Uncertainties in GCMs' Estimates of Cloud Feedbacks and Climate Sensitivity

Sandrine Bony (LMD / IPSL, Paris)

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Thanks to : Jean-Louis Dufresne (LMD), Mark Webb & Keith Williams (Hadley Centr
Matthew Wyant (Washington Univ), Minghua Zhang (Stony Brook Univ)

(WGNE conference, San Francisco, Februar

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Martin Miller

- What did we learn from recent studies on cloud feedbacks?
- What particular processes appear to be critical for climate sensitivity? How may we use observations to evaluate GCMs' cloud feedbacks ?

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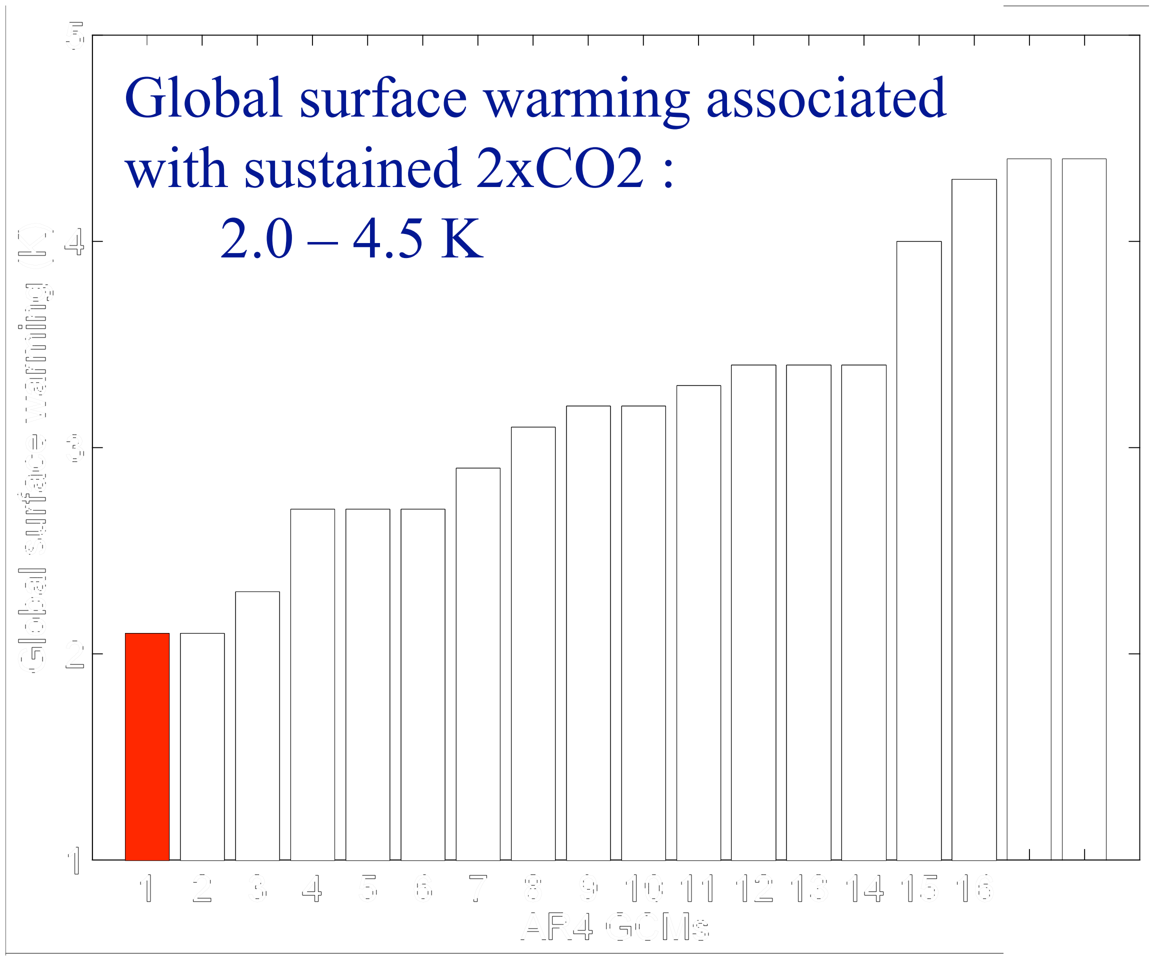
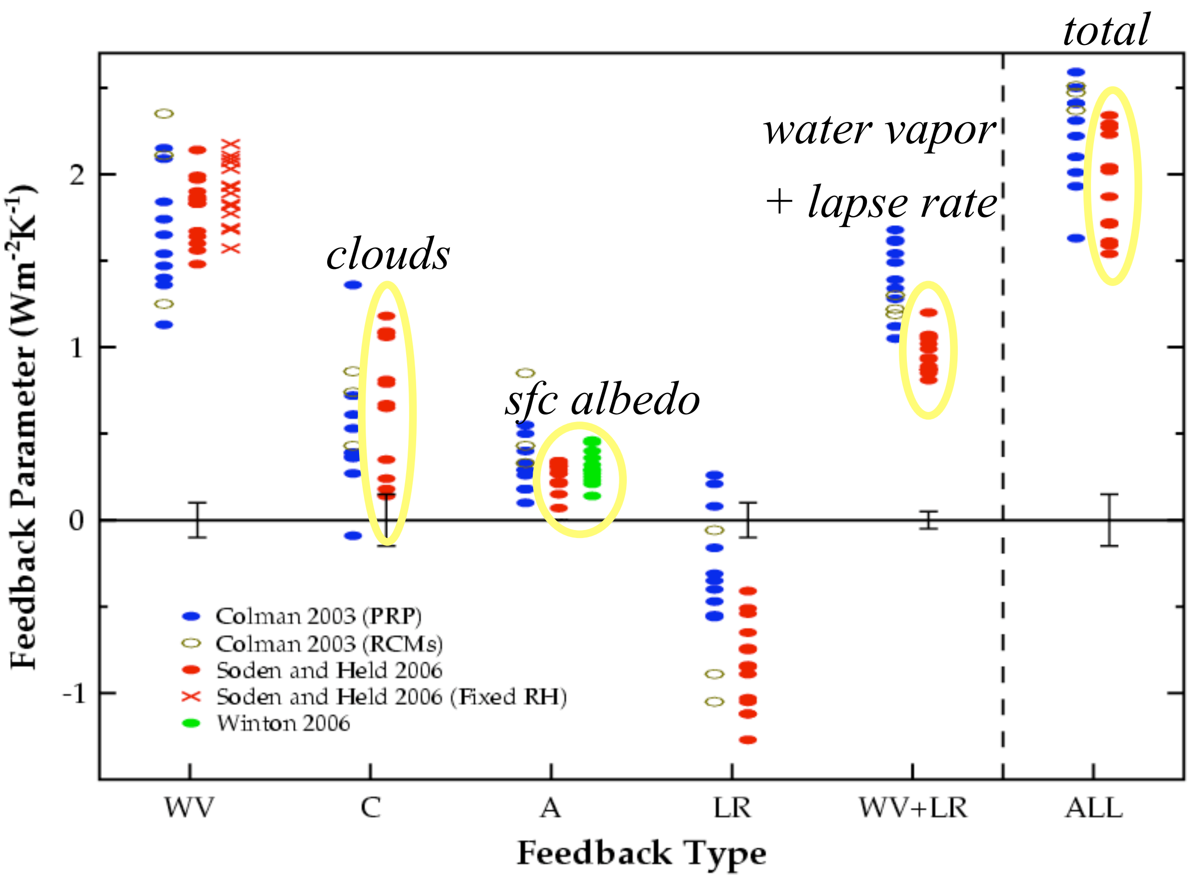
Equilibrium Climate Sensitivity Estimates from AR4 GCMs



IPCC AR4, 2007

Global Climate Feedbacks Diagnosed in AR4 GCMs



- AR4 OAGCMs
- older GCMs

(Bony et al., J. Climate, 2(

after Colman 2003;

Soden and Held 2006

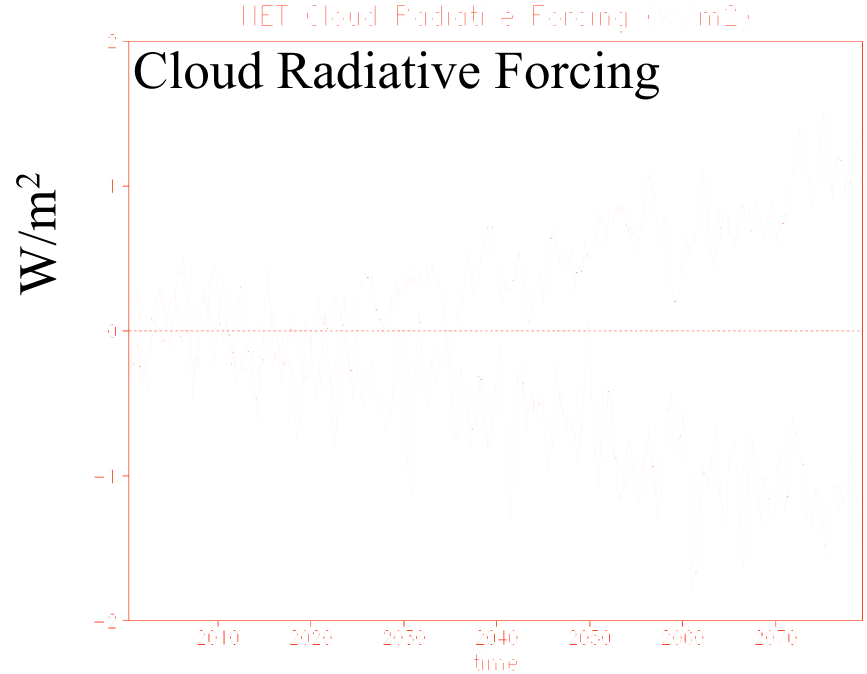
and Winton 2006)

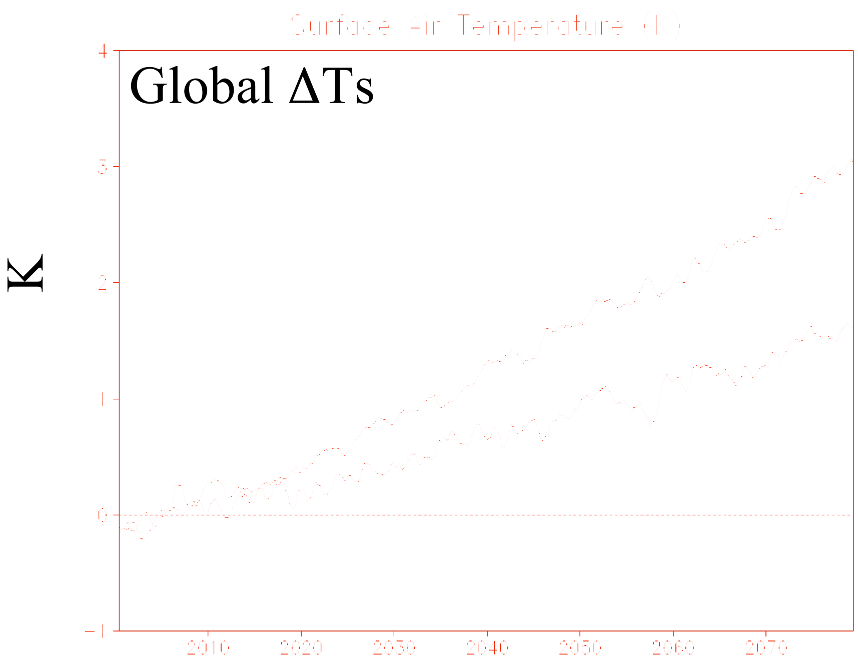
Inter-model differences in cloud feedbacks constitute the primary source of uncertainty in equilibrium climate sensitivity :

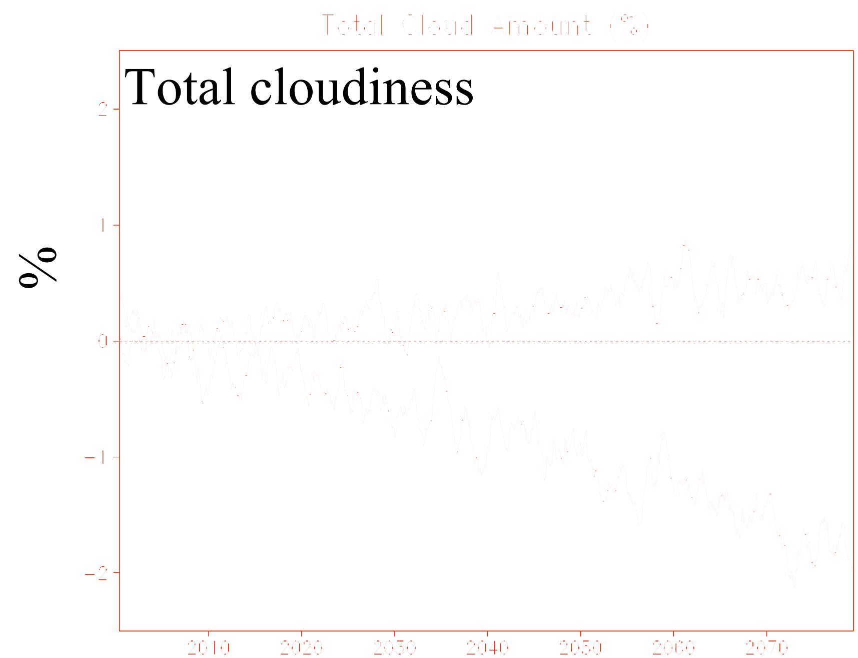
Due to cloud feedbacks, the climate response to a given forcing can differ by a factor of 2 !

AR4 OAGCMs
(+1% CO_2/yr):

MIROC3.2-HIRES
vs
NCAR-CCSM3

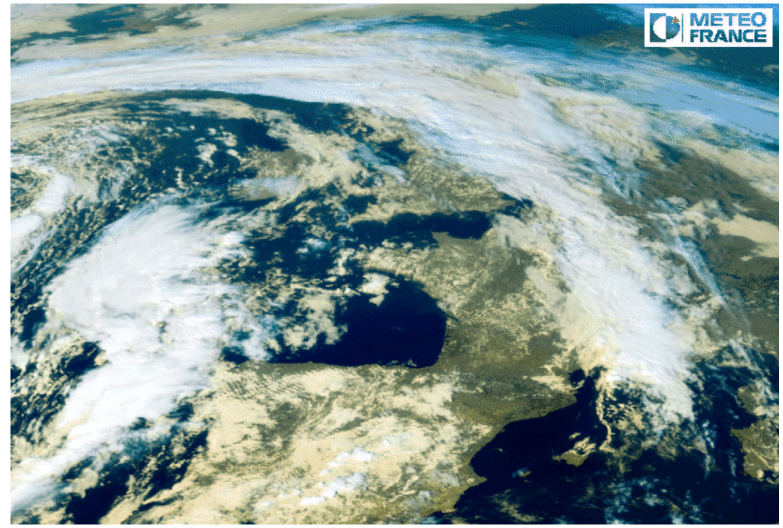






Many factors/processes (physical & dynamical) may explain the spread of GCM cloud feedbacks...

deep convective activity



baroclinic activity & frontal clouds

boundary-layer turbulence and clouds

1. What improvement of climate models would help to reduce the uncertainty in global cloud feedbacks ?

2. How may we use observations to assess the reliability of the climate change feedbacks produced by the different models ?

1. What improvement of climate models would help to reduce the uncertainty in global cloud feedbacks ?

2. How may we use observations to assess the reliability of the climate change feedbacks produced by the different models ?

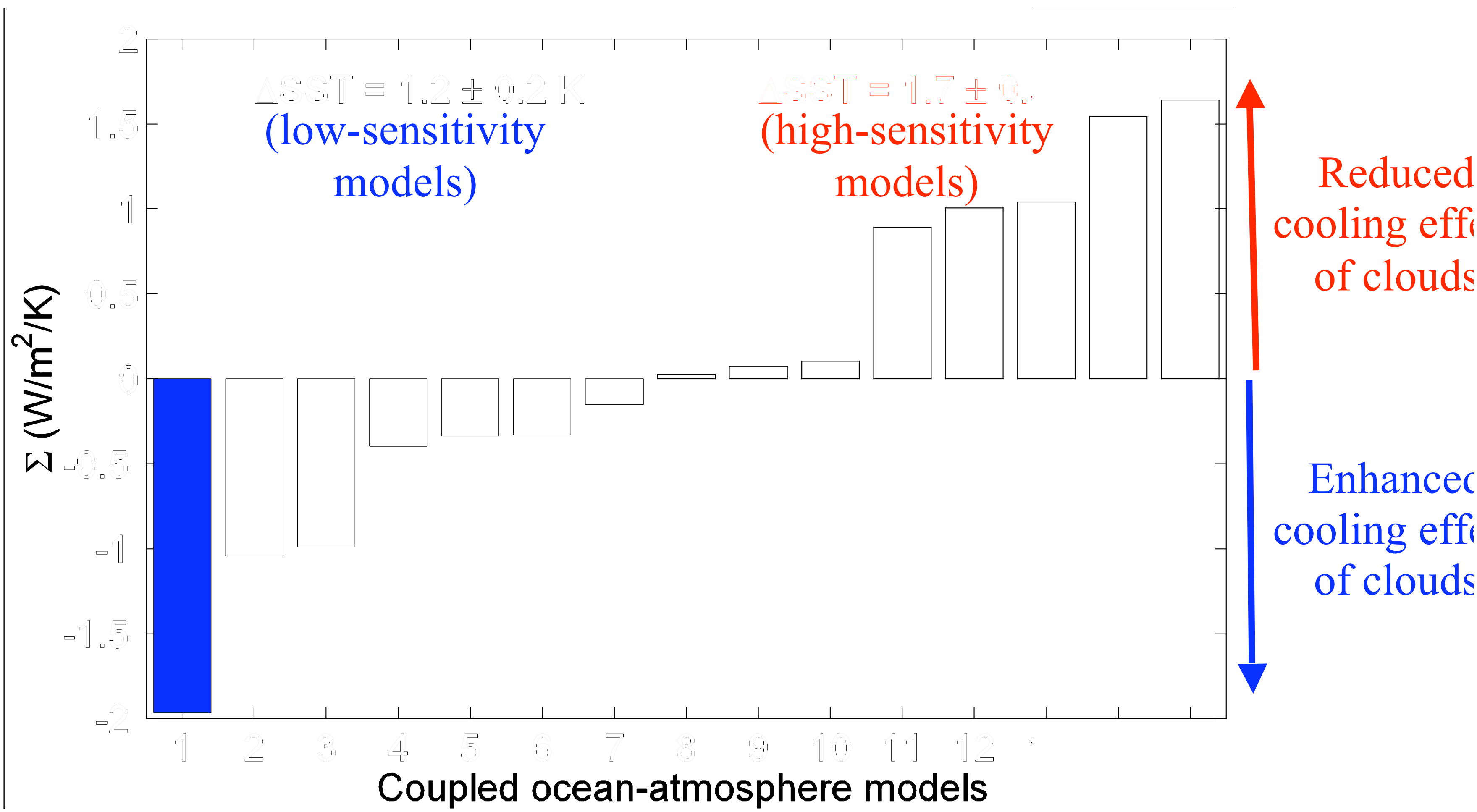
Understand the physical mechanisms underlying the global feedback estimates
&
Identify the processes that are critical for climate change cloud feedbacks

Understand the reasons for intermodel differences

Suggest targeted diagnostics for model-data comparison

Climate Change Simulations (+1%CO_2/yr)
15 OAGCMs (AR4)

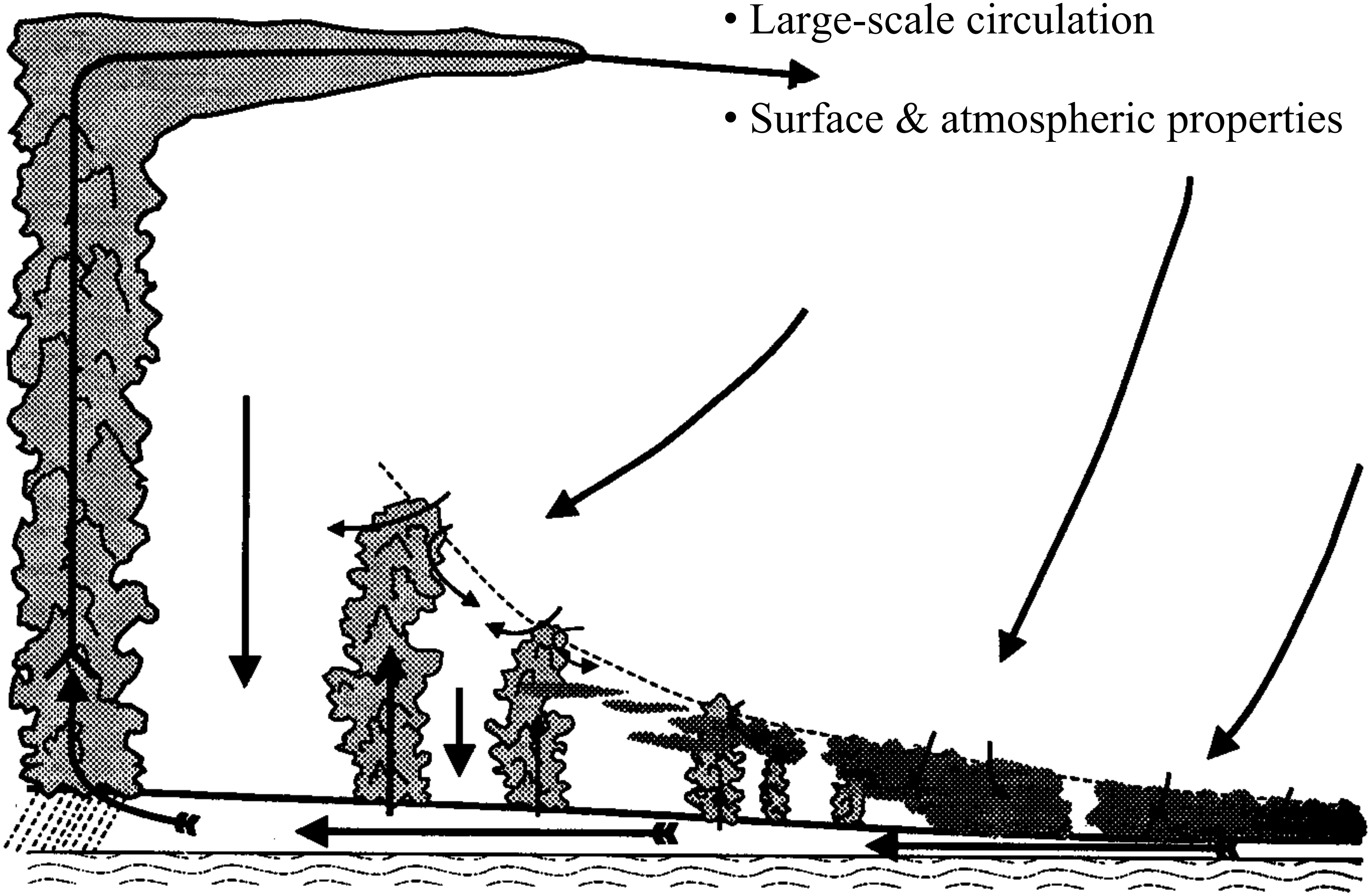
Sensitivity of the Tropical NET Cloud Radiative Forcing (CRF) to surface temperature change (W/m^2/K)



(Bony and Dufresne, GRL, 20

What controls the response of tropical clouds to climate change?

- Large-scale circulation
- Surface & atmospheric properties



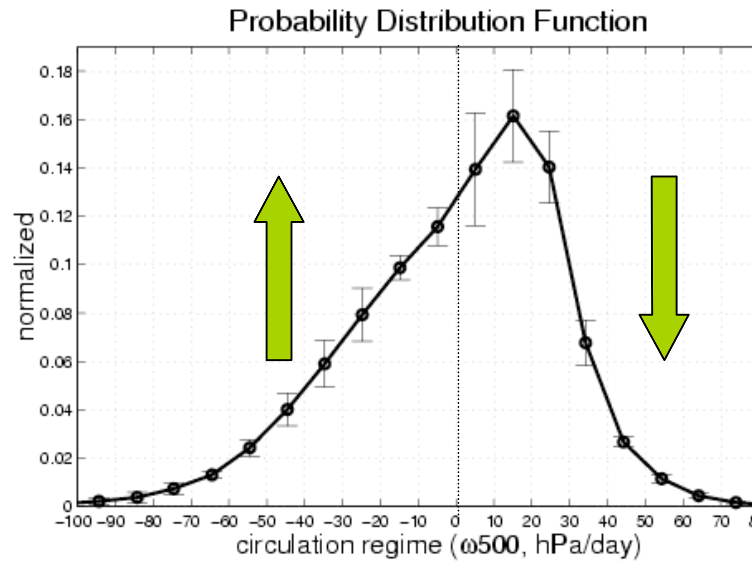
Analysis Method

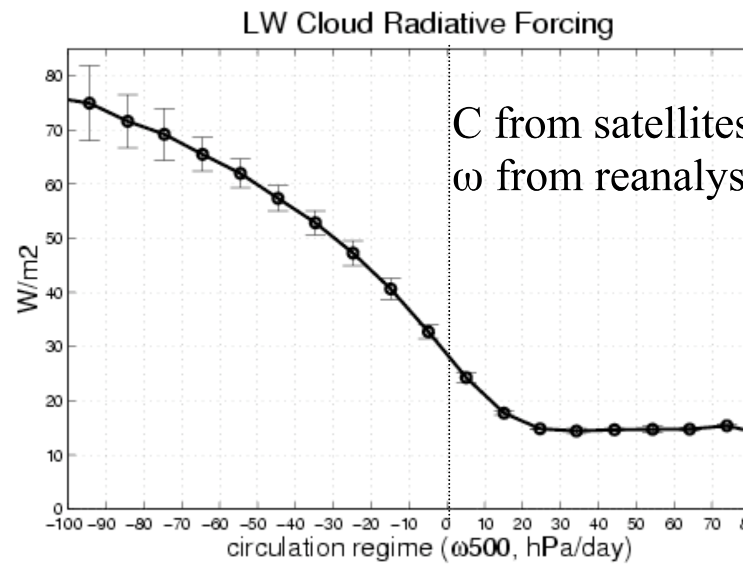
- Proxy ω for large-scale motions: ω_{500hPa}.

- Decomposition of the tropical circulation into dynamical regimes: $\int_{-\infty}^{+\infty} P_\omega \, d\omega = 1$

- Composite of cloud or radiative variables in each dynamical regime: C_ω

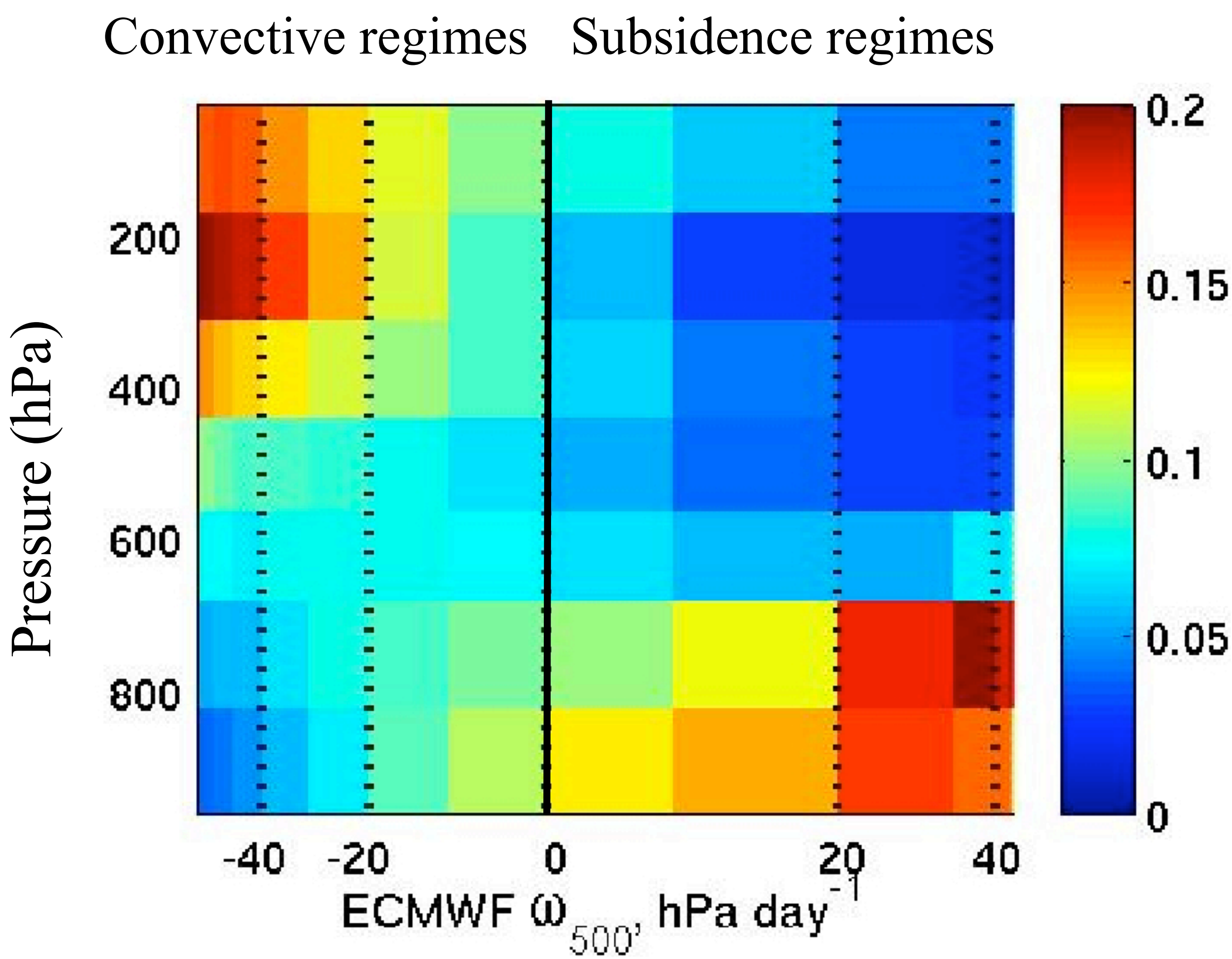
- Tropical average: $\overline{C} = \int_{-\infty}^{+\infty} P_\omega \, C_\omega \, d\omega$





(Bony et al., Climate Dynamics, 2(

ISCCP Cloud Frequency
sorted by dynamical regime and cloud top pressure



(Wyant et al., Climate Dynamics, 2006)

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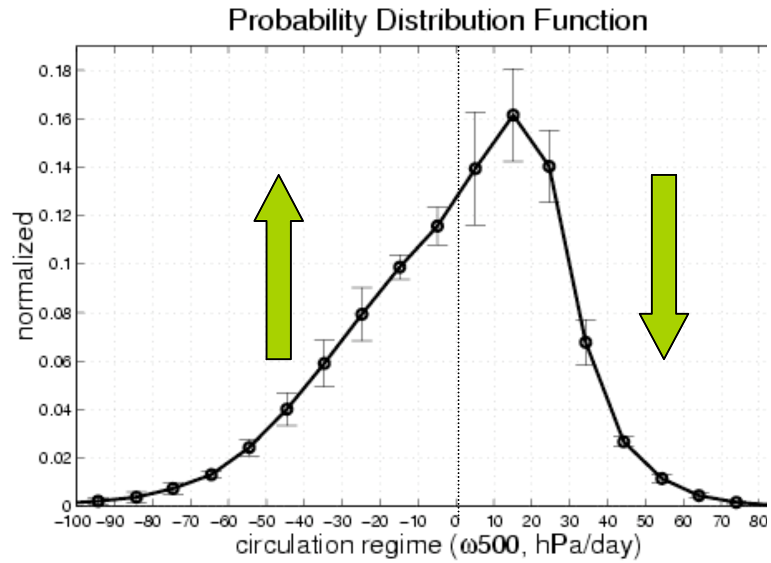

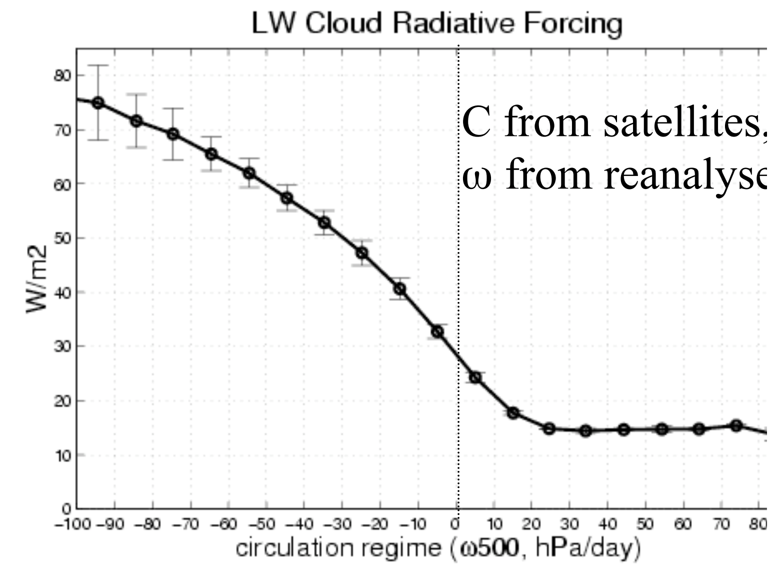

$$\overline{\delta C} = \int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega + \int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega + \int_{-\infty}^{+\infty} \delta P_\omega \, \delta C_\omega \, d\omega$$

dynamic component | **thermodynamic component** | **co-variation**

(Bony et al., Climate Dynamics, 20

Analysis Method

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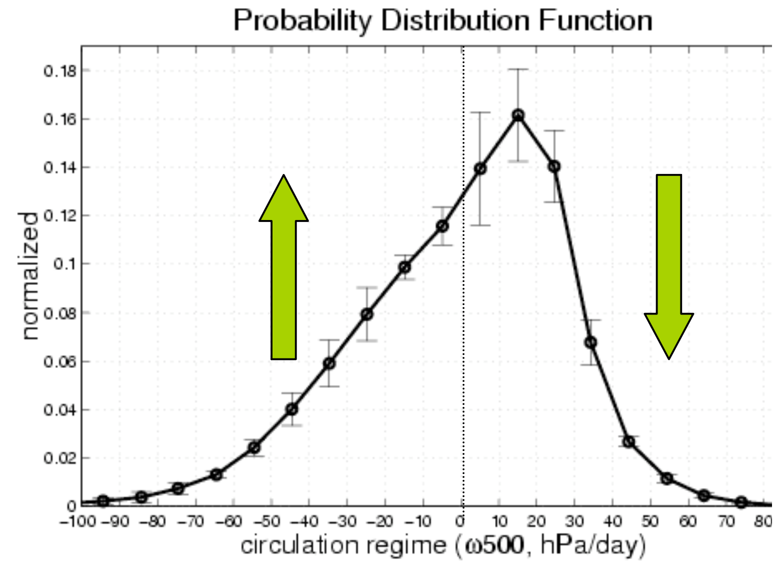
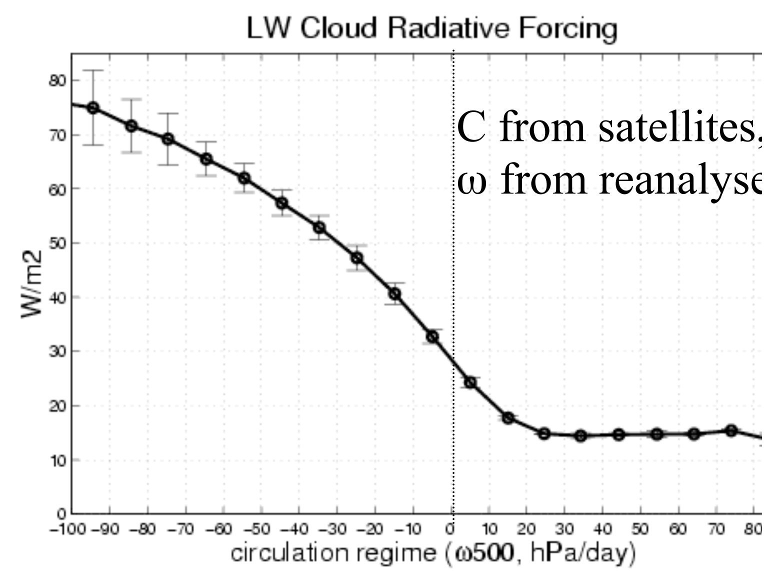


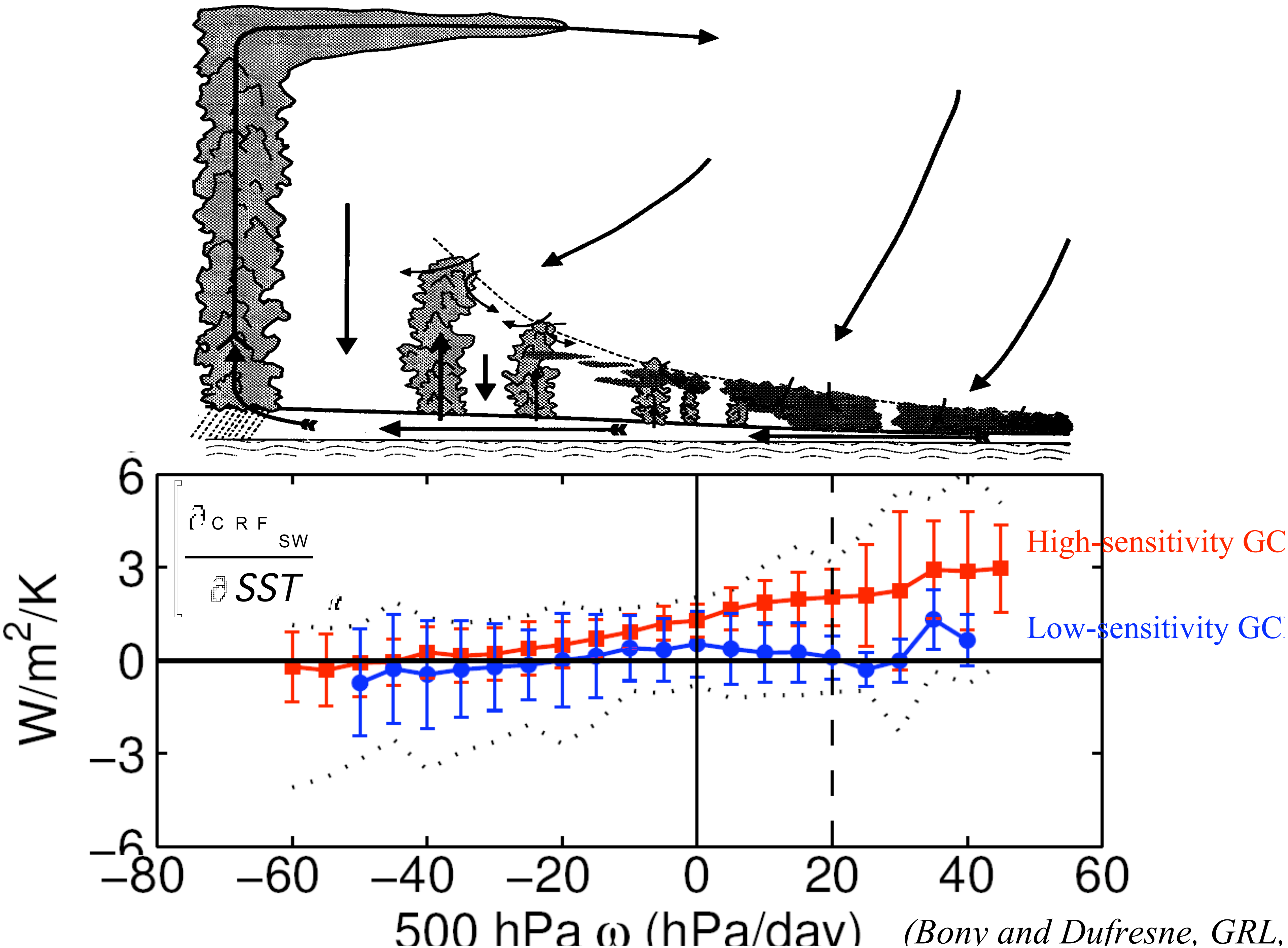


$$\overline{\delta C} = \int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega + \int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega + \int_{-\infty}^{+\infty} \delta P_\omega \, \delta C_\omega \, d\omega$$

dynamic component | **thermodynamic component** | **co-variation**

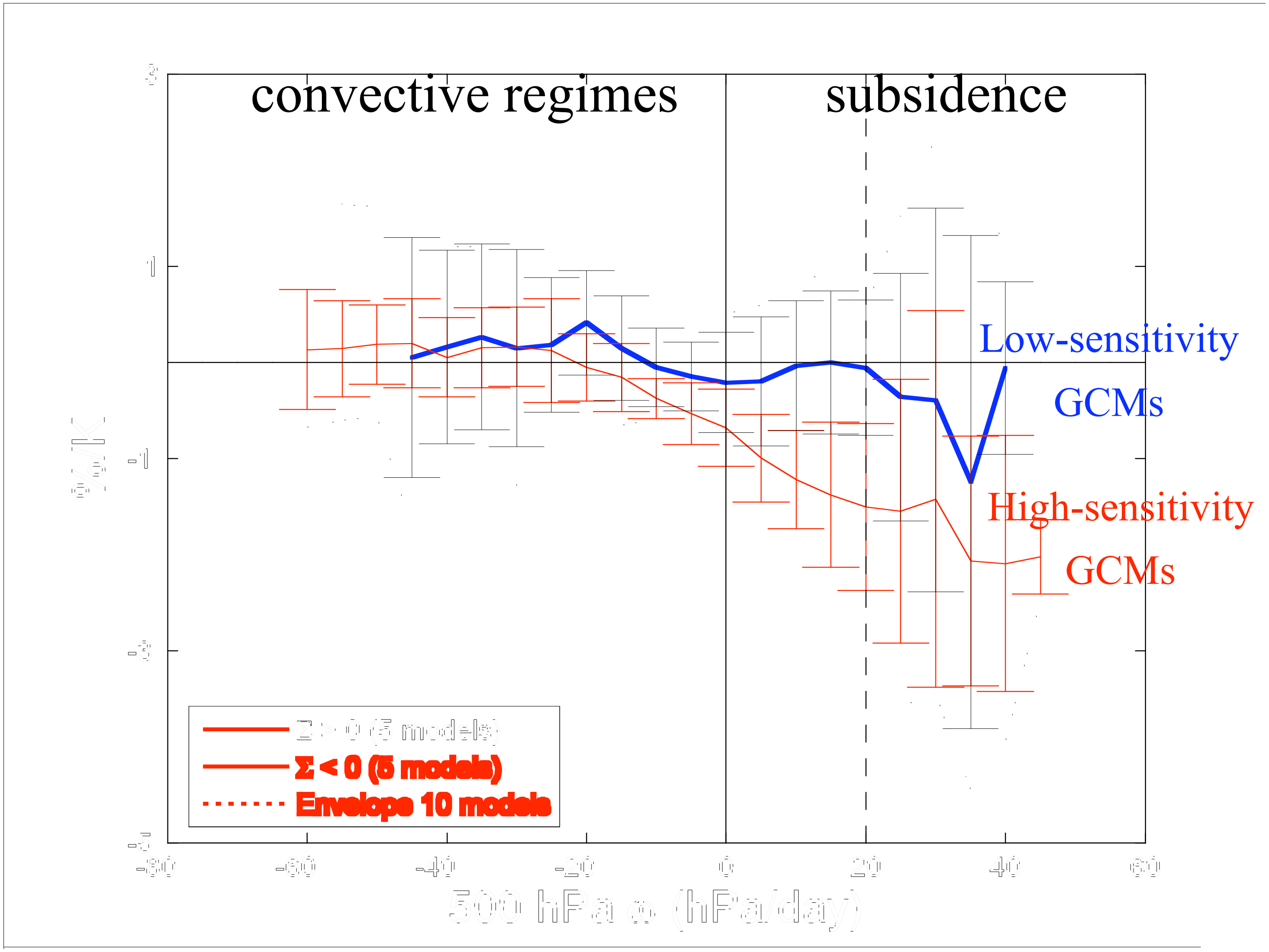
(Bony et al., Climate Dynamics, 2(

Sensitivity of the tropical SW CRF to global warming :



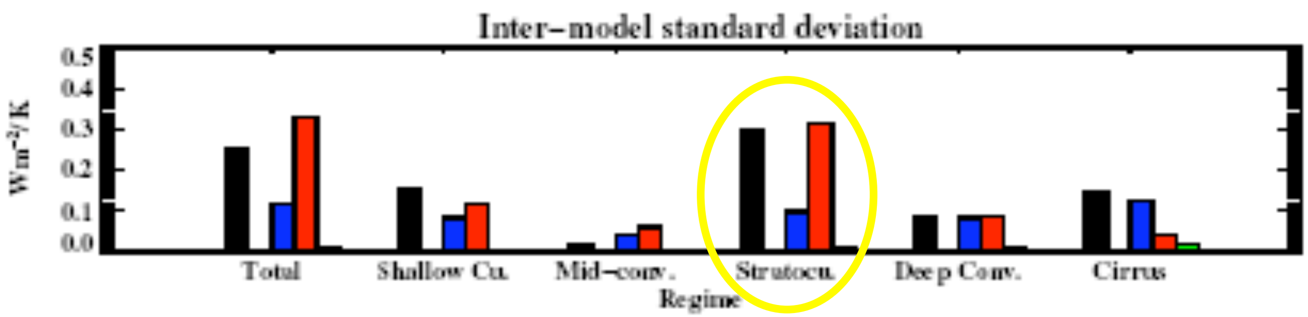
(Bony and Dufresne, GRL,

Sensitivity of the total cloud fraction to climate warming :



Consistently, using a statistical clustering technique to decompose the tropical cloudiness into different "cloud regimes" :

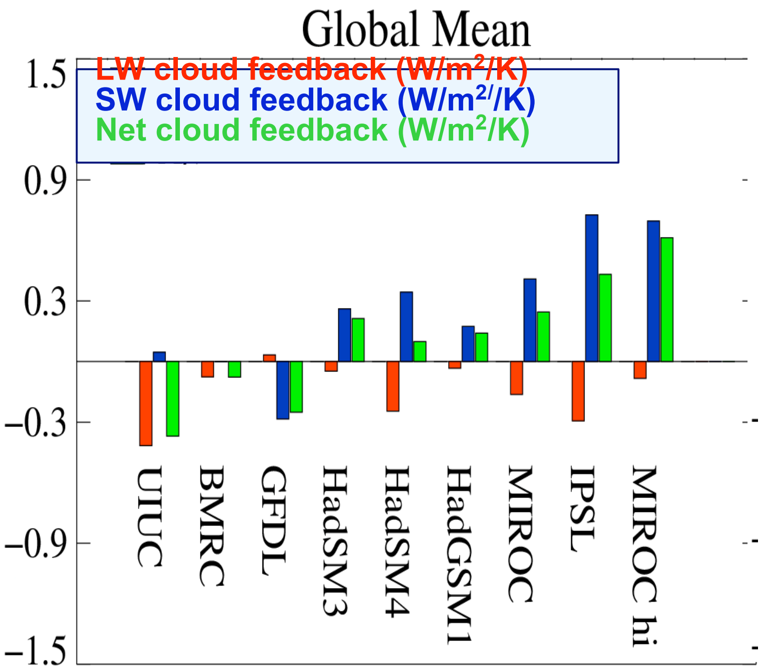
Williams and Tselioudis (2007) found that most of intermodel differences in tropical cloud feedbacks arise from differences in the radiative response of StrCu clouds :

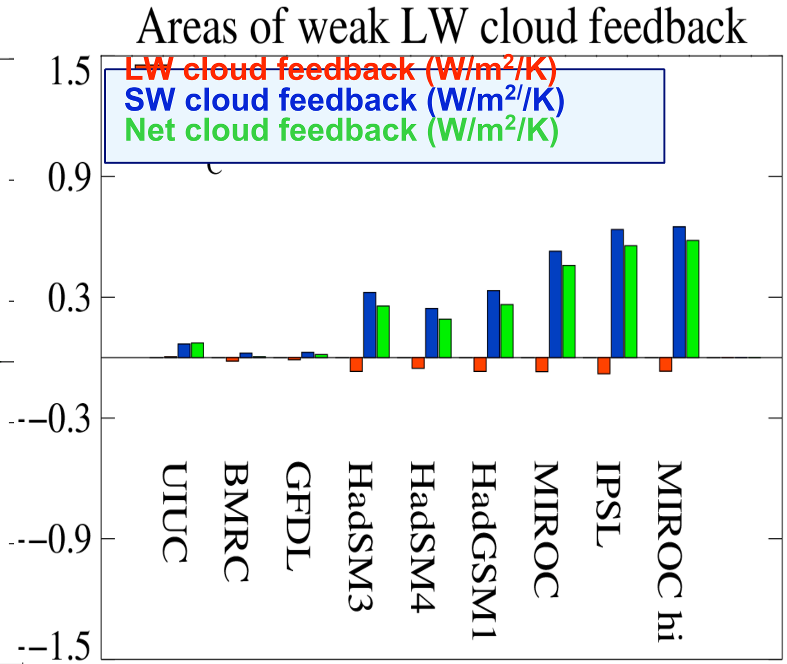


(Williams and Tselioudis, Climate Dynamics, 2007)

<u>cf Next Talk !</u>

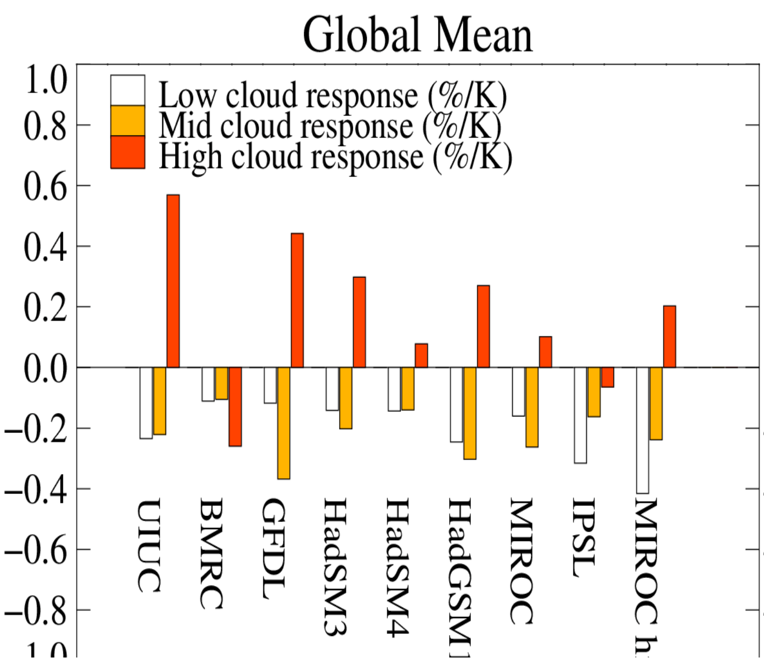
(Webb et al., Climate Dynamics, 2006 – CFMIP model

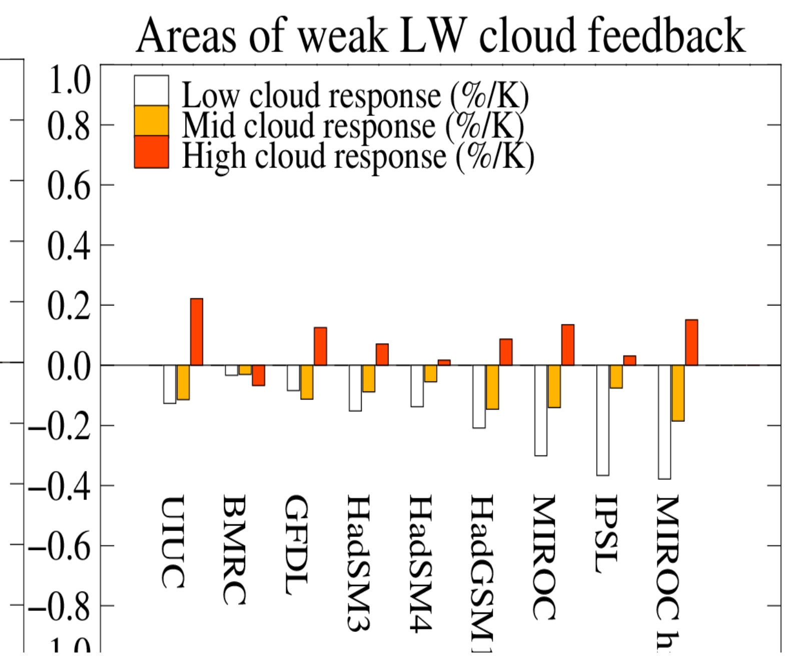




The spread in glo
cloud feedbacks s
mostly from the S
component.

Areas with small
LW cloud feedba
explain 59% of th
NET cloud feedba
ensemble varianc





Cloud feedbacks in
these areas are dor
by changes in **low-**
cloud amount (sh
with ISCCP simula

Cloud feedbacks have been confirmed as the primary source of climate sensitivity uncertainty.

- The SW response of clouds is the most uncertain.
- Recent studies point to low-level clouds as a primary culprit.

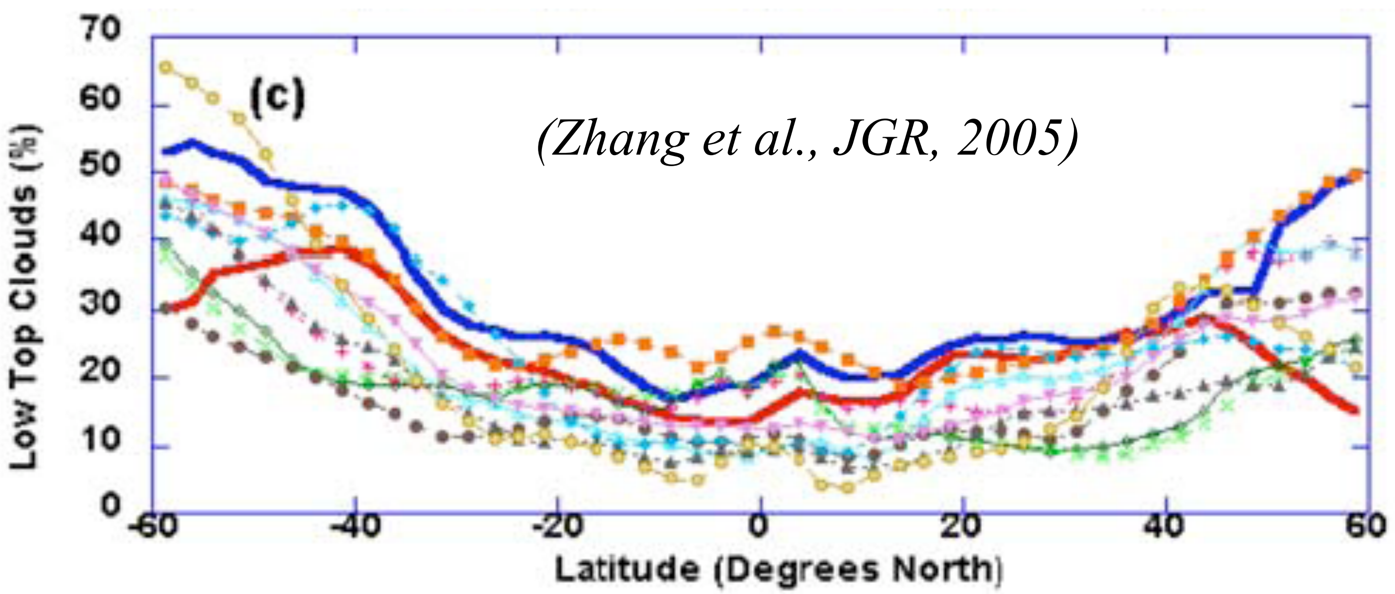
Which of the model cloud feedbacks are the more reliable ?
What cloud properties should we evaluate in GCMs ?

Low-level clouds

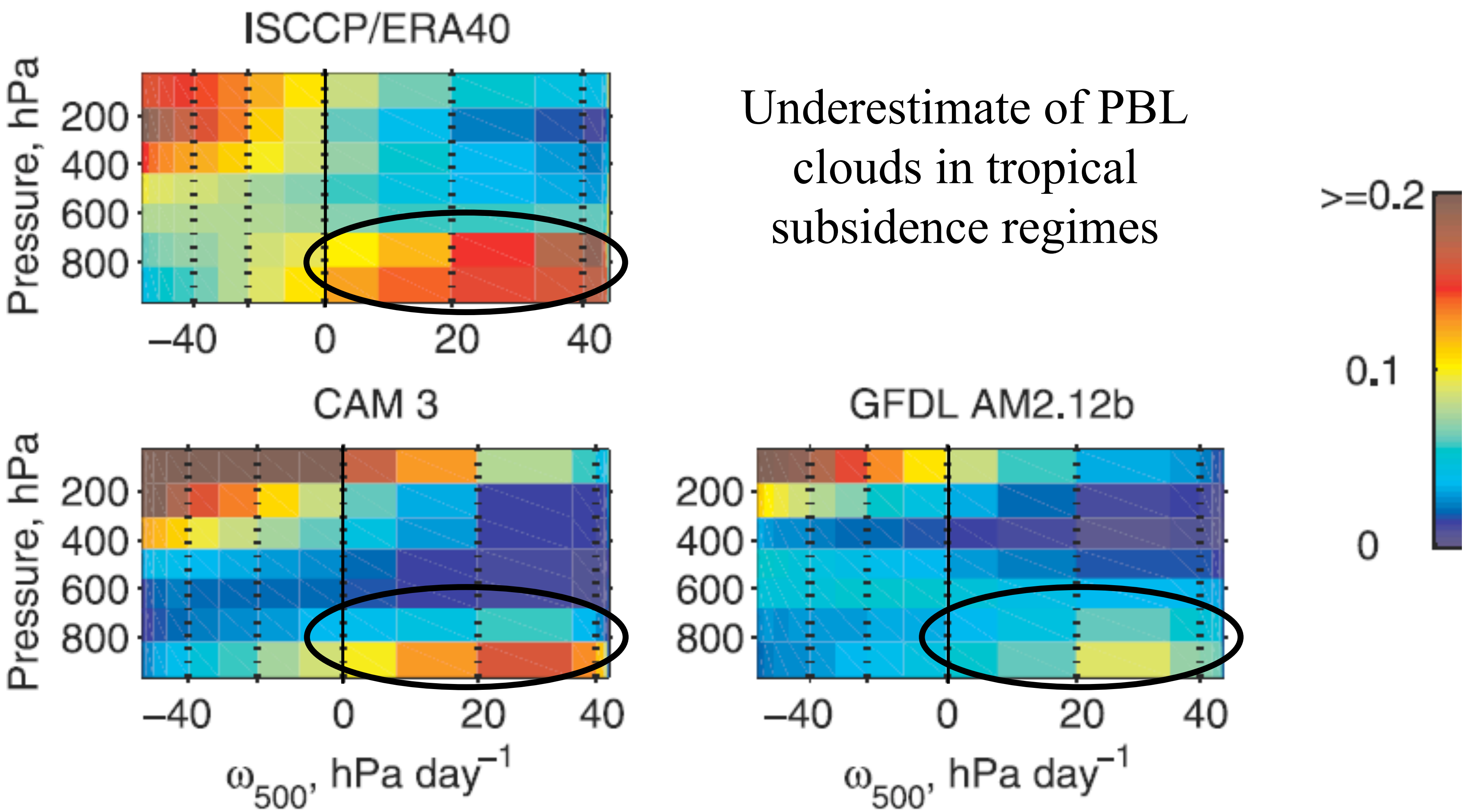
- Their response to climate change constitutes the primary contributor to inter-model differences in cloud feedbacks.

- Low-level clouds are ubiquitous, both in the Tropics and in the Extra-Tropics.

- Most GCMs underestimate low-level clouds :



AR4 GCMs :

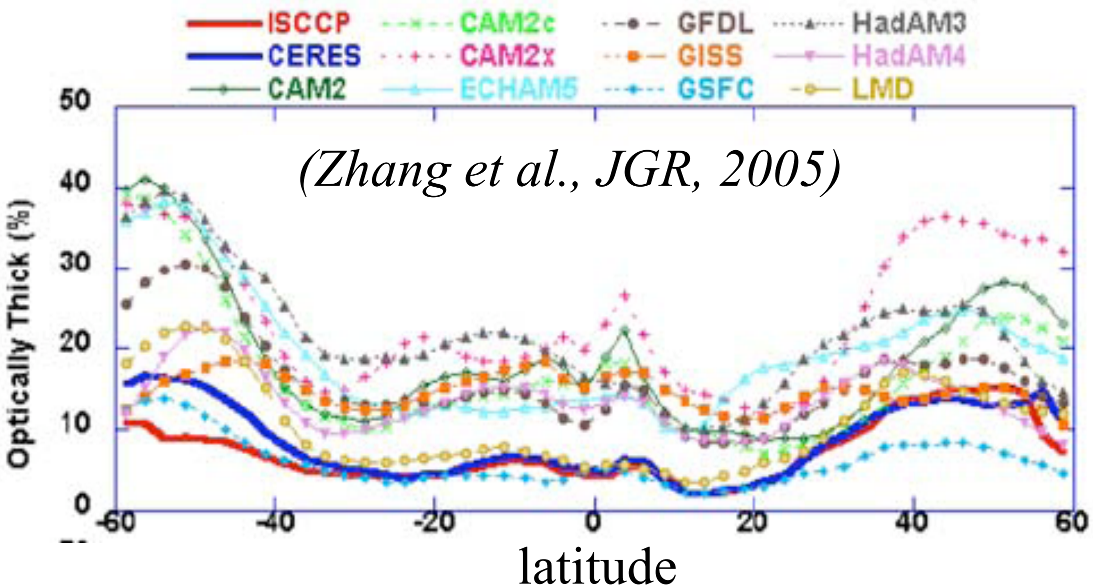


Underestimate of PBL clouds in tropical subsidence regimes

(Wyant et al., GRL, 2007)

Cloud Optical Thickness

• The majority of the models simulate too many optically thick clouds and not enough optically thin and intermediate clouds :



Possible causes :
subgrid-scale cloud scheme,
overlap of cloud layers, inabil
to simulate tilted circulations,

Therefore a good agreement between observed and simulated CRF presumably results from compensating errors.

• *Cloud albedo is not linearily related to cloud optical depth.* This implies that if mean cloud optical depth is wrong, the impact of a given change in cloud water o SW radiation is *also* wrong.

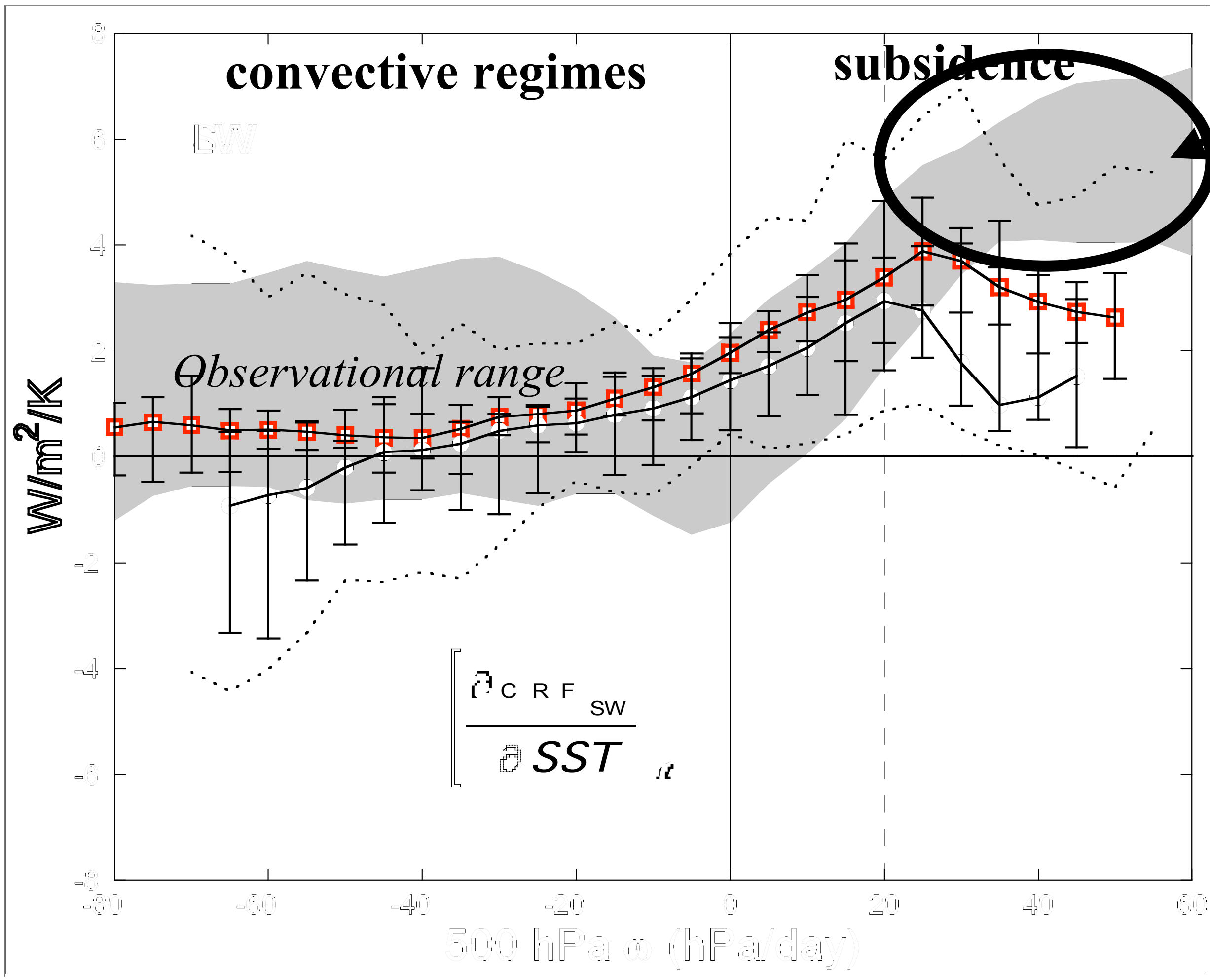
But cloud feedbacks are associated with the RESPONSE of clouds to changing climate conditions.

Therefore, it is NOT SUFFICIENT to evaluate mean cloud properties.

We ALSO have to evaluate the SENSITIVITY of cloud properties to changing environmental conditions.

Sensitivity of the SW CRF to interannual SST changes (an example, not an analogue of climate change)

15 AR4 OAGCMs (20th Century simulations)
vs Observations



Observations sugge
a strong weakening
of the SW CRF as
the SST increases

1984-2000 monthly data

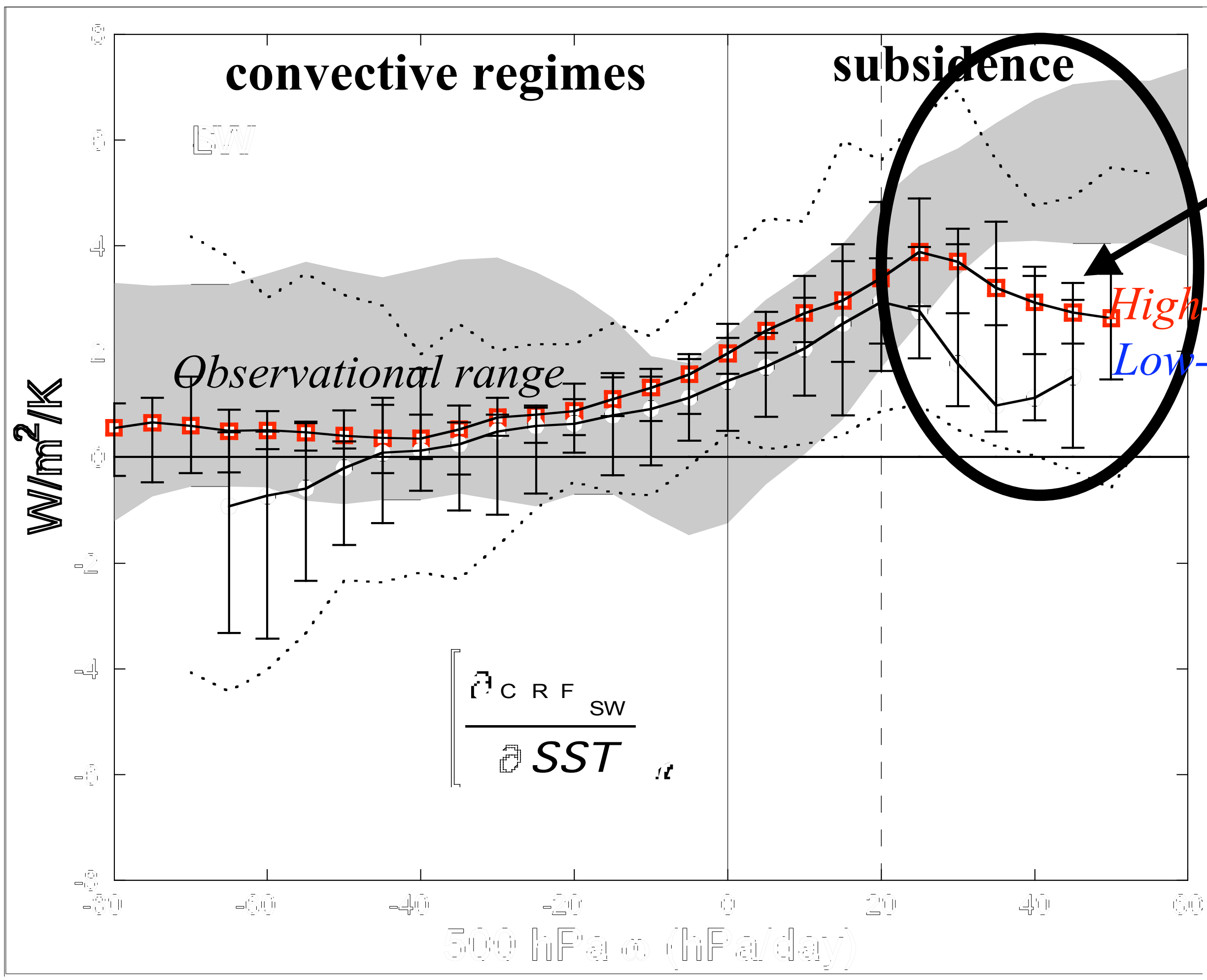
- ISCCP-FD / ERBE rad
- Reynolds SST
- ERA40 / NCEP2 reanal

(Bony and Dufresne, GRL, 2005

Sensitivity of the SW CRF to interannual SST changes
(an example, not an analogue of climate change)

15 AR4 OAGCMs (20th Century simulations)
vs Observations

Systematic underestimation of the SW CRF sensitivity to SST in OAGCMs

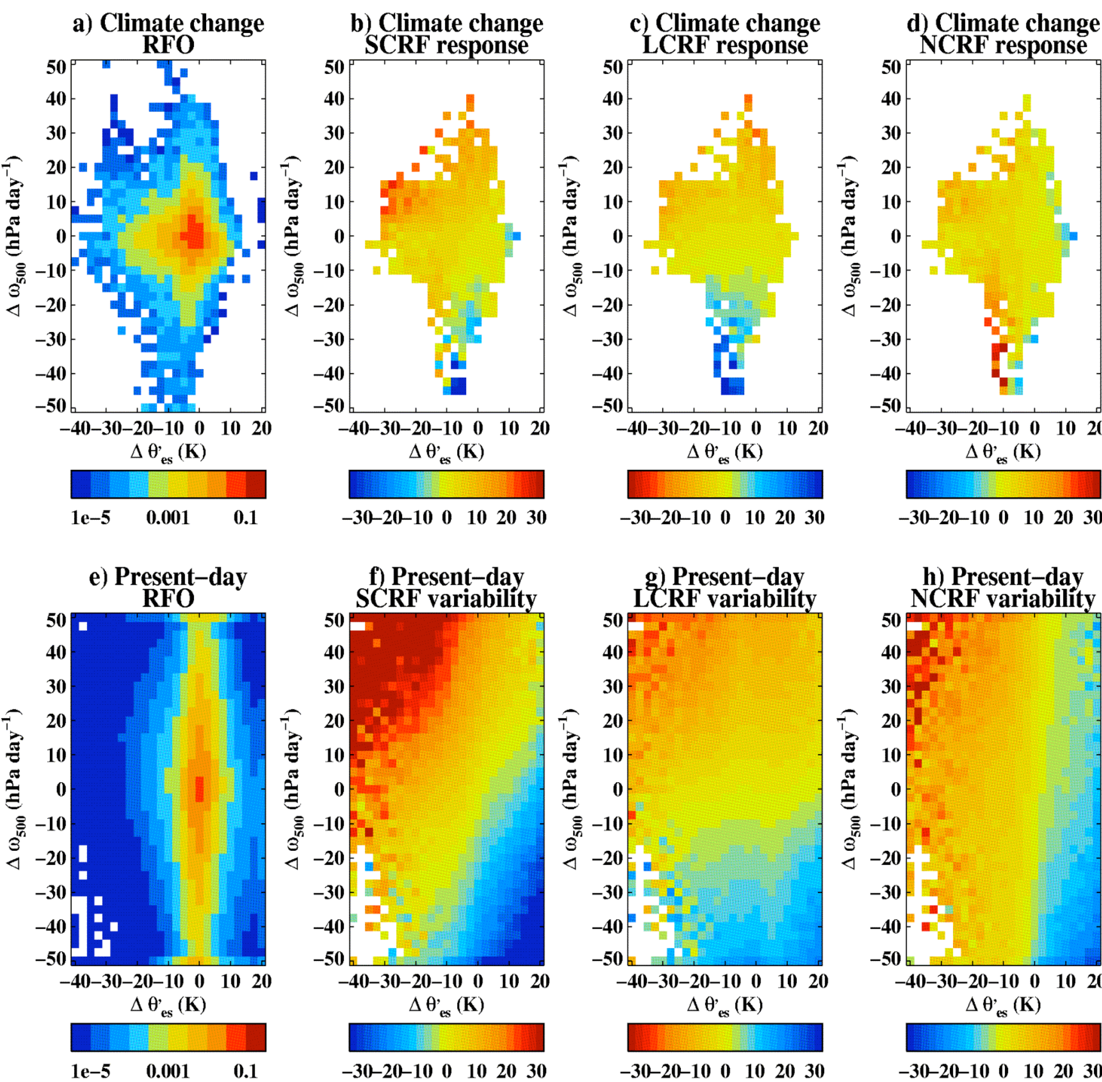


1984-2000 data :

- ISCCP-FD / ERBE rad
- Reynolds SST
- ERA40 / NCEP2 reanal

(Bony and Dufresne, GRL, 2005

Composites of the cloud response to changes in stability and vertical velocity based on present-day variability and climate change



ERBE /ERA SW	ERBE /ERA LW	ERBE/ NCEP SW	ERBE/ NCEP LW	Avg RMS	A C S R
1.2	1.0	1.6	0.9	1.2	3
1.3	1.2	1.3	1.1	1.2	
1.5	1.0	1.9	1.0	1.4	2
1.8	1.2	2.1	1.1	1.5	-4
1.7	1.1	2.2	1.2	1.5	
2.1	1.1	2.3	1.0	1.6	3
2.4	1.0	3.0	1.0	1.9	
1.7	1.6	2.2	1.9	1.9	2
2.2	1.4	2.8	1.5	2.0	-3
3.4	1.3	3.7	1.1	2.4	

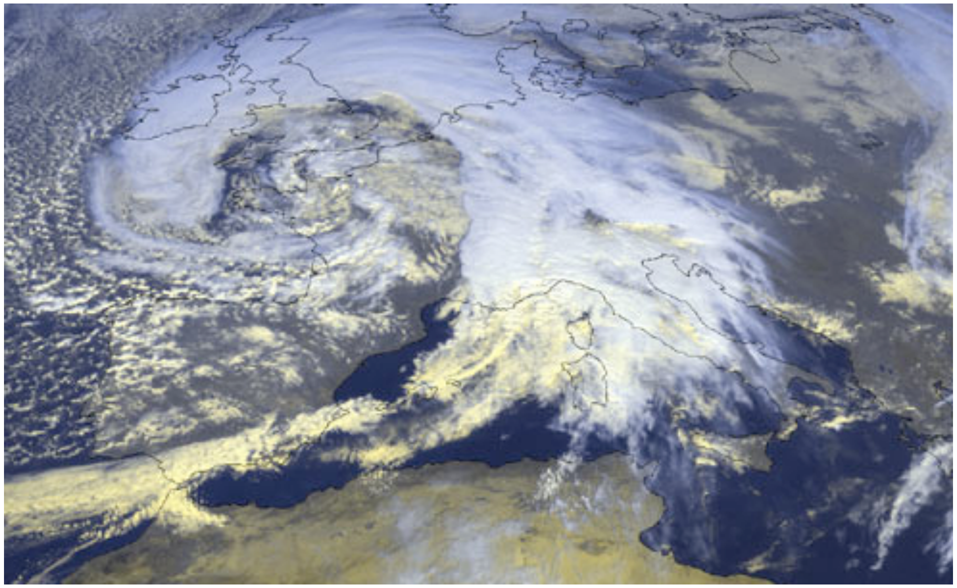
RMS-differences of present-day varia
composites against observations for
10 CFMIP/CMIP model versions.

The five models with smallest RMS e
tend to have higher climate sensitiviti

(Williams et al., Climate Dynamics, 2006 – CFMIP mo

Other examples of processes potentially important for climate change cloud feedbacks:

• Sensitivity of the mid-latitude radiation budget to a change in the frequency / strength of extratropical storms (e.g. Tselioudis and Rossow 2006)



AR4 OAGCMs suggest **a reduction i** **the total number** of extratropical sto but a tendency for **more intense stor**

• Sensitivity of extratropical clouds to a change in surface temperature (e.g. Norris and Iacobellis 2005, Del Genio and Wolf 2000)

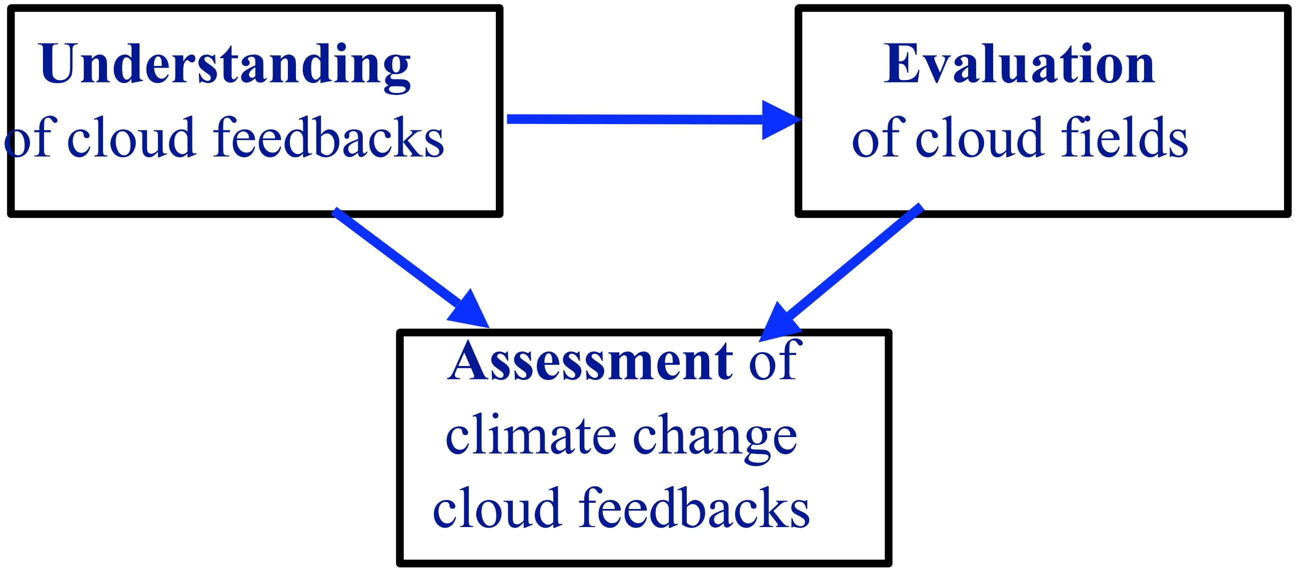
These sensitivities may/should be assessed in a large ensemble of GC

Cloud Feedback Model Intercomparison Project (CFMIP)

CFMIP: a WCRP/WGCM initiative launched in 2003 to encourage coordinated research in the area of cloud feedbacks in climate models (http://www.cfmip.ne

CFMIP-2 (co-coordinators: M. Webb, S. Bony and R. Colman)

Main objective : A better assessment of climate change cloud feedbacks

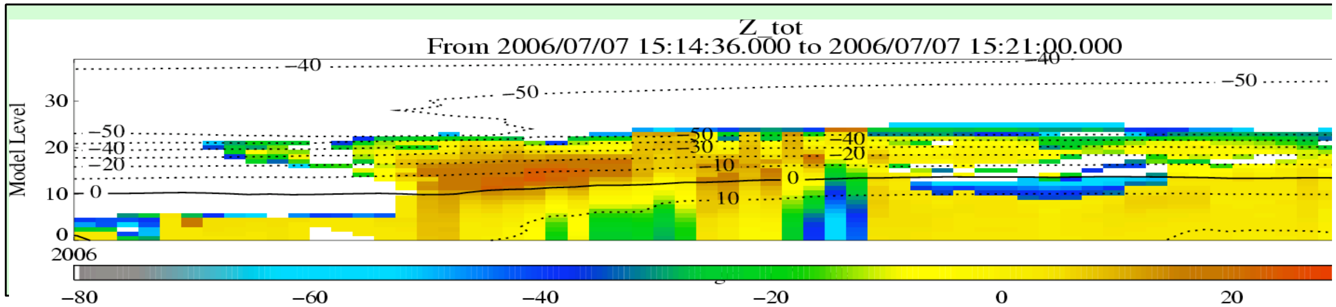


Encourage research in these different areas ;
Distribute and use tools (e.g. ISCCP/CloudSat/CALIPSO simulator) ;
Develop interactions between the different "cloud communities" (GEWEX/GCSS

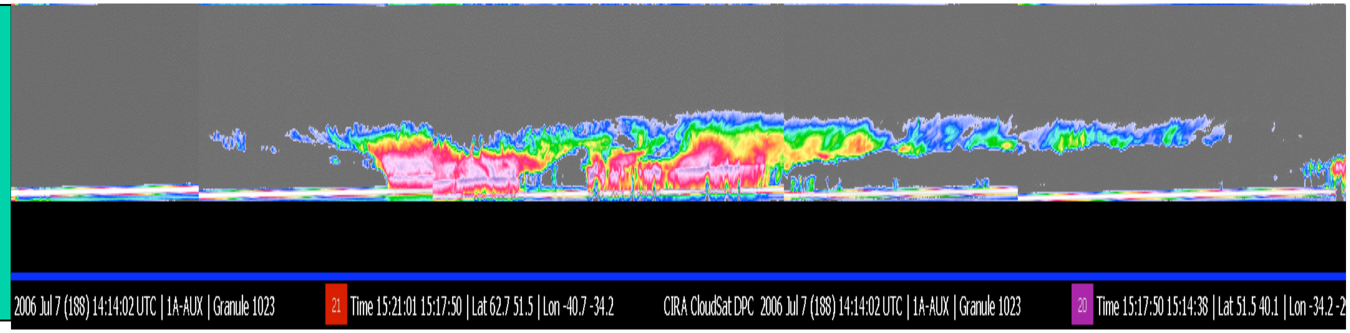
CloudSat / CALIPSO simulators

Alejandro Bodas-Salcedo (Hadley Centre), Marlolaine Chiriaco (LMD/IPSL)

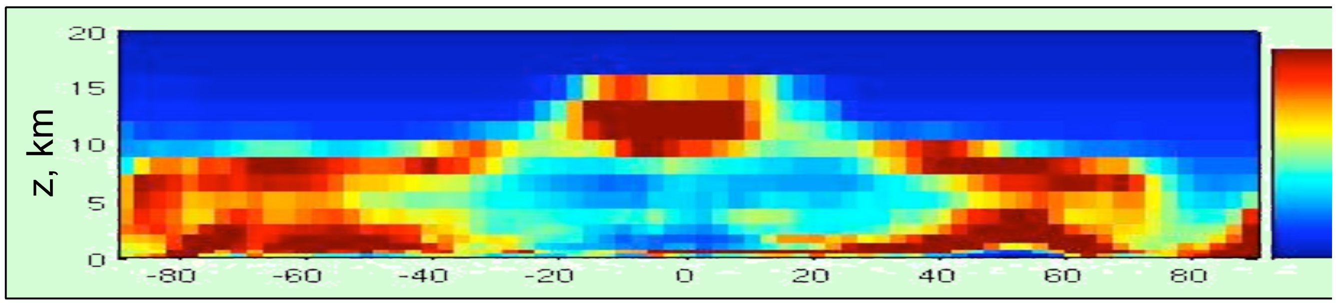
RADAR signal **simulated** from UKMO model



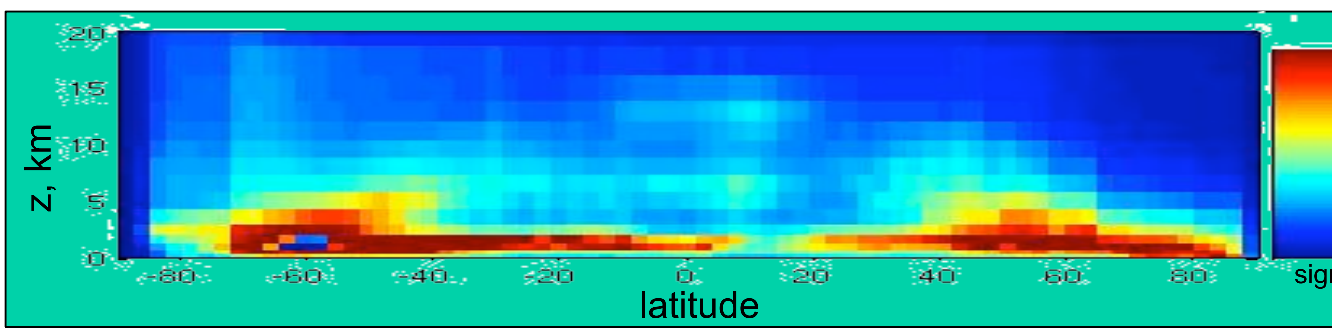
RADAR signal **observed** from CloudSat



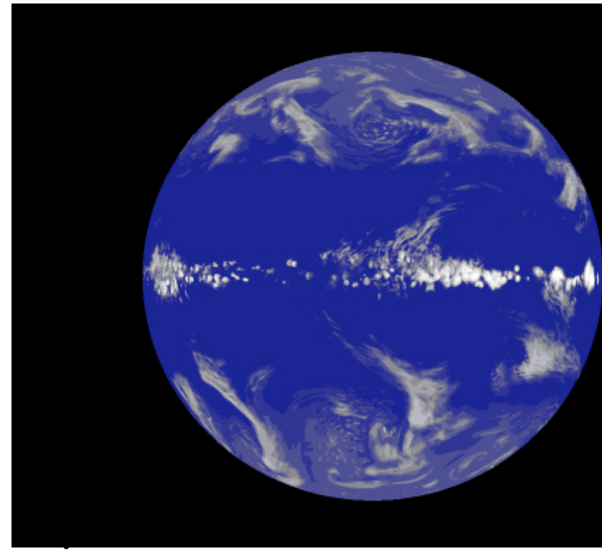
Lidar signal **simulated** from GCM



Lidar signal **observed** from GLAS spatial lidar



What do Models using Cloud-Resolving Models instead of Parameterizations tell us about Cloud Feedbacks ?



Climate sensitivity tests (SST+2K) have been performed using:

• a global aquaplanet CRM *(Miura et al., GRL, 2005)*

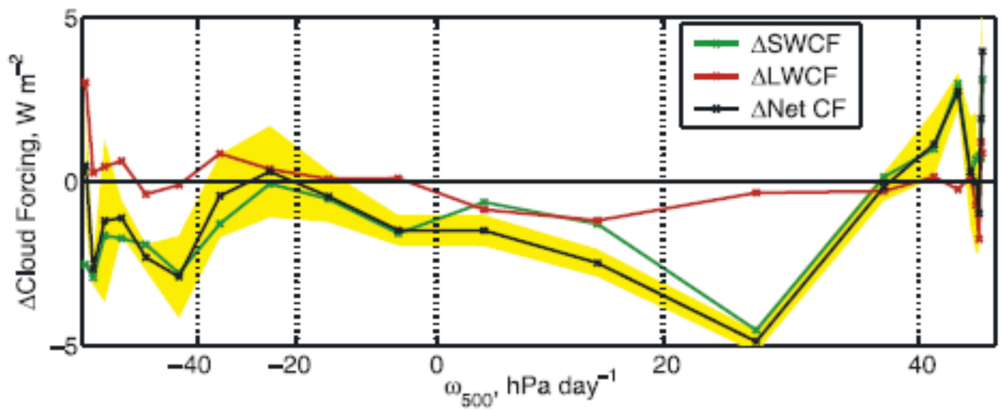
• a CRM embedded in each column of a GCM *(Wyant et al., GRL, 2006)*

What do they tell us ?

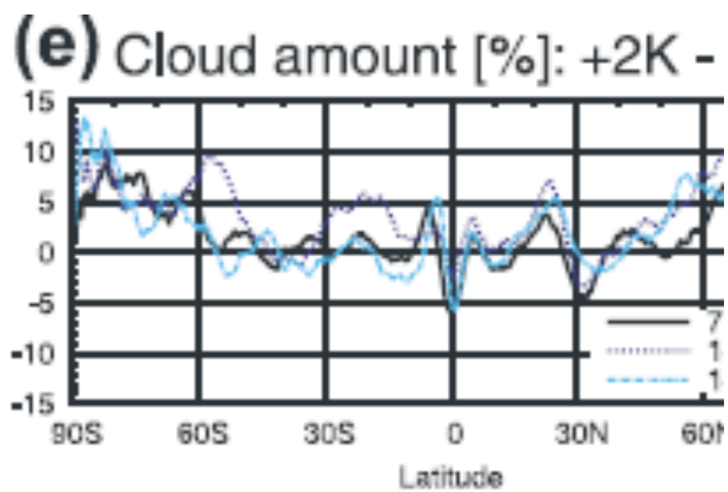
• predict a weaker climate sensitivity than most GCMs

• both predict an increased cloud fraction in the extratropics

• don't agree as well in tropical / subtropical regions



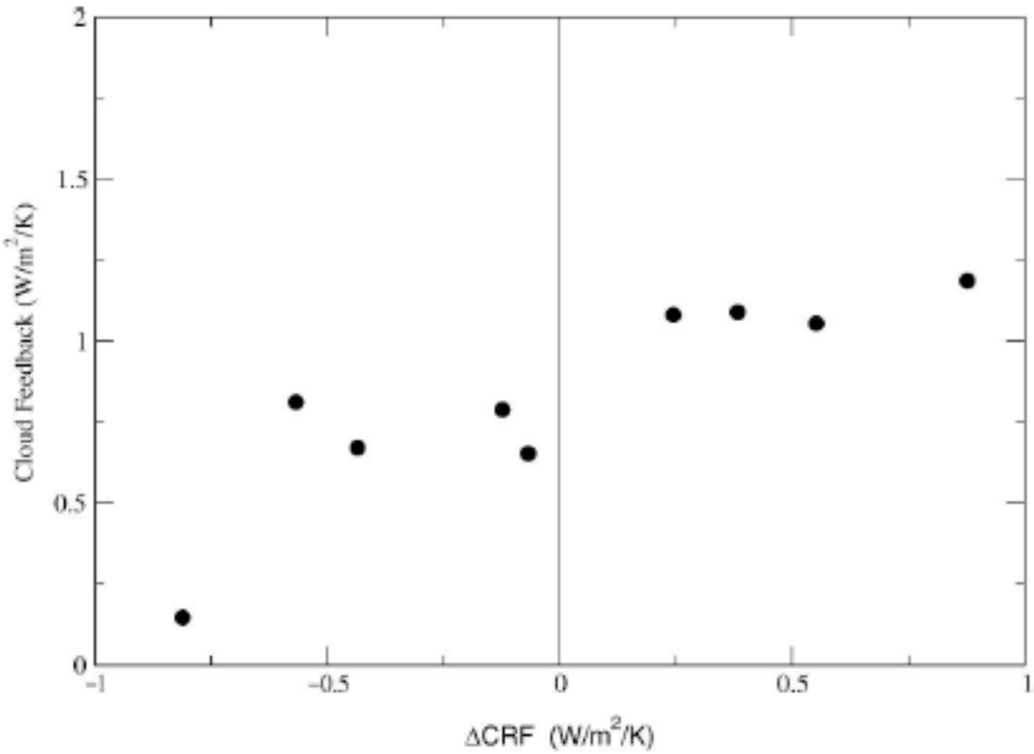
(Wyant et al., GRL, 2006)



(Miura et al., GRL, 2

Thank you

PRP cloud feedback (W/m^2/K)

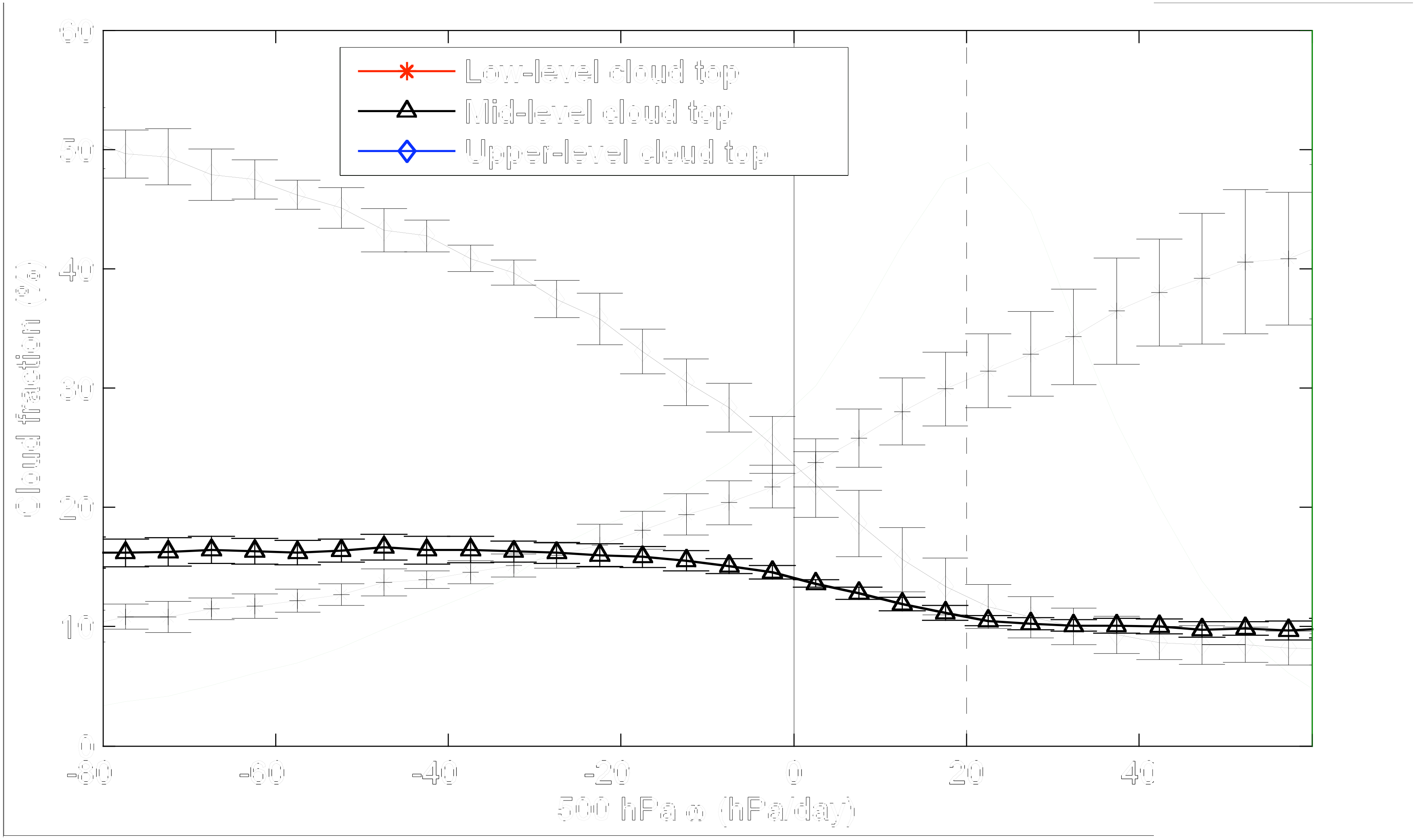


ΔCRF (W/m^2/K)

(Soden and Held, 2006)

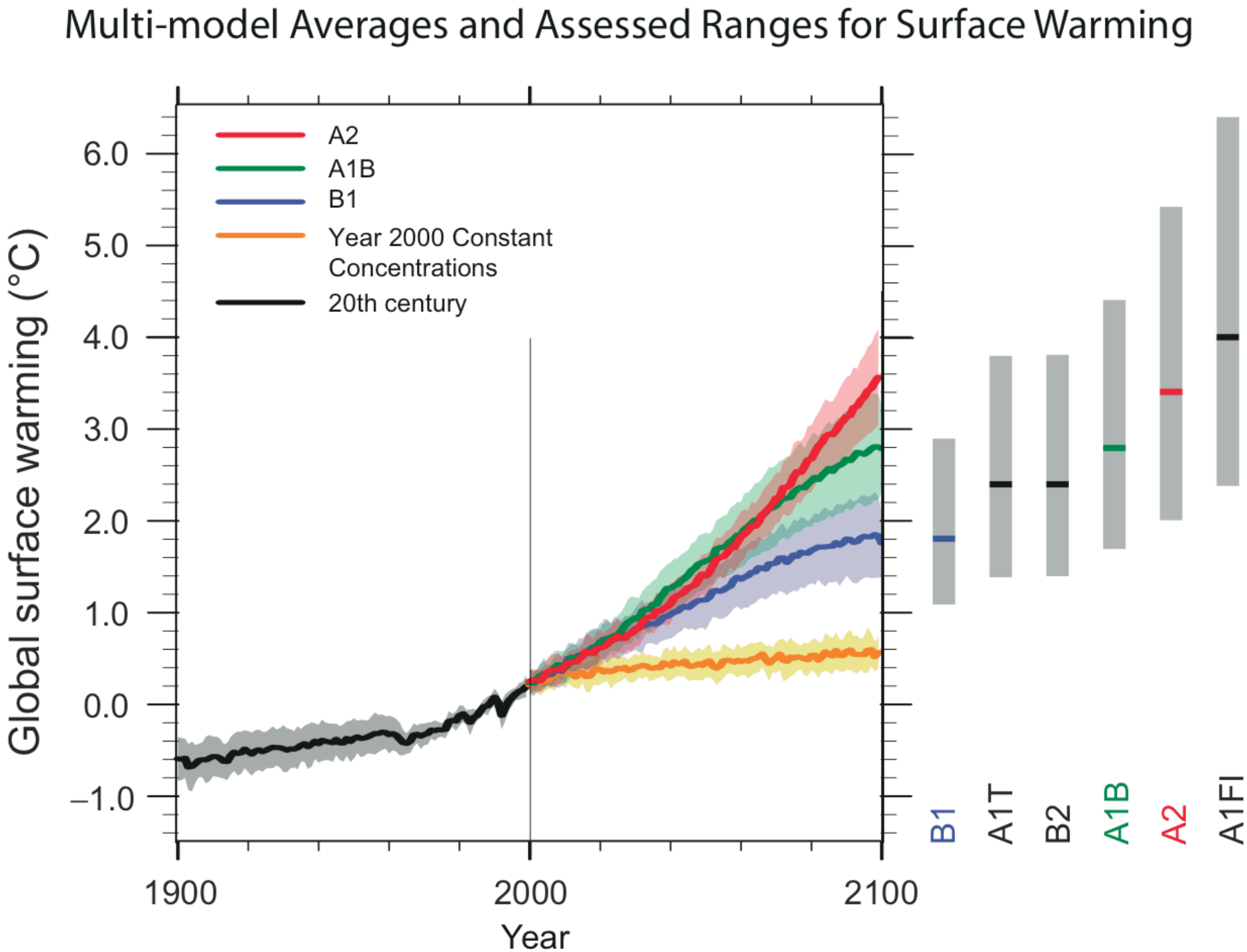
ISCCP Cloud Types sorted by dynamical regimes

Convective regimes Subsidence regimes



(Bony and Dufresne, GRL, 2005

AR4 Global Climate Projections :

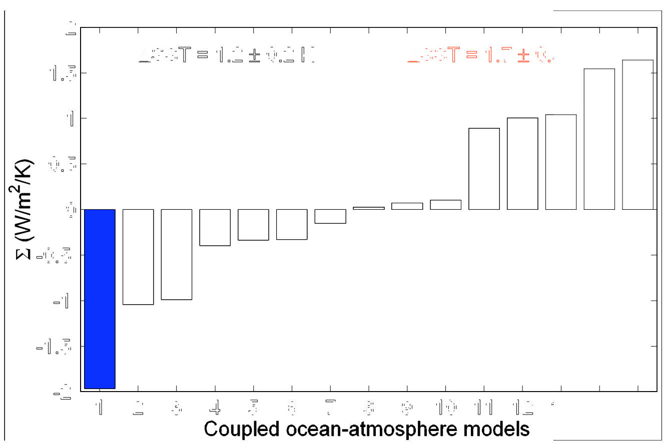


IPCC AR4, 2007

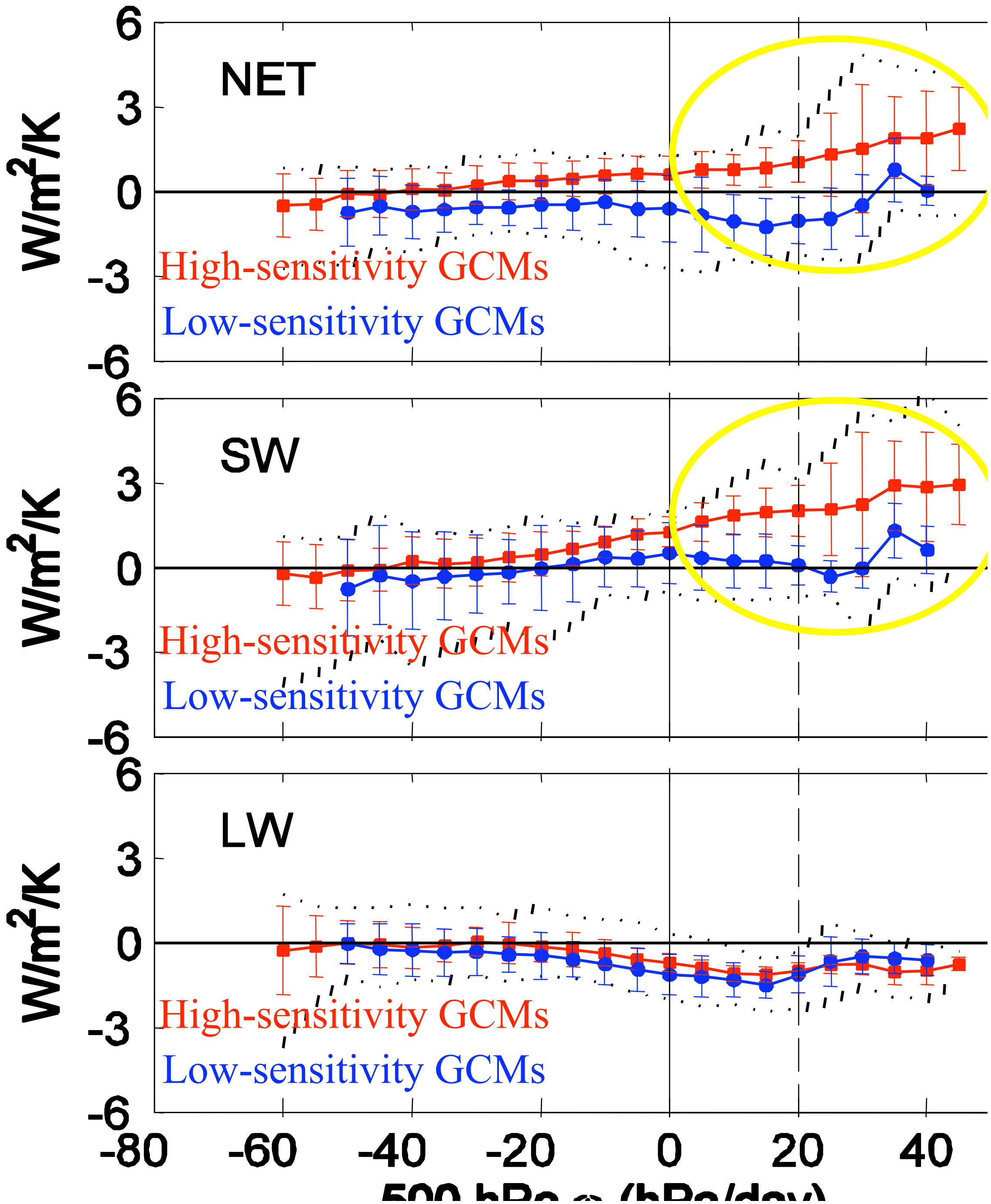
15 AR4 OAGCMs
(+1%/yr CO_2)

Sensitivity of the tropical CRF to long-term SST changes in global warming experiments :

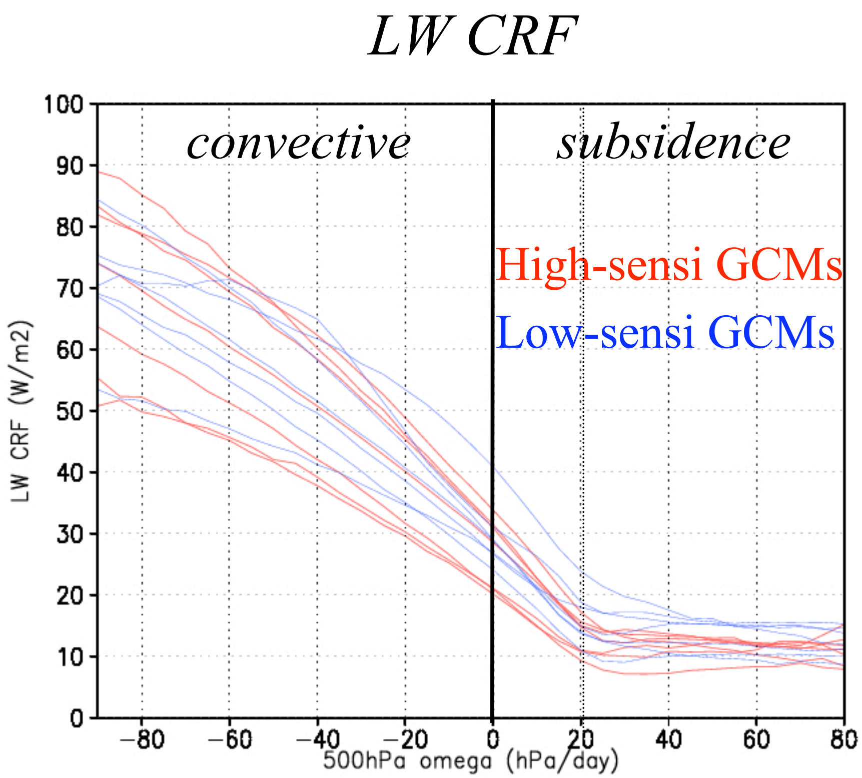
$$\left[\frac{\partial CRF}{\partial SST} \right]_{\omega} \quad (W/m^2/K)$$

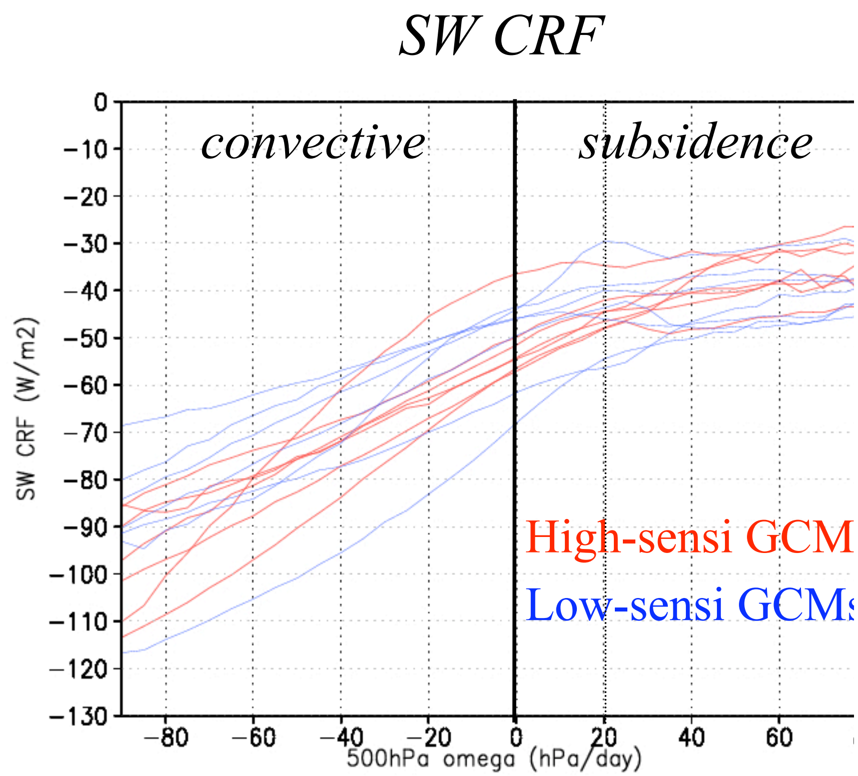


(Bony and Dufresne, GRL, 2005)



AR4 OAGCMs :


LW CRF
convective
subsidence
High-sensi GCMs
Low-sensi GCMs
LW CRF (W/m2)
500hPa omega (hPa/day)


SW CRF
convective
subsidence
High-sensi GCM
Low-sensi GCM
SW CRF (W/m2)
500hPa omega (hPa/day)