Cloud Radiative Feedbacks in GCMs: A Challenge for the Simulation of Climate Sensitivity and Variability

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Thanks to :
Jean-Louis Dufresne & V. Sathiyamoorthy (LMD)
Kerry Emanuel & Dance Zurovac-Jevtic (MIT)
Mark Webb & Keith Williams (Hadley Centre)

Cloud feedbacks have long been recognized as a key source of uncertainty for GCM estimates of climate sensitivity :

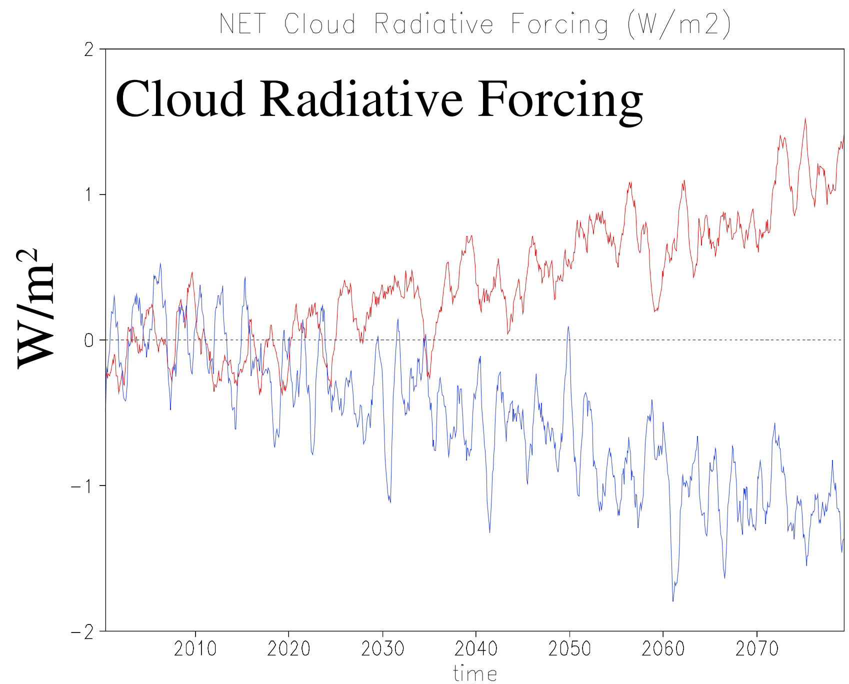
➡ What have we learned from recent (AR4) studies on cloud feedbacks?

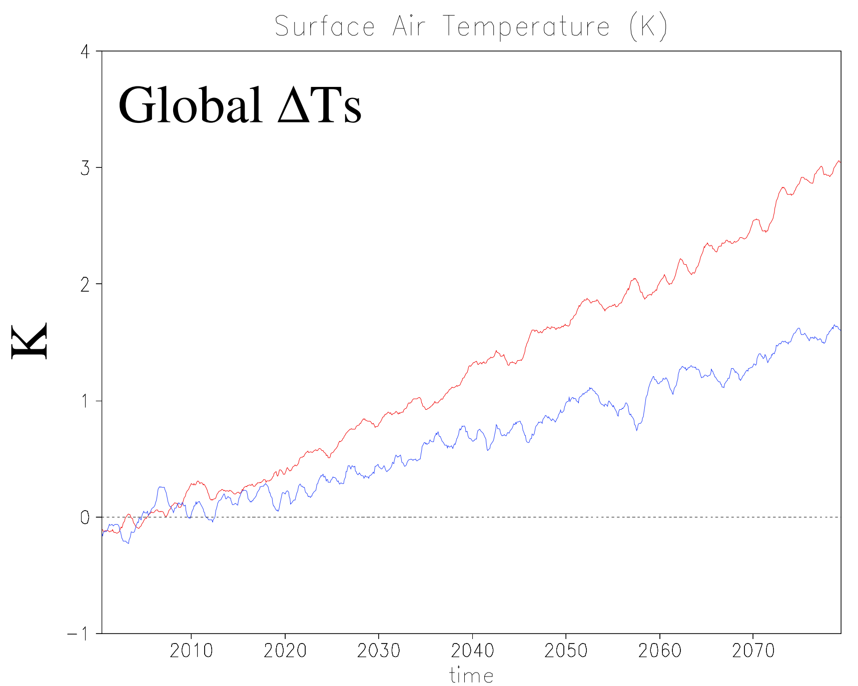
Cloud radiative feedbacks are also a concern for the simulation of natural climate variability by GCMs :

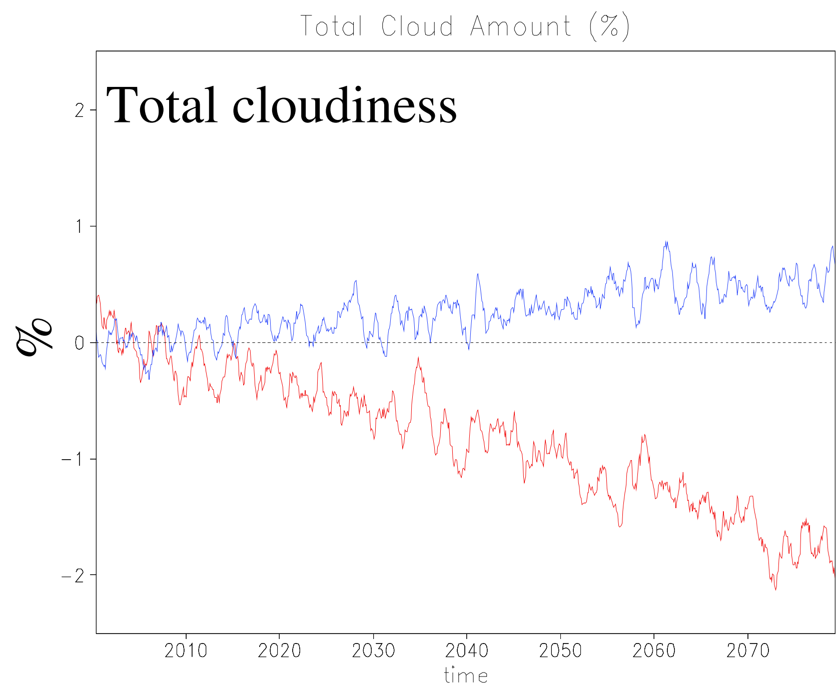
➡ The example of tropical intraseasonal variability…

AR4 OAGCMs
(+1% CO_2/yr):

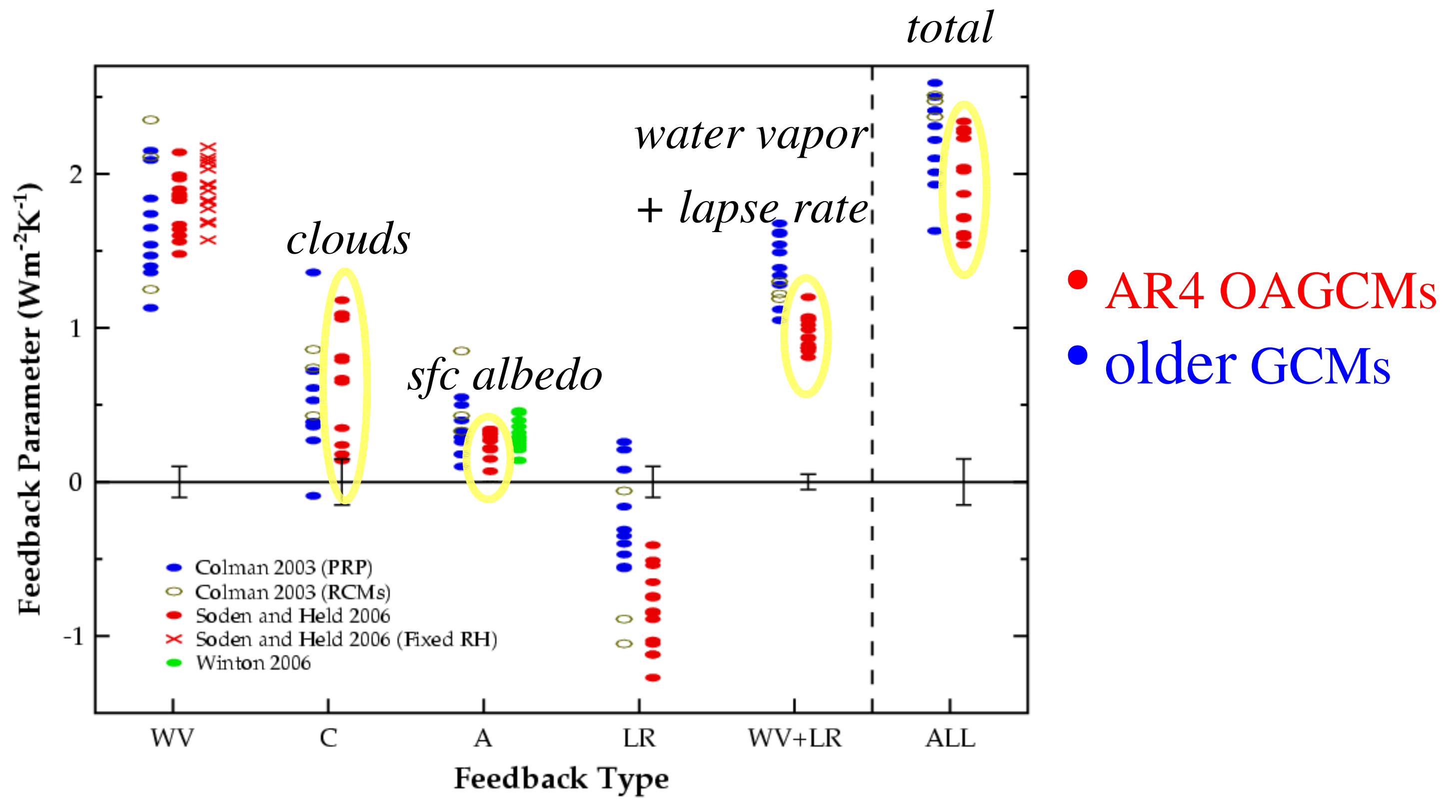
MIROC-HIRES vs NCAR CCSM3







• Cloud feedbacks remain the primary source of inter-model differences in equilibrium Climate Sensitivity!



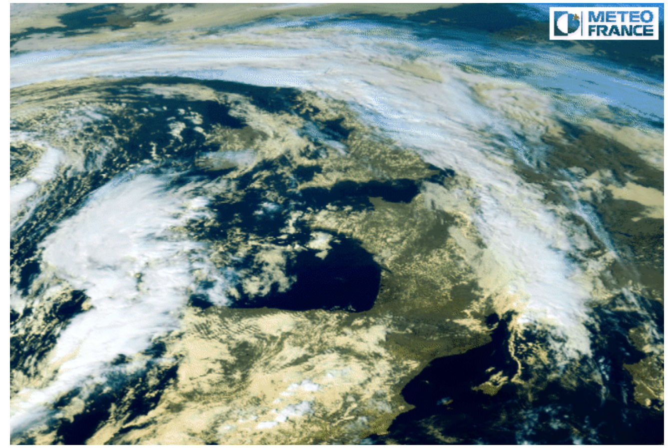
(Bony et al., J. Climate, 2006

after Colman 2003; Soden and Held 2006; Winton 2006)

The spread in cloud feedbacks makes the GCMs' estimates of climate sensitivity vary by roughly a factor of 2 !

Many factors/processes may explain the spread of GCMs' cloud feedbacks...

deep convective clouds



frontal clouds

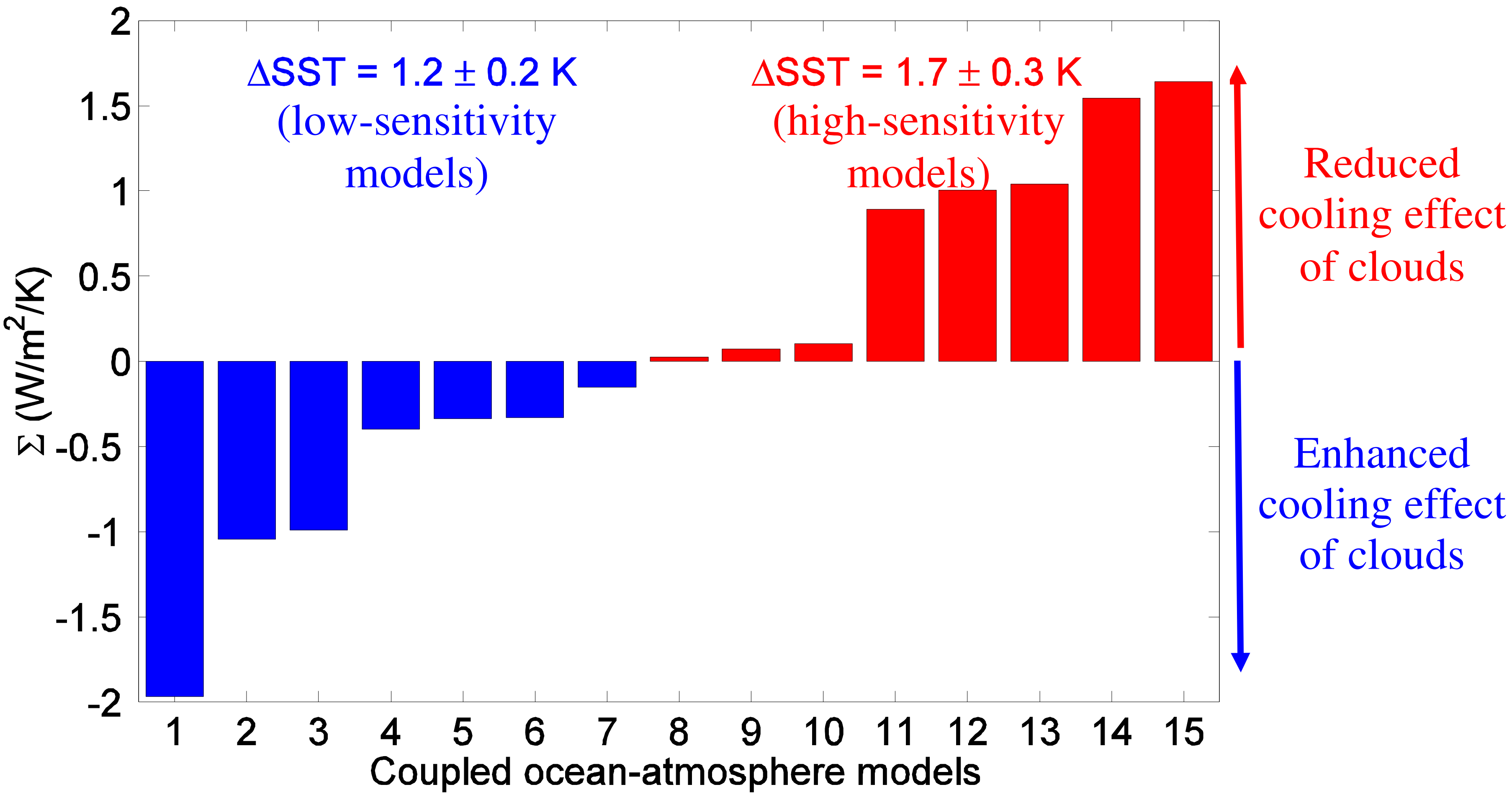
boundary-layer clouds

Thanks to recent model intercomparisons, now we better understand where the spread of cloud feedbacks comes from ...

Coupled Model Intercomparison Project (CMIP)

+1%CO2/yr experiments; 15 OAGCMs (AR4)

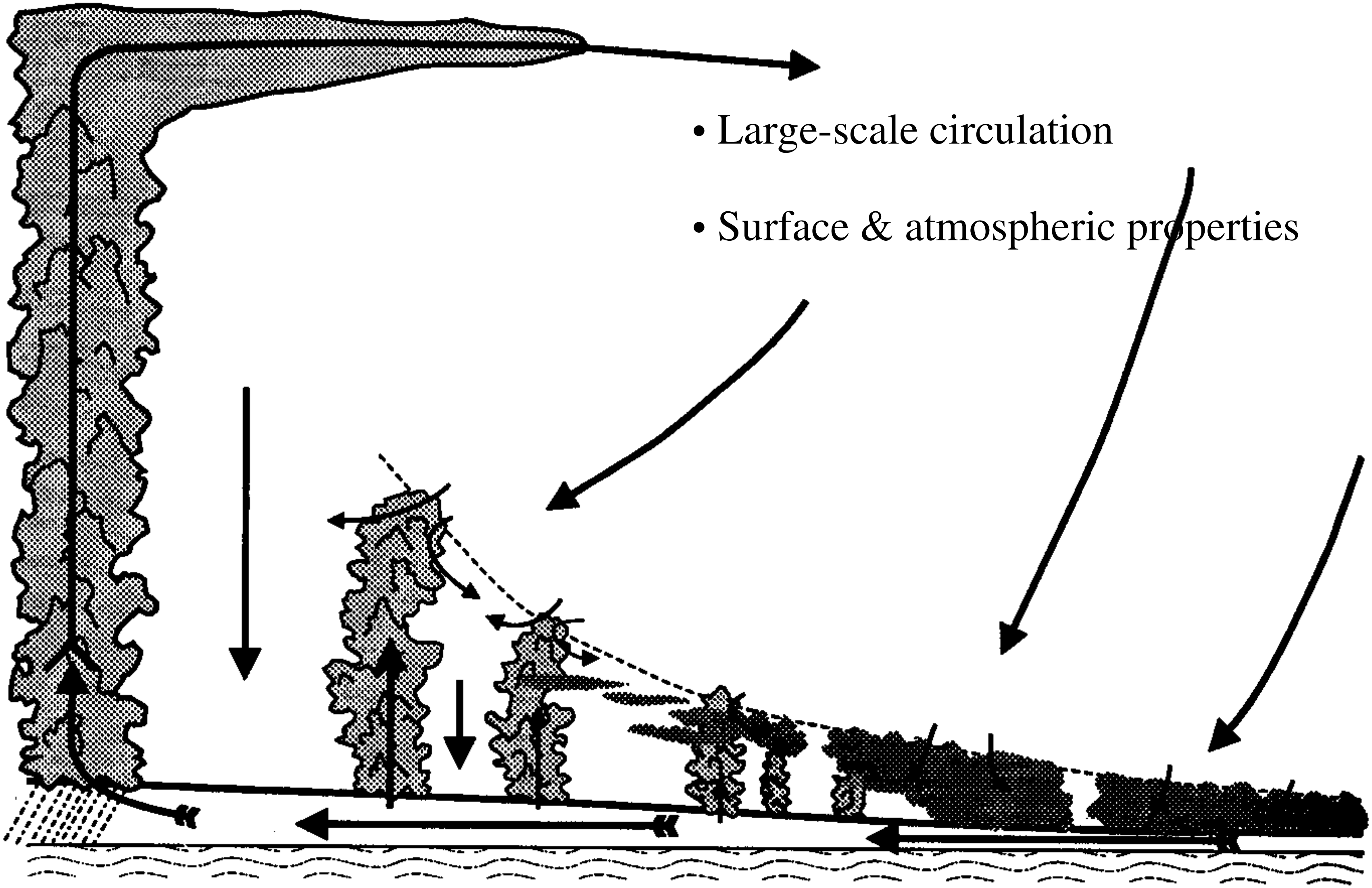
Sensitivity of the tropical NET CRF to surface temperature change in global warming experiments ($W/m^2/K$)



(Bony and Dufresne, GRL, 2005)

What controls the response of tropical clouds to climate change?

- Large-scale circulation
- Surface & atmospheric properties



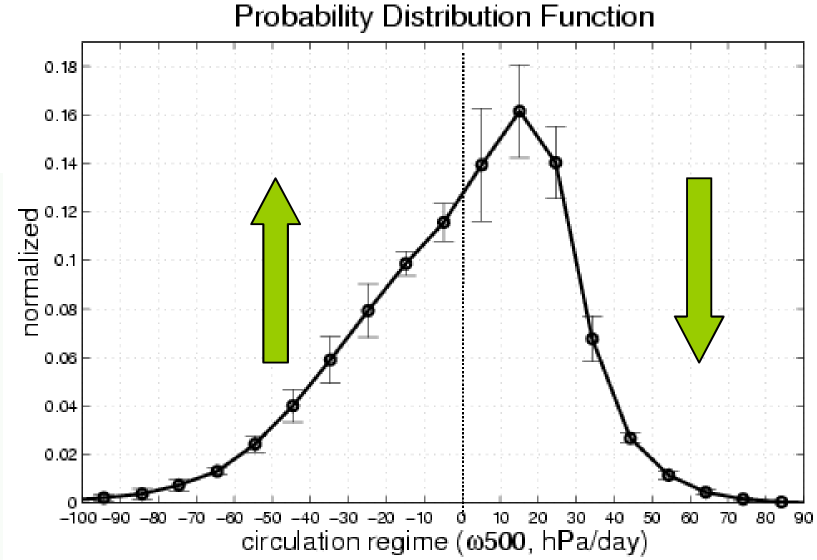
Analysis method

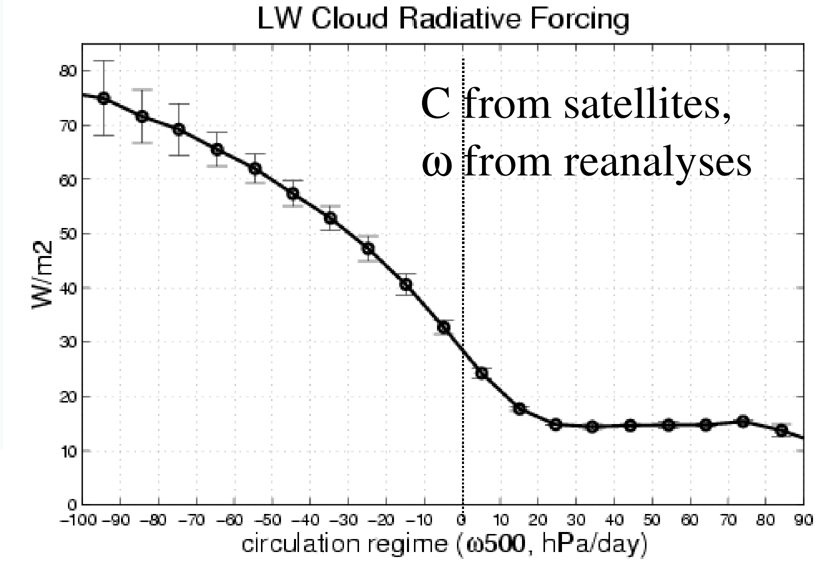
- Proxy ω of large-scale motions: ω_{500hPa}.

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

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

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



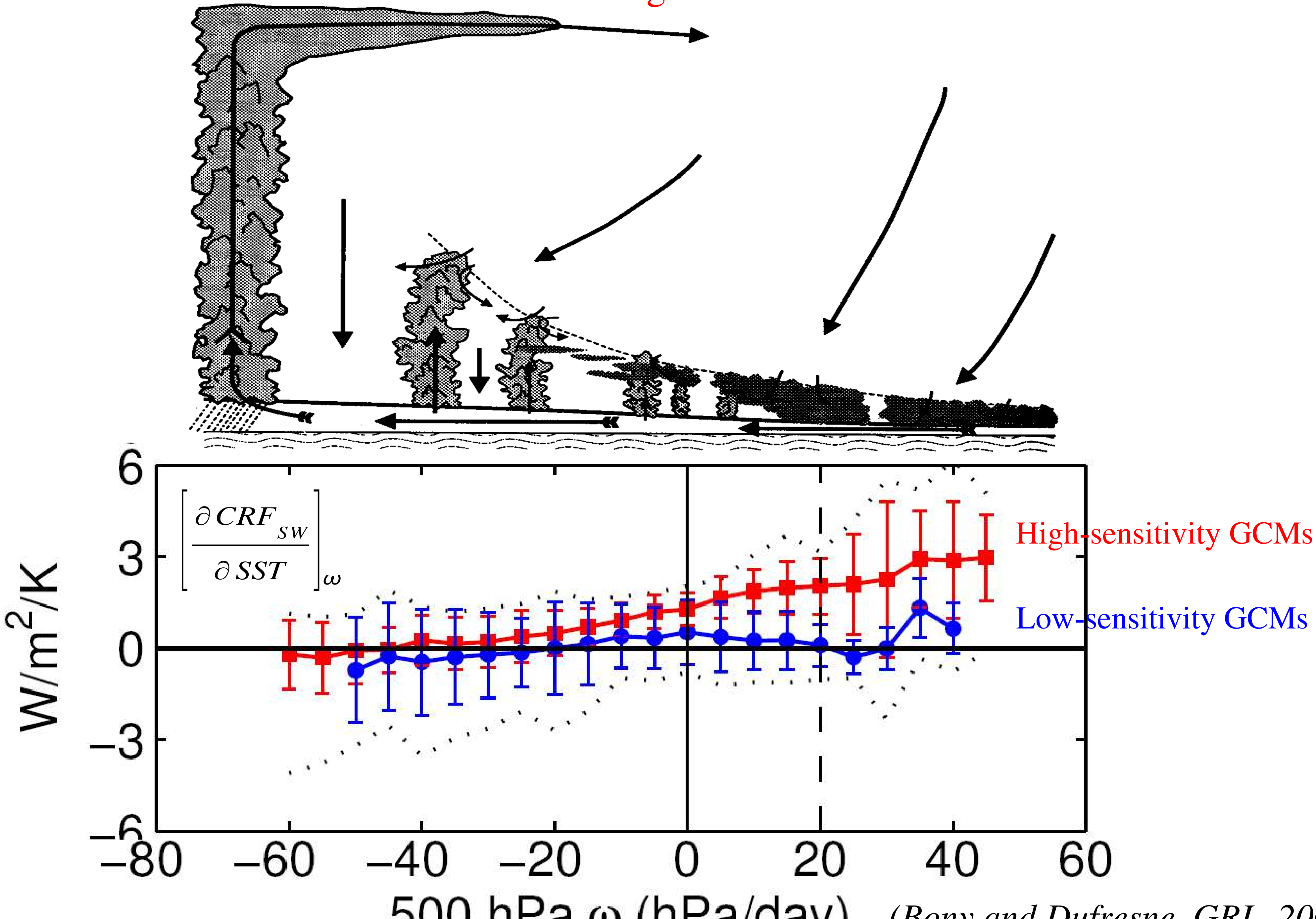


$$\overline{\delta C} = \int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega + \int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega + \int_{-\infty}^{+\infty} \delta P_\omega \, \delta C_\omega \, d\omega$$

dynamic component | **thermodynamic component** | **Co-variation**

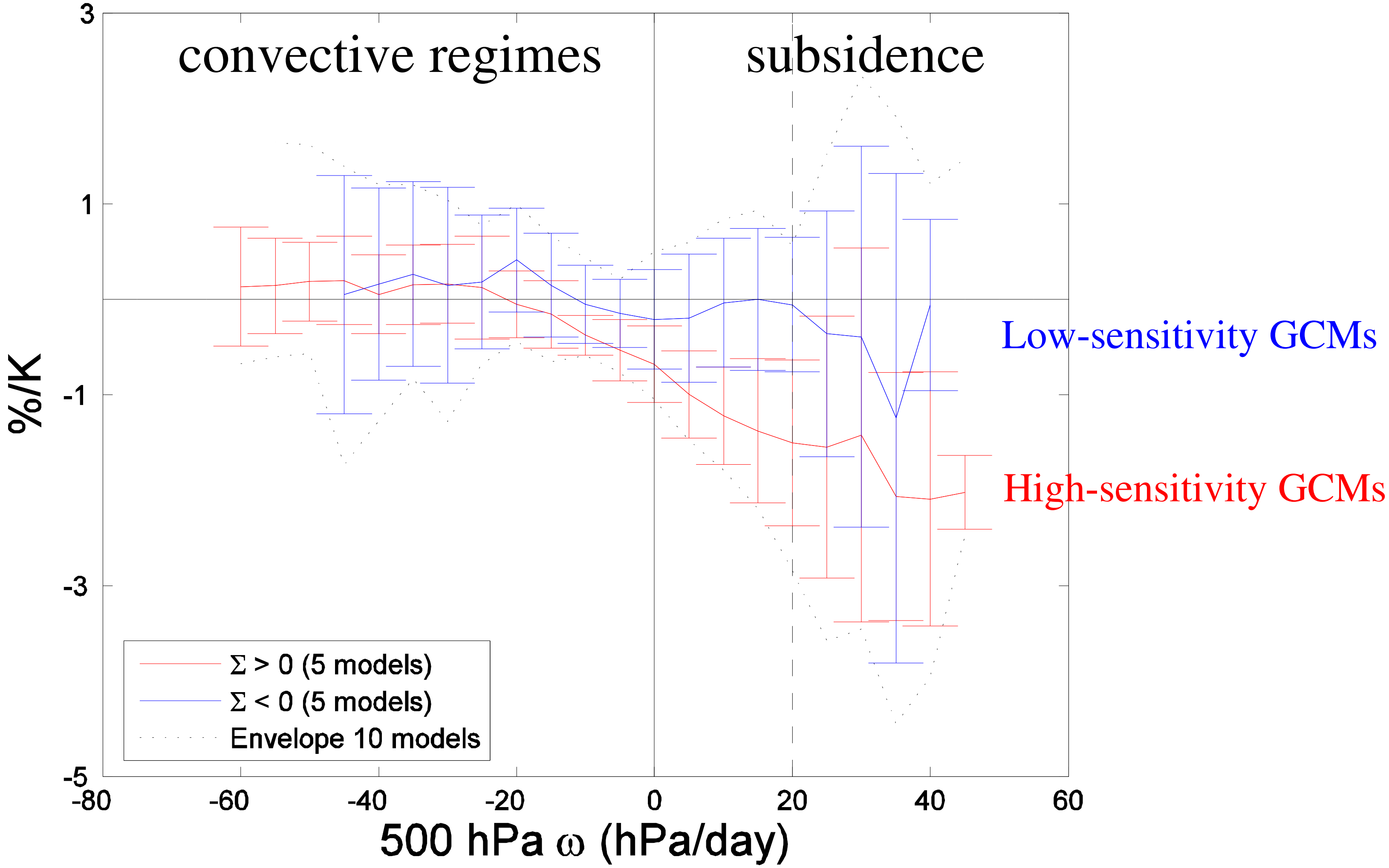
(Bony et al., Climate Dynamics, 2004)

Sensitivity of the Tropical Cloud Radiative Forcing to Global Warming in 15 AR4 OAGCMs



(Bony and Dufresne, GRL, 2005)

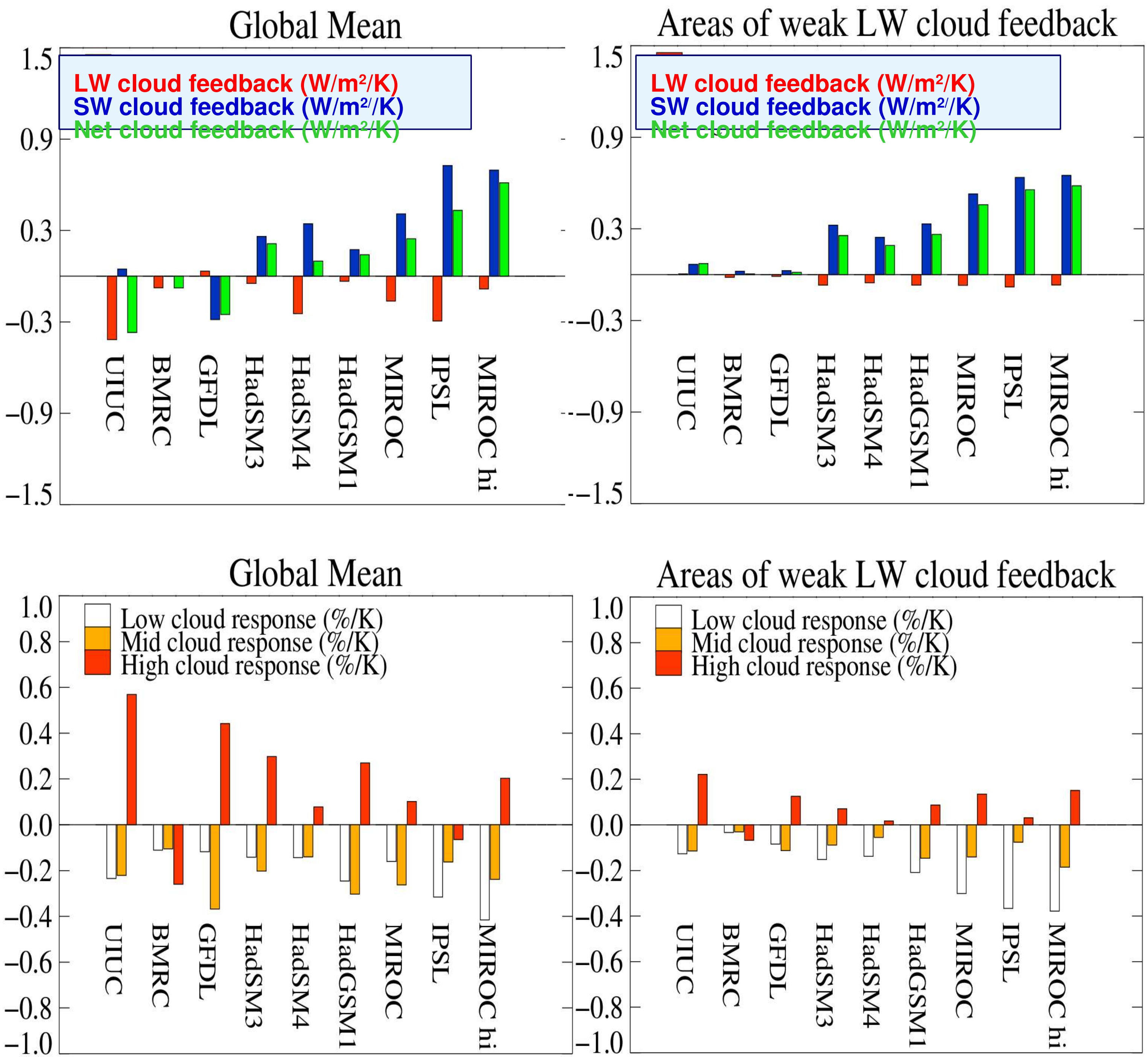
Sensitivity of the total cloud fraction to climate warming :



(V. Sathiyamoorthy)

Huge inter-model differences in subsidence regions !

(Webb et al., Climate Dynamics, 2006 – CFMIP models)



Areas with small LW cloud feedbacks explain 59% of the NET cloud feedback ensemble variance

Cloud feedbacks in these areas are dominated by changes in **low-level cloud amount** (shown with ISCCP simulator)

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

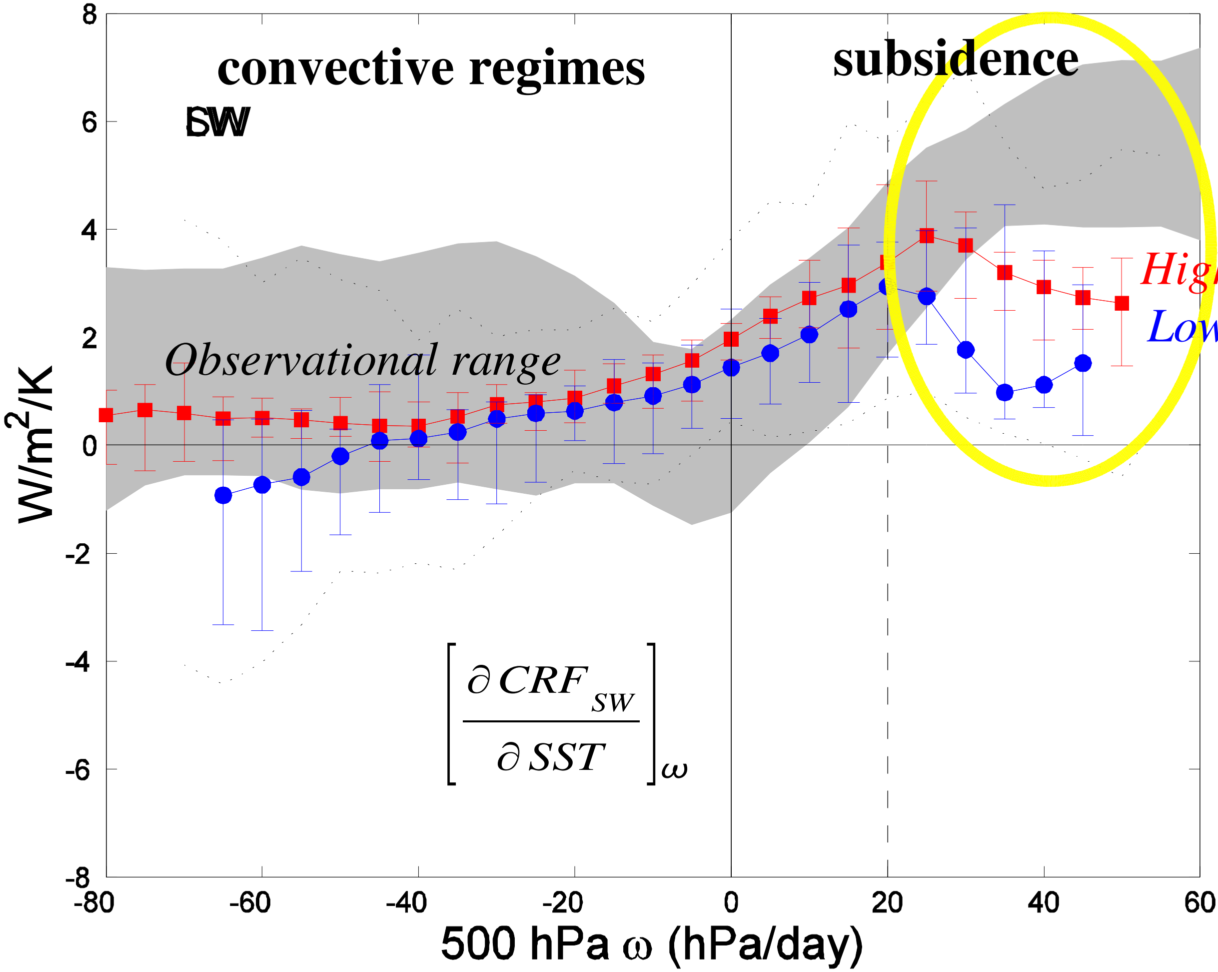
- Recent studies point to low-cloud cover as a primary culprit.

... Which of the model cloud feedbacks are the more reliable ?

This we don't know yet ...

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

15 AR4 OAGCMs (20th Century simulations) vs Observations



High-Sensitivity models

Low-Sensitivity models

Observational estimates :

- ISCCP-FD or ERBE fluxes
- Reynolds SST
- ERA40 or NCEP2 reanalyses

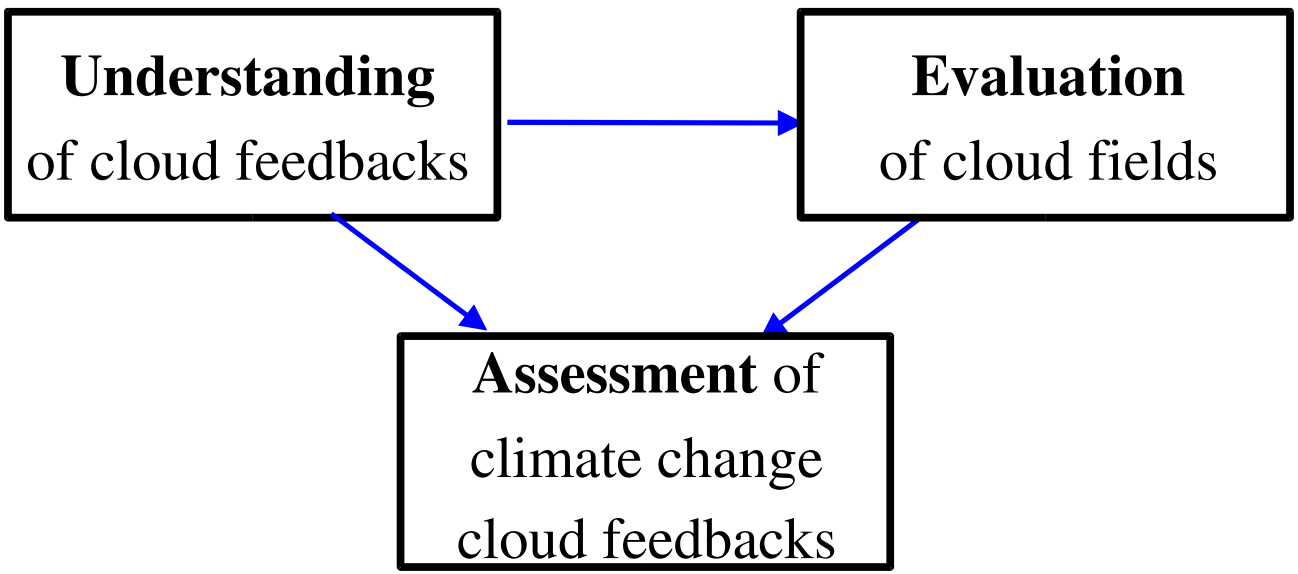
(Bony and Dufresne, GRL, 2005)

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.net).

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

Main objective : A better assessment of climate change cloud feedbacks



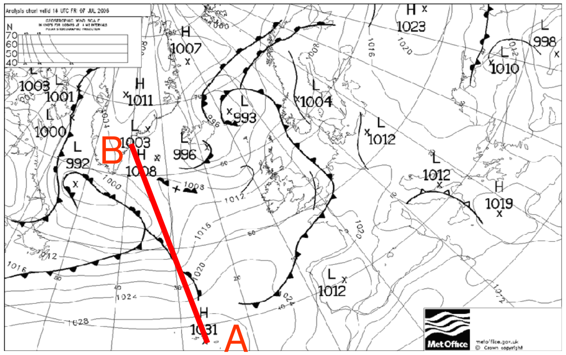
Encourage research in these different areas ;

Develop interactions between the different "cloud communities" (e.g. GCSS) ;

Develop and distribute tools (e.g. ISCCP/CloudSat/CALIPSO simulator) ;

CloudSat simulator

(Alejandro Bodas-Salcedo & Mark Webb, Hadley Centre)

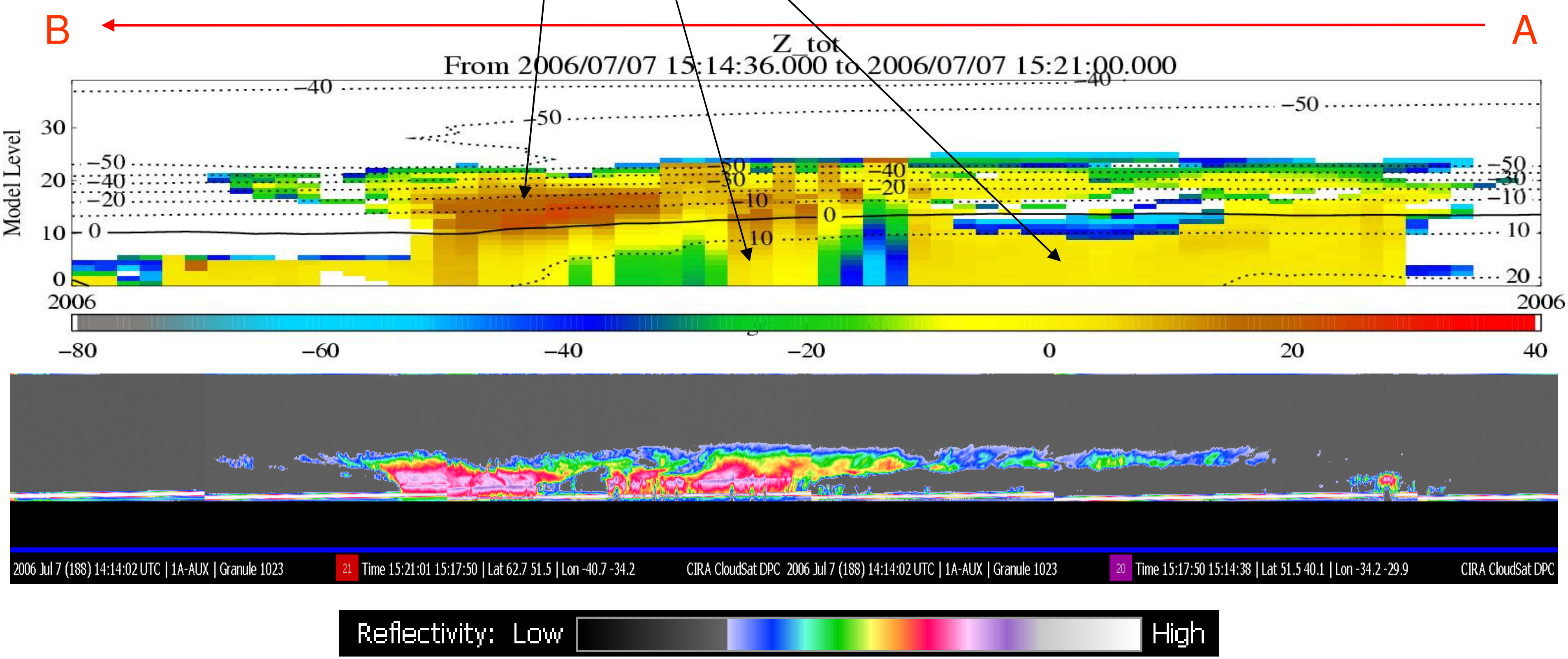


Transect trough a mature extra-tropical system

Strong signal from ice clouds

Strong signal from precipitation

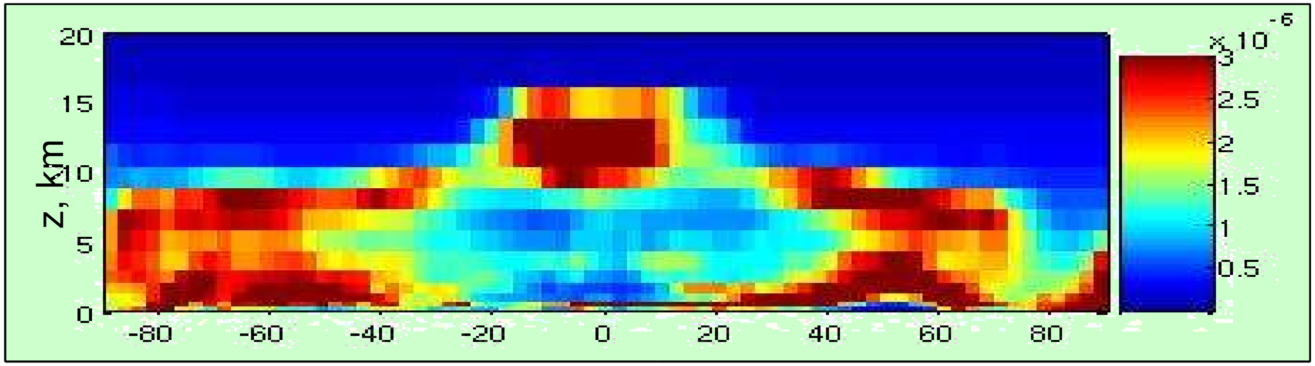
Cloud and precip not present in obs



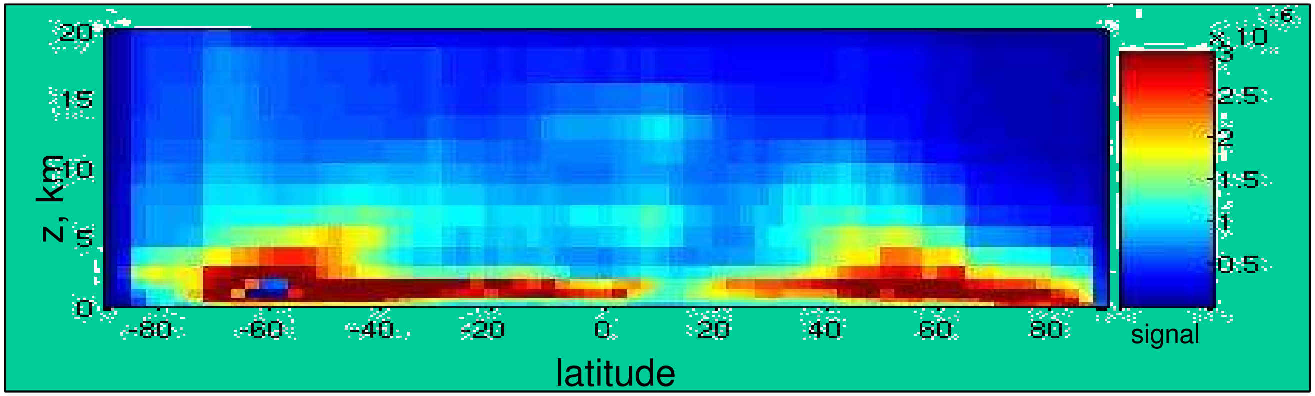
ACTSIM/CALIPSO simulator

(Marjolaine Chiriaco & Helene Chepfer, LMD/IPSL)

<u>Lidar signal</u> **simulated**
from GCM outputs



<u>Lidar signal</u> **observed**
from GLAS spatial lidar



NB: preliminary result (no subgrid-scale sampling)

Evaluation (at the global scale) of the vertical structure

of clouds simulated by GCMs !

Tropical Intraseasonal Variability in 14 IPCC AR4 Climate Models. Part I: Convective Signals

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Journal of Climate (June 2006)

- Current state-of-the art GCMs still have significant problems and display a wide range of skill in simulating the tropical intraseasonal variability.

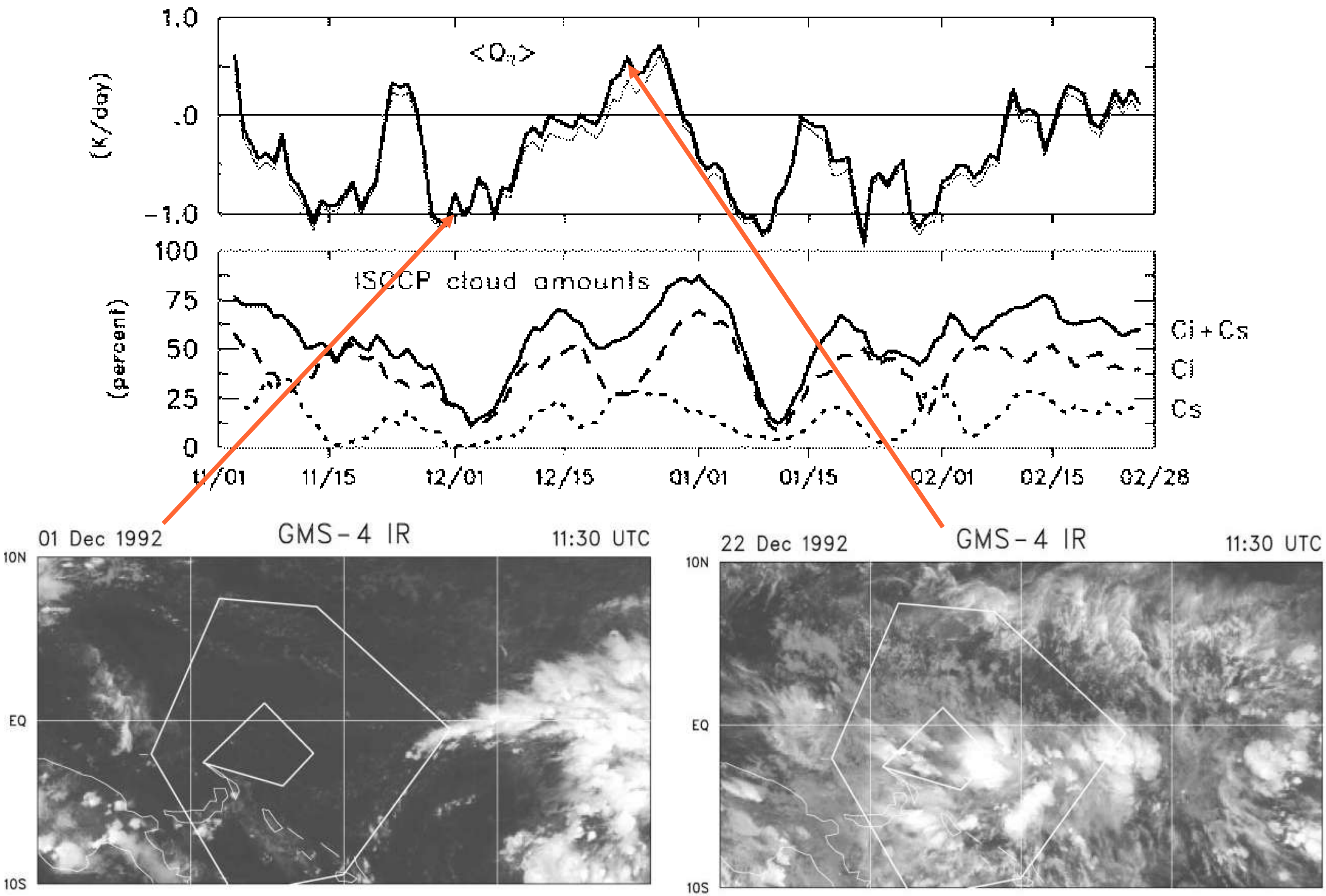
- Lack of highly coherent eastward propagation of the MJO in many models.

- The phase speeds of convectively coupled equatorial waves are generally too fast, suggesting that these models may not have a large enough reduction in their “effective static stability” by diabatic heating.

May the simulation of cloud radiative processes and feedbacks explain part of these problems ?

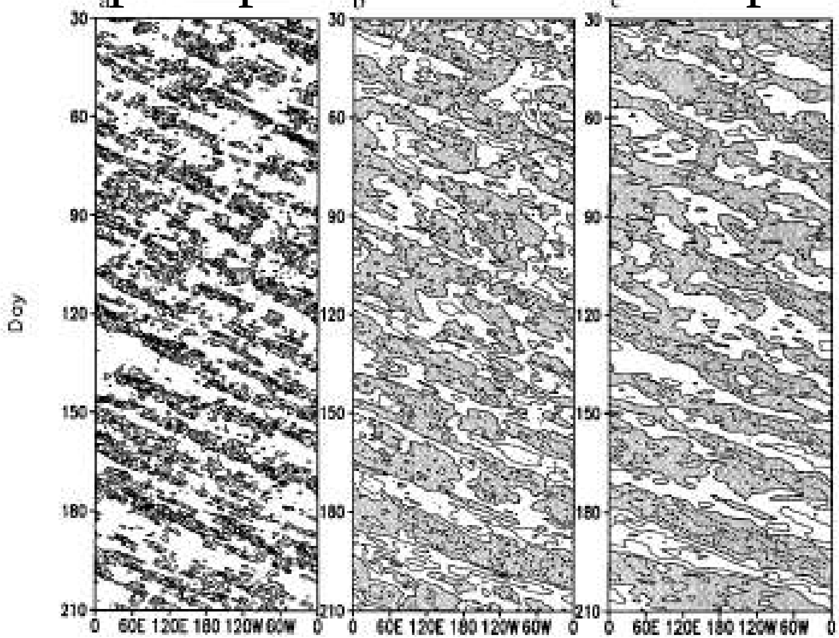
TOGA COARE has revealed large variations of the tropospheric radiative cooling in the tropical atmosphere:

(Johnson and Ciesielski 2000)

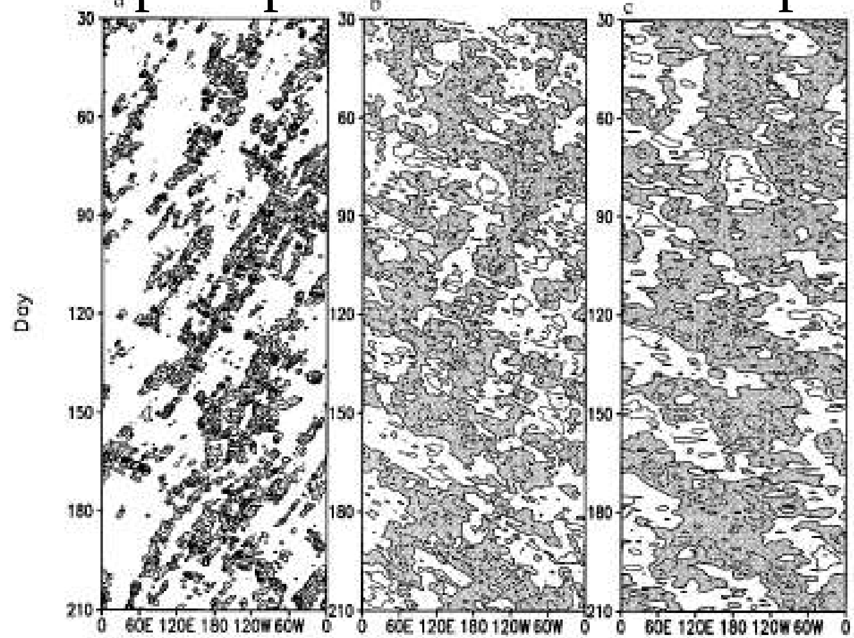


Influence of cloud-radiation interaction on simulating tropical intraseasonal oscillation with a GCM (Lee et al. 2001)

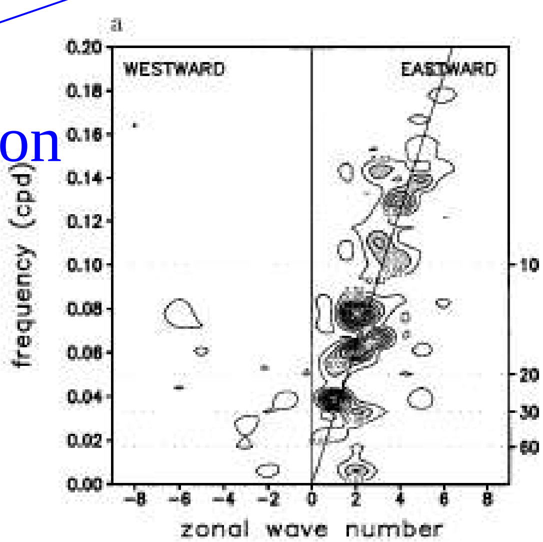
precip u200 200vel.pot.

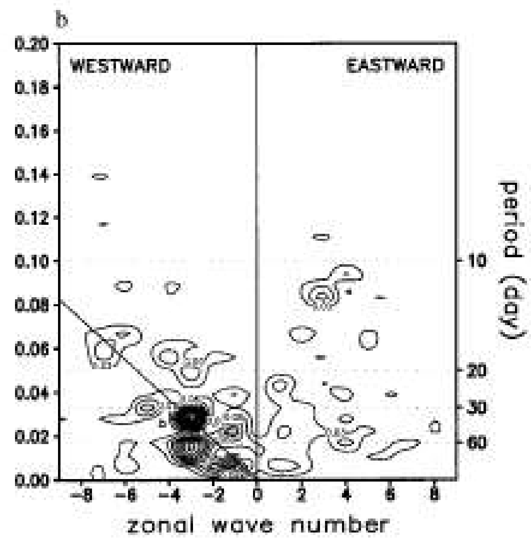


precip u200 200vel.pot.



Fixed
Cloud-radiation

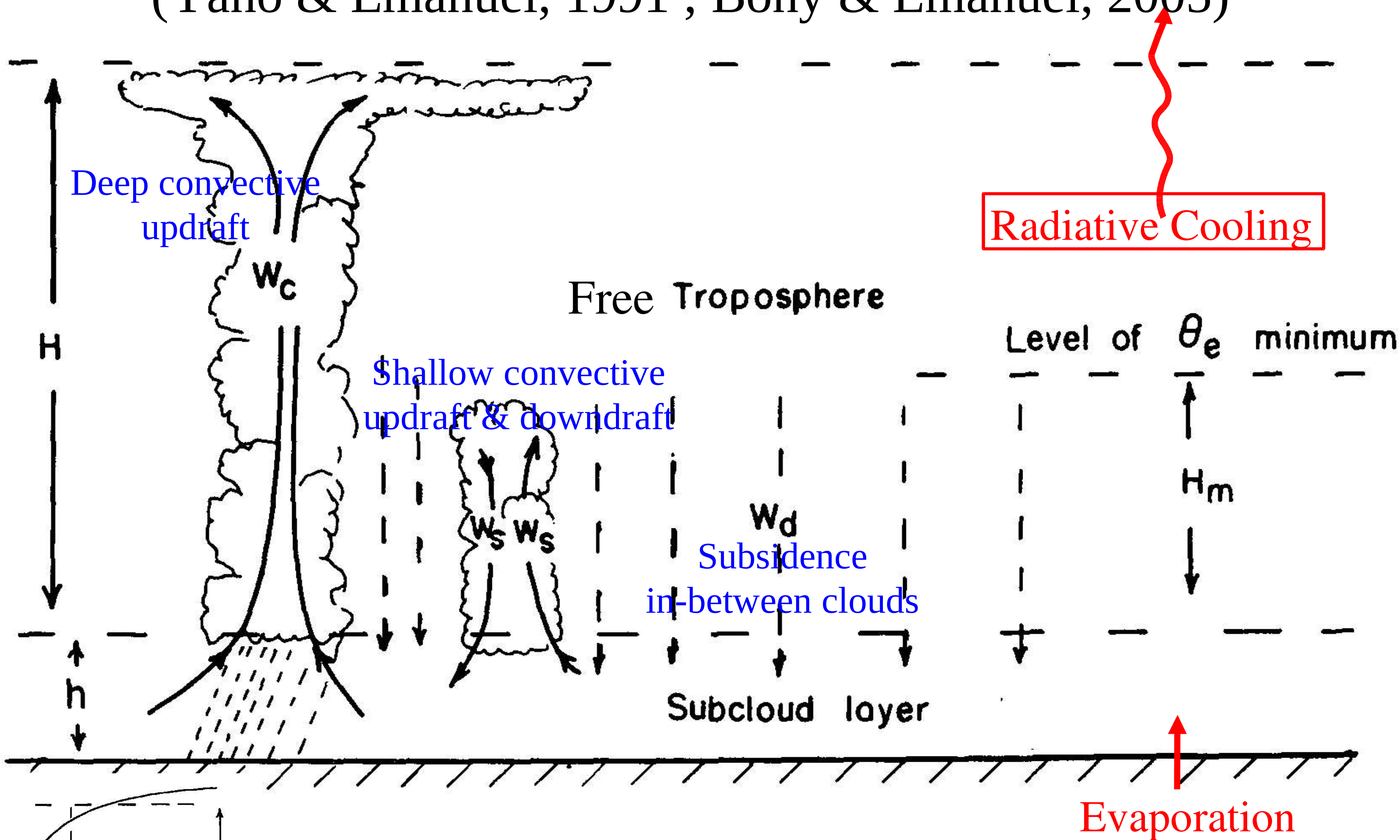


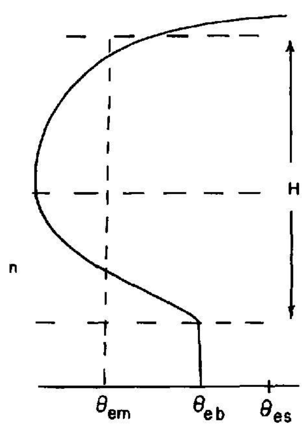


Interactive
Cloud-radiation

Simple Linear Model of the Equatorial Atmosphere

(Yano & Emanuel, 1991 ; Bony & Emanuel, 2005)



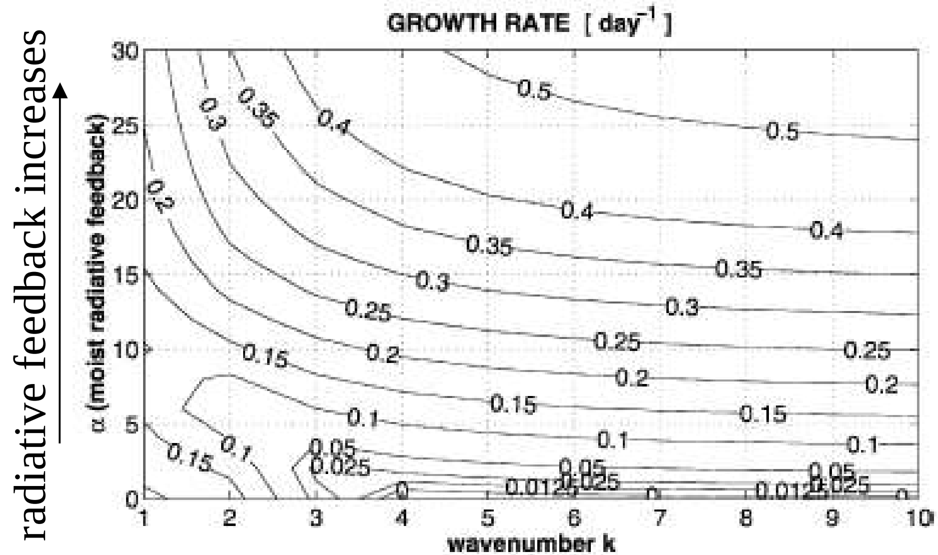


- Moist entropy exchange processes, sources and sinks
- Tropospheric radiative cooling depends on the moist entropy deficit (proxy for clouds and moisture) :

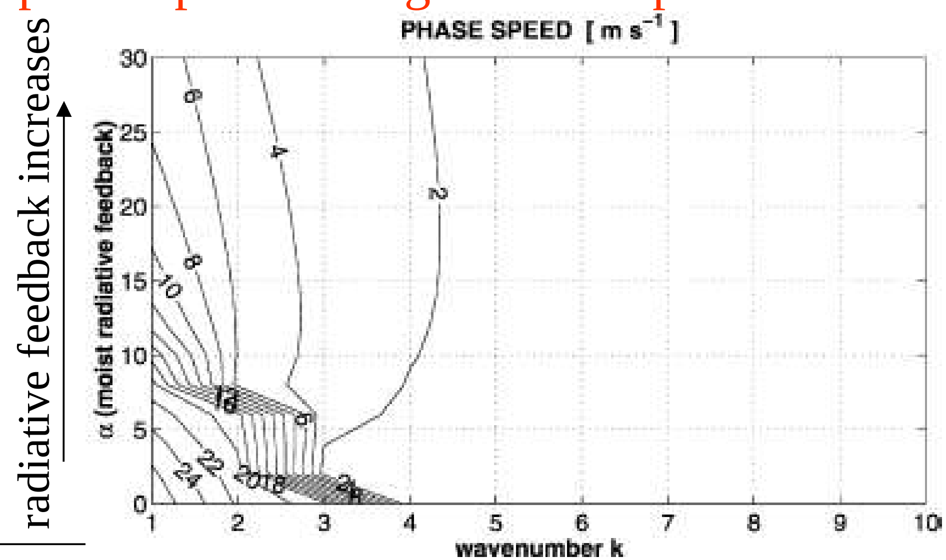
$$\dot{R} = \dot{R}_0 \left\{ 1 + \alpha \frac{\delta(\ln\theta_{eb} - \ln\theta_{em})}{[\ln\theta_{eb} - \ln\theta_{em}]} \right\}$$

(1) Cloud-radiative feedbacks affect the growth rate of unstable modes of the tropical atmosphere; In particular, strong cloud-radiative feedbacks excite small-scale advective disturbances traveling with the mean flow.

➡ The prominent mode of variability of the atmosphere depends on the intensity of cloud-radiative feedbacks (and of moisture-convection feedbacks, not shown).

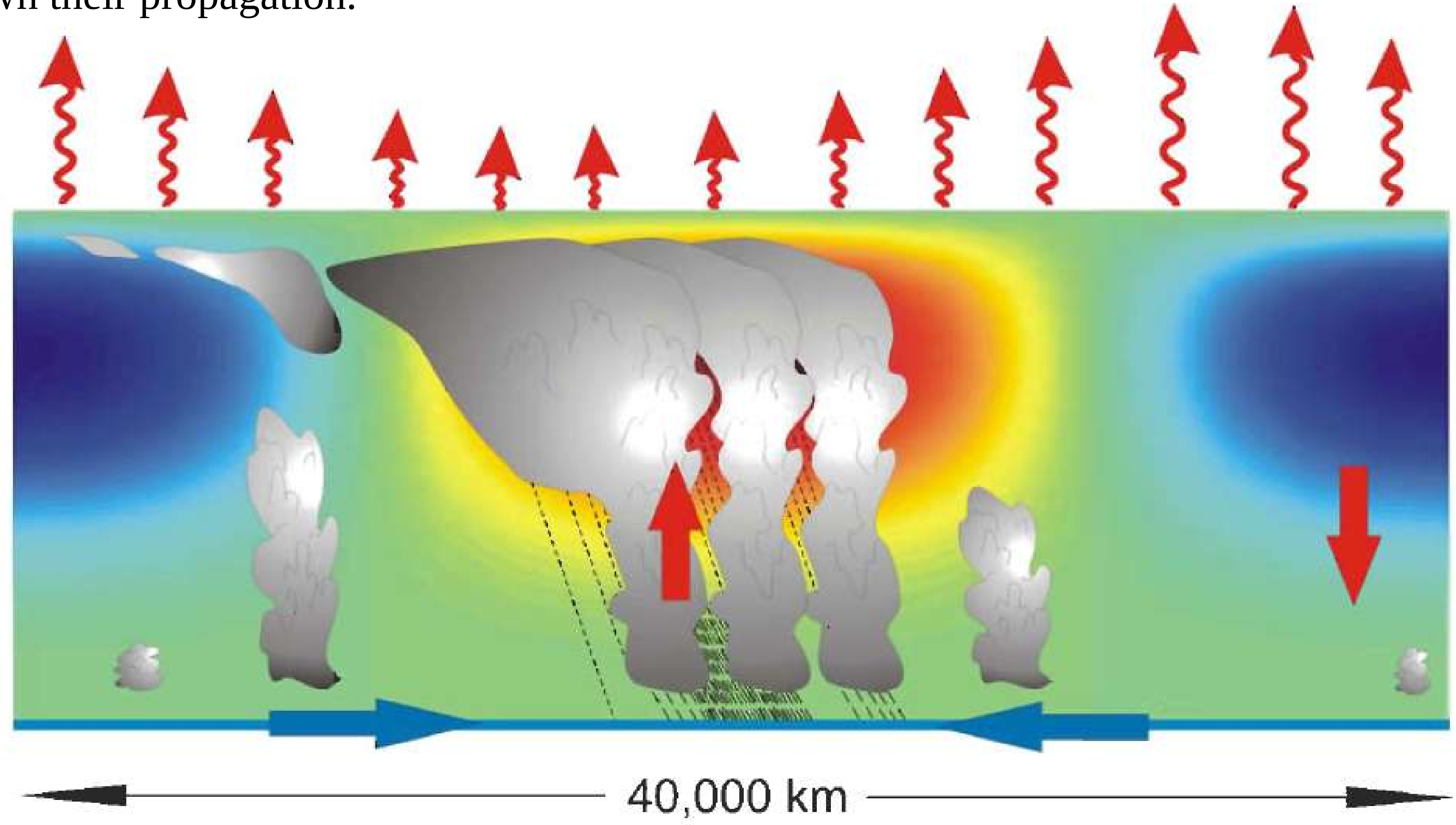


(2) They reduce the phase speed of large-scale tropical disturbances



Slowing down of large-scale tropical disturbances by cloud radiative feedback :

By reducing the radiative cooling of the troposphere in the rising phase of the oscillations, cloud-radiation interactions partly oppose the thermodynamical effect of adiabatic motions. This reduces the effective stratification felt by propagating waves and slows down their propagation.



Numerical simulations using an equatorial (aquaplanet) GCM

- 2D model (equatorial plane, 1.5 deg, 40 levels), fixed SSTs (300 K), uniform background flow.

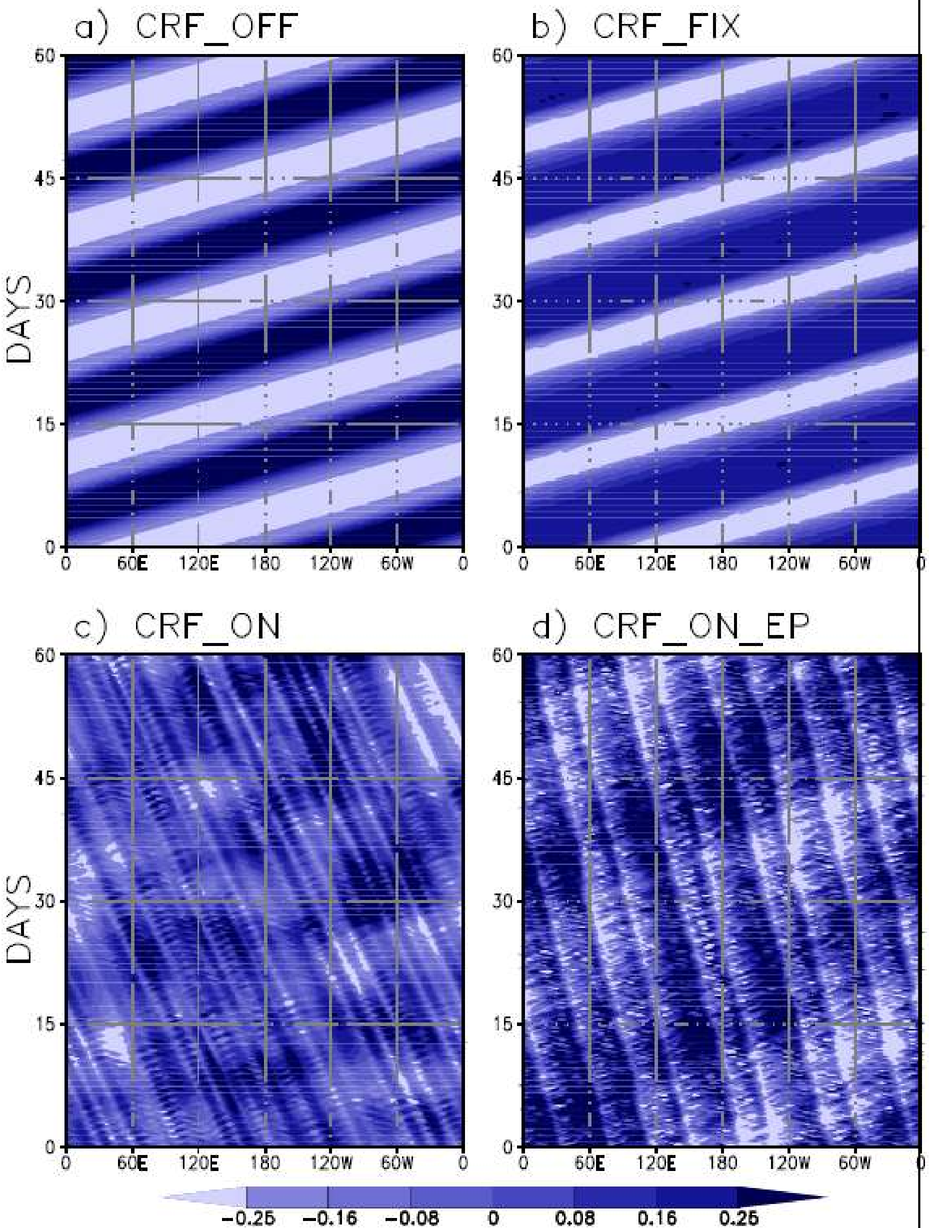
- Radiative (Morcrette 1991), convective (Emanuel and Zivkovic-Rothman 1999) and cloud (Bony and Emanuel 2001) parameterizations

As in the simple linear model and in the GCM results from Lee et al. (2001), cloud-radiative feedbacks affect:

- the phase speed of planetary-scale disturbances

- the relative prominence of small-scale vs planetary-scale modes of variability of the equatorial atmosphere

The simulation of (deep convective) cloud-radiative processes matters for the simulation of tropical variability by large-scale models!



(Zurovac-Jevtic, Bony & Emanuel, JAS, 2006)

CONCLUSION

1. The simulation of cloud radiative feedbacks is still a challenge for GCMs :

- Cloud feedbacks still constitute the primary source of uncertainty for climate sensitivity. This uncertainty stems primarily from the response of low-level clouds.

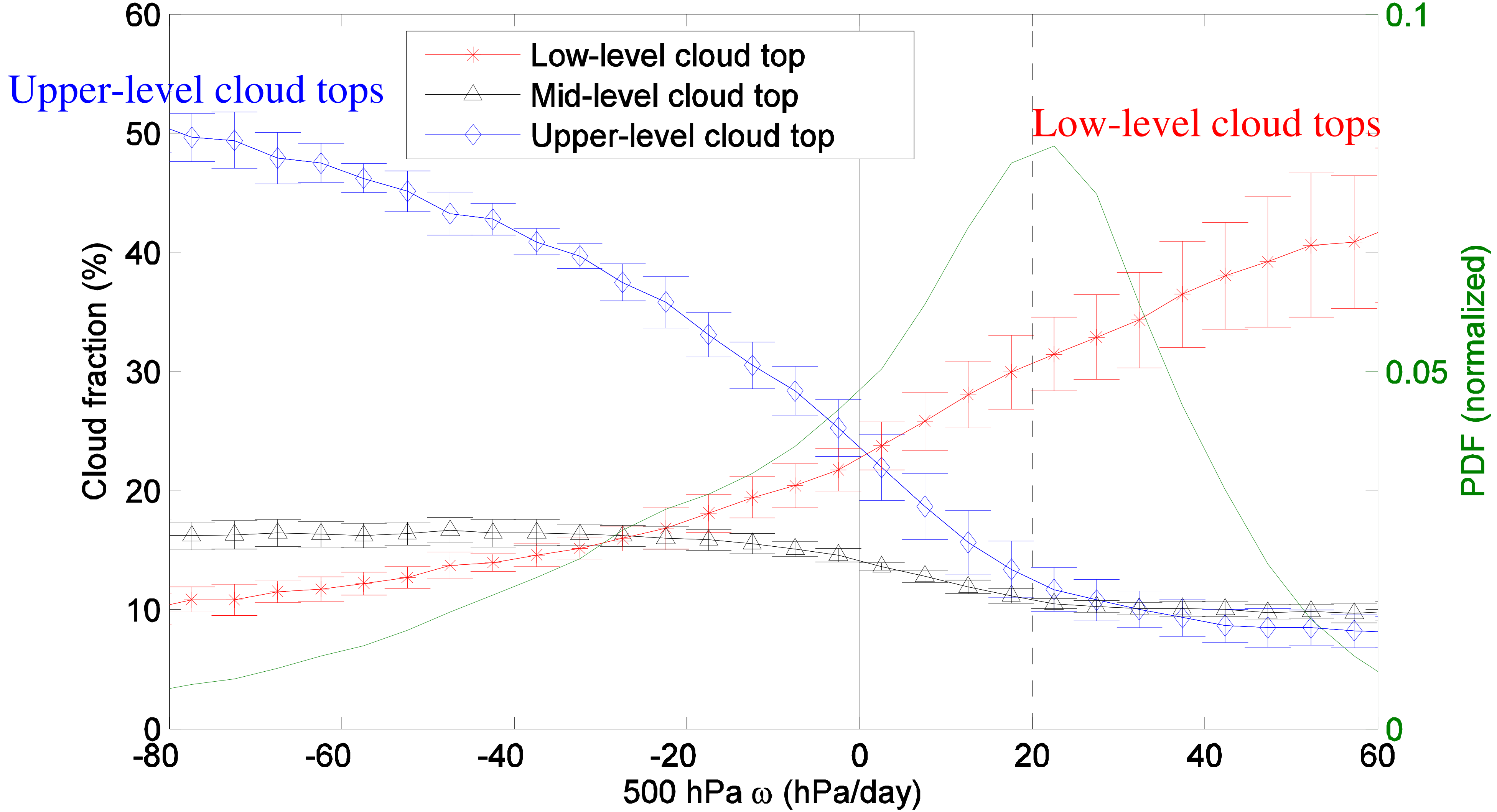
- Biases in the representation of convective cloud-radiative processes are likely to explain part of GCMs' biases in the simulation of tropical intraseasonal variability.

2. Much progress is expected in the next few years with the arrival of new data (e.g. CloudSat, CALIPSO) ... if modellers are ready to use these data promptly!

Hopefully, projects such as CFMIP will help to fill the gap between GCMs, observations, and process studies.

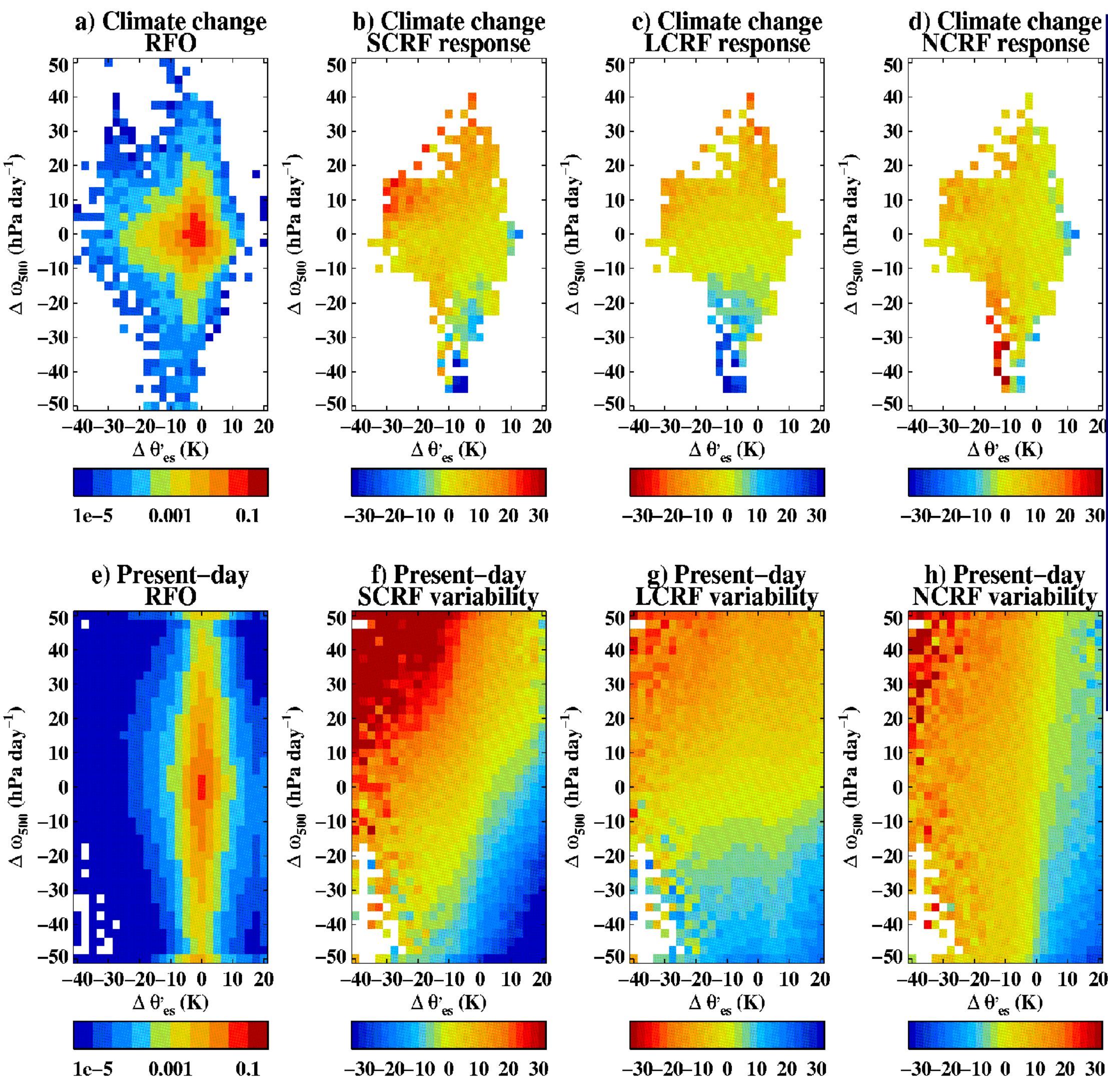
Thank you !

ISCCP cloud amounts and ERA40 ω500
(tropical oceans, 1984-2000)



(Bony & 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	Avg Climate Sens.& Range
1.2	1.0	1.6	0.9	1.2	3.8K
1.3	1.2	1.3	1.1	1.2	
1.5	1.0	1.9	1.0	1.4	2.9
1.8	1.2	2.1	1.1	1.5	-4.4K
1.7	1.1	2.2	1.2	1.5	
2.1	1.1	2.3	1.0	1.6	3.0K
2.4	1.0	3.0	1.0	1.9	
1.7	1.6	2.2	1.9	1.9	2.3
2.2	1.4	2.8	1.5	2.0	-3.5K
3.4	1.3	3.7	1.1	2.4	

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

The five models with smallest RMS errors tend to have higher climate sensitivities.

(Williams et al., Climate Dynamics, 2006 – CFMIP models)