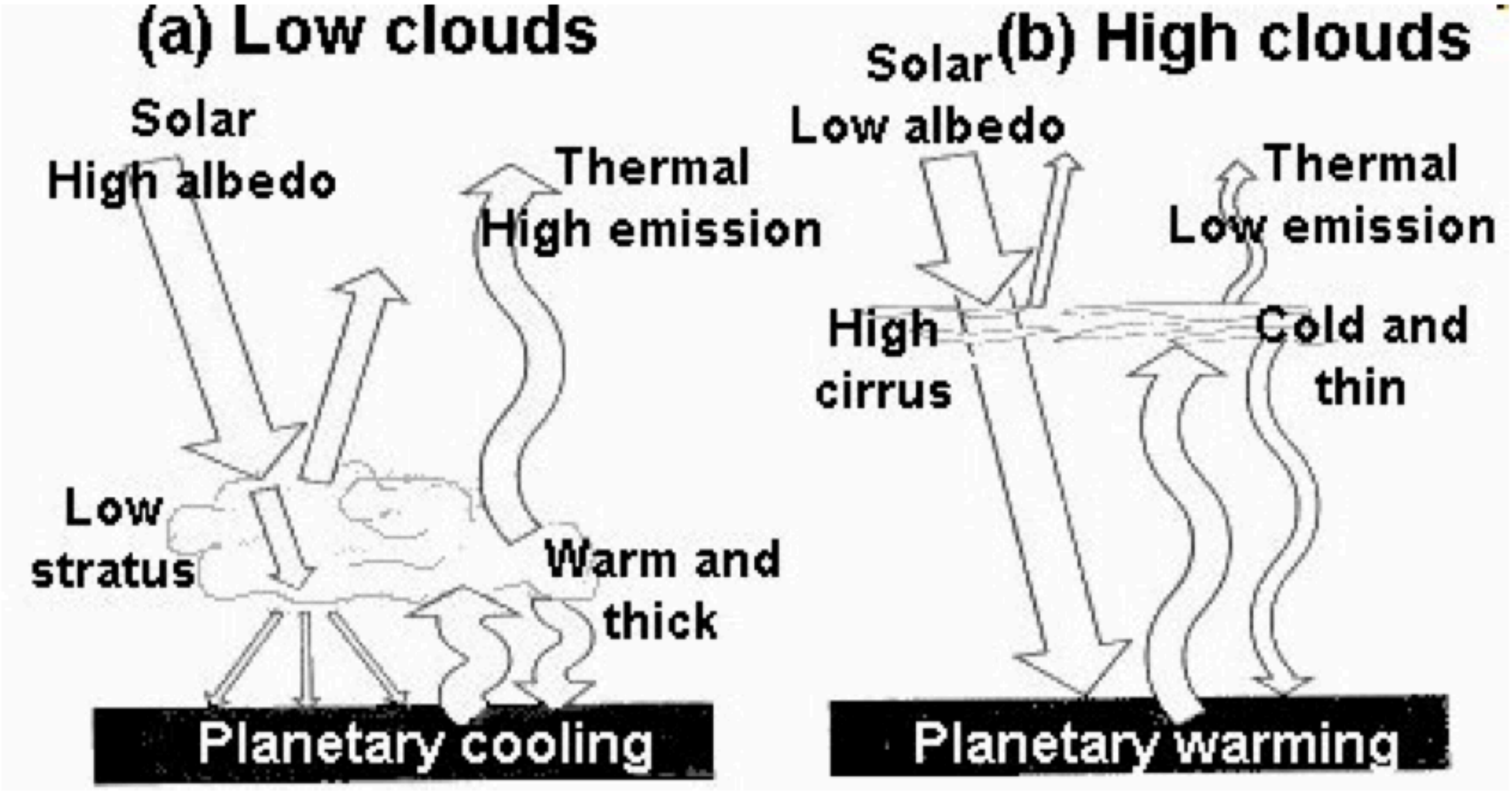


Clouds in a changing climate

OUTLINE

- Climate sensitivity
- Quantifying climate feedbacks
- Cloud feedback processes

Clouds and radiation



More low clouds:

Little LW effect (~σT^4, T~Tsfc)

Strong SW cooling

More high clouds:

Strong LW warming (~σT^4, T<<Tsfc)

Little SW effect

Clouds and radiation

Cloud radiative effect: measure of cloud impact on earth energy budget (incoming radiation at TOA - *or tropopause*)

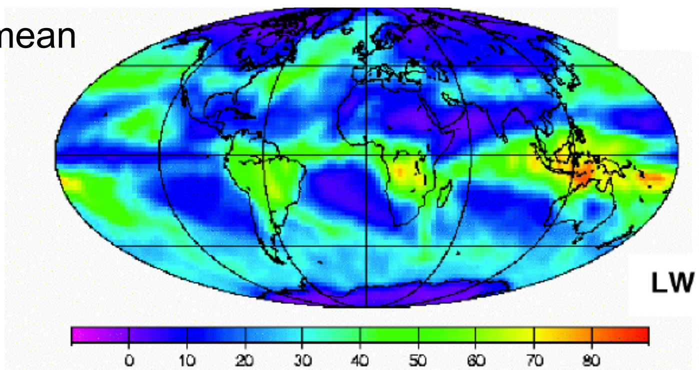
Difference between all- and clear-sky flux (> 0 ⇔ warming):

SW_{in} all sky – SW_{in} clear sky (< 0 due to low clouds cooling)

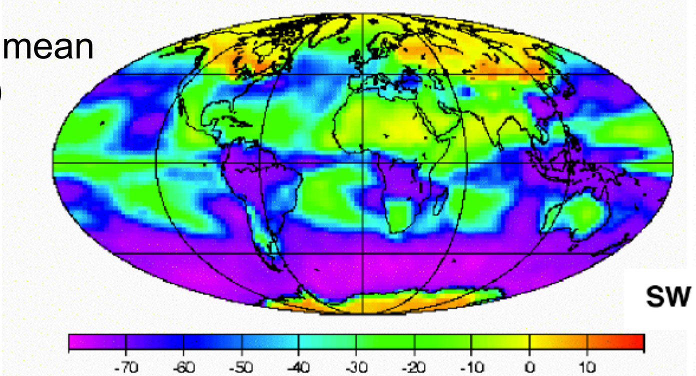
LW_{in} all sky – LW_{in} clear sky (> 0 due to high clouds warming)

Cloud radiative effects in present-day climate (maps for JFM):

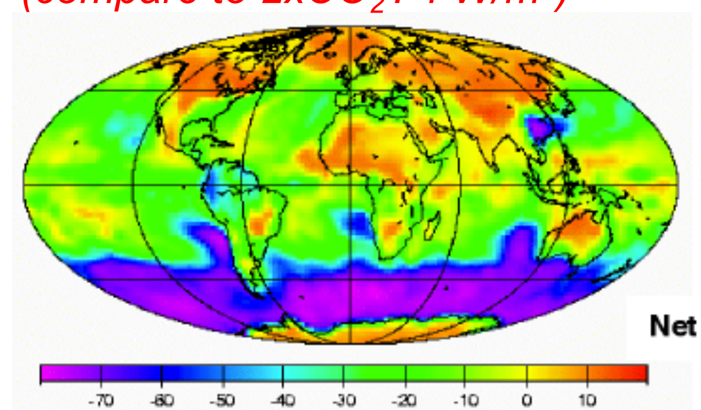
LW (annual mean ~ + 30W/m2)



SW (annual mean ~ - 50W/m2)



Net (annual mean ~ - 20W/m2)
(compare to $2xCO_2$: 4 W/m^2)



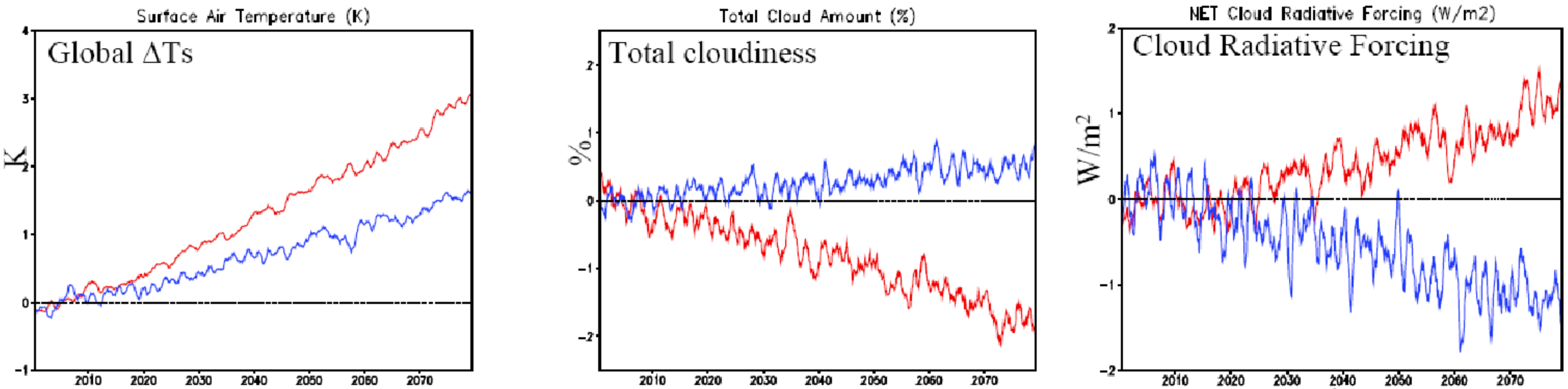
Clouds and radiation

Cloud radiative forcing: difference between all- and clear-sky flux changes providing a measure of the contribution of clouds to the climate sensitivity.

Net CRF = LW CRF + SW CRF
- < 0 : clouds oppose warming
- > 0 : clouds strengthen warming

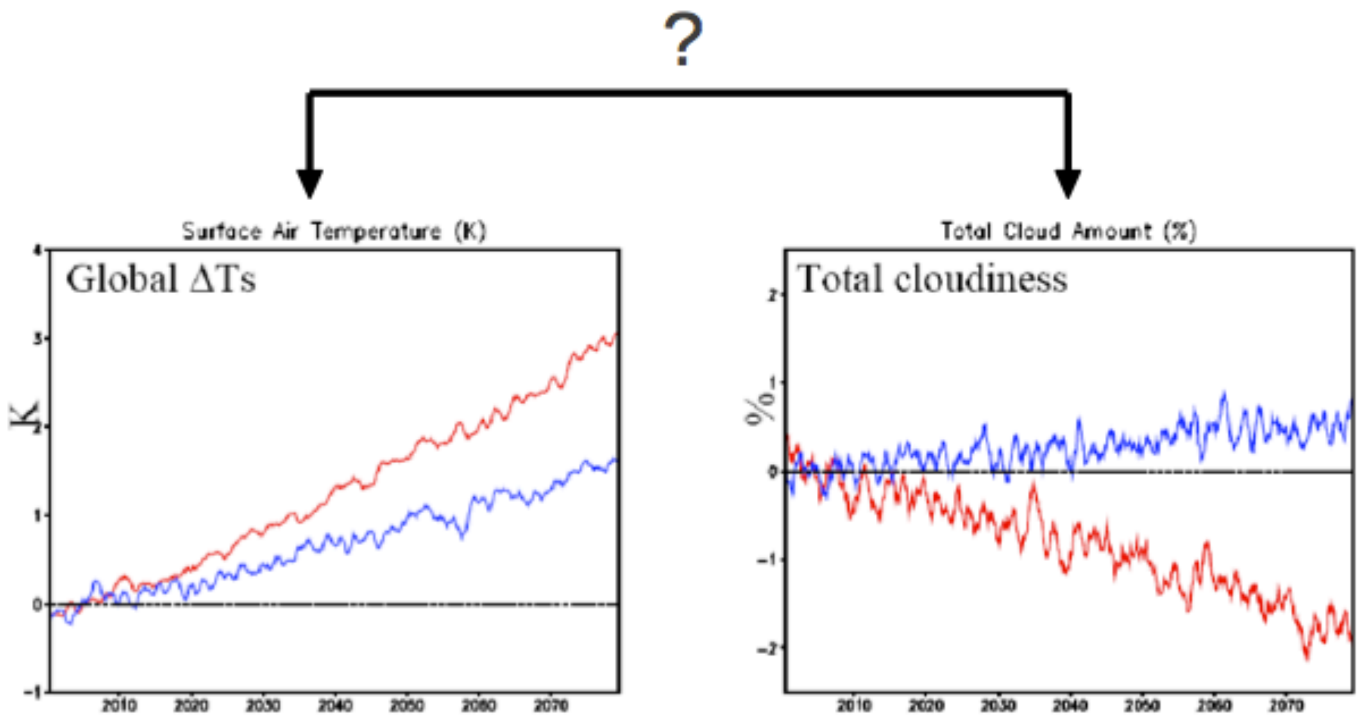
How will clouds respond to increased CO_2 ?
How will that feed back on climate ?

Results from 2 different climate models (+ 1% CO_2/yr) MIROC and NCAR



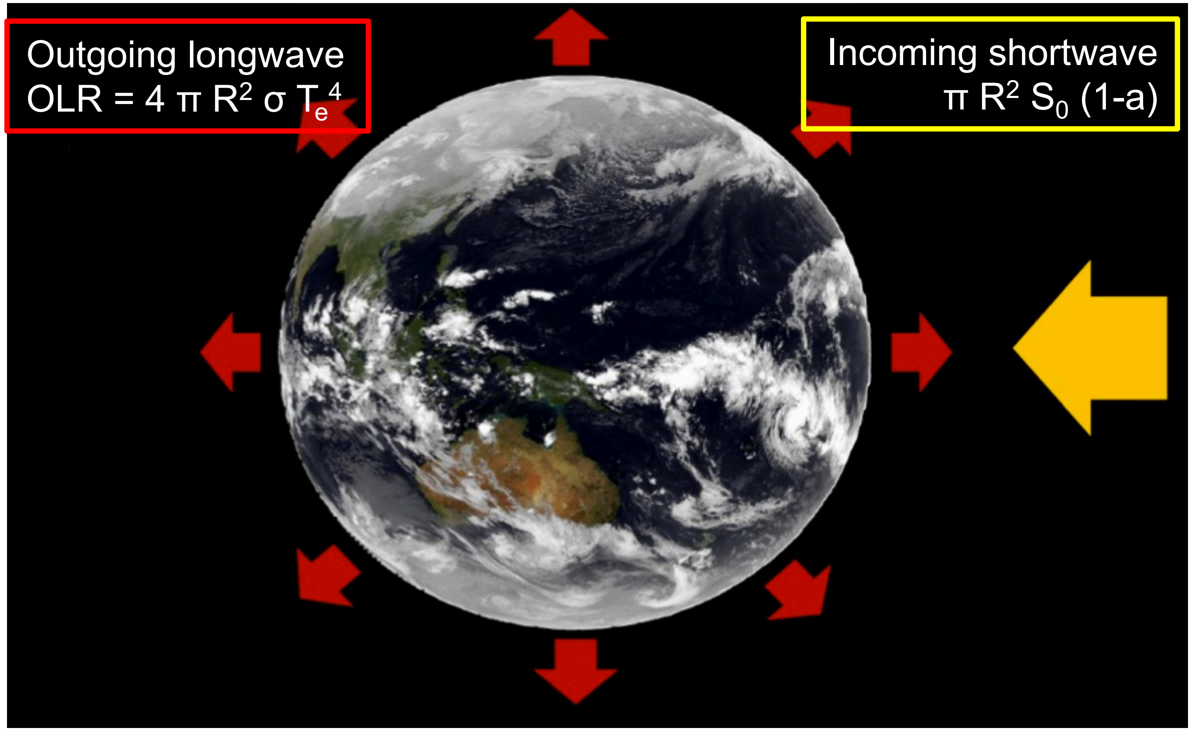
Quantifying Climate Feedbacks

Can we formalize the link between clouds and climate sensitivity?



Quantifying Climate Feedbacks

Earth TOA energy balance



a = albedo

Net incoming: $R = \frac{S_0(1-a)}{4} - OLR, \quad OLR = \sigma T_e^{\,4}$ At equilibrium: $R = 0$

Forcing $\Rightarrow \Delta R > 0$ At equilibrium: $\Delta R = 0$

Dependence of OLR on temperature constitutes the main restoring force towards Earth's energy balance

It has been found from model experiments that the radiative response is proportional to the global average surface air temperature change

Quantifying Climate Feedbacks

$$R = \frac{S_0(1-a)}{4} - OLR$$

Assume $OLR = f(CO_2, wv, cld\ldots)\ \sigma\, T_s^4$

Quantifying Climate Feedbacks

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If CO_2 abruptly increases => lower OLR => ΔR=F>0

Quantifying Climate Feedbacks

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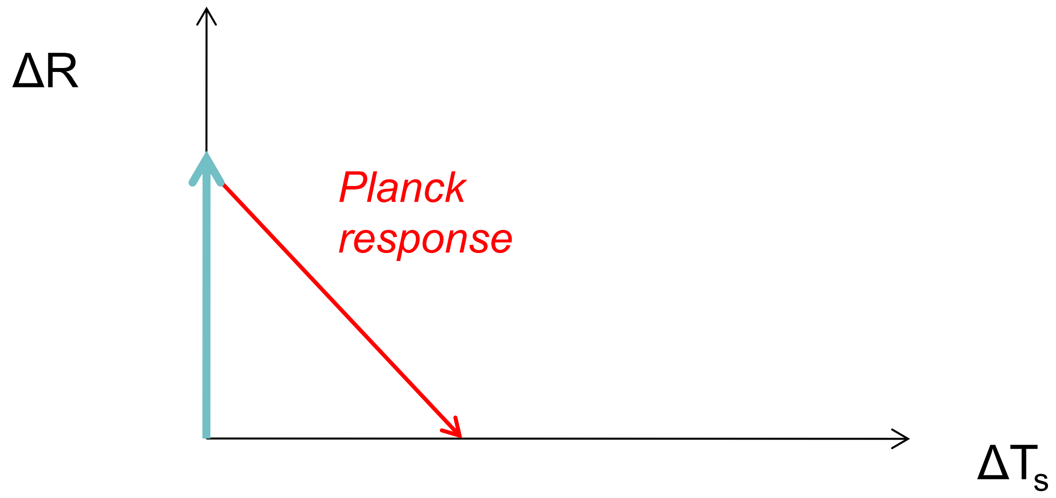
Assume $OLR = f(CO_2, wv, cld...)\ \sigma T_s^4$

If CO_2 abruptly increases => lower OLR => $\Delta R = F > 0$
If only T_s responds to the perturbation => $\Delta T_s > 0$ needed for $\Delta R = 0$



Quantifying Climate Feedbacks

$$R = \frac{S_0(1-a)}{4} - OLR$$

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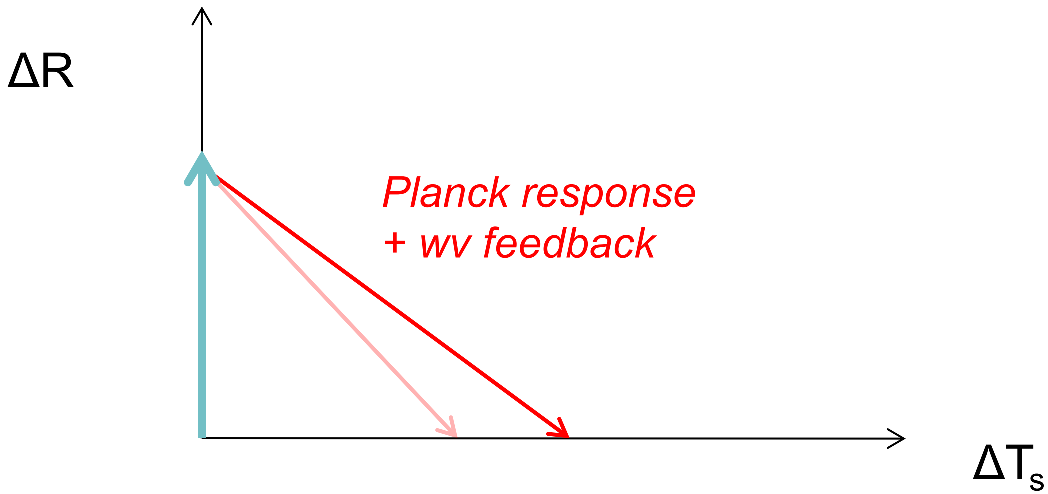
If only T_s responds to the perturbation => ΔT_s>0 needed for ΔR=0
Now if wv increases with T_s => even larger ΔT_s needed

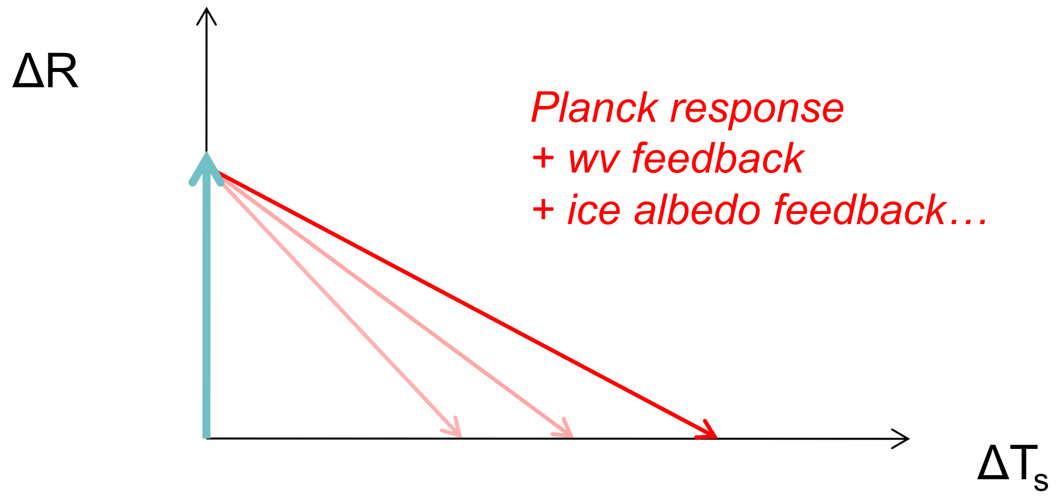


Quantifying Climate Feedbacks

$$R = \frac{S_0(1-a)}{4} - OLR$$

Assume $OLR = f(CO_2, wv, cld\ldots)\ \sigma T_s^4$

If CO_2 abruptly increases => lower OLR => $\Delta R = F > 0$
If only T_s responds to the perturbation => $\Delta T_s > 0$ needed for $\Delta R = 0$
Now if wv increases with T_s => even larger ΔT_s needed
And if a_{ice} decreases when T_s increases => even larger ΔT_s needed …



Quantifying Climate Feedbacks

Classical framework

Assume $R = R(CO_2, T_s)$

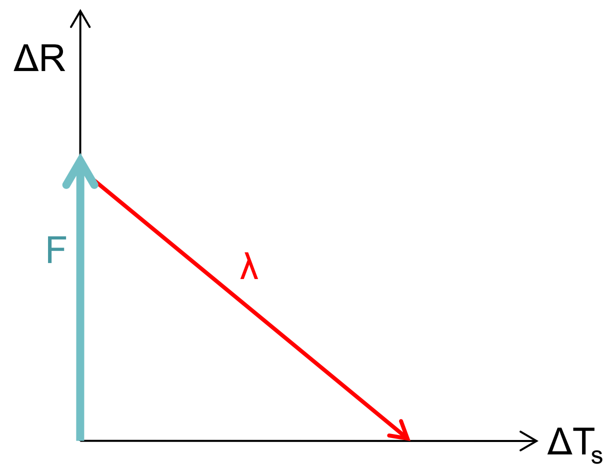
(can be generalized to any external perturbation f: $R = R(f, T_s)$)

$$\Delta R = \left(\frac{\partial R}{\partial CO_2}\right)_{Ts} \Delta CO_2 + \left(\frac{\partial R}{\partial T_s}\right)_{CO_2} \Delta T_s$$

$$\Delta R = F + \lambda \Delta T_s$$

Instantaneous radiative forcing due to increased CO_2 (W/m²)

Climate response



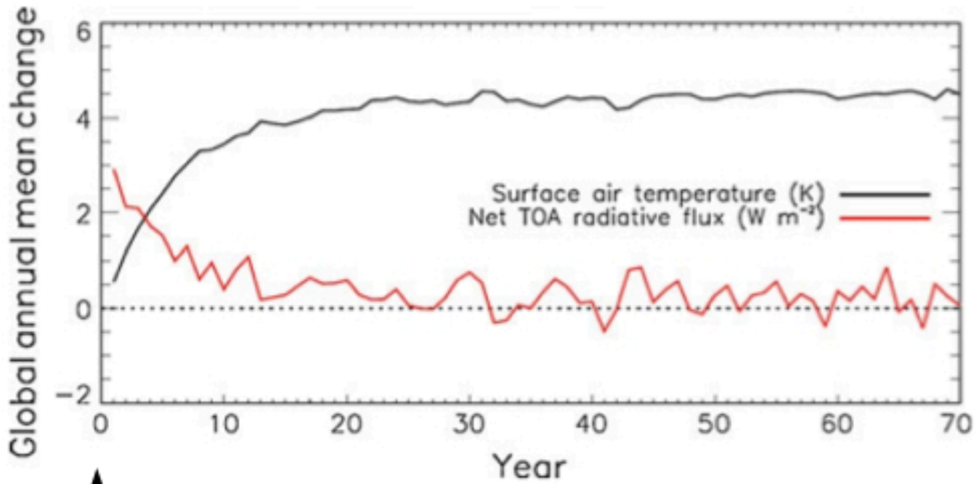
$\lambda = \left(\frac{\partial R}{\partial T_s}\right)_{CO_2}$: feedback parameter (W/m²/K); $\lambda < 0$ stabilizing; $\lambda > 0$ destabilizing.

$\Delta R = 0 \Rightarrow \Delta T_{eq} = -\frac{F}{\lambda}$ For a doubling of CO2, this quantity is named Equilibrium Climate Sensitivity (ECS)

Quantifying Climate Feedbacks

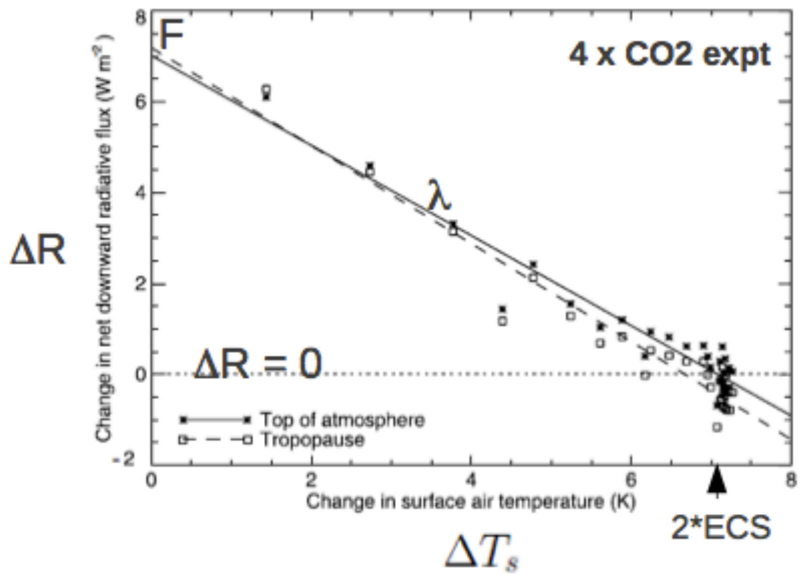
Model estimates of climate sensitivity

$$\Delta R = F + \lambda \Delta T_s$$



Abrupt CO2 increase

« Gregory plot »

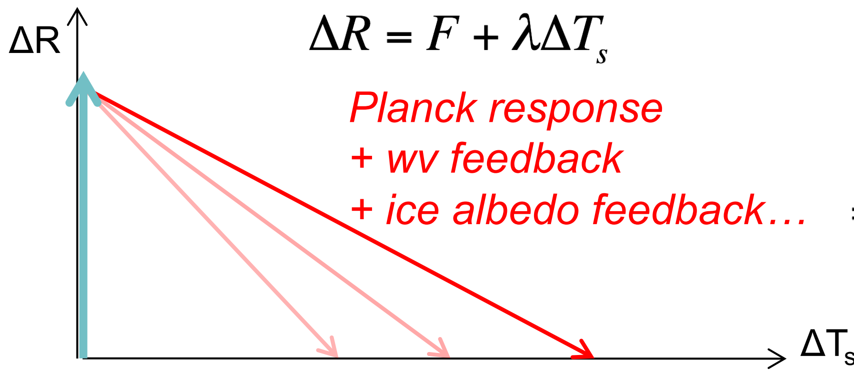


Gregory et al., J. Climate, 2004

Quantifying Climate Feedbacks

Recall:

$$\Delta R = F + \lambda \Delta T_s$$



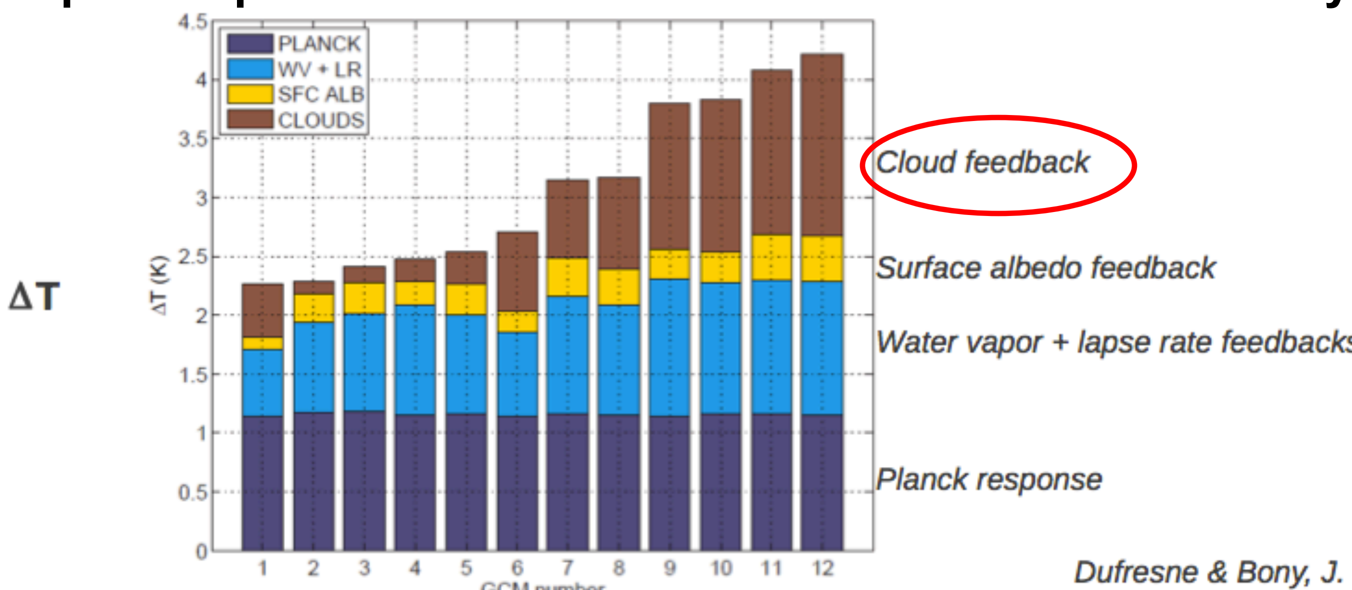
$$\Rightarrow \lambda = \lambda_{Planck} + \lambda_{wv} + \lambda_{cld} + \lambda_{ice} \ldots$$

$$\lambda = \frac{\partial R}{\partial T_s} = \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} = \lambda_{Planck} + \sum_{x \neq Planck} \lambda_x$$

Planck reponse

Influence of each feedback x on climate sensitivity

Helps interpret inter-model differences in climate sensitivity :



Dufresne & Bony, J. Clim., 2008

Clouds in a changing climate

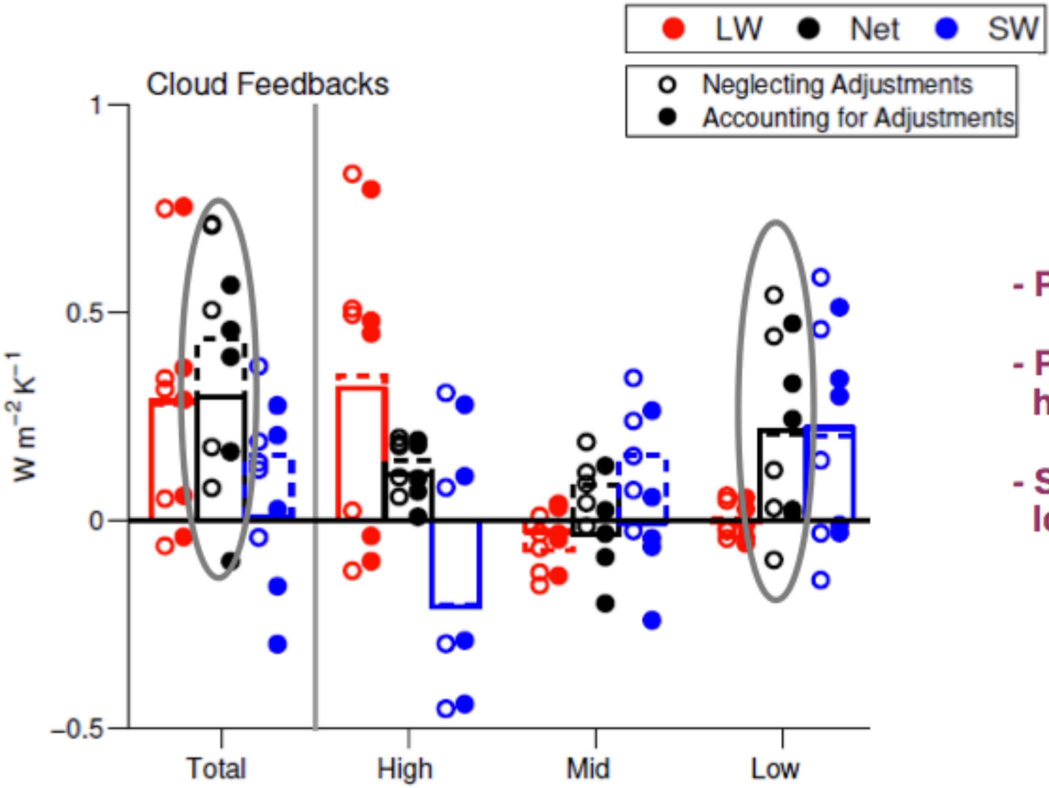
OUTLINE

- Climate sensitivity
- Quantifying climate feedbacks
- Cloud feedback processes

Cloud Feedback Processes

How do the different cloud types contribute to global cloud feebdacks ?
=> **Low-cloud feedbacks dominate the spread of model cloud feedbacks**

CMIP5 Cloud Feedbacks



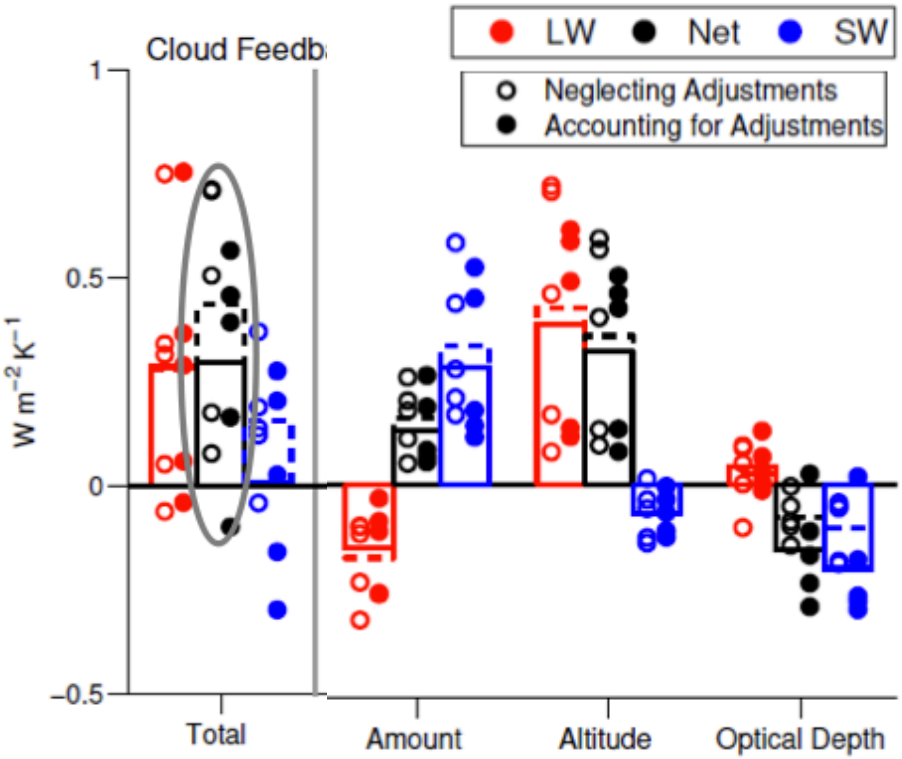
- **Positive cloud feedback**
- **Primarily arises from low-level and high-level cloud feedbacks**
- **Spread primarily arises from low-level cloud feedbacks**

Zelinka et al., J. Climate, 2013

Cloud Feedback Processes

How do the different cloud types contribute to global cloud feebdacks ?
=> **Low-cloud feedbacks dominate the spread of model cloud feedbacks**

CMIP5 Cloud Feedbacks



In a warmer climate :

Fewer clouds (positive feedback)

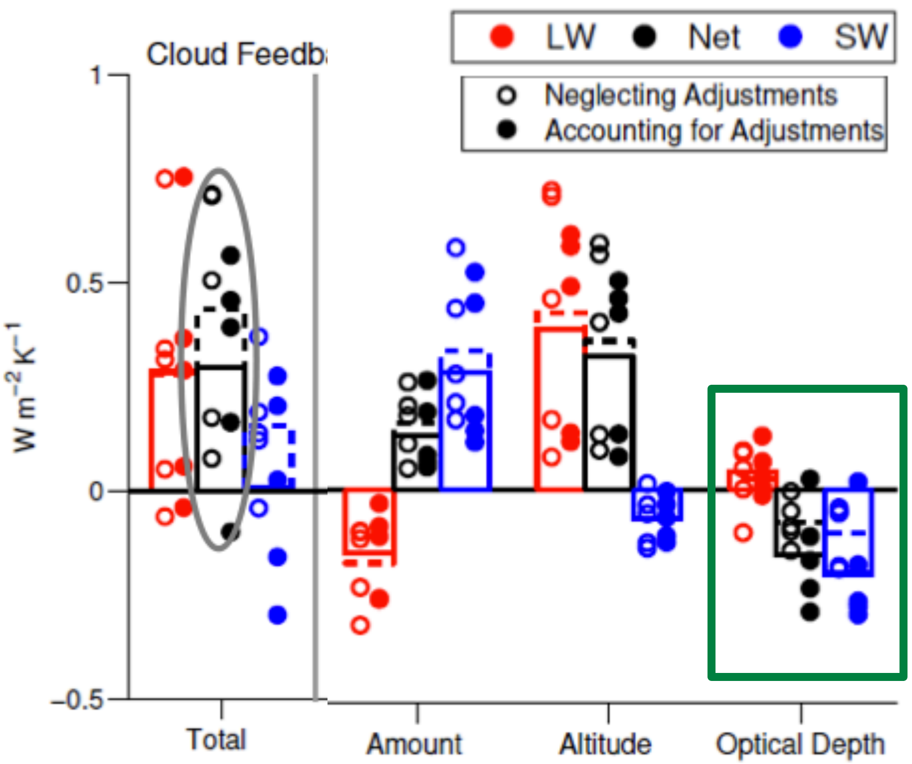
Higher clouds (positive feedback)

Optically thicker clouds (negative feedback)

Zelinka et al., J. Climate, 2013

Cloud Feedback Processes

CMIP5 Cloud Feedbacks

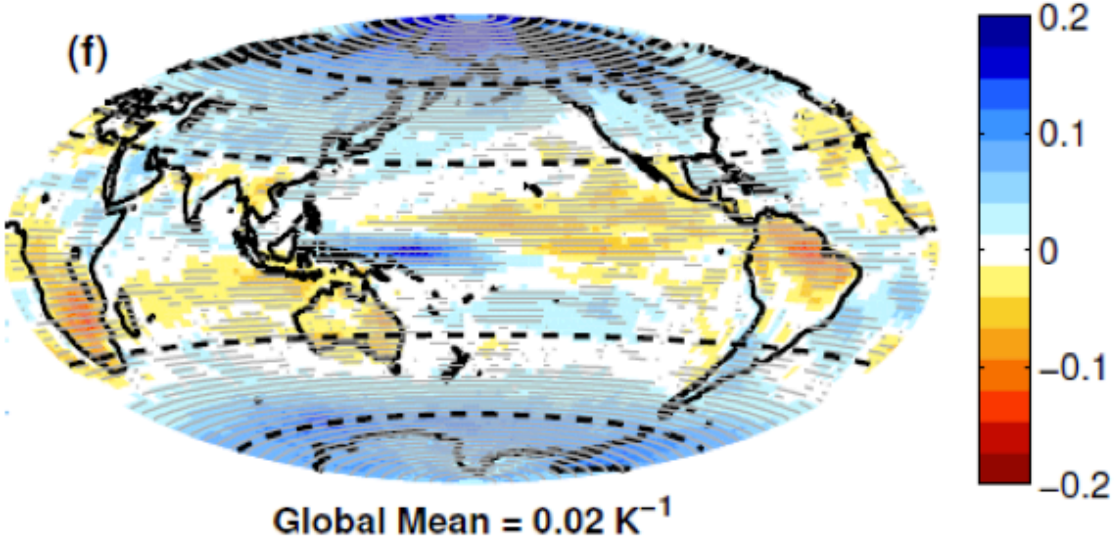


Negative cloud feedback associated with increased cloud optical depth

Zelinka et al., J. Climate, 2013

Cloud Feedback Processes

Change in Cloud Optical Depth

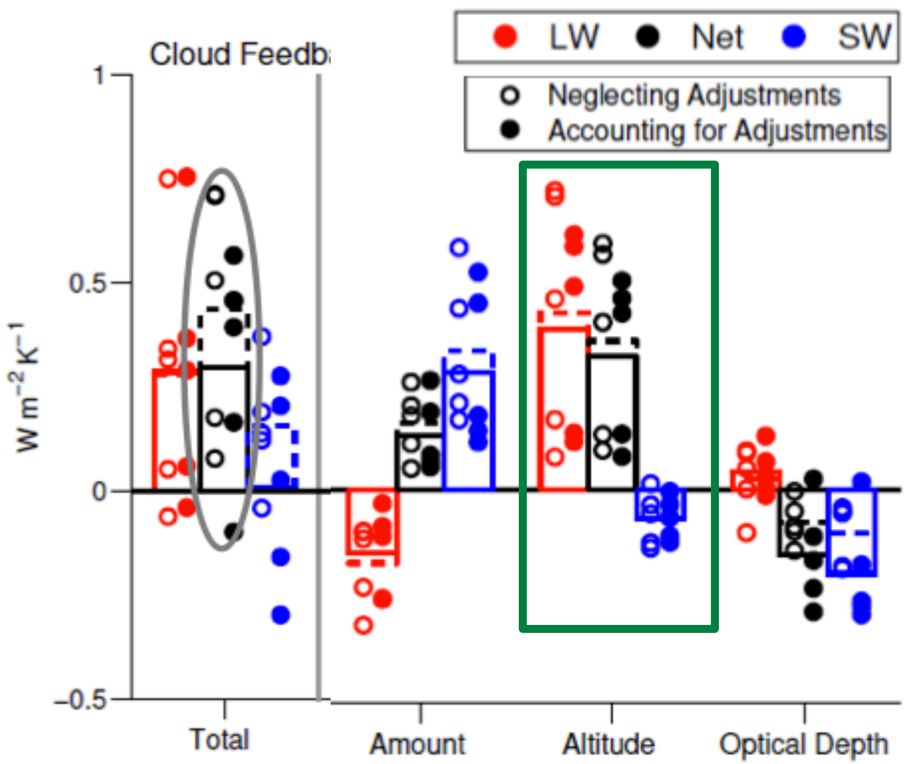


- Robust increase in cloud optical depth at latitudes poleward of about 40 deg.
- Negative cloud optical depth feedback arises mostly from the extratropics.
- High-latitude cloud optical thickness response likely related to changes in the phase and/or total water content of clouds.

Zelinka et al., J. Climate, 2013

Cloud Feedback Processes

CMIP5 Cloud Feedbacks

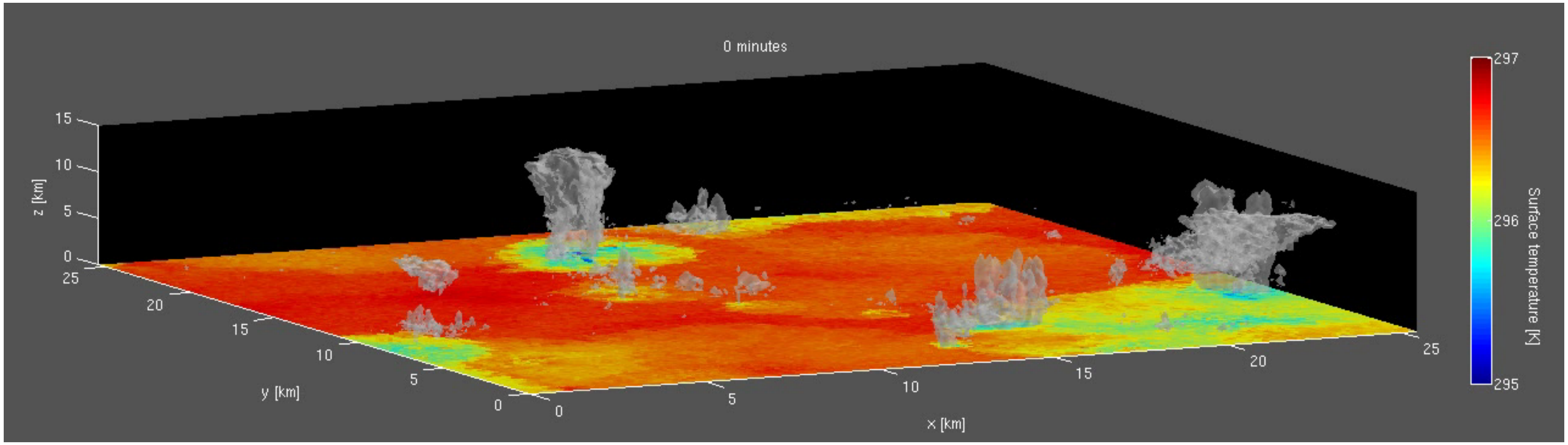


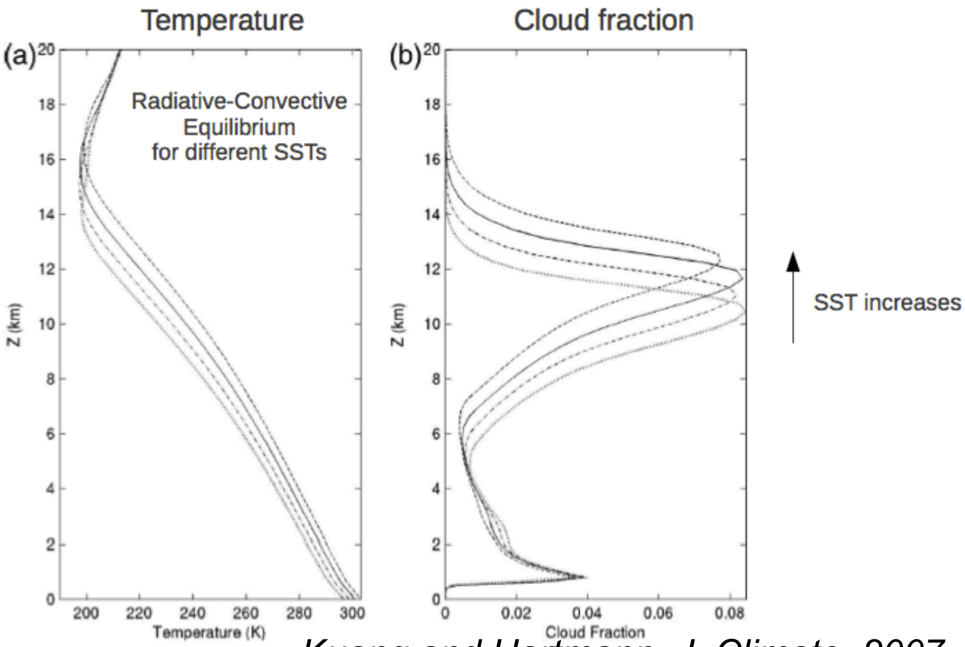
Positive cloud feedback associated with higher clouds

Zelinka et al., J. Climate, 2013

Cloud Feedback Processes

In a warmer climate, climate models robustly predict a rise of upper-level clouds
So do cloud resolving models Why?





Kuang and Hartmann, J. Climate, 2007

Cloud Feedback Processes

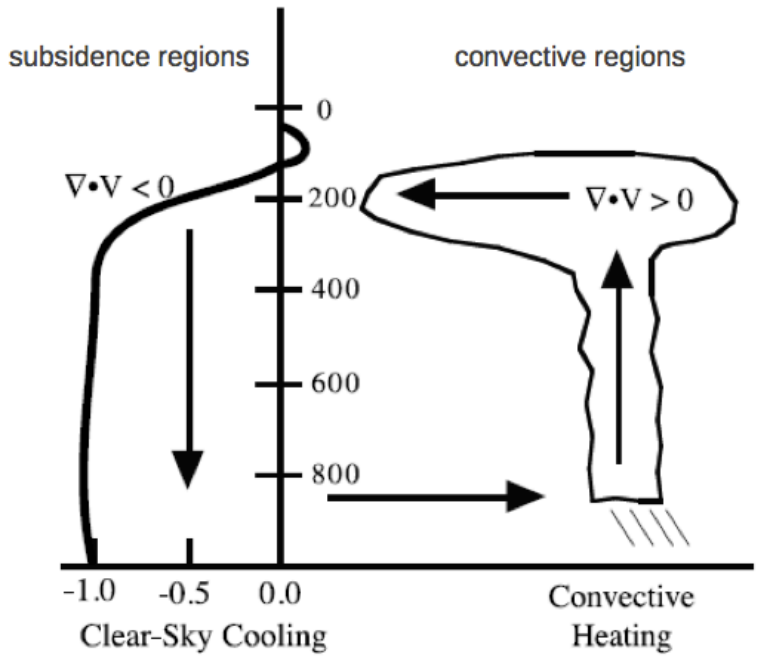
What controls the high-level cloud top altitude / temperature ?

In radiative-convective equilibrium, in clear skies, **the radiative cooling is balanced by adiabatic heating** : w=Q/σ (σ ~ stratification).

dQ/dp ➔ dw/dp ➔ $-\nabla_H \cdot \mathbf{U} = \frac{\partial \omega}{\partial p}$ ➔ **convergence in clear skies**

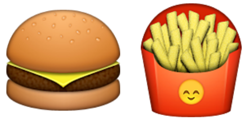
⇒ **Divergence from convection ➔ cloud top altitude**

Q decreases when water molecules become scarce, strong function of T (CC)

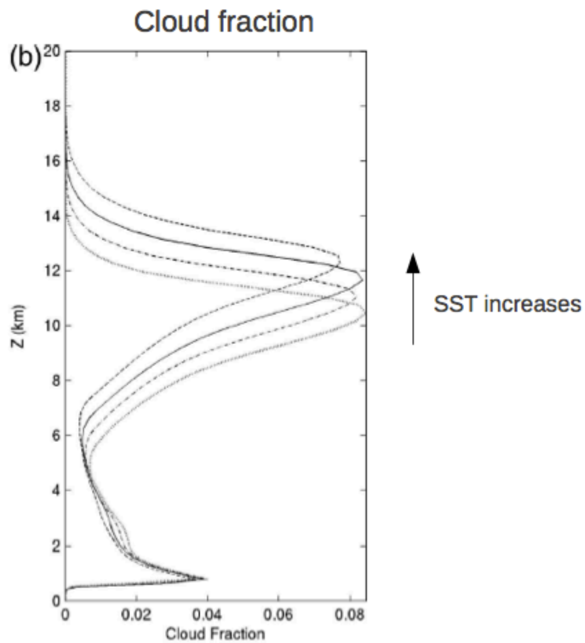


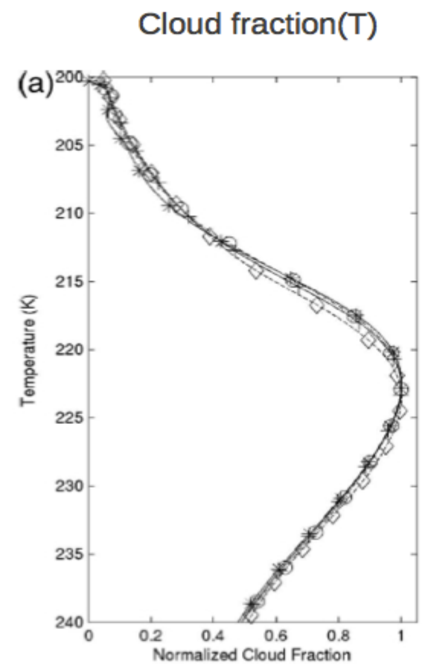
Hartmann and Larson, GRL, 2002

Cloud Feedback Processes



Fixed Anvil Temperature « FAT » mechanism





Kuang & Hartmann, J. Climate, 2007

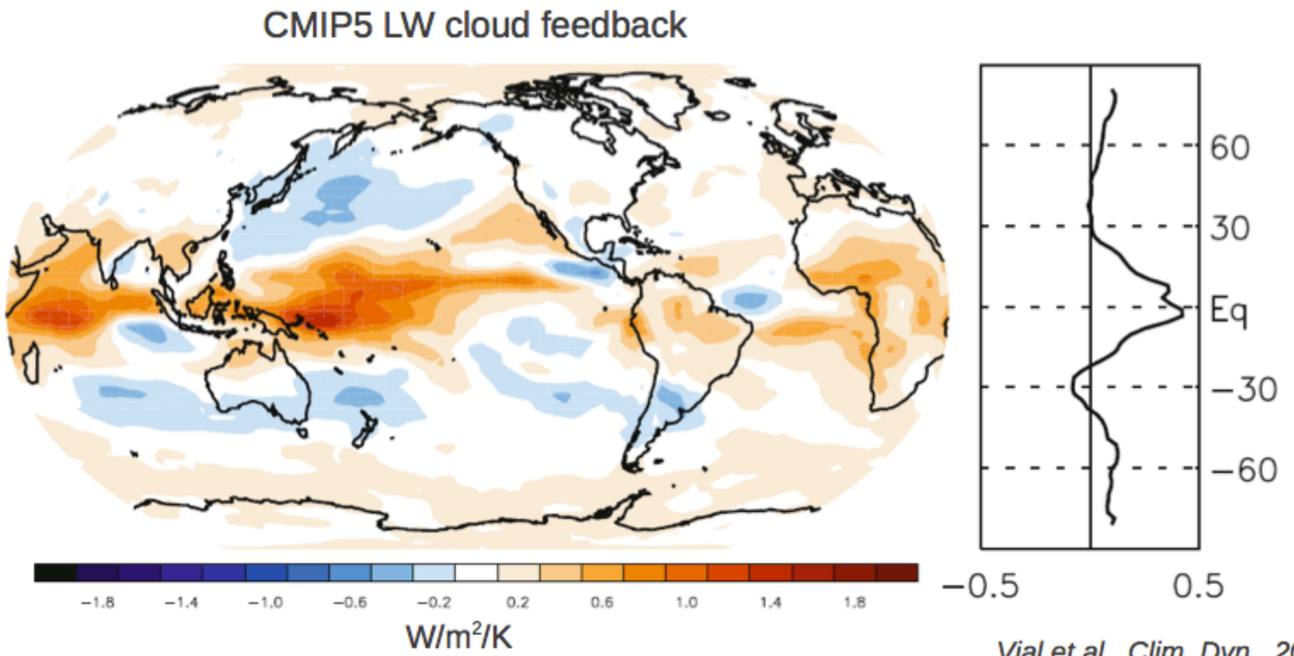
Revisited as FiTT (Fixed Tropopause Temperature), anvil amount NOT dictated by environmental Qrad but by convective detrainment and dissipation of clouds, slower at high altitudes. => T of high clouds can change (seem to warm ~ 50% of surface warming) *Jacob Seeley*

Cloud Feedback Processes

Implications of FAT/FiTT for cloud feedbacks ?

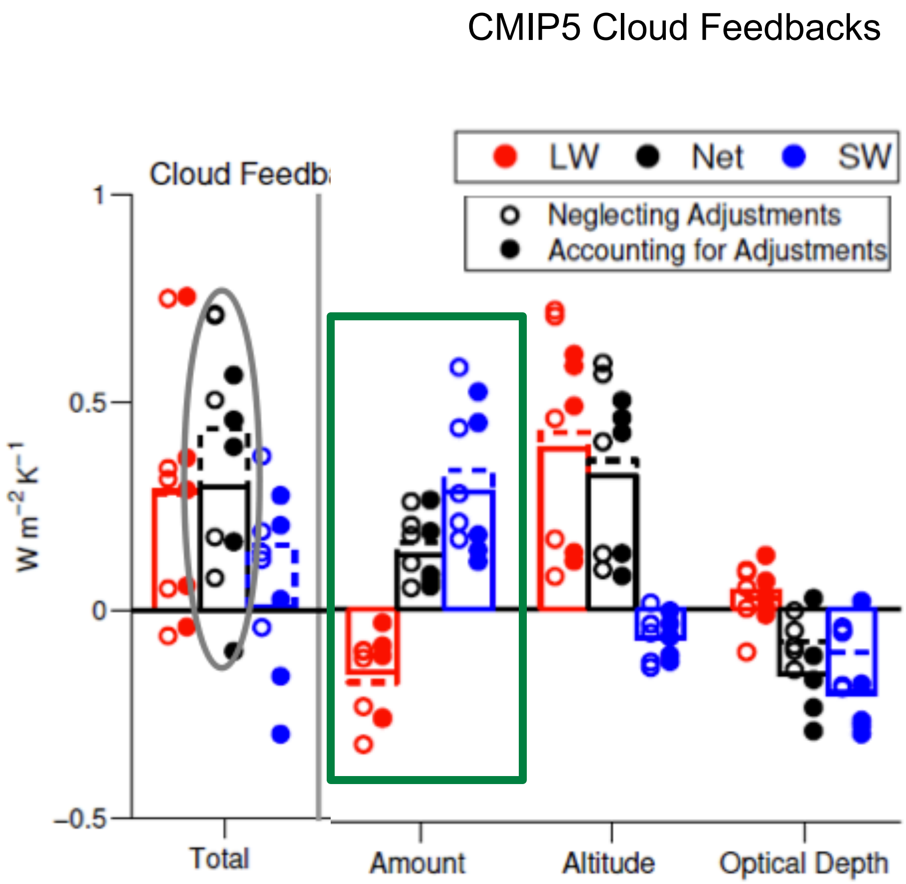
Because cloud tops are not warming in step with surface and atmospheric temperatures, the tropics become less efficient at radiating away heat

⇒ positive LW cloud feedback



Vial et al., Clim. Dyn., 2013

Cloud Feedback Processes



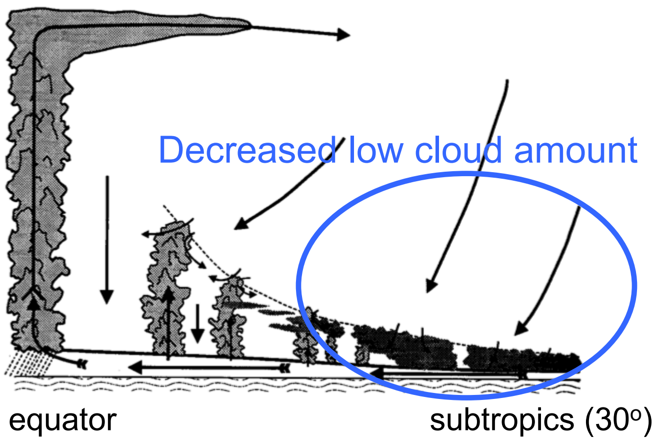
Positive cloud feedback associated with decreased cloud fraction

Zelinka et al., J. Climate, 2013

Cloud Feedback Processes

What controls the tropical cloud amount and its radiative impact ?

In many regions, the cloud amount feedback is not robust



Low-cloud fraction and low-tropospheric stability (LTS) related in present-day climate *Klein and Hartmann, J. Clim., 1993*

LTS expected to increase in a warmer climate.
But even models that reproduce this relationship in present-day climate can predict a decrease of low cloud amount in climate change…

True for polar clouds as well that LTS is not a good predictor of low clouds fraction change (Xiyue Zhang)

Has to do with enhanced surface fluxes deepening the boundary layer?
...and hence mix more dry and warm air to the surface
...leading to a decreased cloudiness as climate warms.
Rieck, Nuijens and Stevens, JAS, 2012

Radiative effect of clouds important (Low-level clouds contribute to their own maintenance through their radiative effects)? Candidate to explain the spread of low-cloud feedbacks? *Brient and Bony, GRL, 2012*

Cloud Feedback Processes

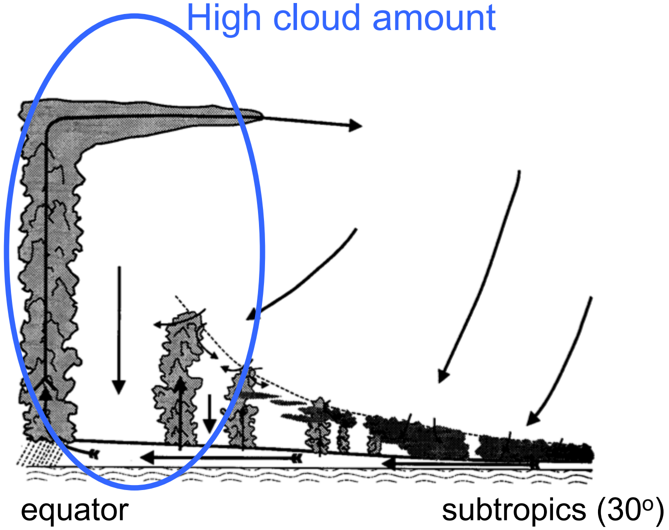
What controls the tropical cloud amount and its radiative impact ?

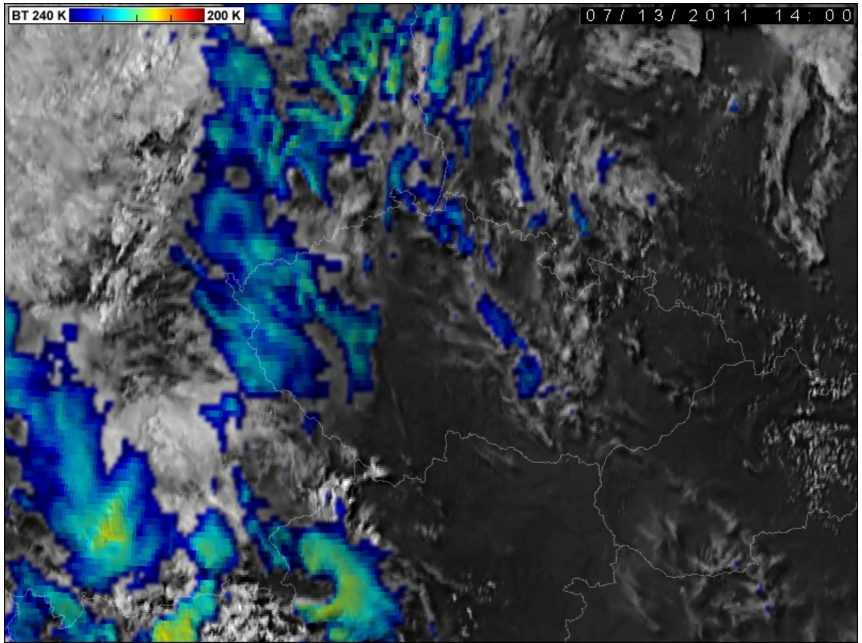
In many regions, the cloud amount feedback is not robust

FAT/FiTT don't say anything about the change in cloud amount

Still very much an open issue

Impact of convective aggregation ?





Clouds in a changing climate

Many remaining questions …

What controls the low cloud fraction ?

What determines the mesoscale organization of low clouds ?

What controls the high cloud fraction ?

FAT or FiTT? Why ?

What determines the organization of deep convection ?

What impact on the hydrological cycle (extreme precipitation, updraft velocities) ?

Clouds and turbulent moist convection

Nuages des Houches