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Fast and slow timescales of the tropical low-cloud response to increasing CO_2 in two climate models

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with
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submitted to Clim Dyn

Outline

- MIROC description for CMIP5
- Climate sensitivity, feedback, and low-cloud response in $4xCO_2$ runs
- Implication for CFMIP2 analyses

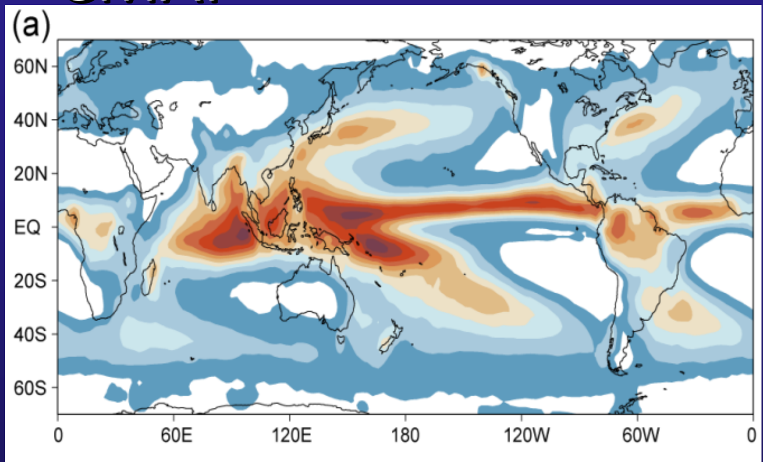
MIROC updates after AR4

		MIROC3.2 (for AR4)	MIROC5 (for AR5)
Atmos.	**Dynamical core**	Spectral+semi-Lagrangian (Lin & Rood 1996)	Spectral+semi-Lagrangian (Lin & Rood 1996)
	V. Coordinate	Sigma	Eta (hybrid sigma-p)
	Radiation	2-stream DOM 37ch (Nakajima et al. 1986)	2-stream DOM 111ch (Sekiguchi et al. 2008)
	Cloud	Diagnostic (LeTreut & Li 1991) + Simple water/ice partition	Prognostic PDF (Watanabe et al. 2009) + Ice microphysics (Wilson & Ballard 1999)
	Turbulence	M-Y Level 2.0 (Mellor & Yamada 1982)	MYNN Level 2.5 (Nakanishi & Niino 2004)
	Convection	Prognostic A-S + critical RH (Pan & Randall 1998, Emori et al. 2001)	Prognostic AS-type, but original scheme (Chikira & Sugiyama 2010)
	Aerosols	simplified SPRINTARS (Takemura et al. 2002)	SPRINTARS + prognostic CCN (Takemura et al. 2009)
Land/ River		MATSIRO+fixed riv flow	new MATSIRO+variable riv flow
Ocean		COCO3.4	COCO4.5
Sea-ice		Single-category EVP	Multi-category EVP

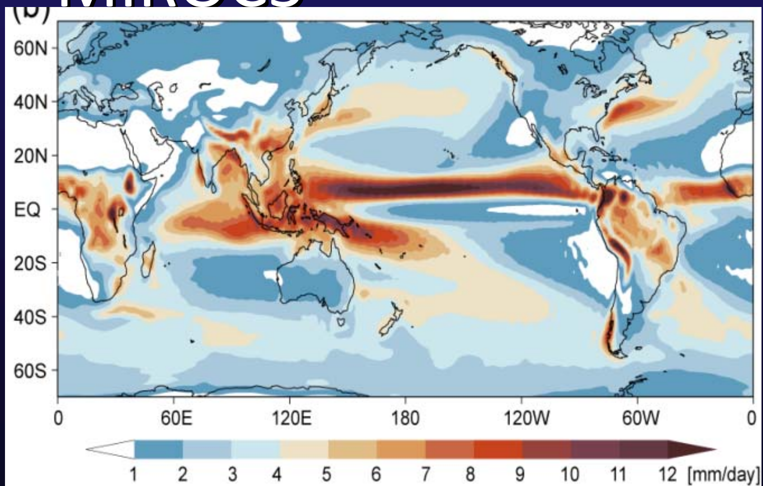
Mean climatology

Annual mean precipitation

CMAP



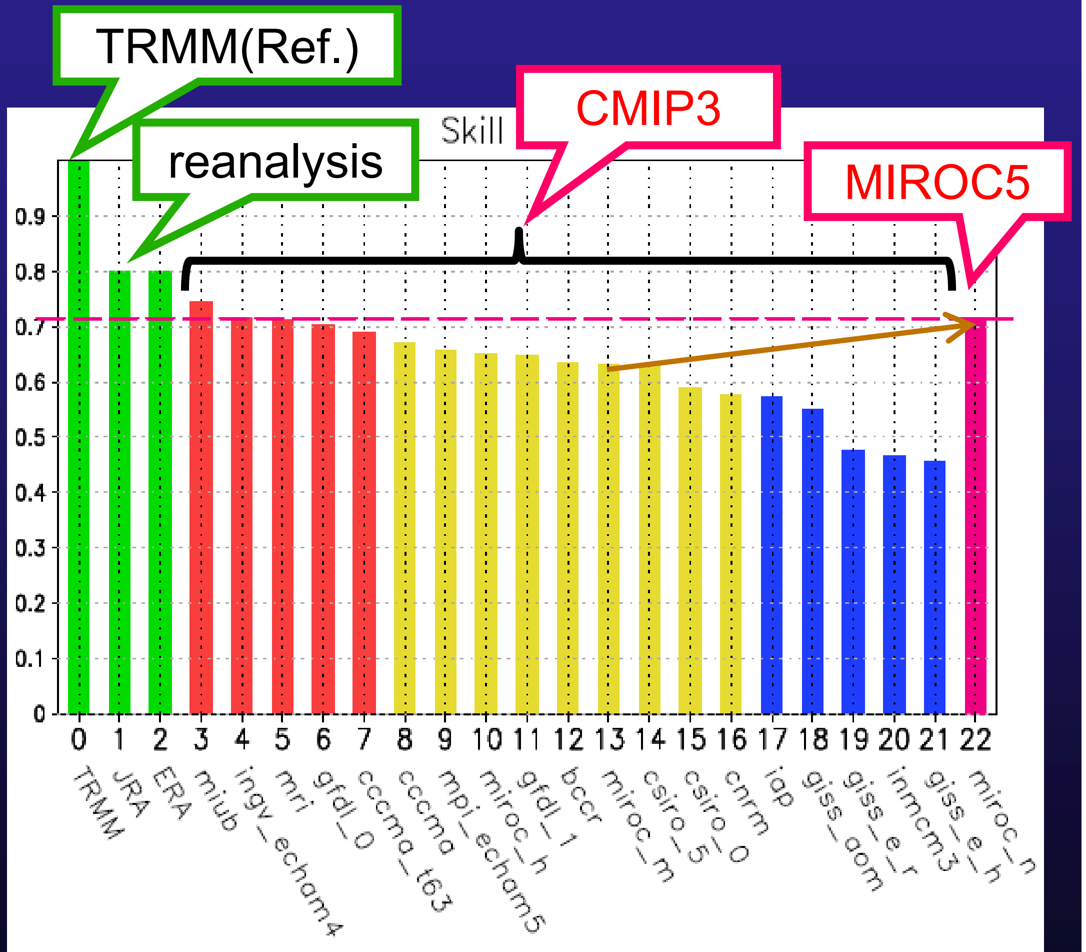
MIROC5



Watanabe et al. (2010, JC)

Taylor skill score (Taylor, 2001)

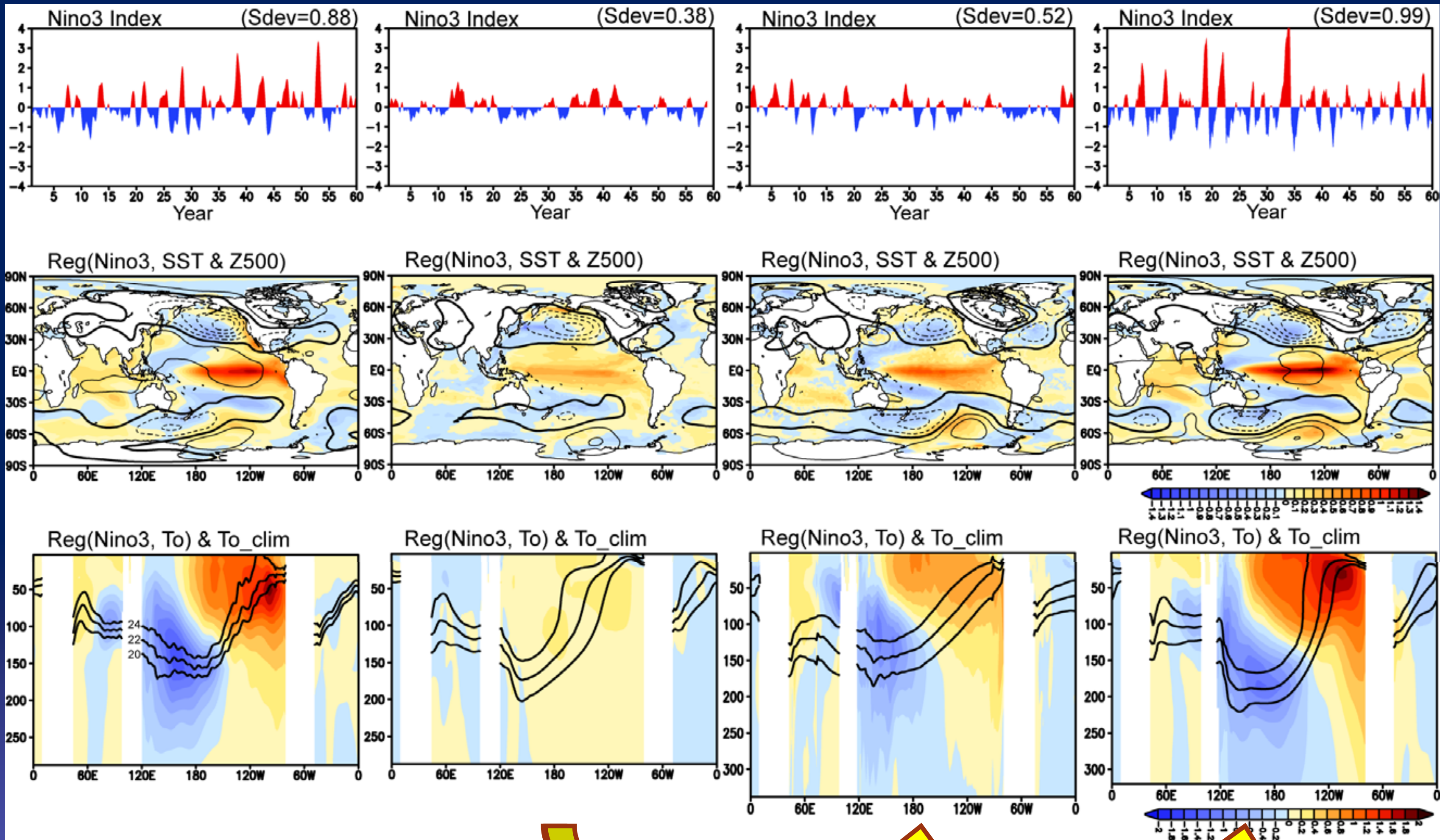
$$S = 4(1+R)^4 / (SDR + 1/SDR)^2$$



Hirota et al. (2011, JC)

Improvements in ENSO simulation

Obs.(ProjD_v6.7&ERA40) MIROC3. T42 MIROC3. T213 MIROC5. T85



impact of resolution

impact of new model physics

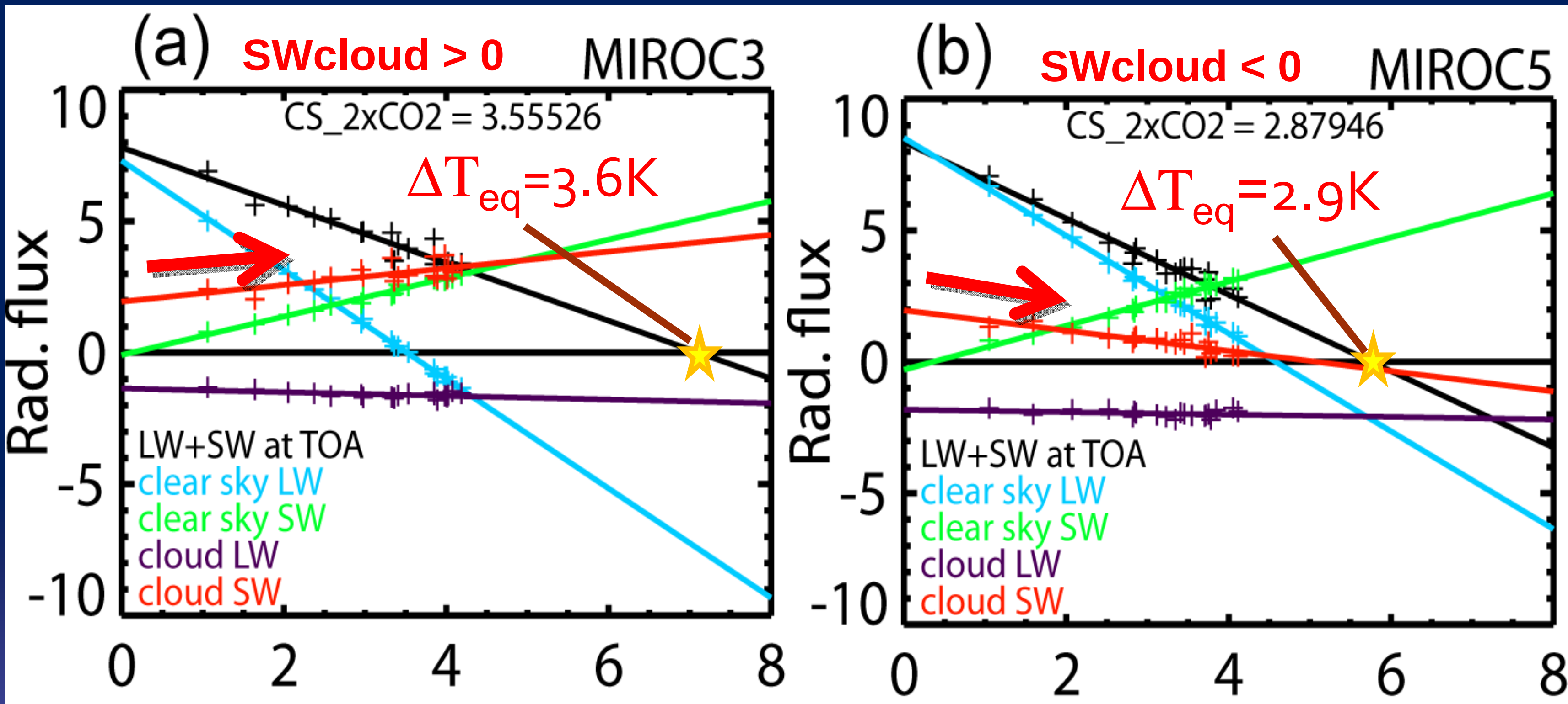
Sakamoto et al. (2011, JMSJ)

Watanabe et al. (2011, JC)

Equilibrium climate sensitivity

LW+SW
LWclr
SWclr
LWcloud
SWcloud

Gregory plots for 4xCO2 $N = F - \alpha \Delta T$



ΔSAT_g ΔSAT_g

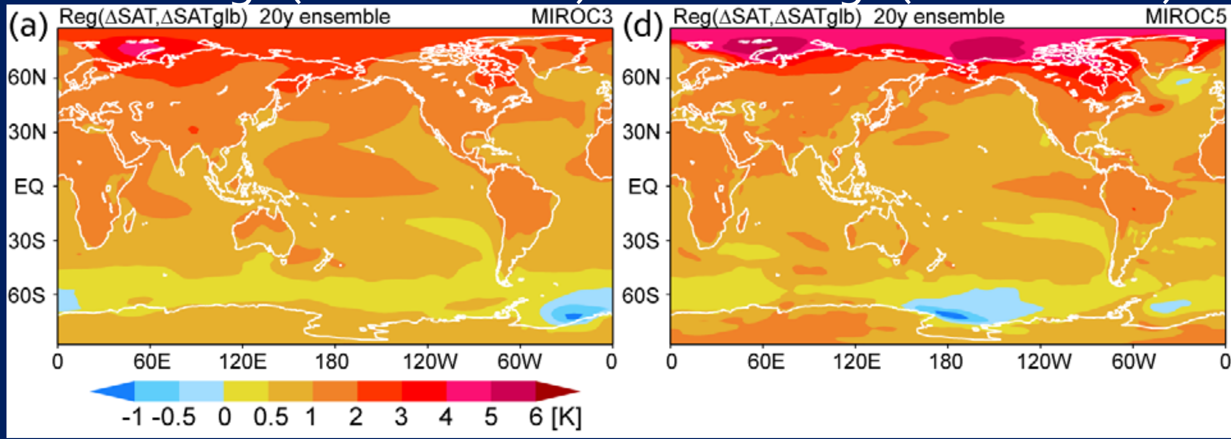
MIROC5 reveals smaller equilibrium sensitivity, probably due to a weak negative cloud-shortwave feedback

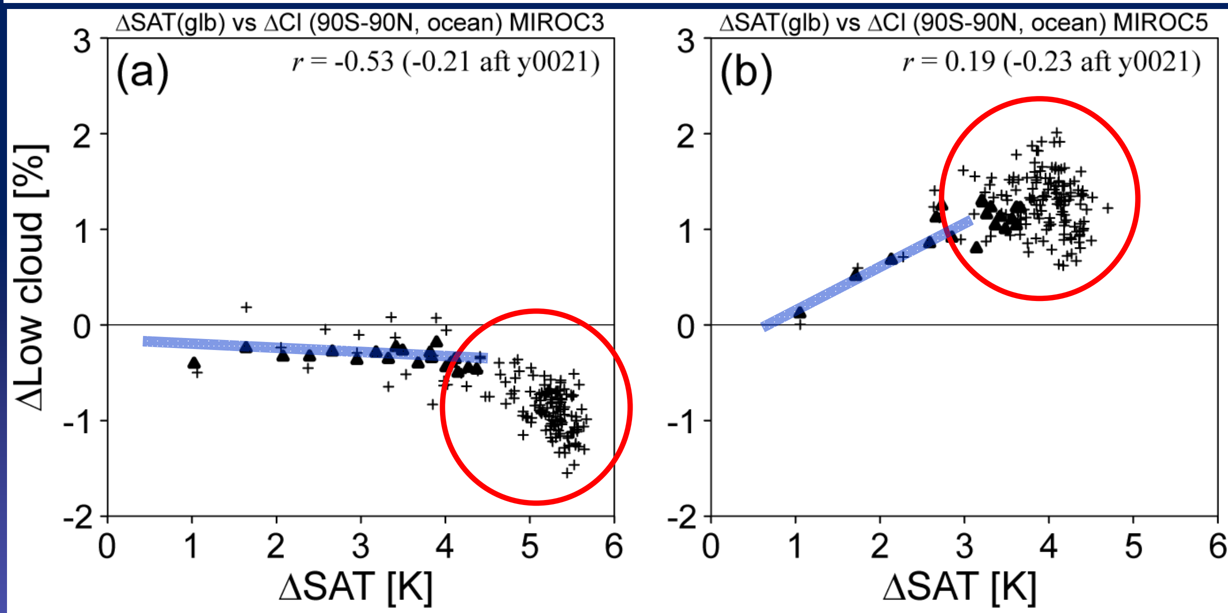
Global warming patterns

4xCO_2 runs

Reg(ΔSAT, ΔSATg)

MIROC3 (10 members)   MIROC5 (6 members)





+ ann. mean, single run (150y)

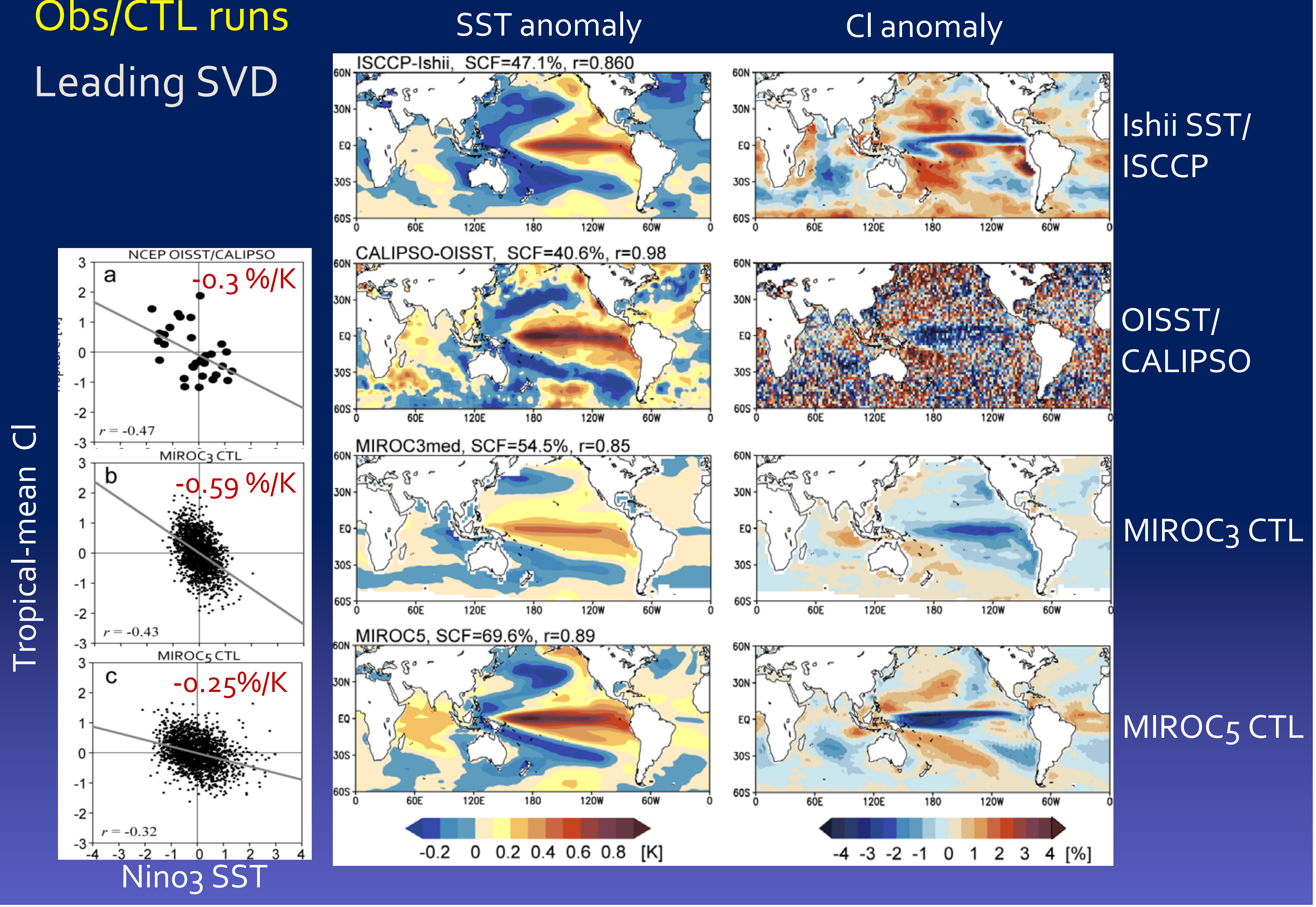
▲ ann. mean, ensemble avg (20y)

ΔSAT_g may not explain global-mean ΔC_l except for initial years

Natural low-cloud (C_l) variability

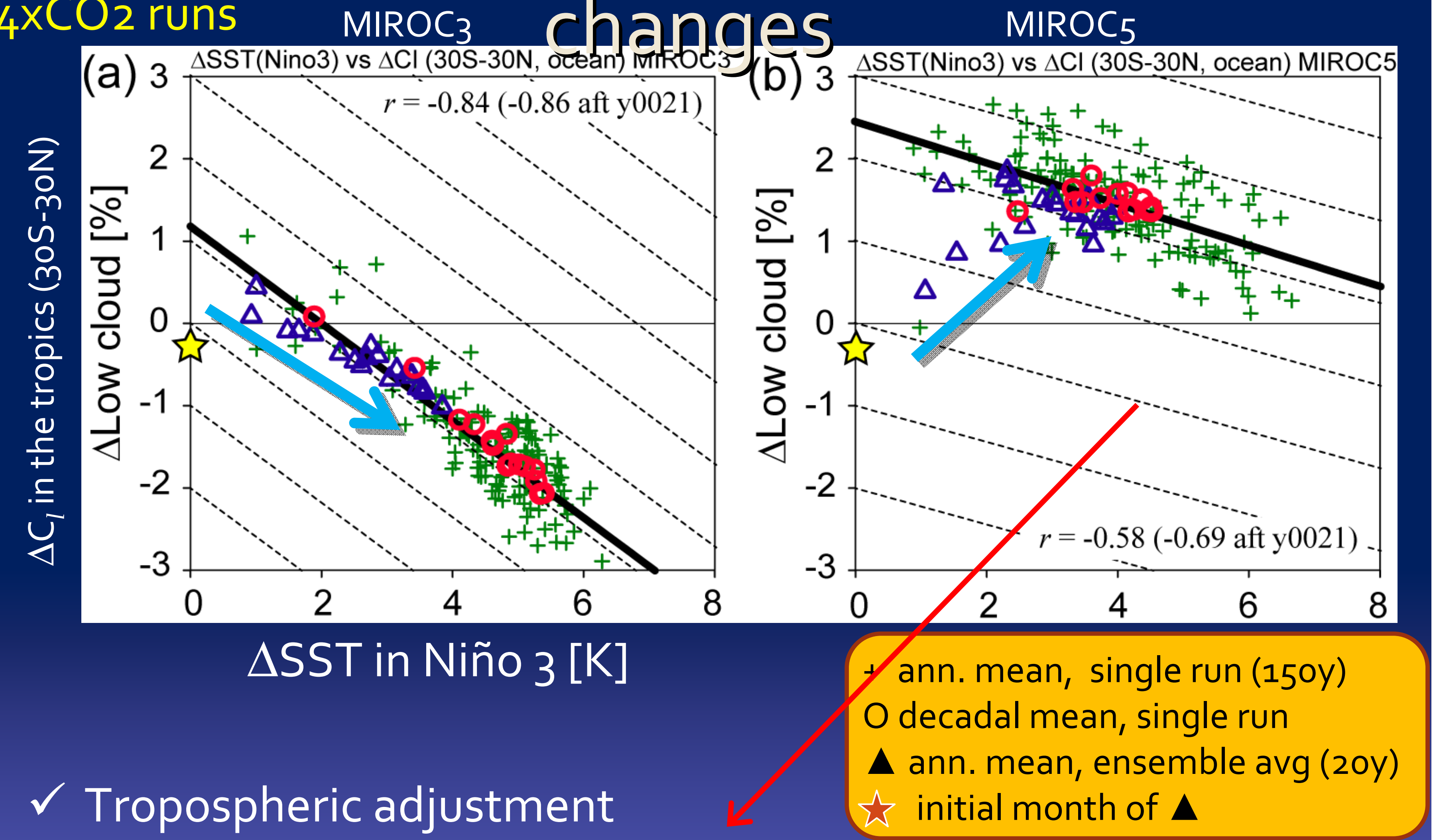
Obs/CTL runs

Leading SVD



Three timescales of low-cloud changes

4xCO2 runs



- ✓ Tropospheric adjustment
- ✓ Slow response (> 20y): $\left(\partial C_l' / \partial T_s'\right)_{CTL}$ matters!
- ✓ Fast response (< 10y): opposite between the models

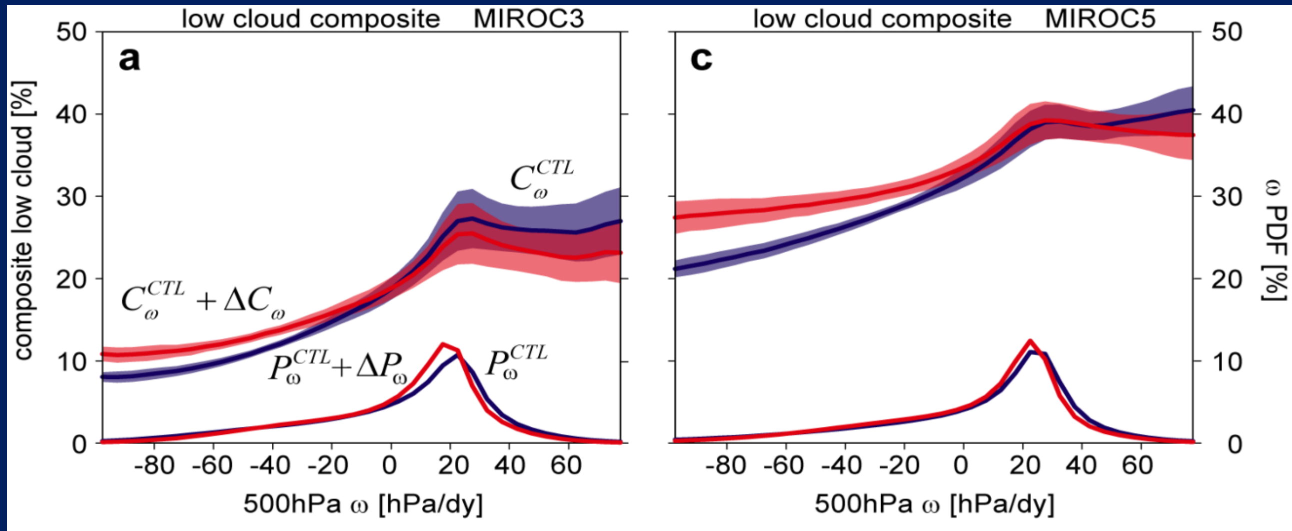
Fast response of low clouds

4xCO2 runs
(20y ensemble)

Regime composite of low cloud (Bony et al. 2004)

wrt ω500

MIROC3 MIROC5



Thermodynamic driving

$$\Delta \tilde{C}_l \simeq \int \Delta P_\omega C_l^{CTL}(\omega) d\omega + \boxed{\int P_\omega^{CTL} \Delta C_l(\omega) d\omega}$$

C_l decrease/increase over the subsidence/ascent region

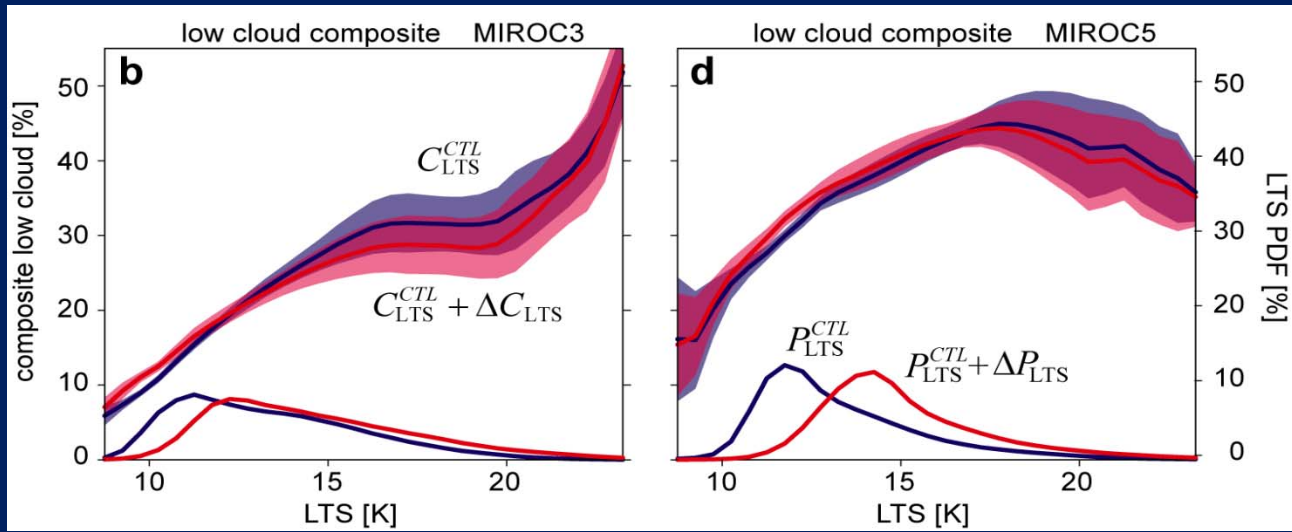
Fast response of low clouds

4xCO2 runs
(20y ensemble)

Regime composite of low cloud

wrt LTS

MIROC3 MIROC5



Thermodynamic driving

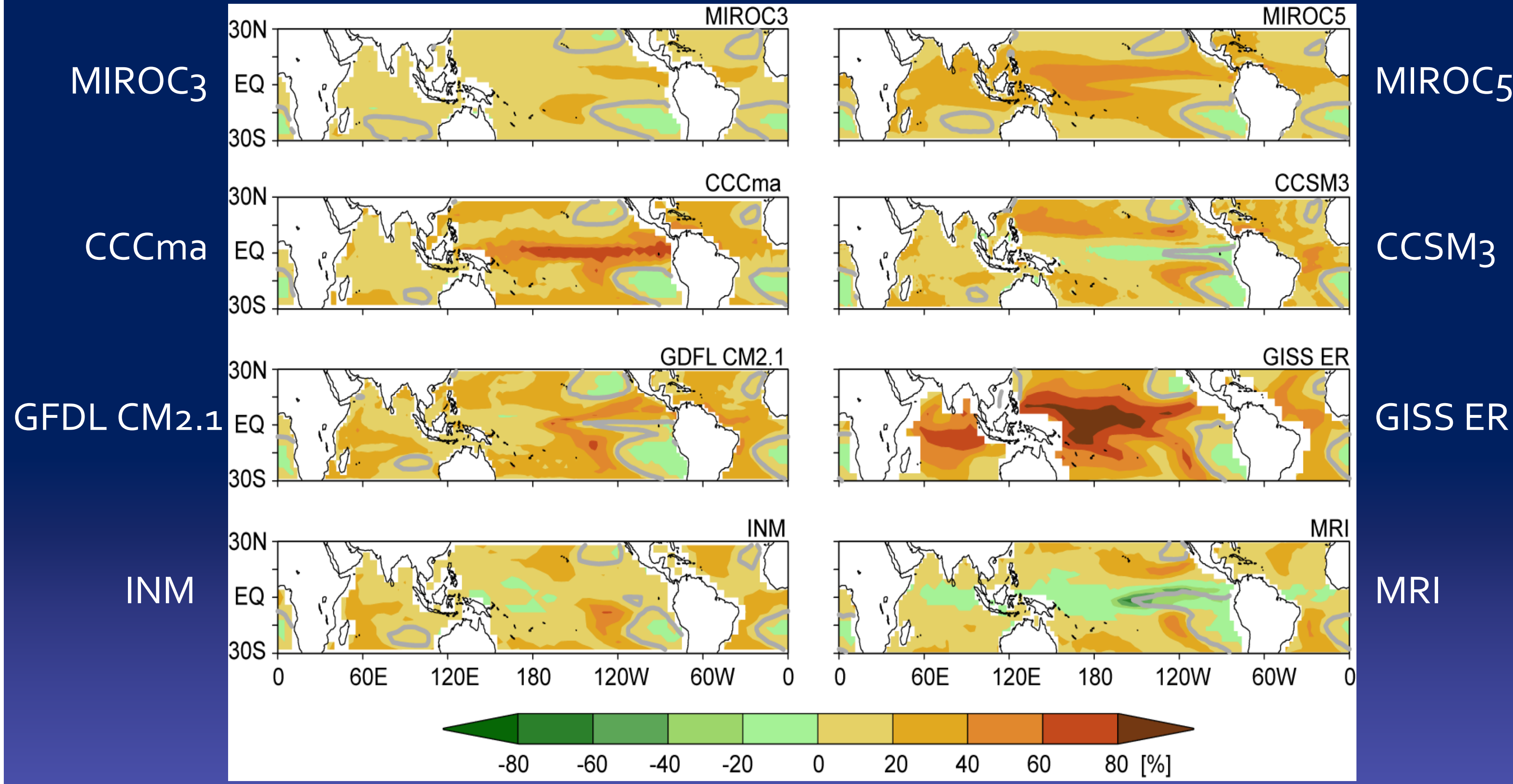
$$\Delta \tilde{C}_l \simeq \boxed{\int \Delta P_s C_l^{CTL}(s)ds} + \int P_s^{CTL} \Delta C_l(s)ds$$

Large/small Shift of the PDF for LTS in MIROC5/MIROC3

What is robust in CFMIP1?

Thermodynamic regime change (Δf_s) in 4xCO2 / 2xCO2 runs

Regime frequency $f_s \equiv \mathrm{freq.}(LTS > LTS^{crit})$



✓ Small change in the mean low-cloud region

✓ More stable condition in the other tropics

Summary

- Opposite SWcld feedback -> high/low clim sensitivity in MIROC
- Three timescales of the low-cloud response in 4xCO2 exps.
  - ✓ Tropospheric adjustment / Fast response / Slow response

- The slow response can be constrained by observations using ENSO-related variability

- But, fast response was critical in MIROC, which may not be constrained by the natural variability

- The fast response determined thru a subtle residual of the regional low-cloud changes
- Dominant thermodynamic driving of low-cloud response
- Change in LTS is robust among CFMIP1 models

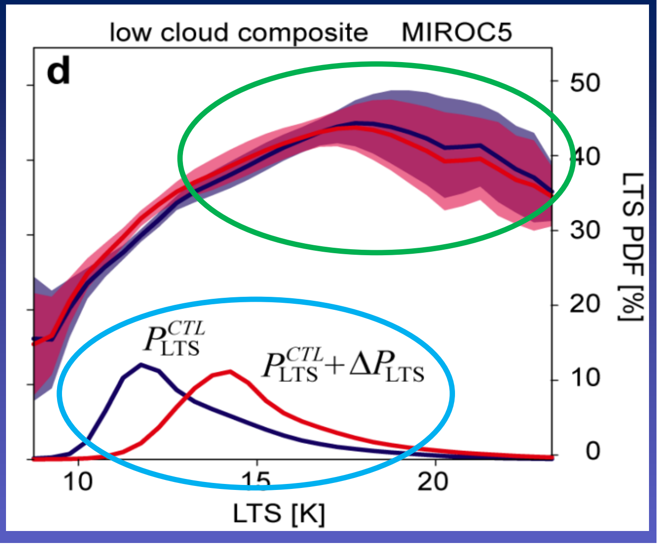
Would like to clarify in CFMIP2 :

- Divergence of the fast response using Exp. 6.3

- Robustness of the LTS change
  (incl. issue of its constraint)

- Mechanism for lower-tropospheric warming
  → degree of the LTS increase

- Cloud change at a given LTS
  (non-thermodynamic
  response)



Remark

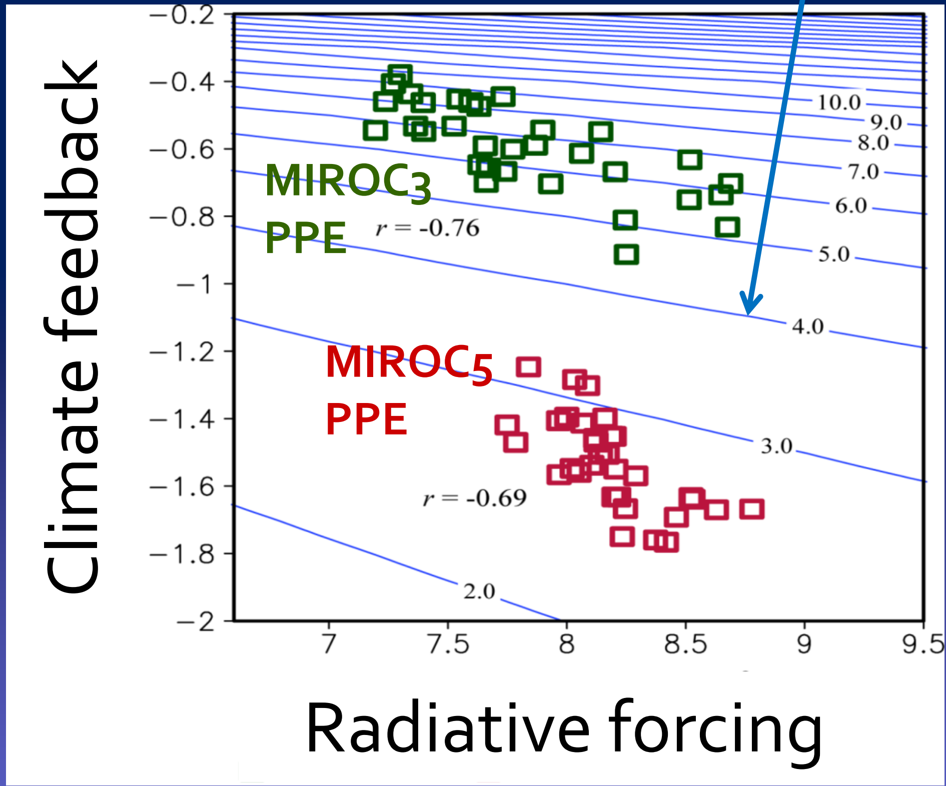
What are the processes making diff between two MIROC models?

- ✓ MIROC3.2 PPE (N=32)
  (e.g. Yokohata et al. 2010 JC)

- ✓ MIROC5 PPE (N=32)
  (ongoing, cf. talk by Tomoo Ogura)

Need to systematically explore the structural differences of the model's physics

Equilibrium climate sensitivity

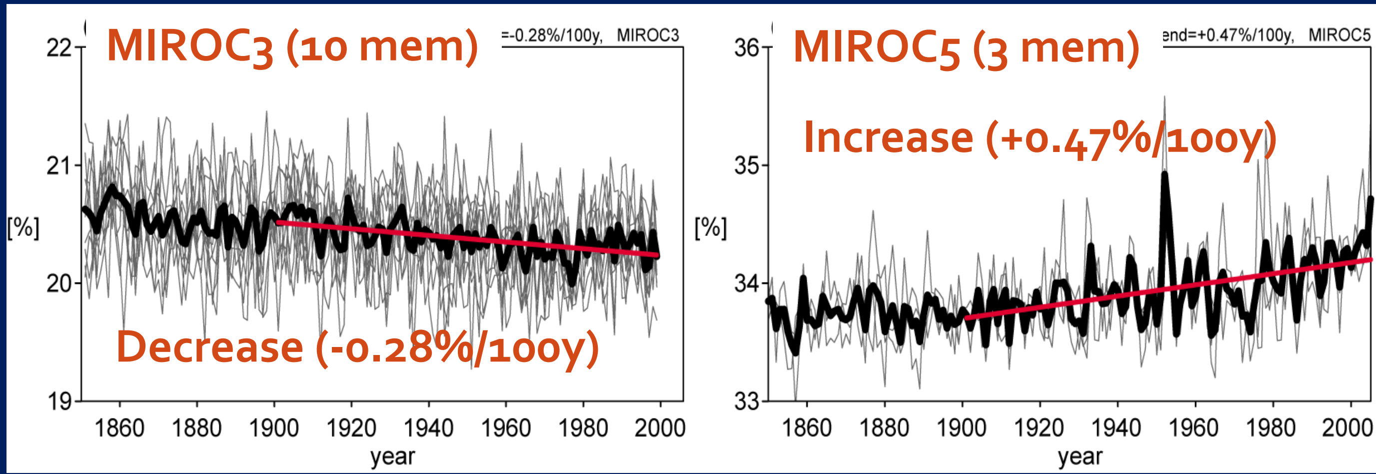


backup

Implication to 20th century trend

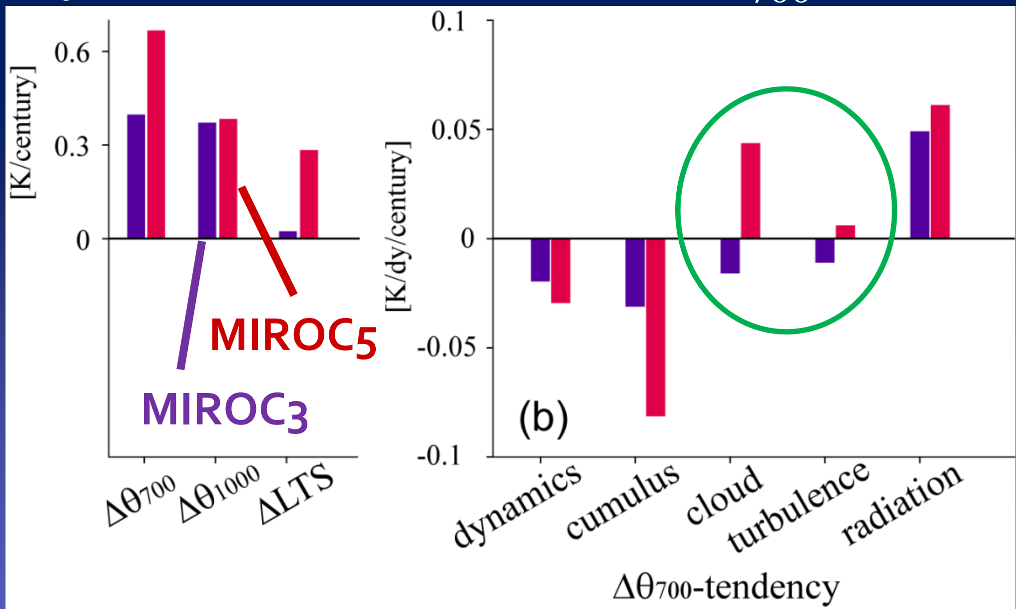
20C runs

Tropical
Cl (30S-30N)



✓ Likely due to 'fast' response (but change is much slower)

Tropical-mean trends in θ & θ_{700}-tendency

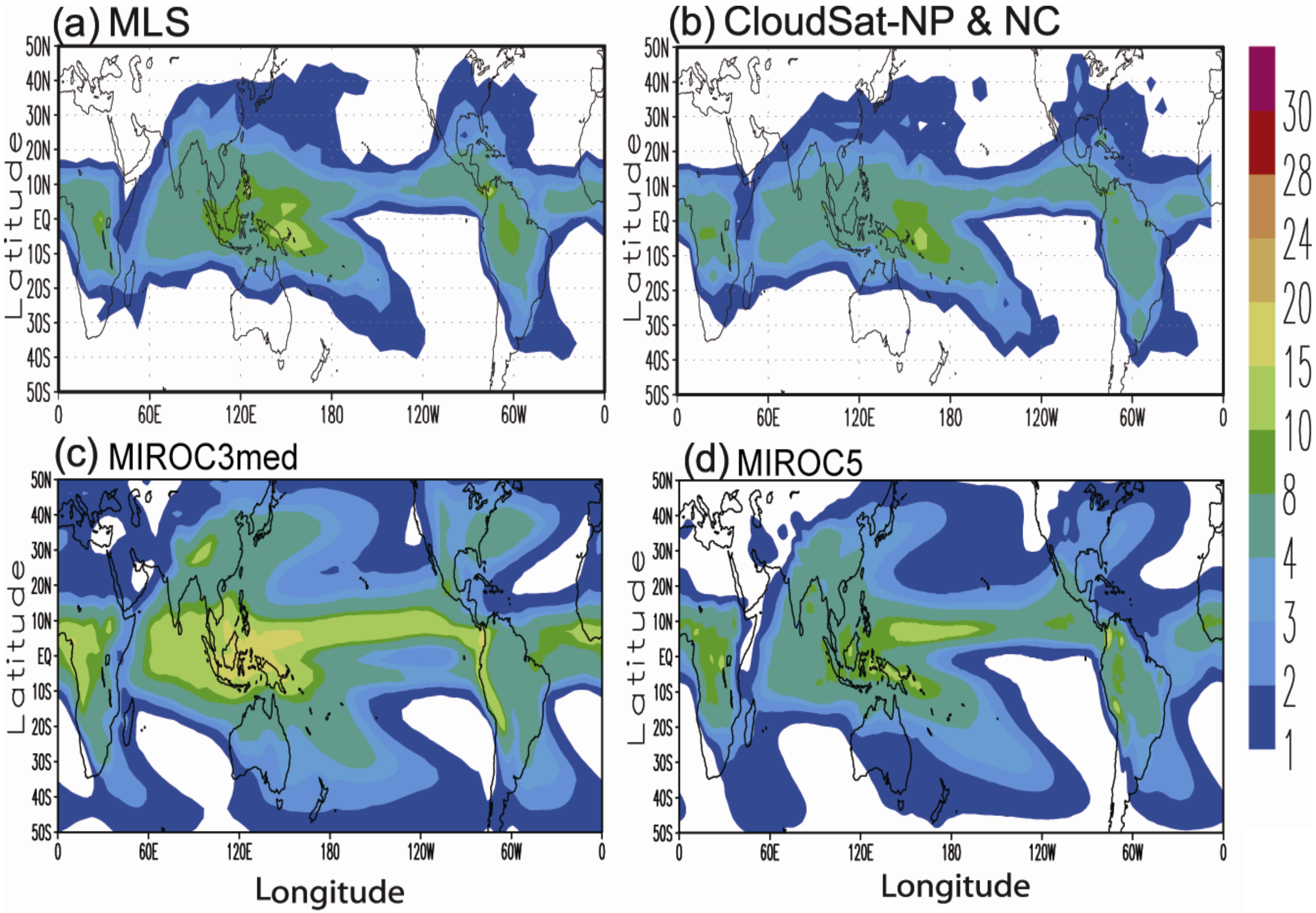


Diff. θ_{700} tendency due to cloud physics & turbulence is essential !

Watanabe et al. (2011, ASL)

Property of MIROC5

215 hPa cloud ice



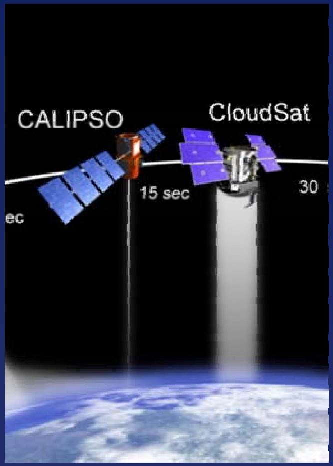
After Waliser et al. (2009)

Property of MIROC5

- ✓ prognostic PDF cloud scheme
- ✓ prognostic ice microphysics
- better representation of cloud and cloud-radiative feedback
- how to validate?

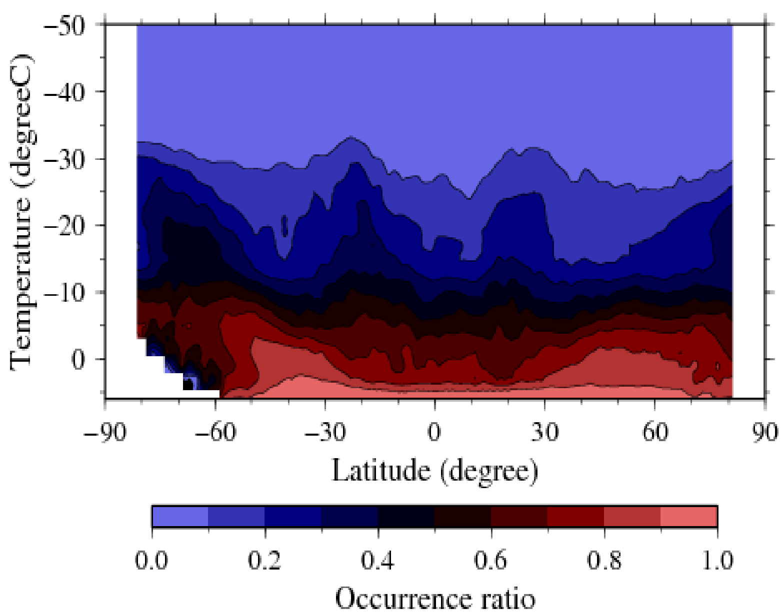
CloudSAT and CALIPSO

* launched in April, 2006
* 3D cloud property w/ rader/ lidar measurements

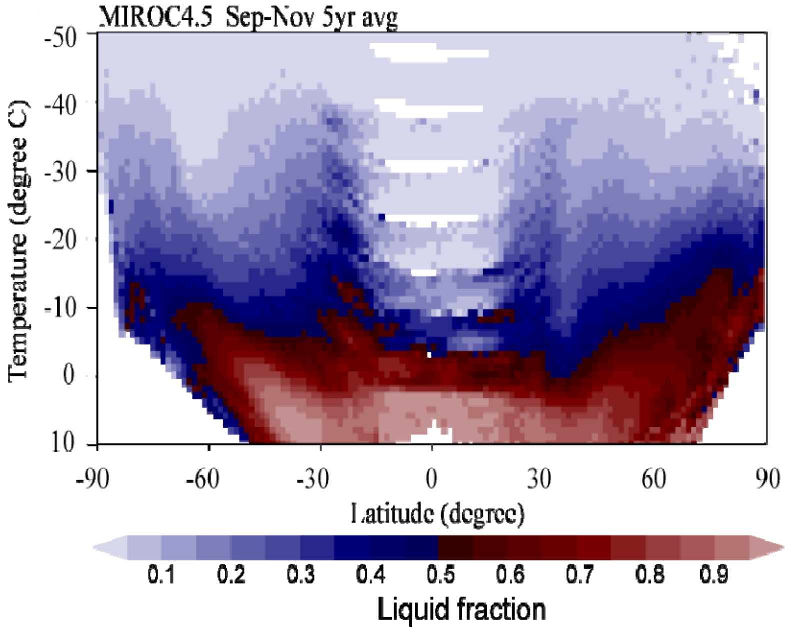


Latitude - temperature cross section of the ratio of cloud particle type

Sep-Nov 2006, CloudSAT/CALIPSO



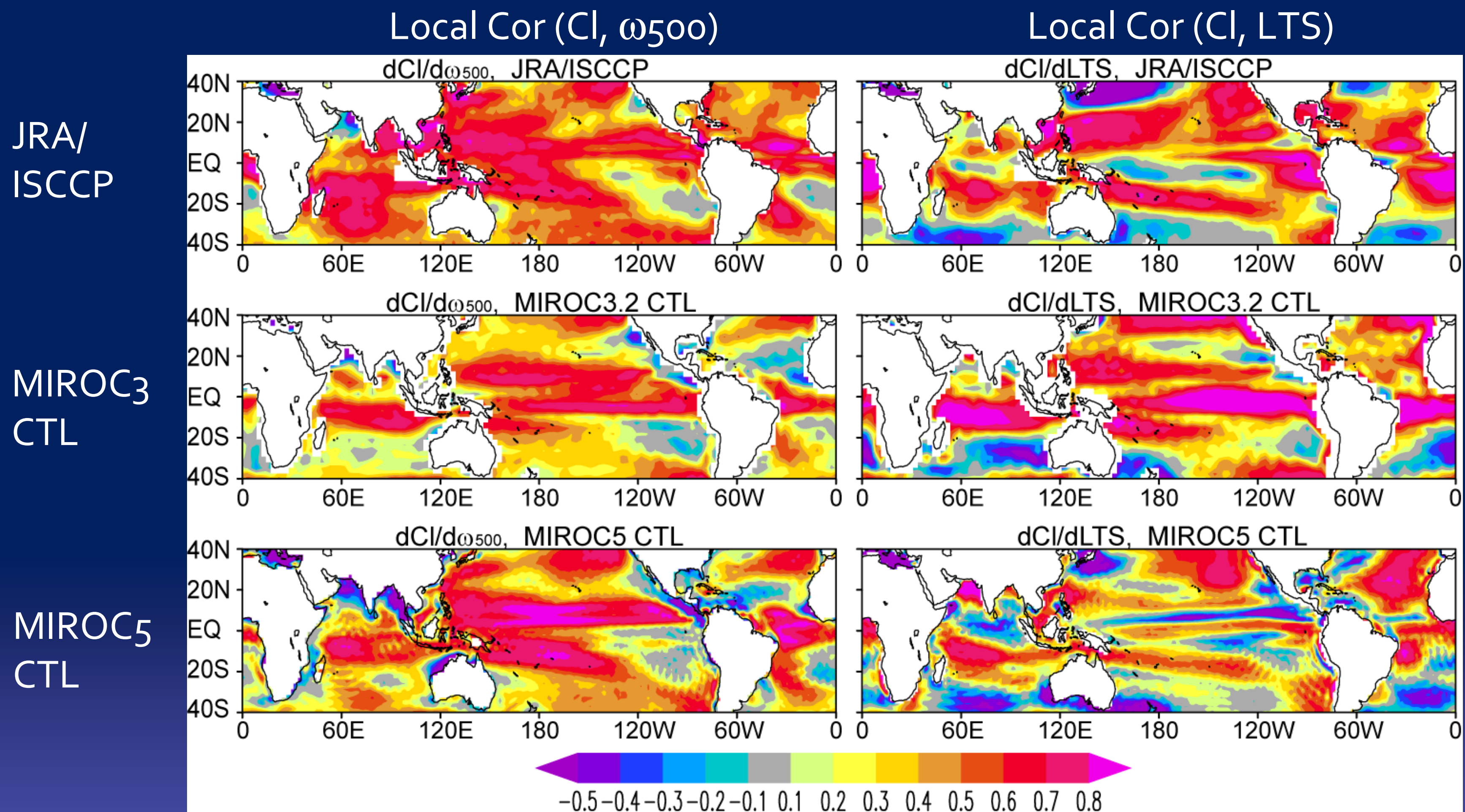
Sep-Nov climatology, MIROC4.5



Courtesy of H Okamoto

Natural low-cloud variability

Obs/CTL runs

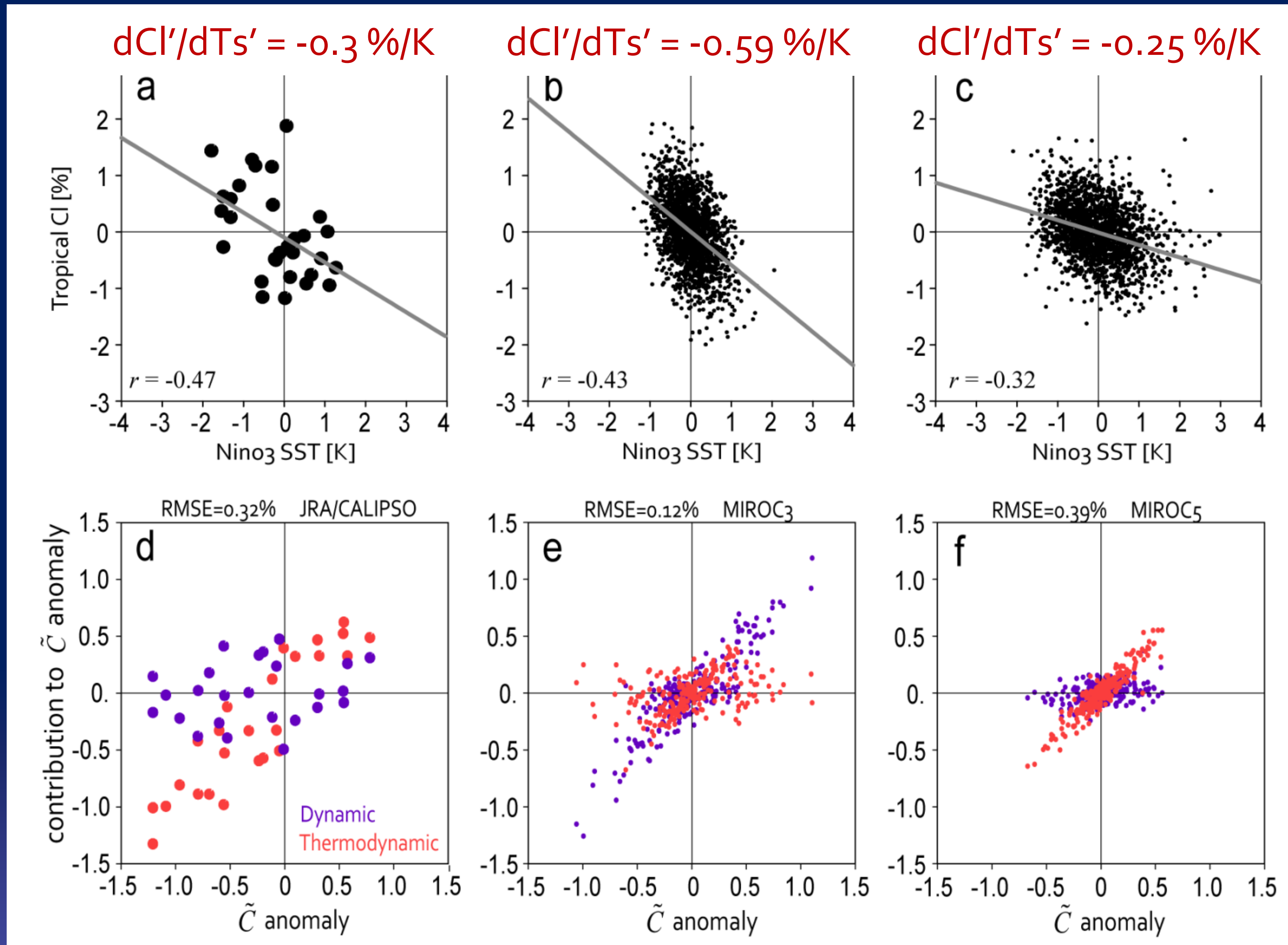


$$\Delta C_l = \frac{\partial C_l}{\partial \omega_{500}} \Delta \omega_{500} + \frac{\partial C_l}{\partial LTS} \Delta LTS = \left(\frac{\partial C_l}{\partial \omega_{500}} \frac{\partial \omega_{500}}{\partial T_s} + \frac{\partial C_l}{\partial LTS} \frac{\partial LTS}{\partial T_s} \right) \Delta T_s \quad ?$$

Natural low-cloud variability

Obs/CTL runs

NCEP OISST/CALIPSO | MIROC3 CTL | MIROC5 CTL



Nino3 SST
vs
Tropical Cl

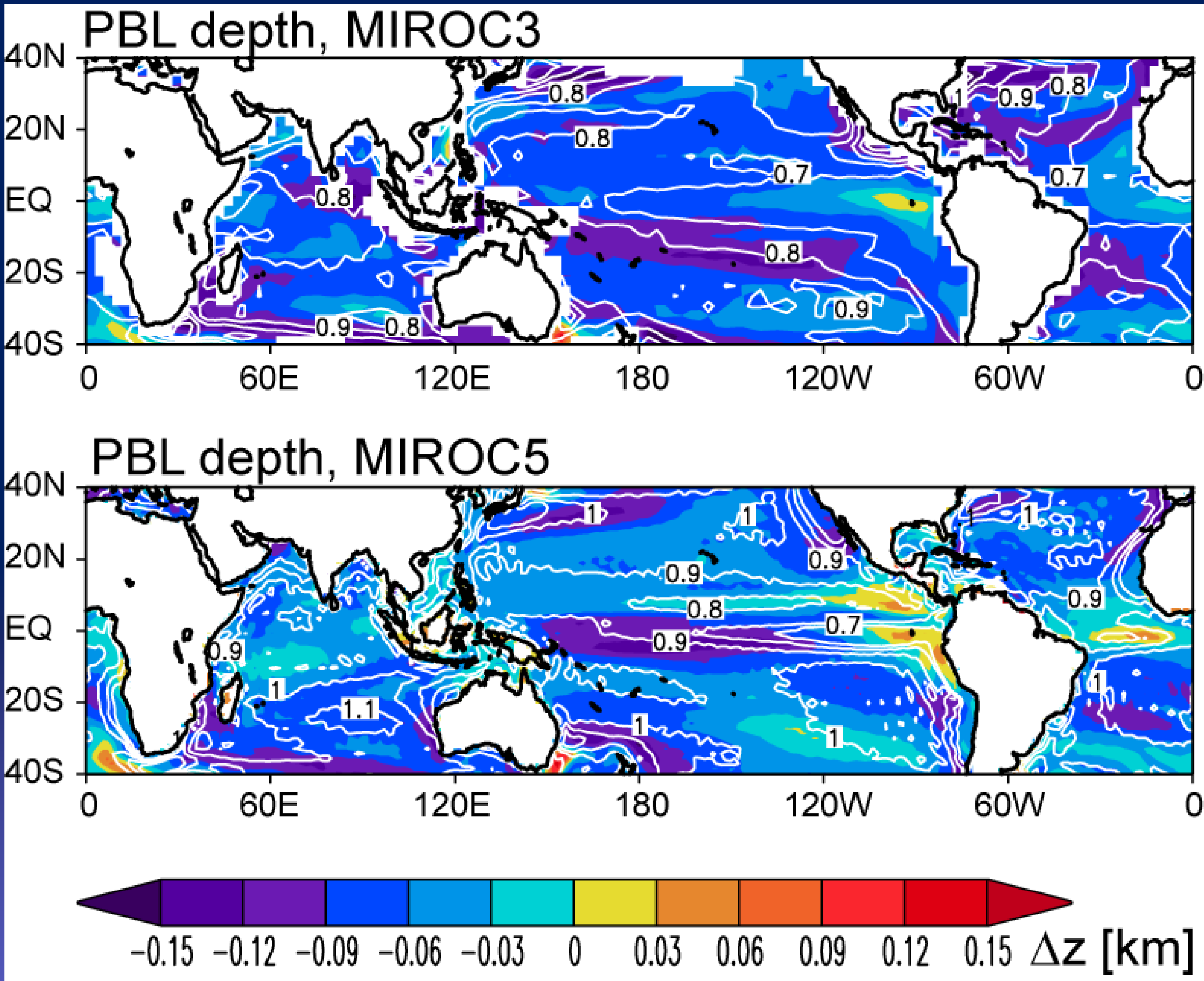
Reconst. Cl′
vs
Dynamic/
Thermodynamic
components

Dynamic | Thermodynamic

Reconst. Cl anomaly: $$\tilde{C}_l' \square \int P_\omega' \overline{C}_l(\omega)d\omega + \int \overline{P}_\omega C_l'(\omega)d\omega$$

Fast response of low clouds

Change in PBL depth



Fast response of low clouds

4xCO_2 runs
(20y ensemble)

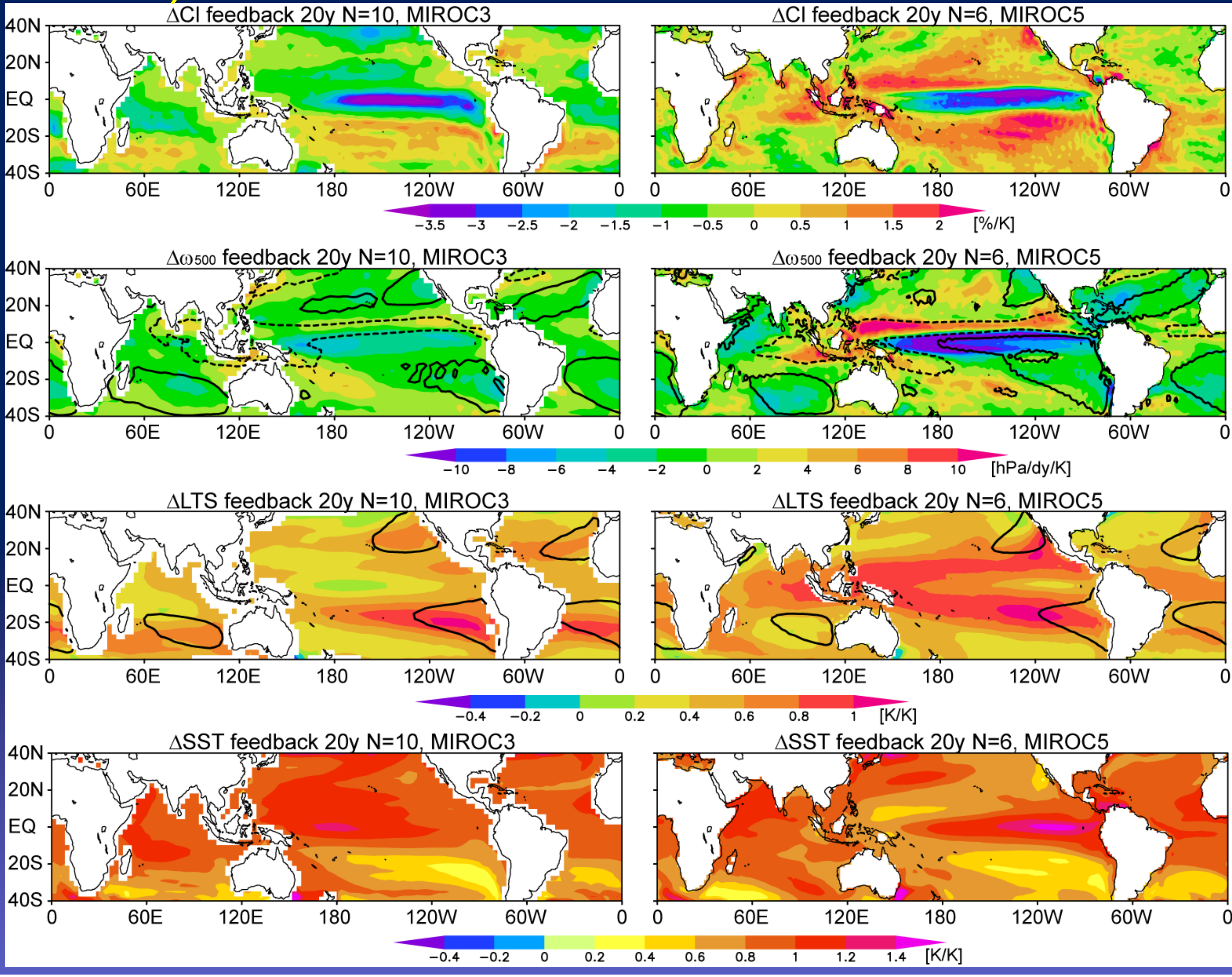
MIROC3 MIROC5

ΔCl

Δω500

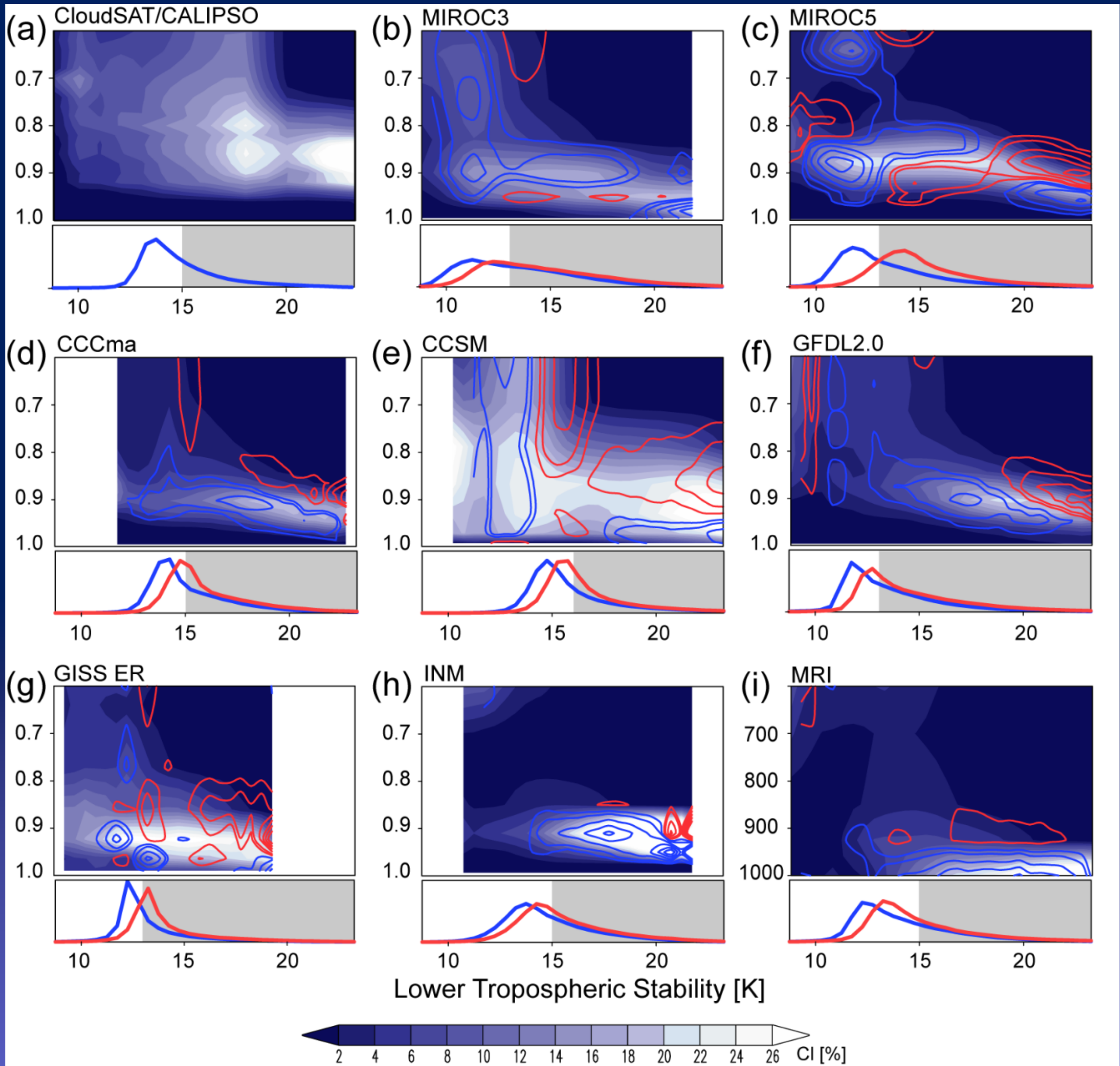
ΔLTS

ΔSST



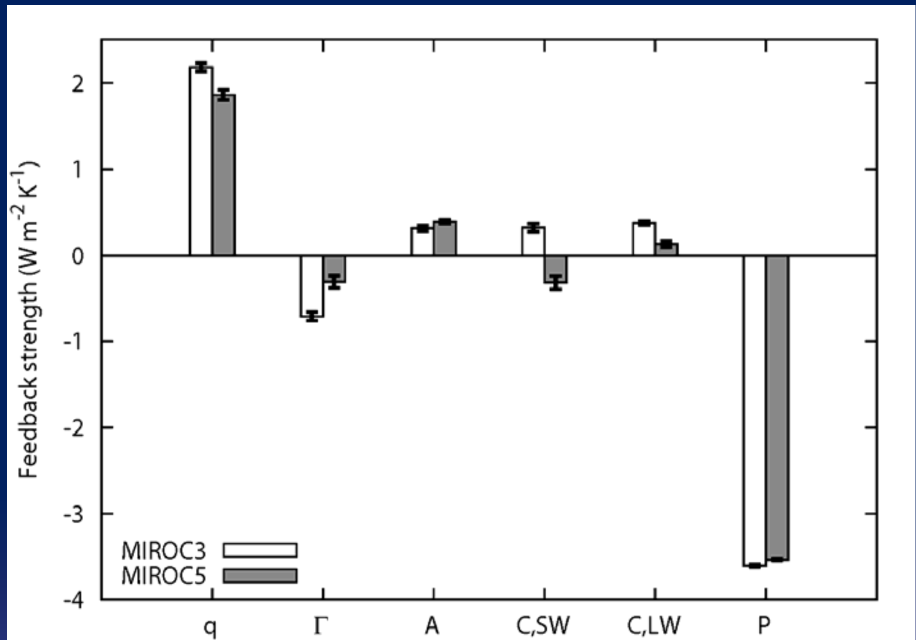
Fast response of low clouds

Cloud regime diagram from 4xCO2 / 2xCO2 runs in CFMIP1



Mean states

Feedback analysis

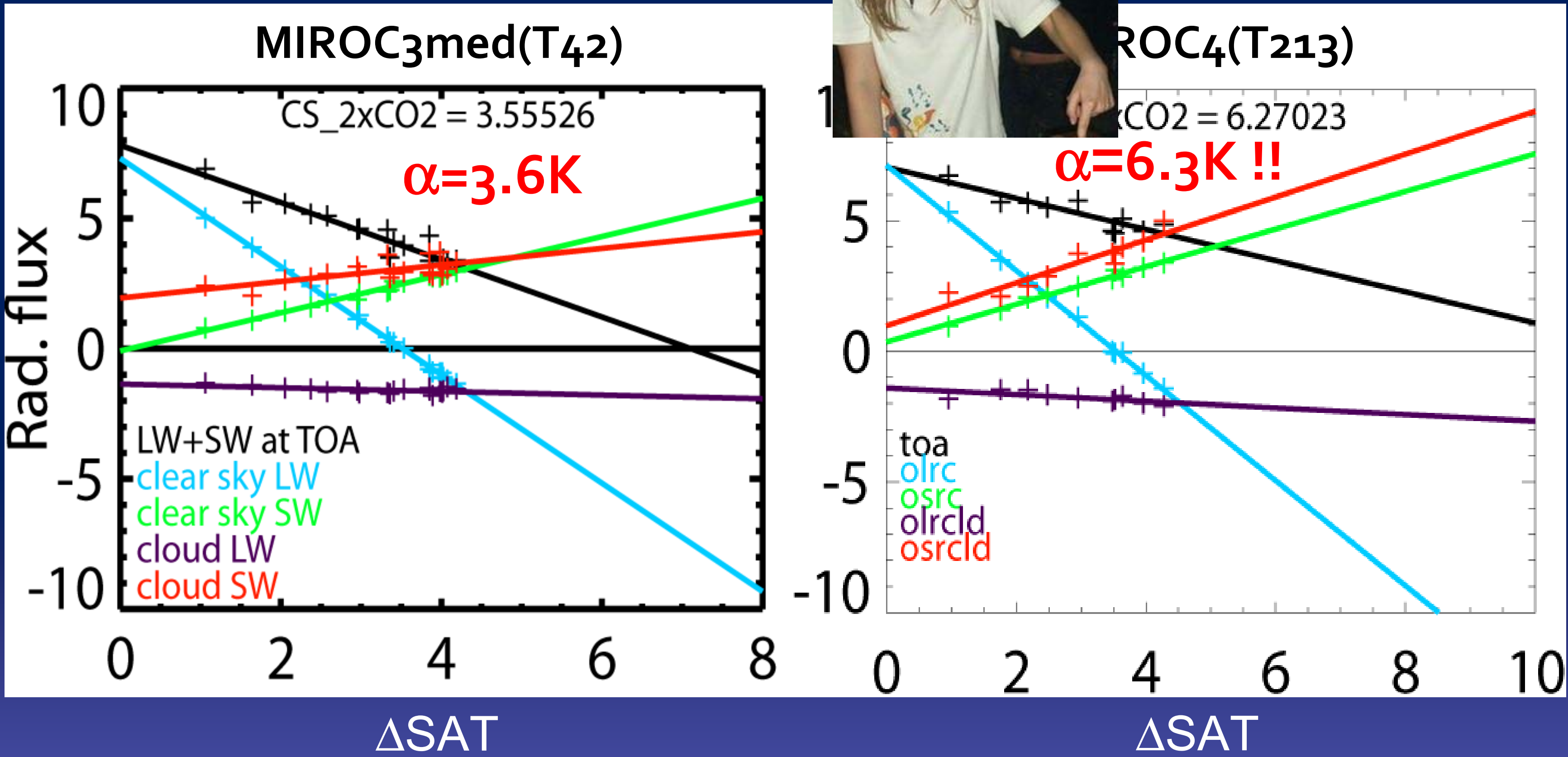


Courtesy of Masa Yoshimori

Equilibrium climate sensitivity

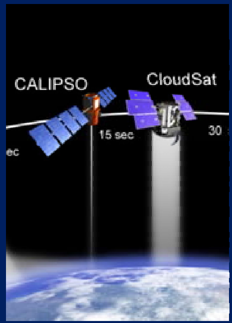
LW+SW
LWclr
SWclr
LWcloud
SWcloud

Gregory plots for 4xCO2 N = F



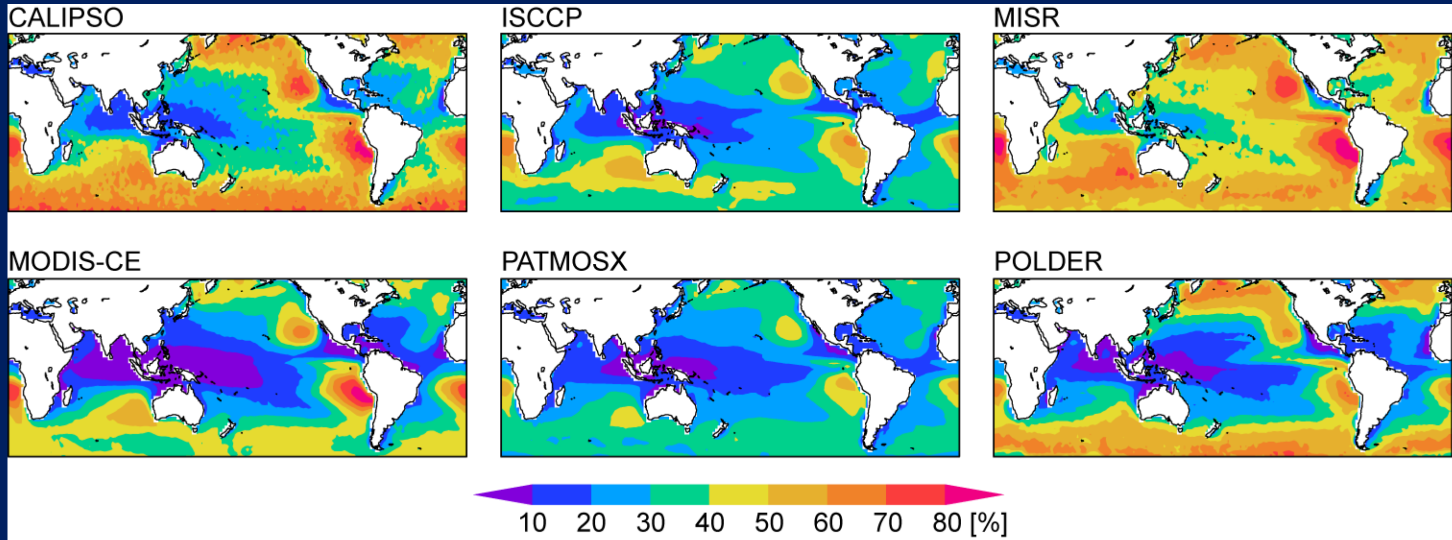
Courtesy of H Shiogama

MIROC3 had two minor (low- and high-sensitivity) versions
MIROC4 even reveals higher sensitivity

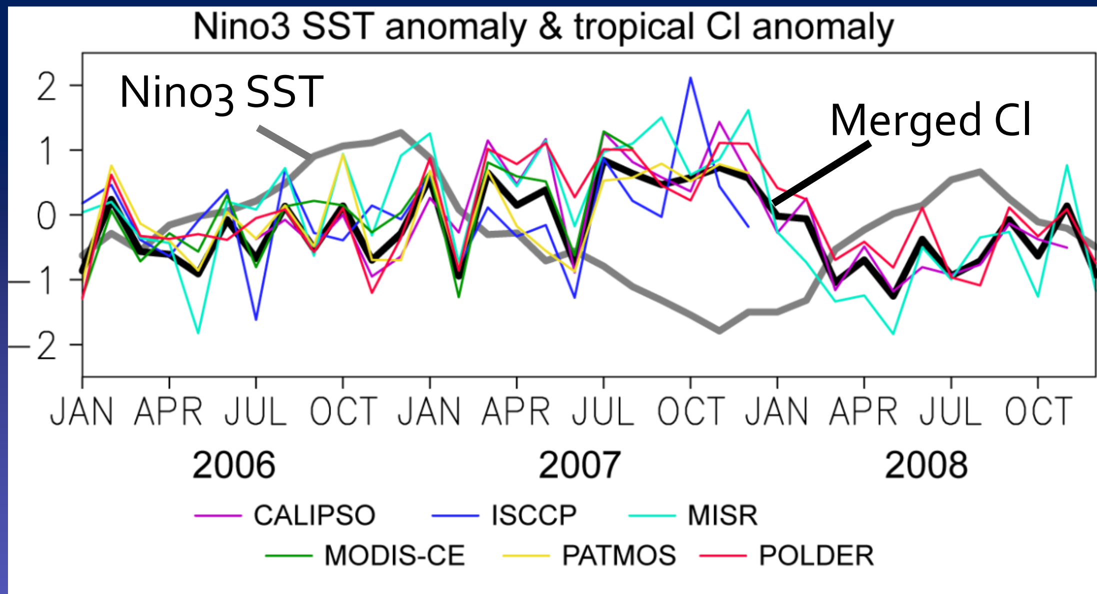


GEWEX cloud data

Annual-mean clim. CI



Data	Period
CALIPSO	Jul2006-Nov2008
ISCCP-D1	Jan1984-Dec2007
MISR	Jan2001-Dec2008
MODIS-CE	Jan2003-Aug2007
PATMOSX	Jan1982-Dec2007
POLDER	Jan2006-Dec2008



Courtesy of T Kubota (JAXA)

Aquaplanet exp.

SST+2/control diff

"climate sensitivity"

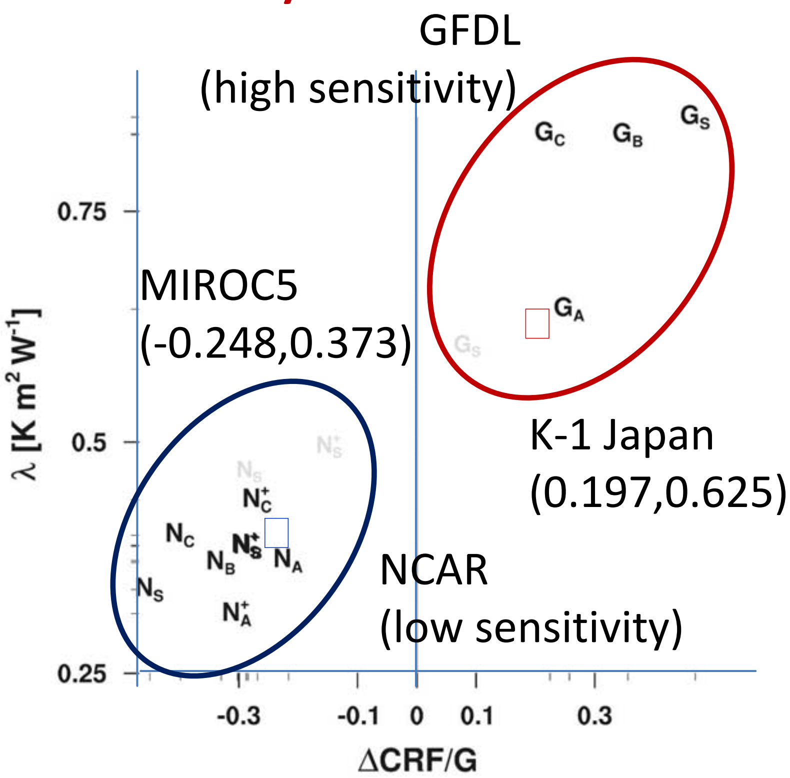
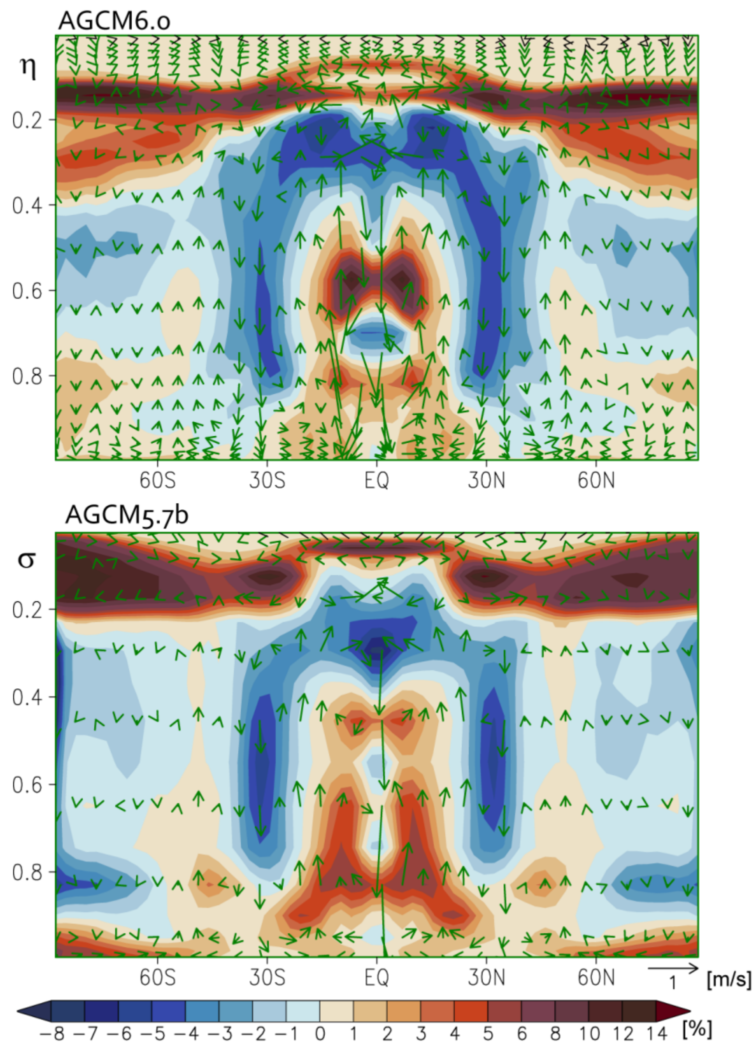


FIG. 4. Climate sensitivity parameter λ vs ΔCRF/*G* for all configurations of both GCMs; black symbols represent the tropically averaged values. The symbols correspond to abbreviations of each configuration, where the large letter gives the GCM being used (G = GFDL AM, N = NCAR CAM), the subscript is the SST configuration (S for standard, A–C for aquaplanets), and a superscript "+" denotes the T85 version of the NCAR CAM. The two nearly overlain symbols are the T85 versions of the standard and aquaplanet B configurations. Gray symbols denote the globally averaged values from the standard configurations.

Medeiros et al. (2008)

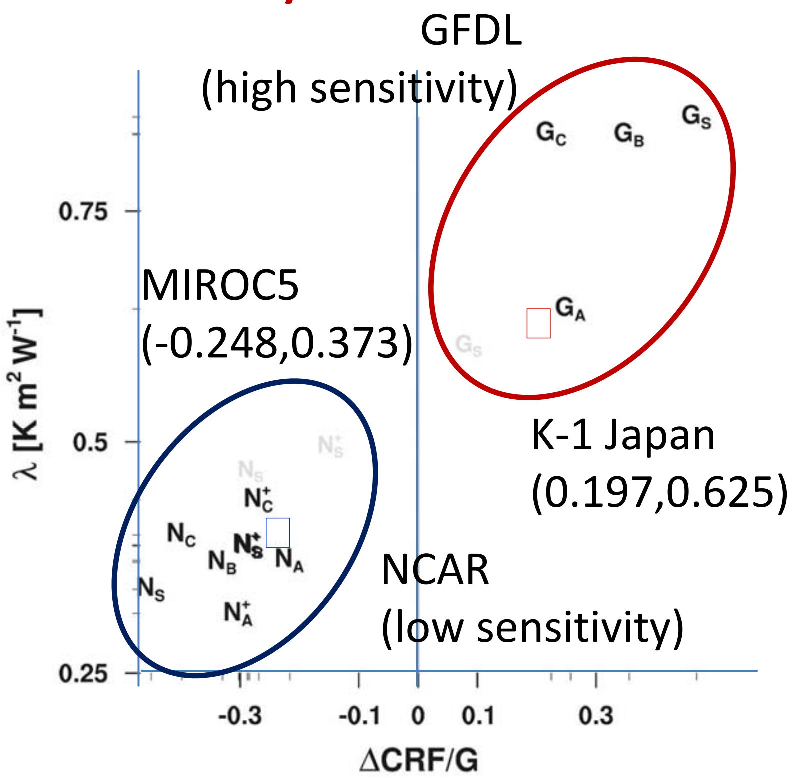
Relative humidity diff.



Aquaplanet exp.

SST+2/control diff

"climate sensitivity"



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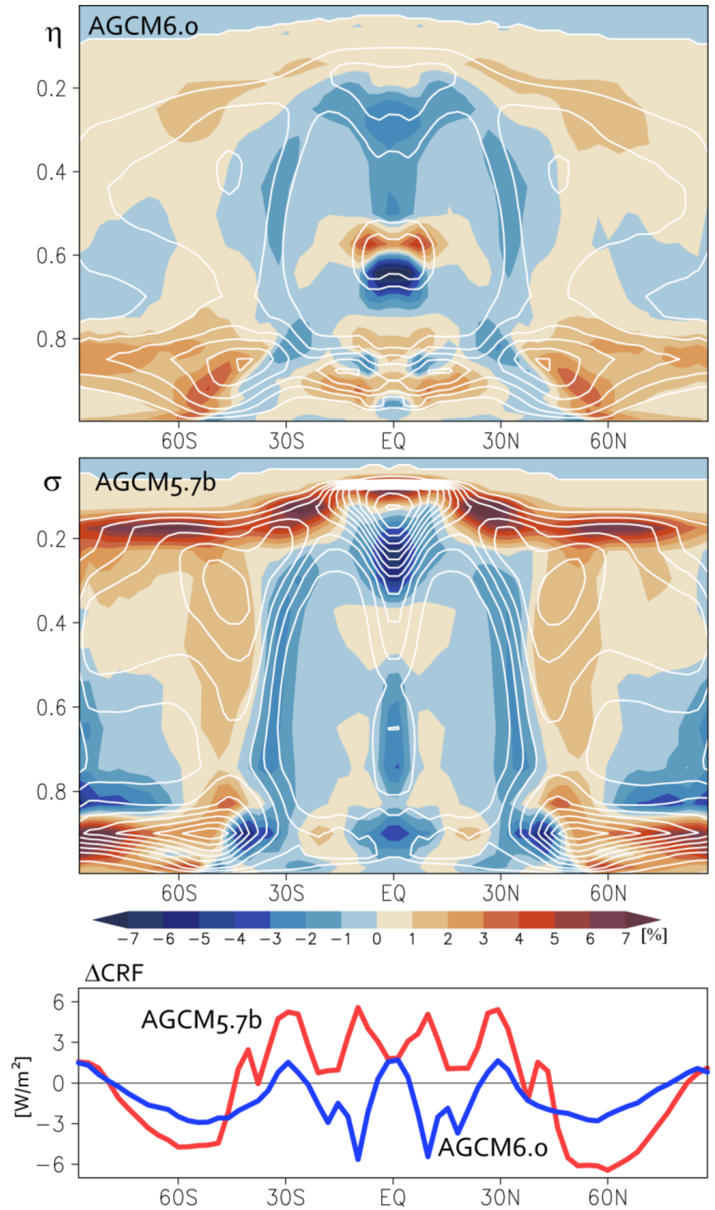
Medeiros et al. (2008)

Cloud fraction diff.



Aquaplanet exp.

SST+2/control diff

“climate sensitivity”

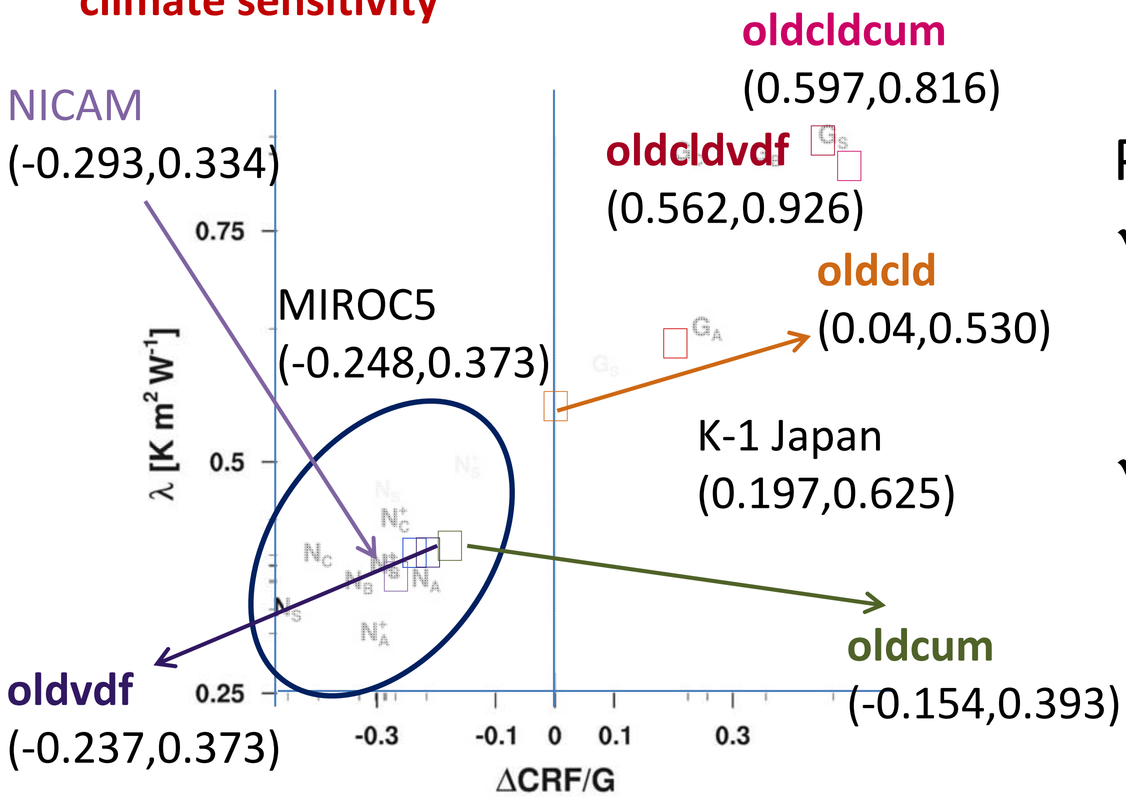


FIG. 4. Climate sensitivity parameter λ vs ΔCRF/*G* for all configurations of both GCMs; black symbols represent the tropically averaged values. The symbols correspond to abbreviations of each configuration, where the large letter gives the GCM being used (G = GFDL AM, N = NCAR CAM), the subscript is the SST configuration (S for standard, A–C for aquaplanets), and a superscript “+” denotes the T85 version of the NCAR CAM. The two nearly overlain symbols are the T85 versions of the standard and aquaplanet B configurations. Gray symbols denote the globally averaged values from the standard configurations.

Medeiros et al. (2008)

Preliminary arguments

✓Different non-convective cloud scheme is of importance

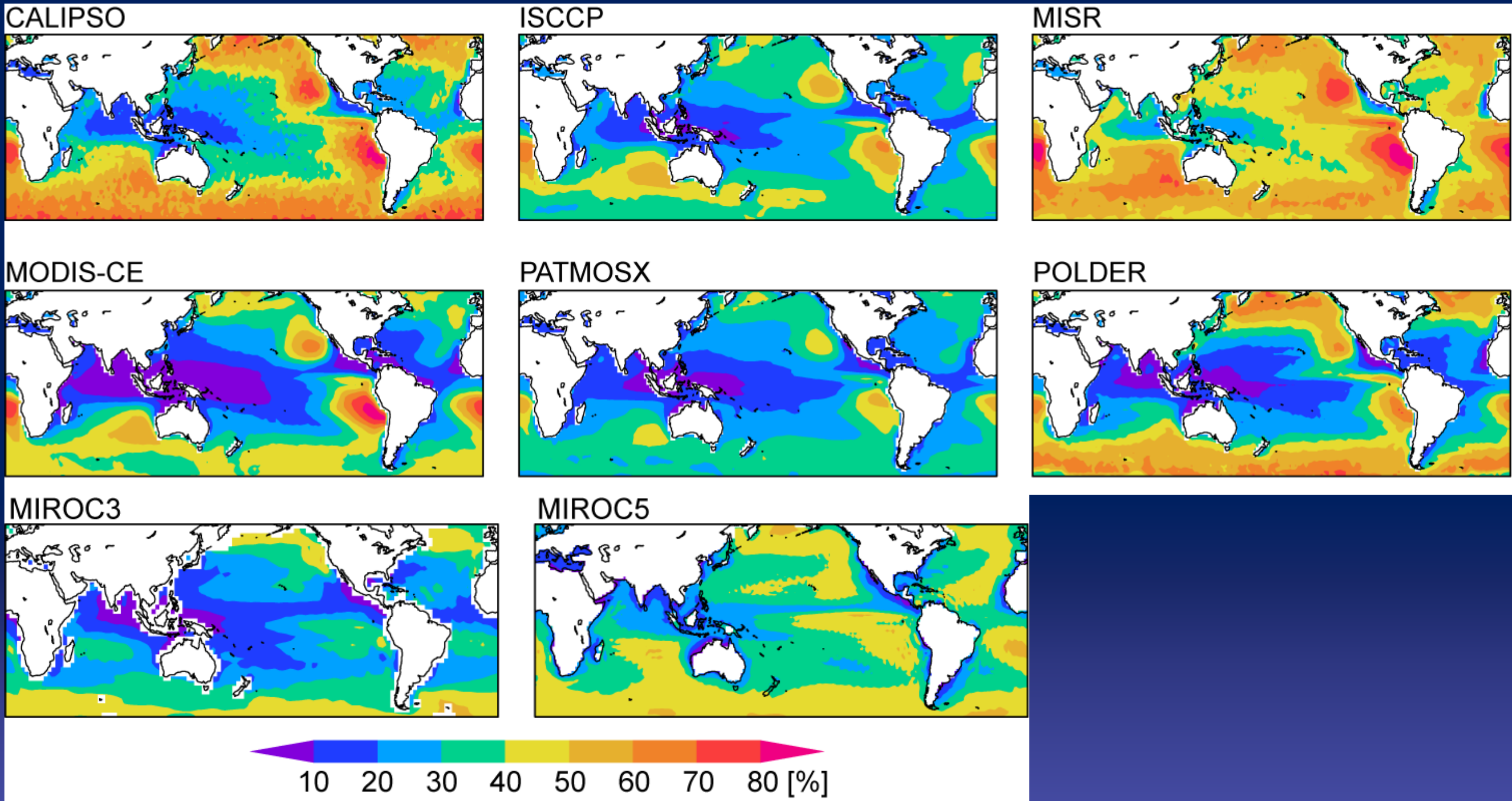
✓But, coupling between the sub-grid processes is also a major source for different climate sensitivity (cf. Zhang & Bretherton 2008)

GEWEX cloud data

Data	Period	
AIRS	Jan2003-Dec2009	
ATSR	Jan2002-Dec2009	
CALIPSO	Jul2006-Nov2008	
ISCCP-D1	Jan1984-Dec2007	
MISR	Jan2001-Dec2008	
MODIS-CE	Jan2003-Aug2007	
PATMOSX	Jan1982-Dec2007	
POLDER	Jan2006-Dec2008	
TOVSB	Jan1987-Dec1990	

Mean Cl

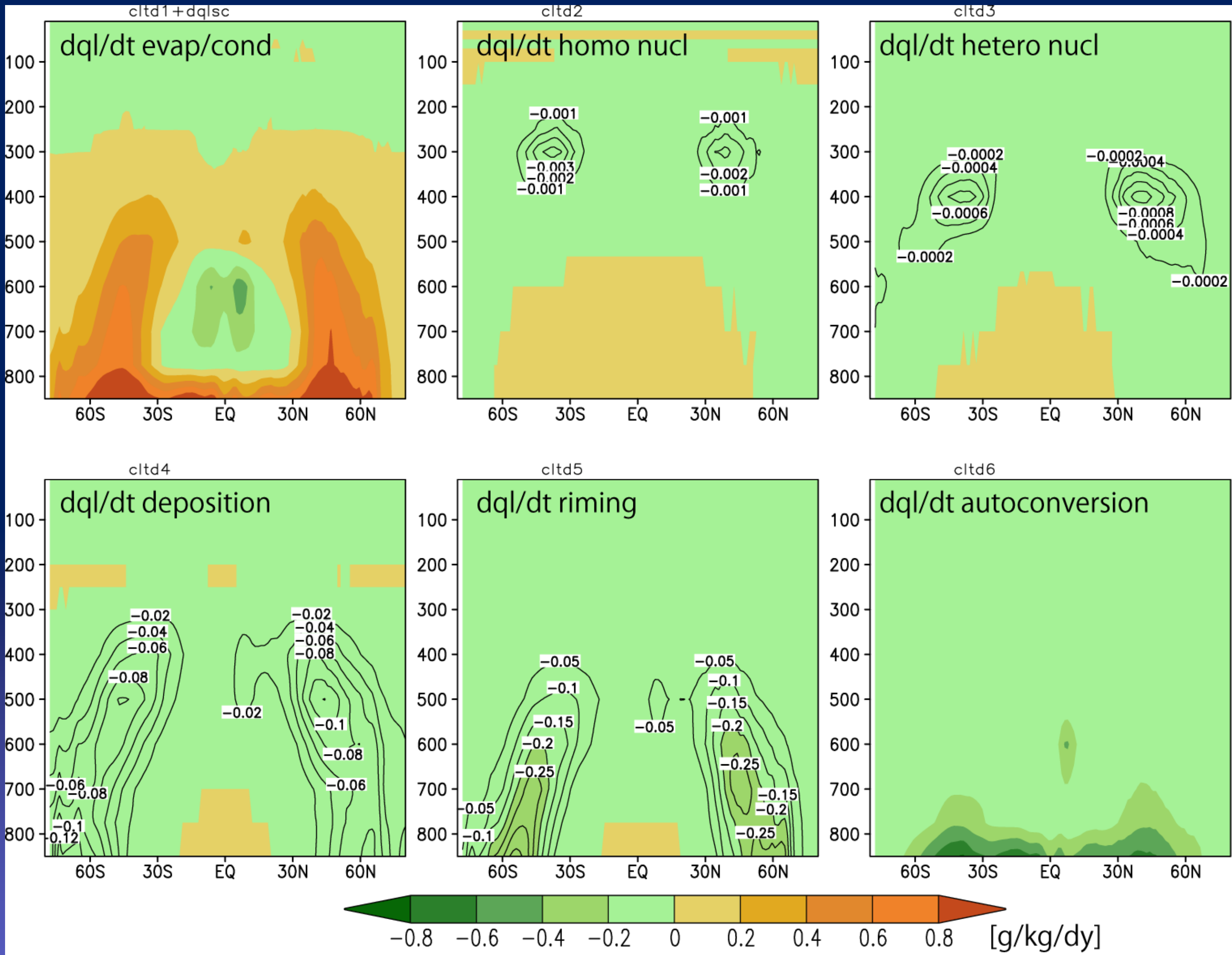
Annual-mean clim.



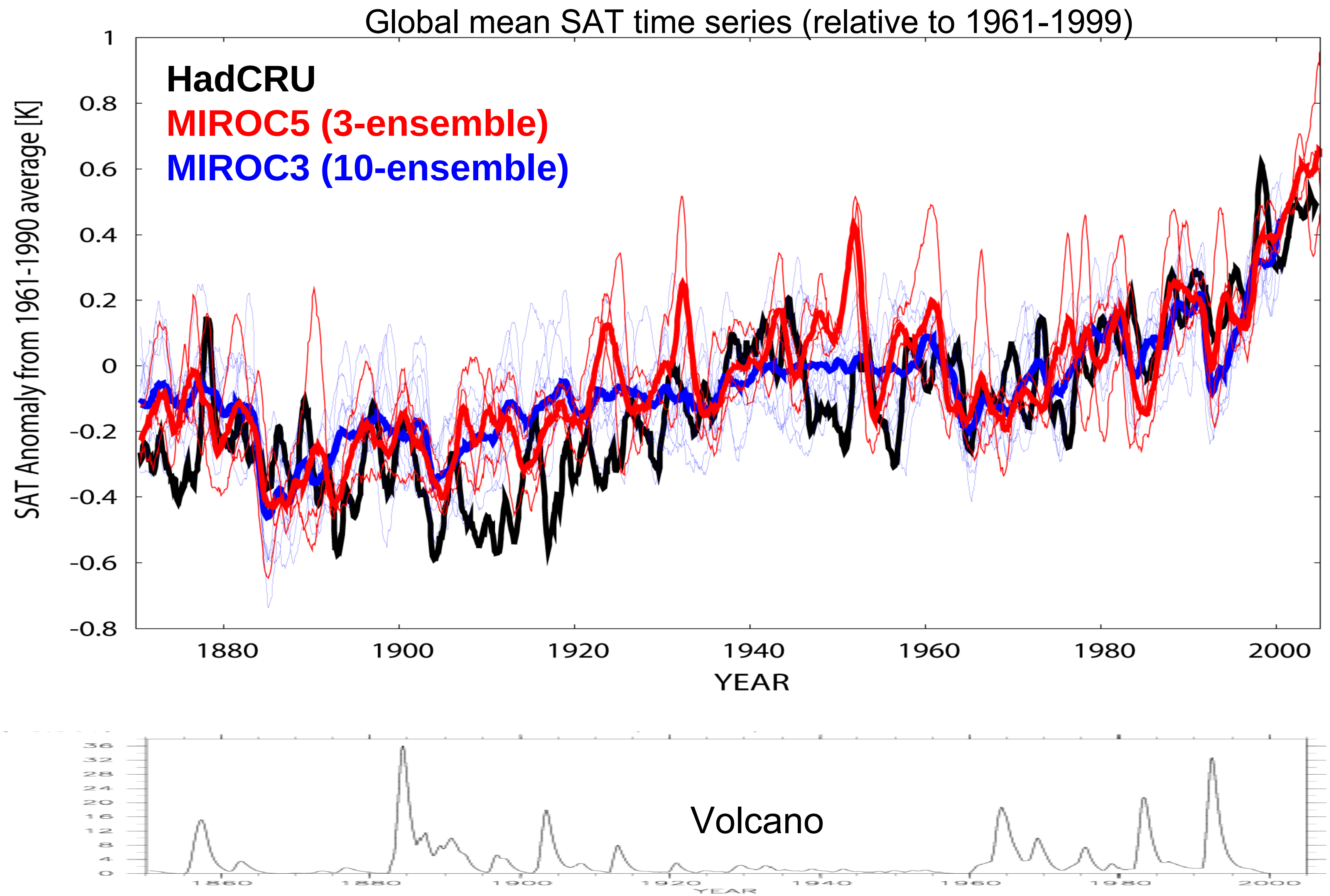
What determines the Cl trend?

20C runs

Zonal-mean cloud water budgets in MIROC5



MIROC5-MIROC3, 20C experiment



Courtesy of T Yokohata

What determines the CI trend?

20C runs

Spatial cor. for 30S-30N trend patterns

	ΔCI	$\Delta\omega_{500}$	ΔLTS	ΔSST
ΔCI		0.62	0.40	-0.54
$\Delta\omega_{500}$	0.38		0.23	-0.50
ΔLTS	0.73	0.40		-0.75
ΔSST	-0.68	-0.52	-0.86	

MIROC5

MIROC3

How uniform SST increase works?

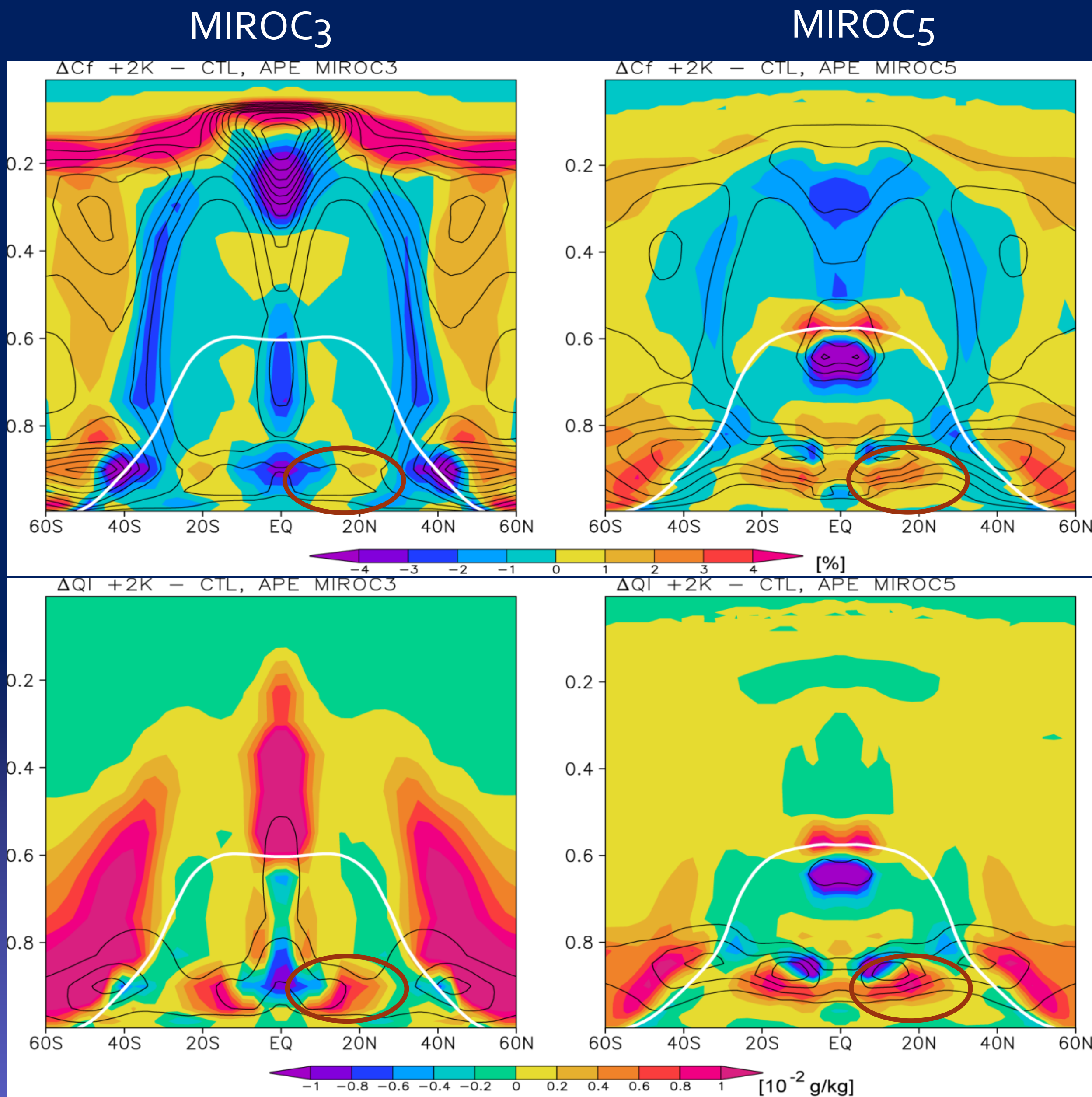
Aquaplanet runs
(SST+2K minus CTL)

ΔCf

MIROC3:
Equatorial decrease
> Subtropical increase
MIROC5:
Equatorial decrease
< Subtropical increase

ΔQl

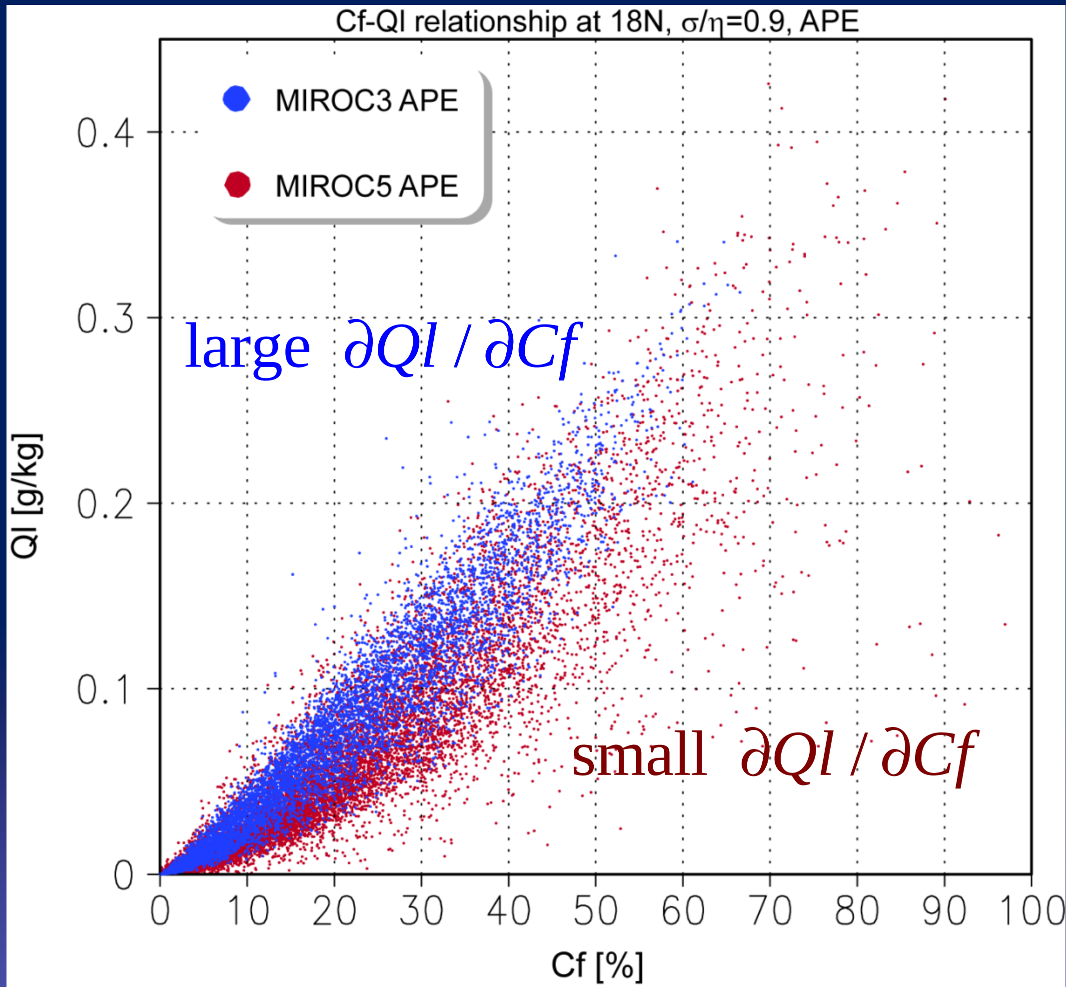
Subtropical increase
MIROC3 ~ MIROC5



How uniform SST increase works?

Aquaplanet runs

Cf-Ql relationship at 18N, σ or η=0.9



✓ In MIROC5, more Cf change is required for the same amount of change in Ql

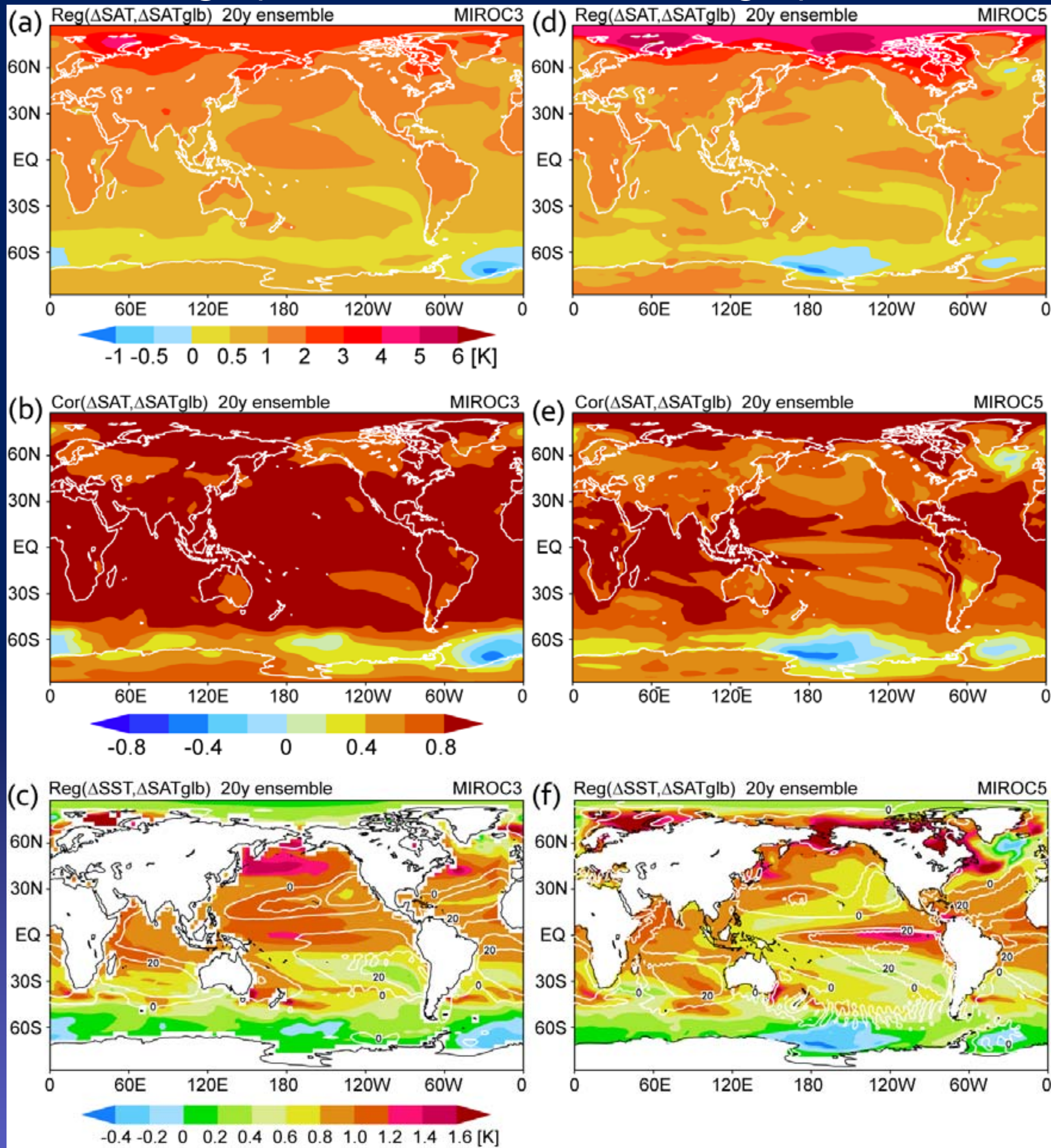
Global warming patterns

MIROC3 4xCO2 - CTL   MIROC5 4xCO2 - CTL

Reg(ΔSAT, ΔSATg)

Cor(ΔSAT, ΔSATg)

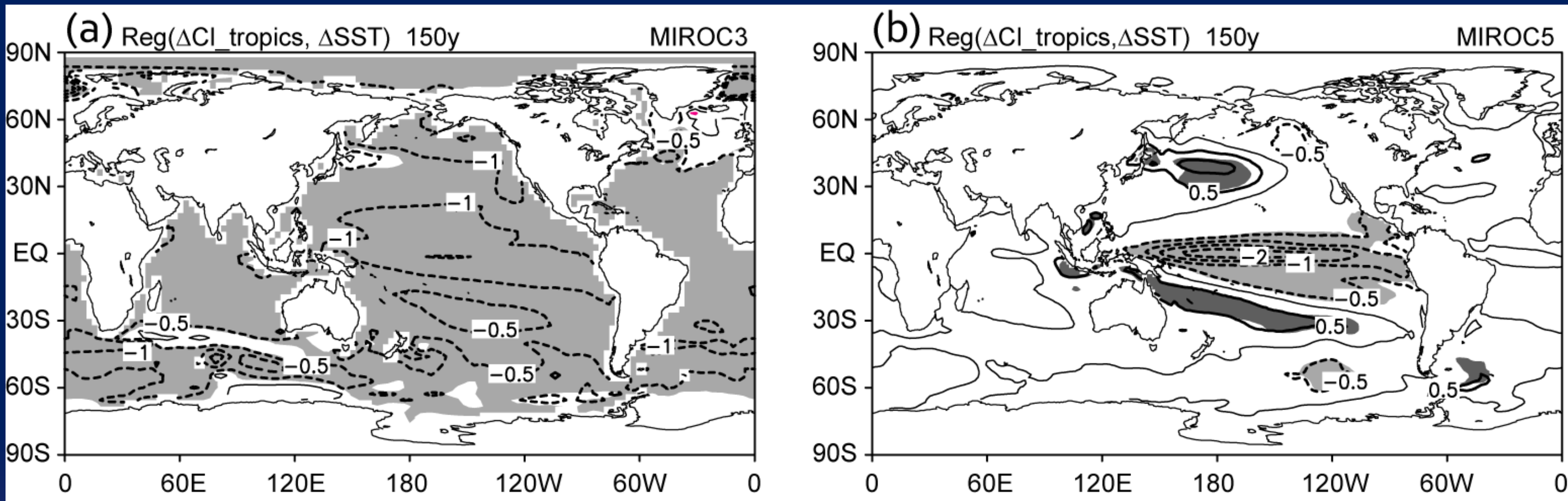
Reg(ΔSST, ΔSATg)



Low-cloud changes in 4xCO_2

Regression between ΔSST & $\langle \Delta Cl \rangle_{tropics}$

MIROC3 MIROC5

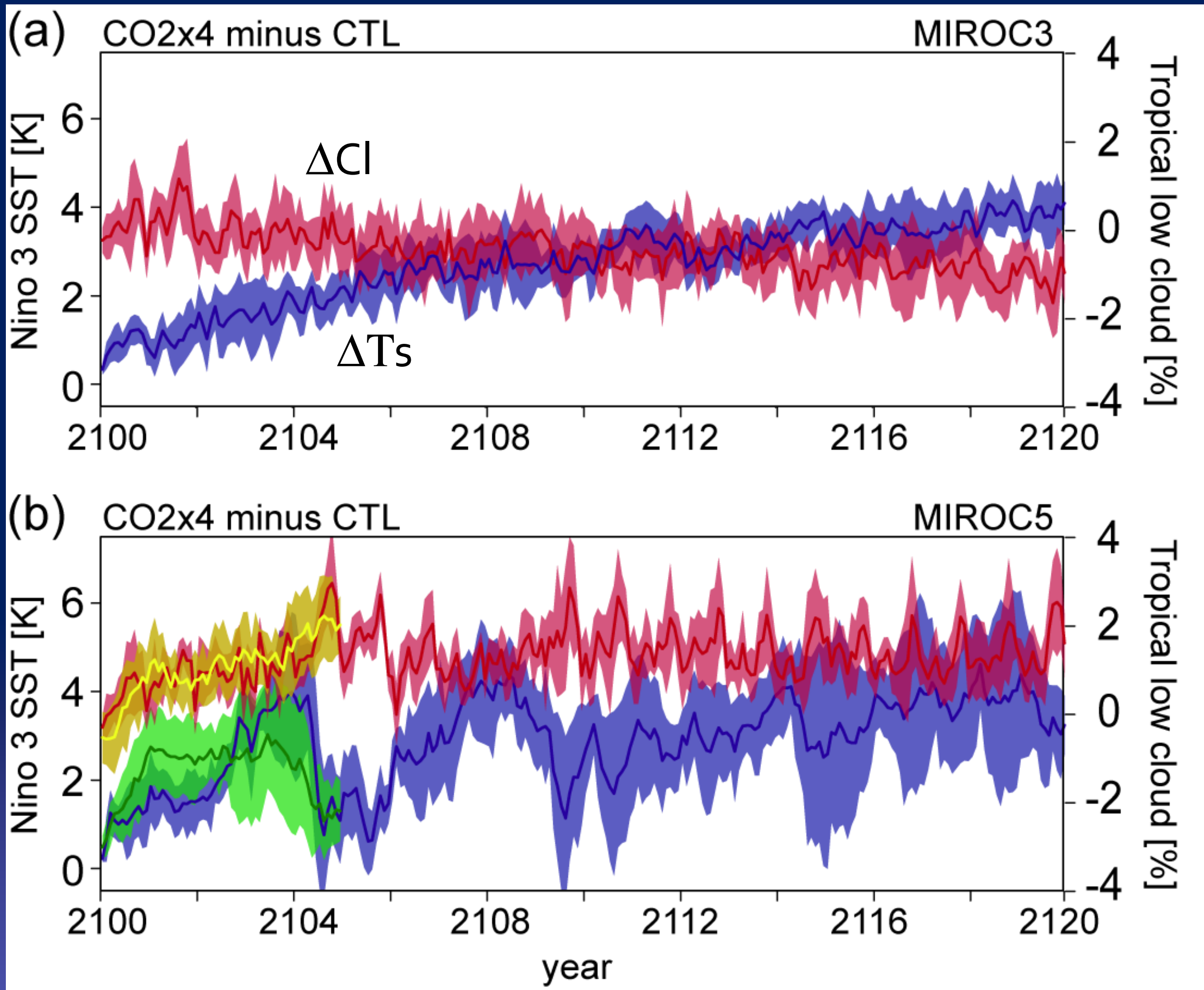


In general, mean SST increases -> tropical low cloud decreases

Initial evolution

MIROC3

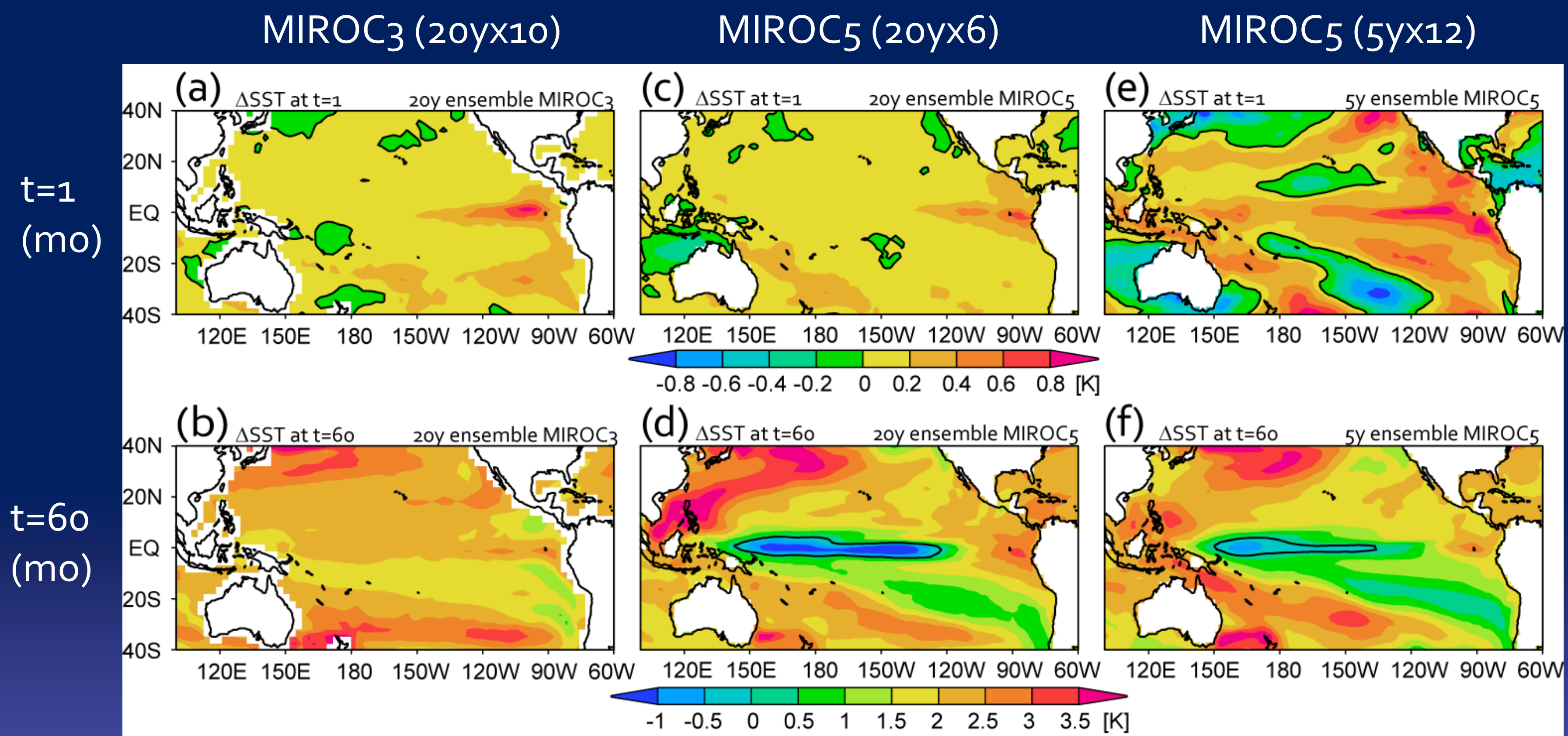
MIROC5



Initial 20y

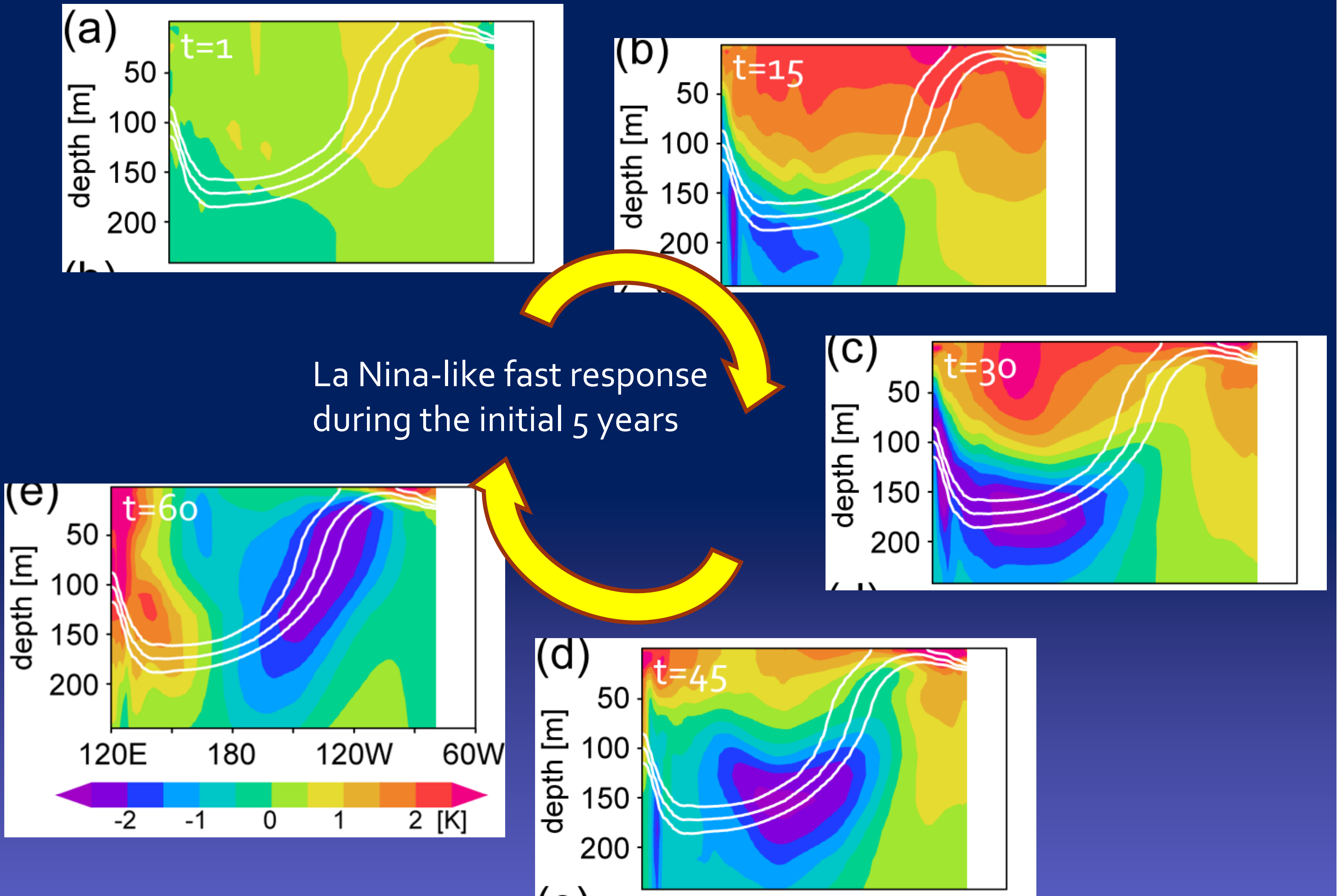
Initial evolution

ΔSST



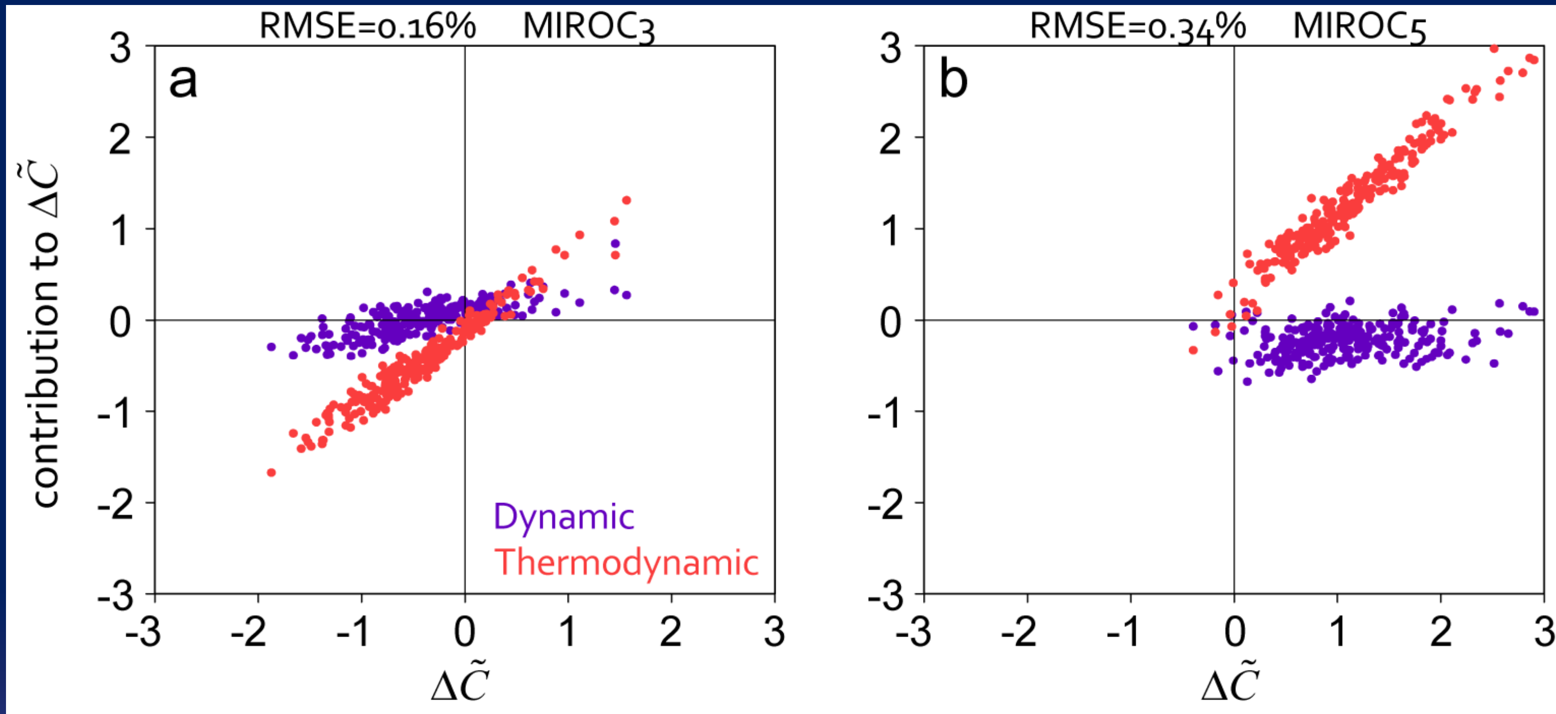
Initial evolution

ΔT_o along EQ in MIROC5 (5yx12)



Fast response of low clouds

MIROC3 MIROC5



$$\Delta\tilde{C}_l \approx \int \Delta P_\omega C_l^{CTL}(\omega)\,d\omega + \int P_\omega^{CTL}\Delta C_l(\omega)\,d\omega$$

ΔCl primarily determined by ΔCl(ω) with fixed Pω

Change in Pω can be negligible

Implication to 20th century trend

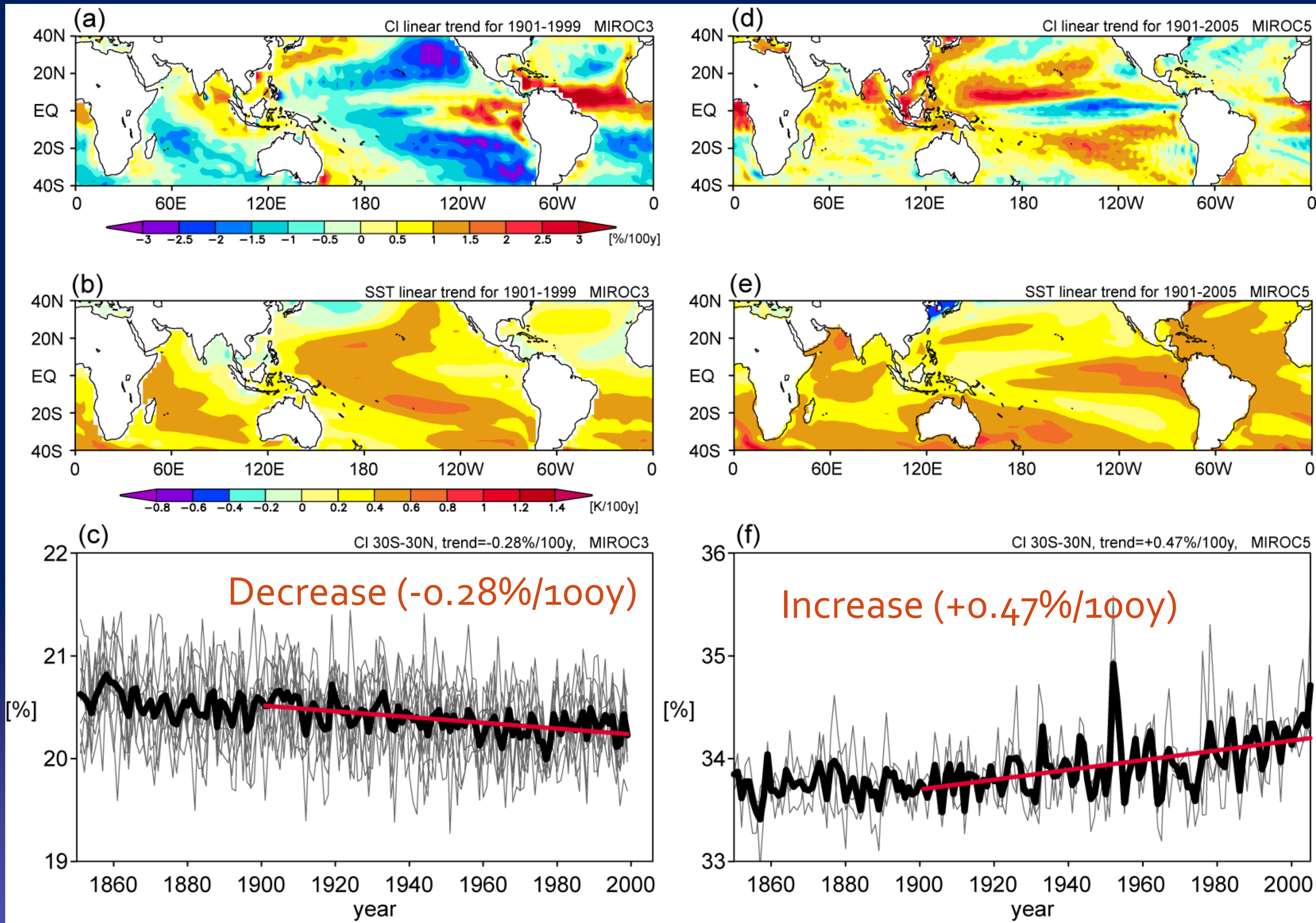
20C runs

MIROC3 (10 mem) MIROC5 (3 mem)

Cl trend (%/100y)

SST trend (K/100y)

Tropical Cl (30S-30N)



- ✓ Likely due to fast response (but change is much slower)
- ✓ τ(CO2 increase; abrupt vs gradual) -> τ(fast response)?

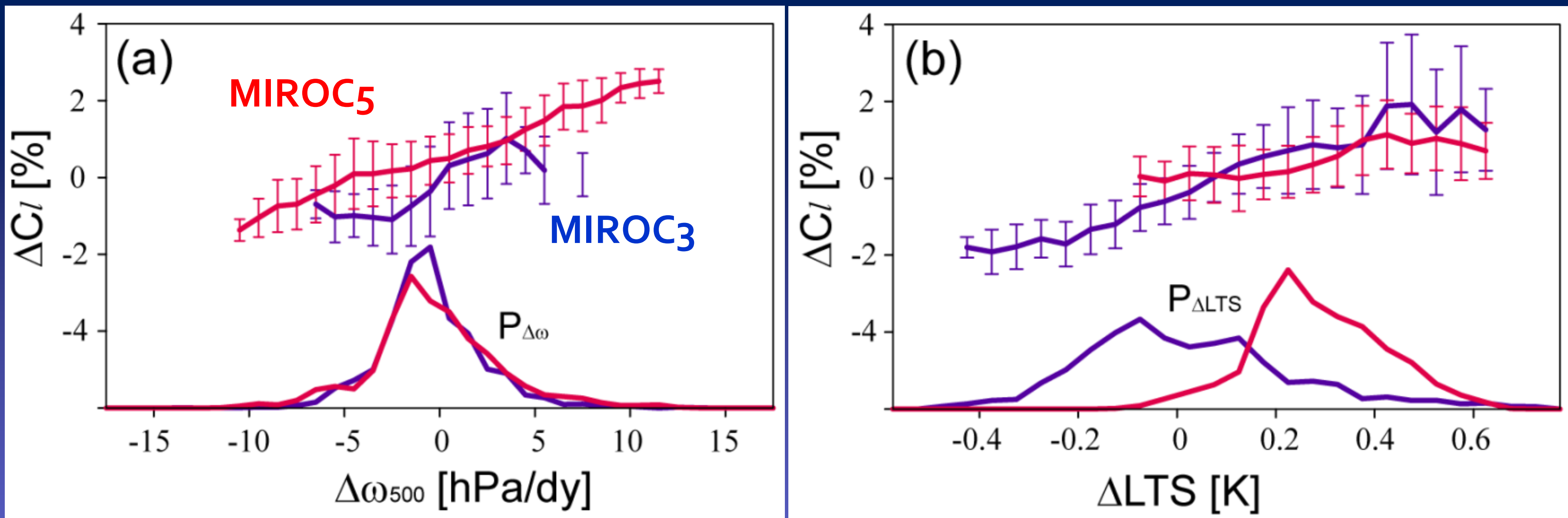
What determines the Cl trend?

20C runs (Δ: linear trend)

- ✓ ΔCl is highly coherent with ΔSST *relative to* its tropical mean
- ✓ Two direct constraints to ΔCl:
- ✓ Δω (at 500 hPa): cannot be uniform because of the conservation of mass
  -> important for the regional feature of ΔCl
- ✓ ΔLTS (lower-tropospheric stability) may be free from dynamical constraints
  -> important for the tropical-mean ΔCl

ΔCl composite wrt Δω

ΔCl composite wrt ΔLTS



Implication to 20th century trend

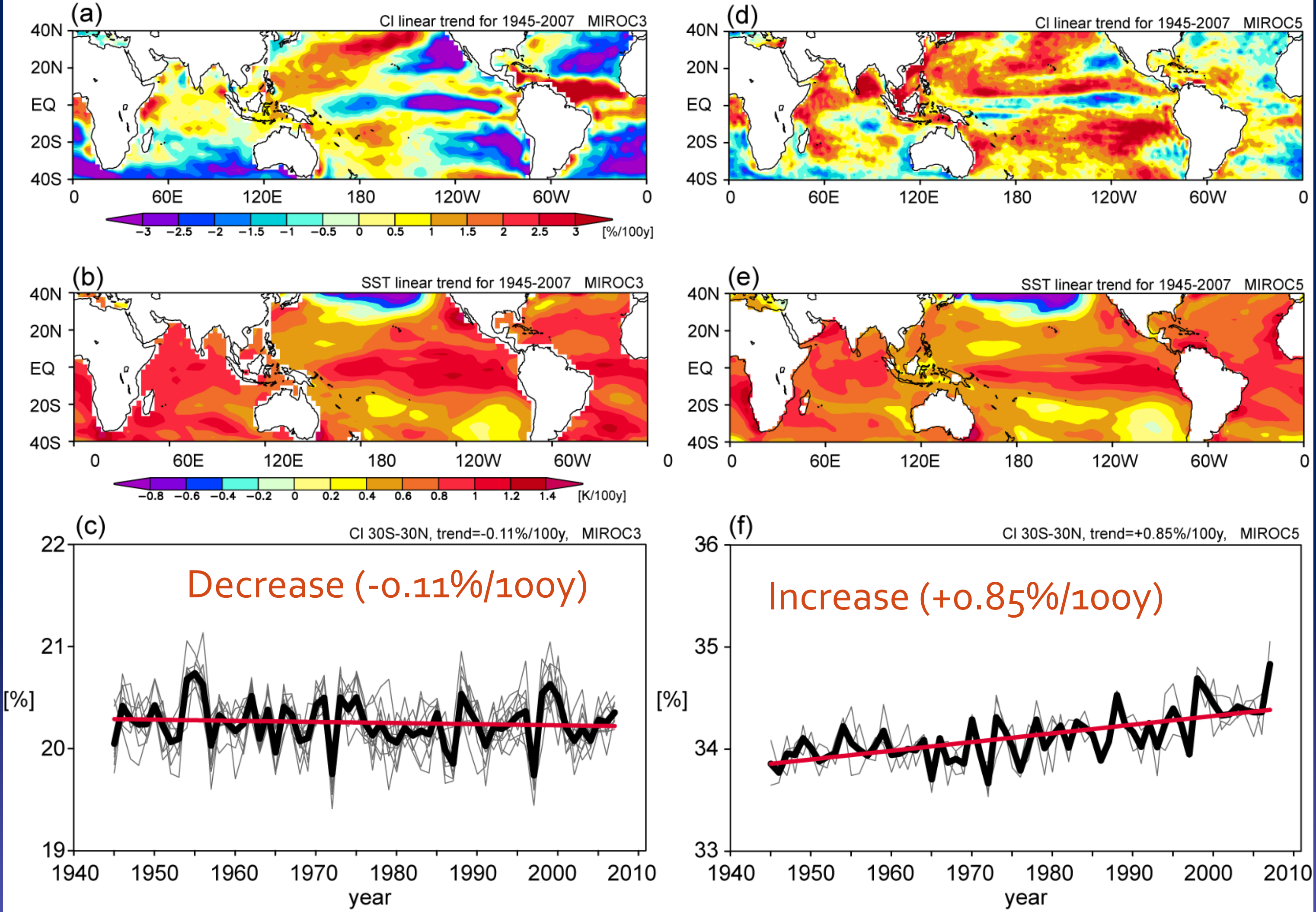
20C assimilations

MIROC3 MIROC5

Cl trend (%/100y)

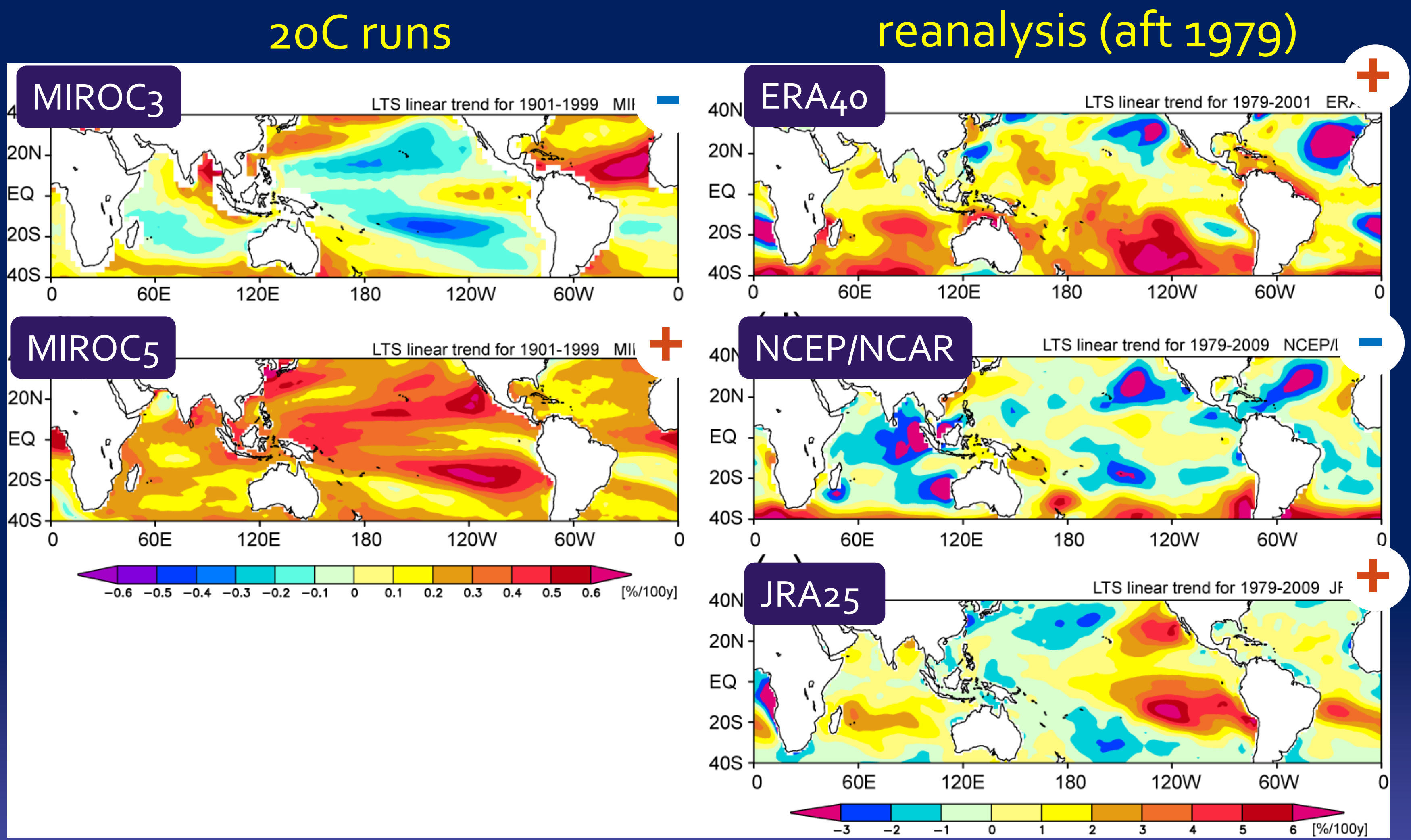
SST trend (K/100y)

Tropical Cl (30S-30N)



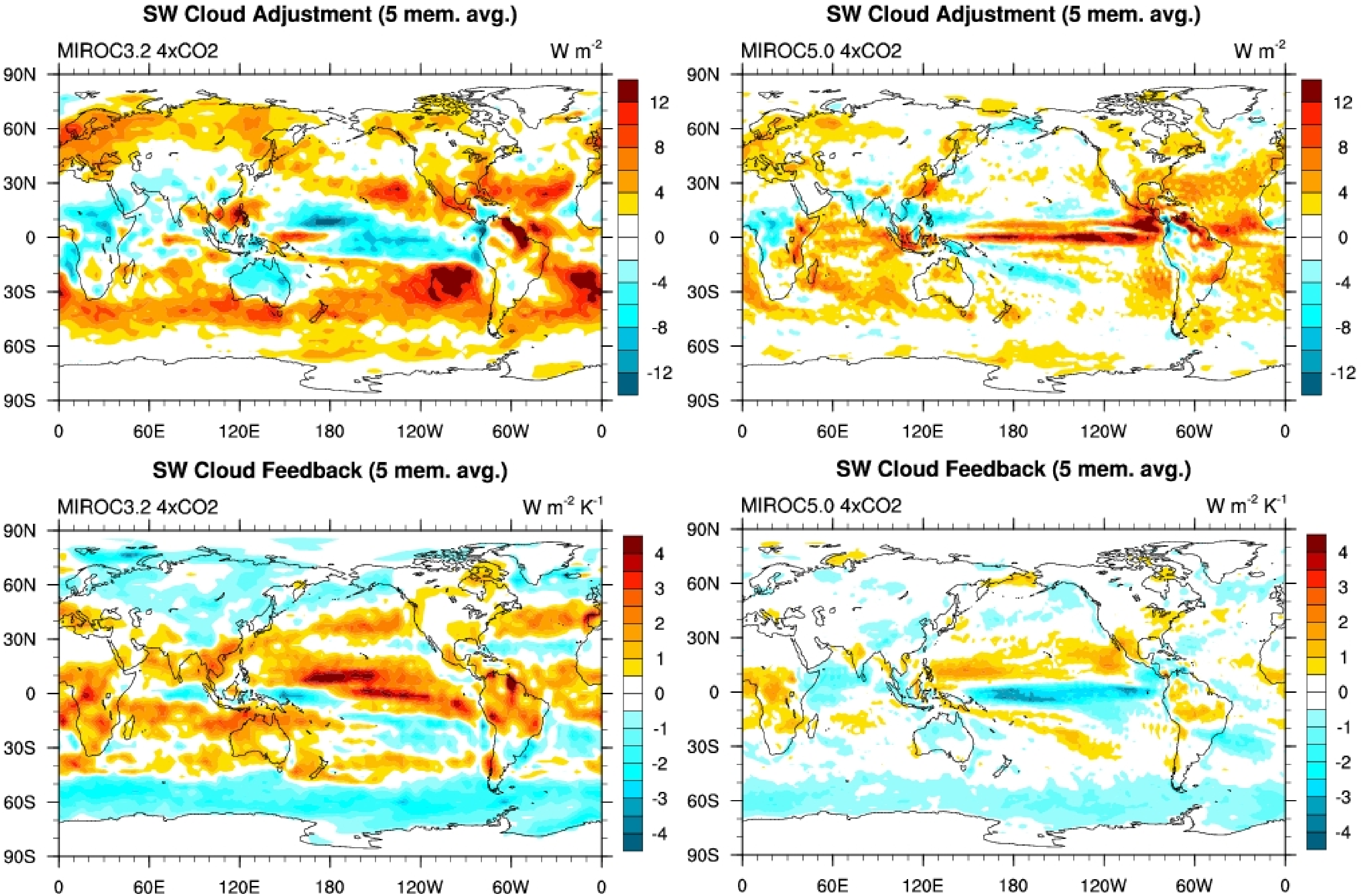
- ✓ Likely due to fast response (but change is much slower)
- ✓ τ(CO_2 increase; abrupt vs gradual) -> τ(fast response)?

LTS trend: positive or negative ?

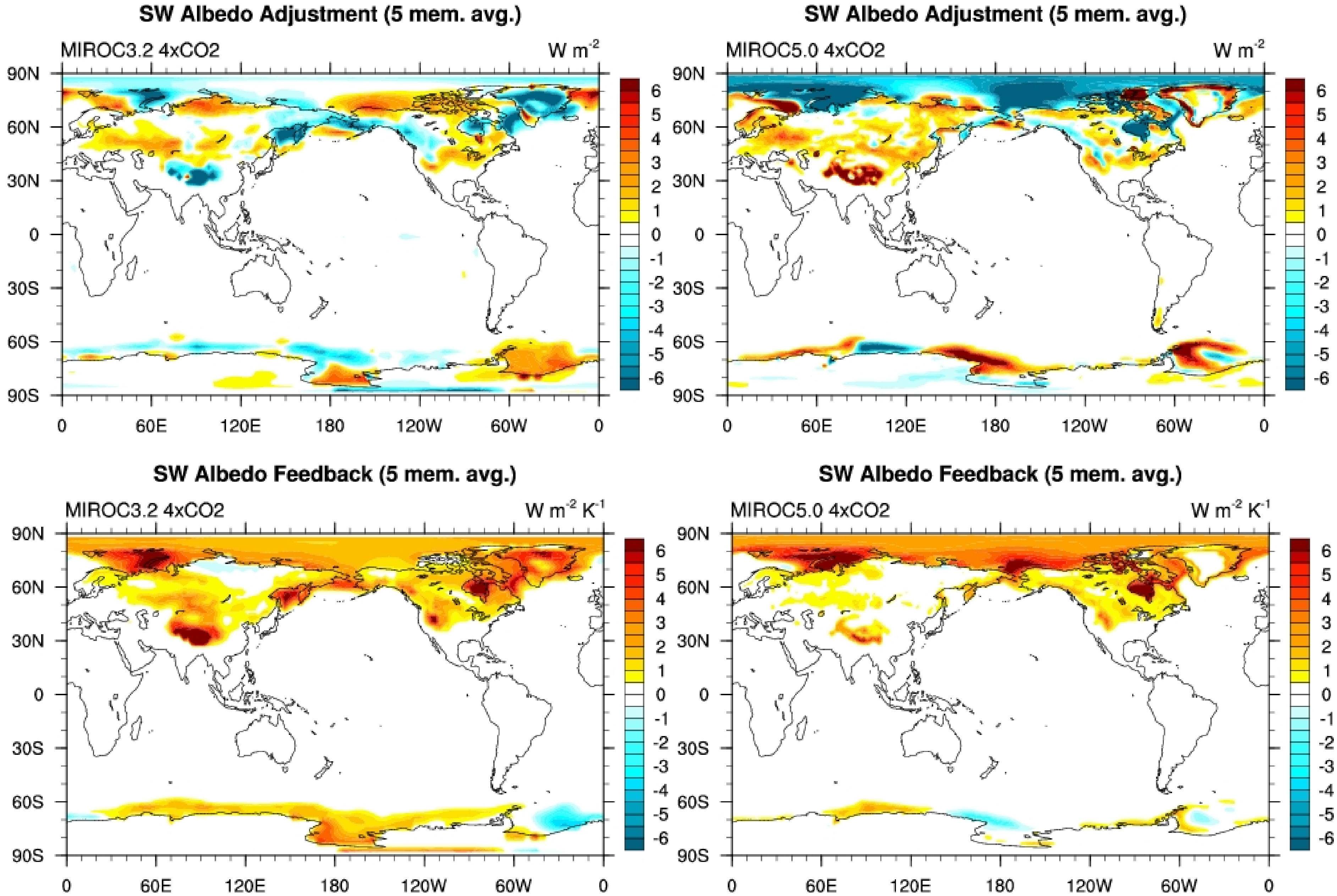


- ✓ Too large LTS trends in reanalysis data (period? noise? error?)
- ✓ Spatial patterns quite different among the products

APRP Cloud SW Analysis: MIROC3.2 vs. MIROC5.0

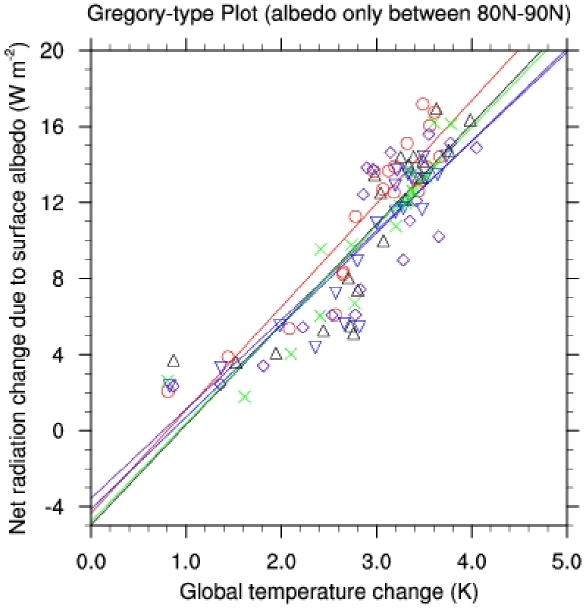


APRP Sfc. Albedo Analysis: MIROC3.2 vs. MIROC5.0

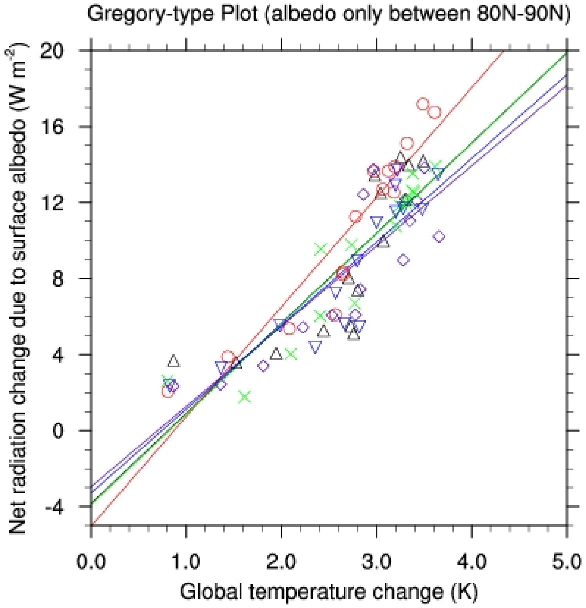


Gregory plotにおける非線形効果（MIROC5,80N-90N平均でテスト,5メンバー）

最初の20年を使用



最初の15年を使用



最初の10年を使用