WS on "Hierarchical Modeling of Climate", ICTP, July 18-22, 2011

Structural and Parametric Uncertainties in Climate Modeling

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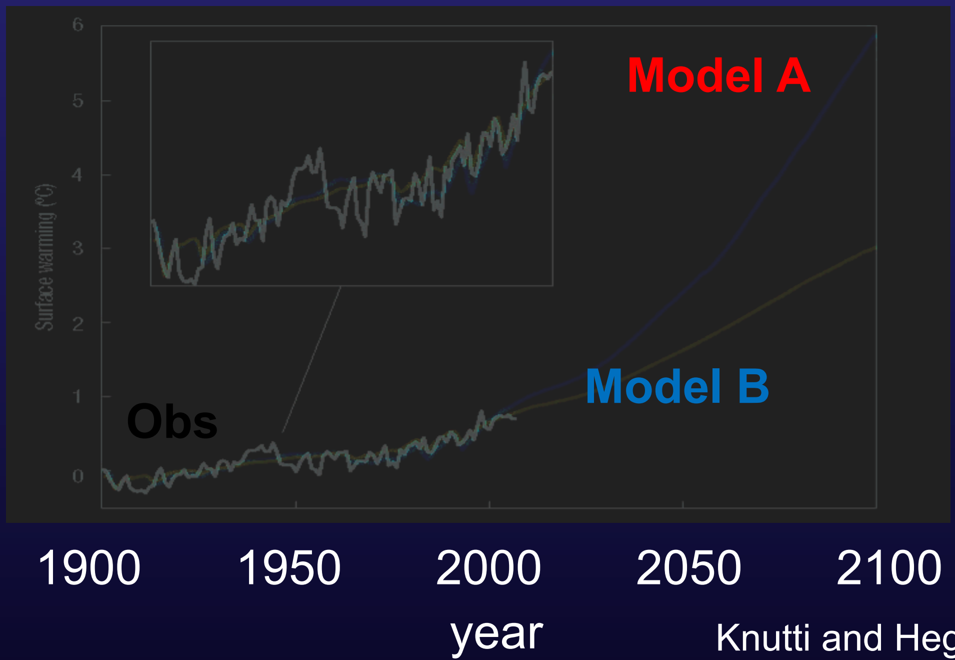
Outline

- ✓ Error and uncertainty in CGCM
- ✓ Approaches for dealing with the uncertainty in climate simulations
- ✓ Examples:
  - #1 ENSO
  - #2 Climate sensitivity
- ✓ Summary

Definition of terms

- ✓ Error : deviations from 'true' when known
- ✓ Uncertainty: spread of solutions when 'true' is not known, ill-sampled, or inherently probabilistic

Global-mean SAT anomaly

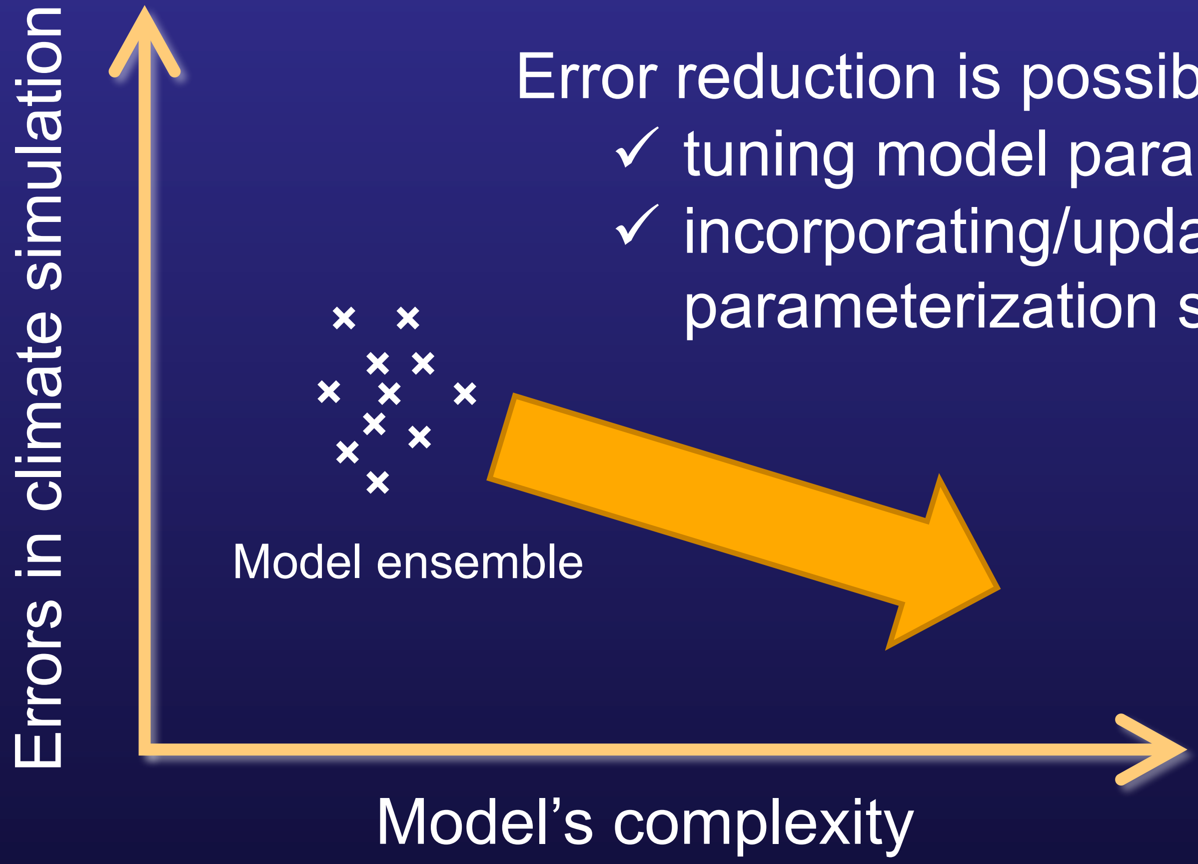


Knutti and Hegerl (2008)

In general …….

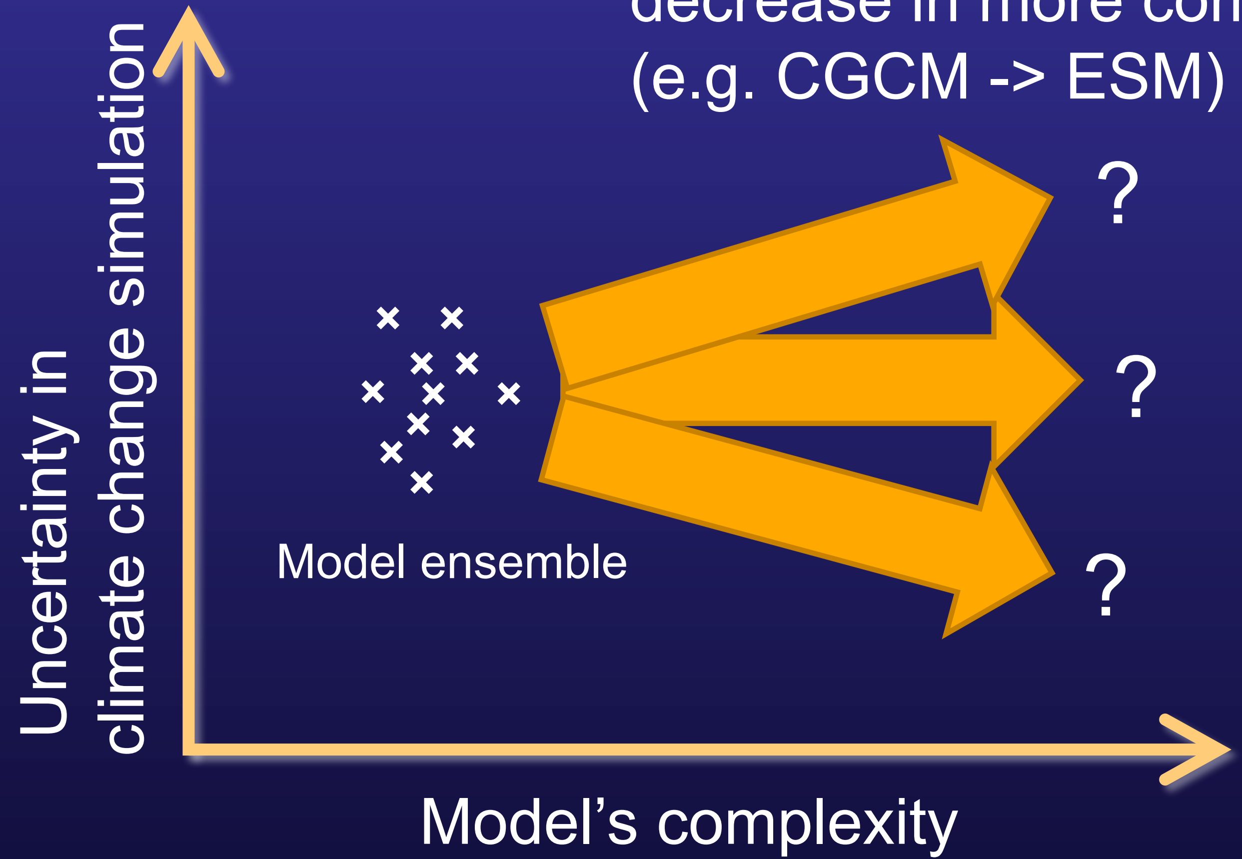
Error reduction is possible by

- ✓ tuning model parameters
- ✓ incorporating/updating parameterization schemes



In general …….

Uncertainty may either increase or decrease in more complex model (e.g. CGCM -> ESM)



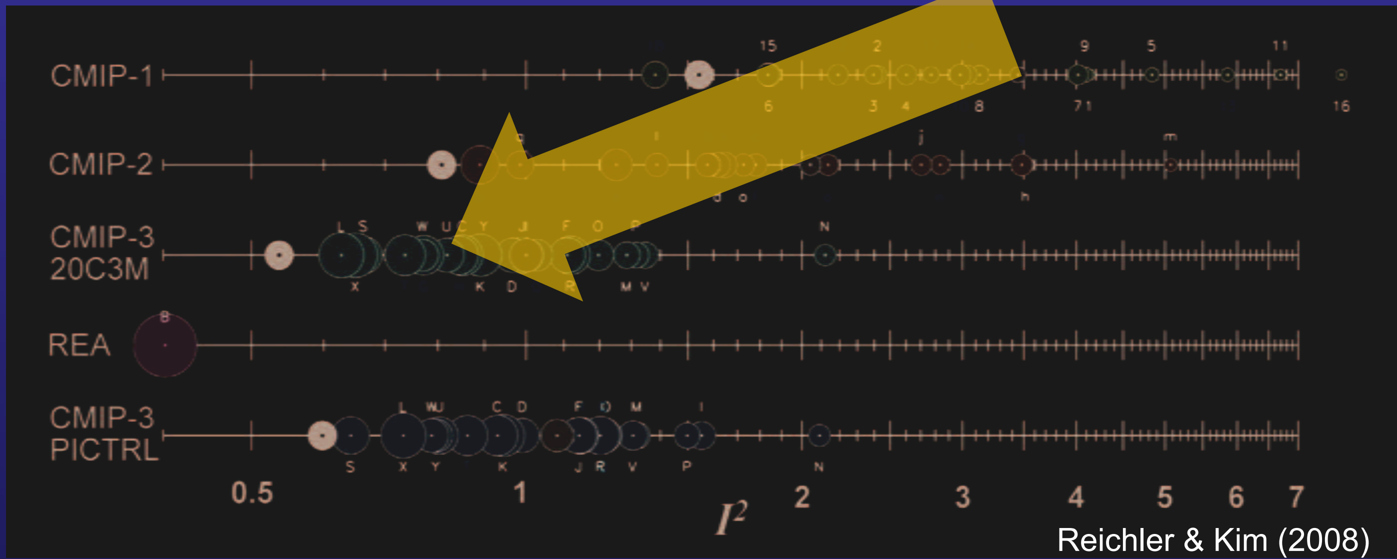
Error is decreasing in CMIP models, but uncertainty remains similar

Combined metric (∝ RMS error)

CMIP1

CMIP2

CMIP3



- Best model in CMIP1 ～worst model in CMIP3
- Increasing no. of models, many of which DO NOT apply q-flux

Equilibrium climate sensitivity to 2xCO_2 in CMIP models

	FAR	SAR	TAR	AR4	AR5
climate sensitivity	1.5-4.5K	1.0-3.5K	1.5-4.5K	2.1-4.4K	??

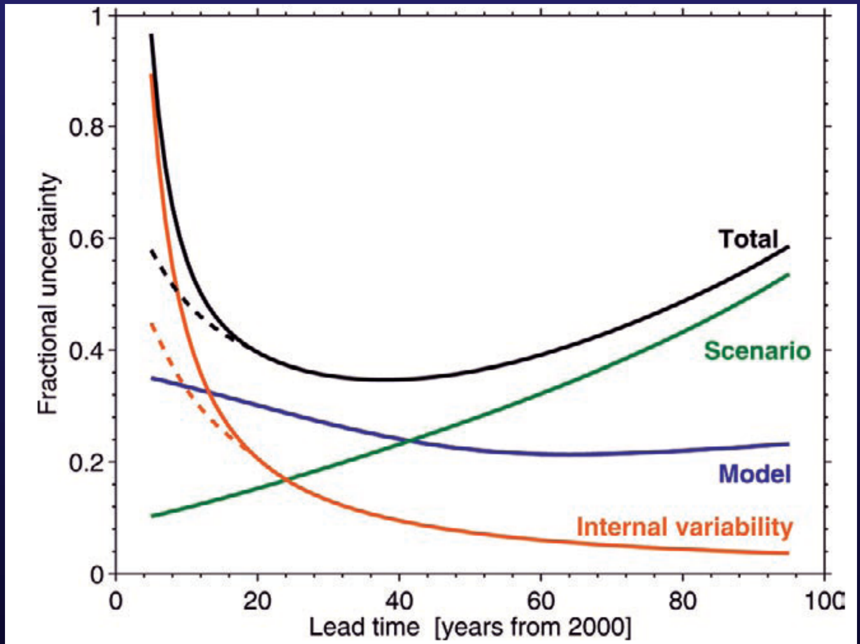
Mitchell et al. (1990), Kattenberg et al. (1996), Cubasch et al. (2001), IPCC (2007)

What can we do for the uncertainty?

- ✓ Reducing uncertainty – Use of observations (reanalysis / satellites / palaeo)
- ✓ Quantifying uncertainty
- ✓ Understanding sources of uncertainty

Sources of climate projection uncertainty wrt the lead time

Fractional uncertainty
in global-mean SAT change



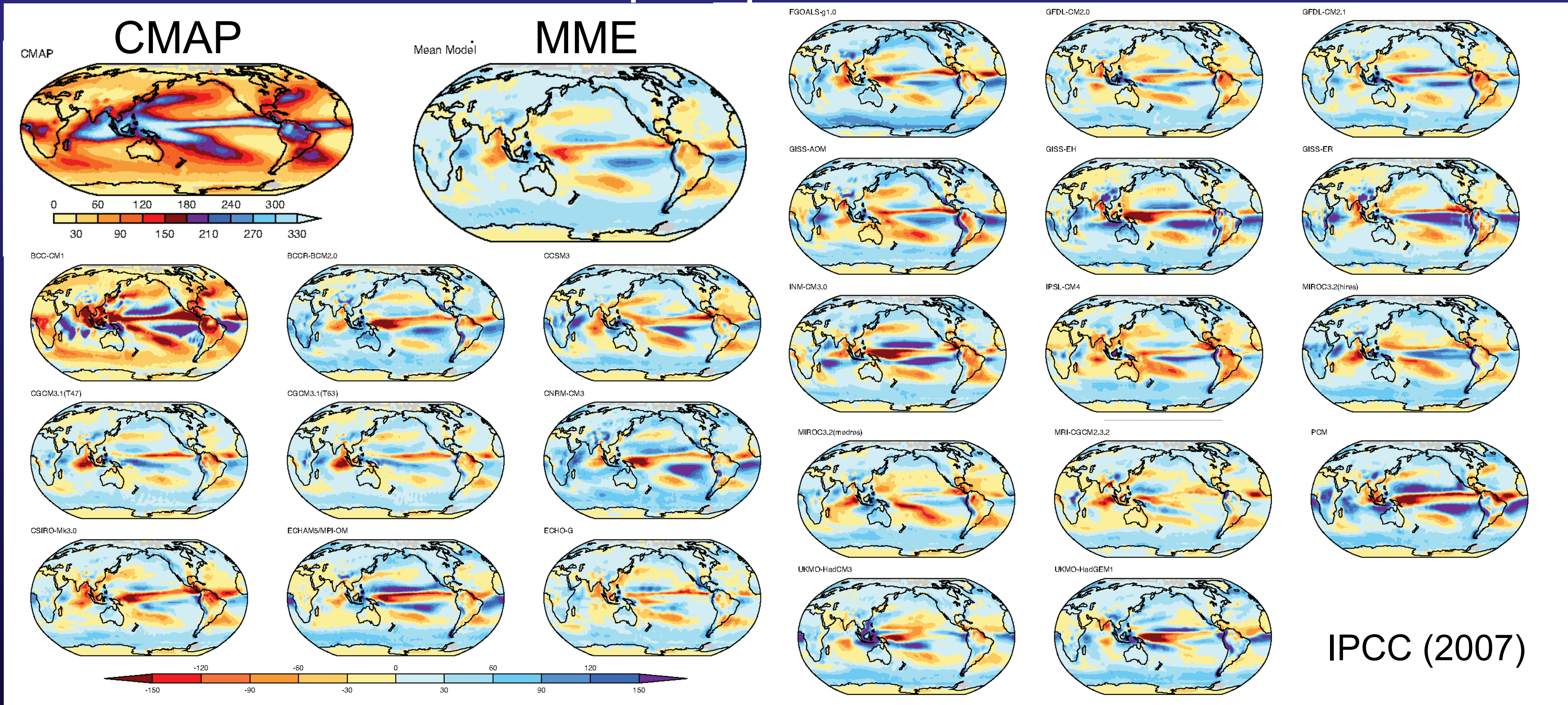
Uncertainty due to model
—— where does it come from?

Hawkins and Sutton (2008)

Two types of model's uncertainty

✓Uncertainty due to structural differences (<- MME)
✓Uncertainty due to parametric differences (<- PPE)

Annual-mean precipitation biases in



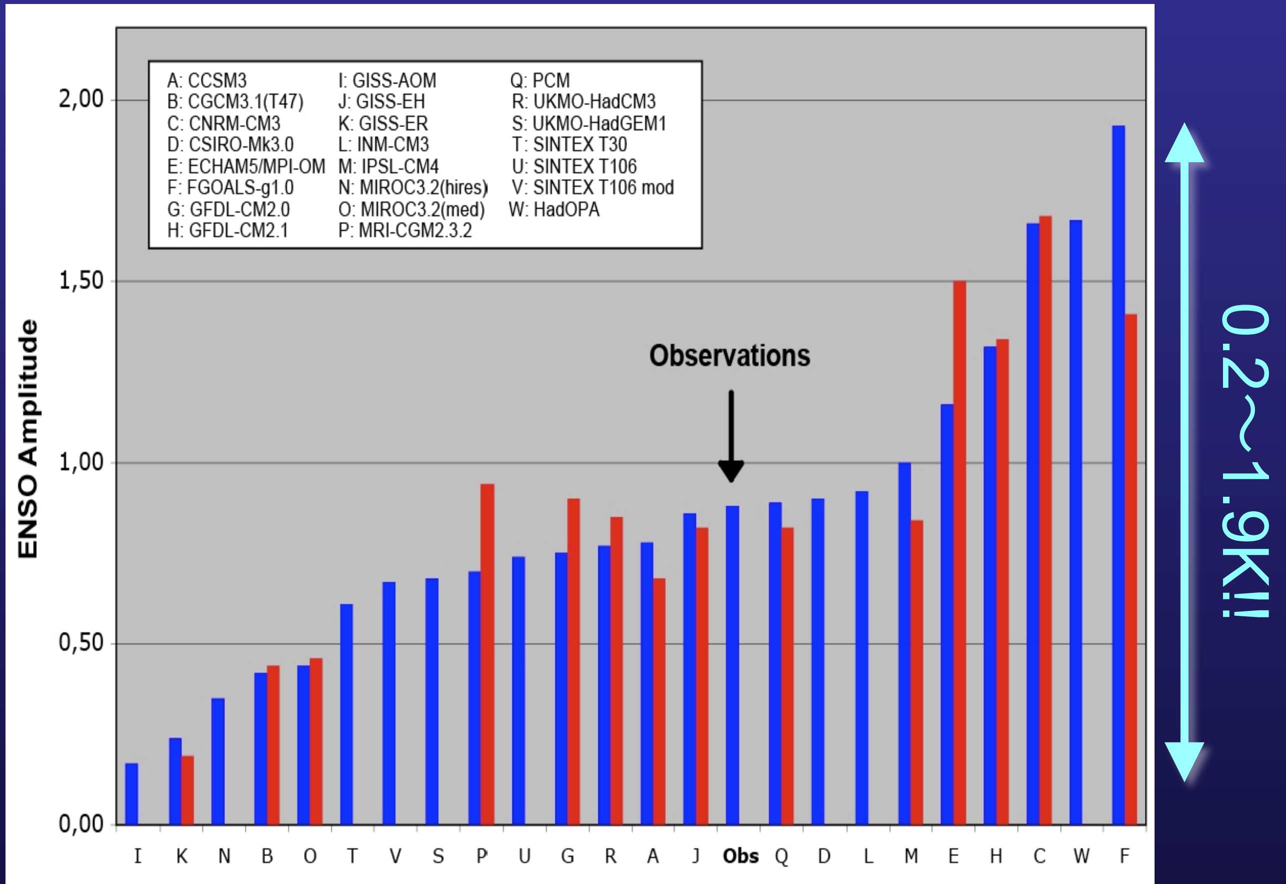
IPCC (2007)

Structural similarity as well as differences among models

Uncertainty in ENSO simulation

Diversity in ENSO simulations

Std Dev of the Nino 3 SST anomaly in CMIP3 models



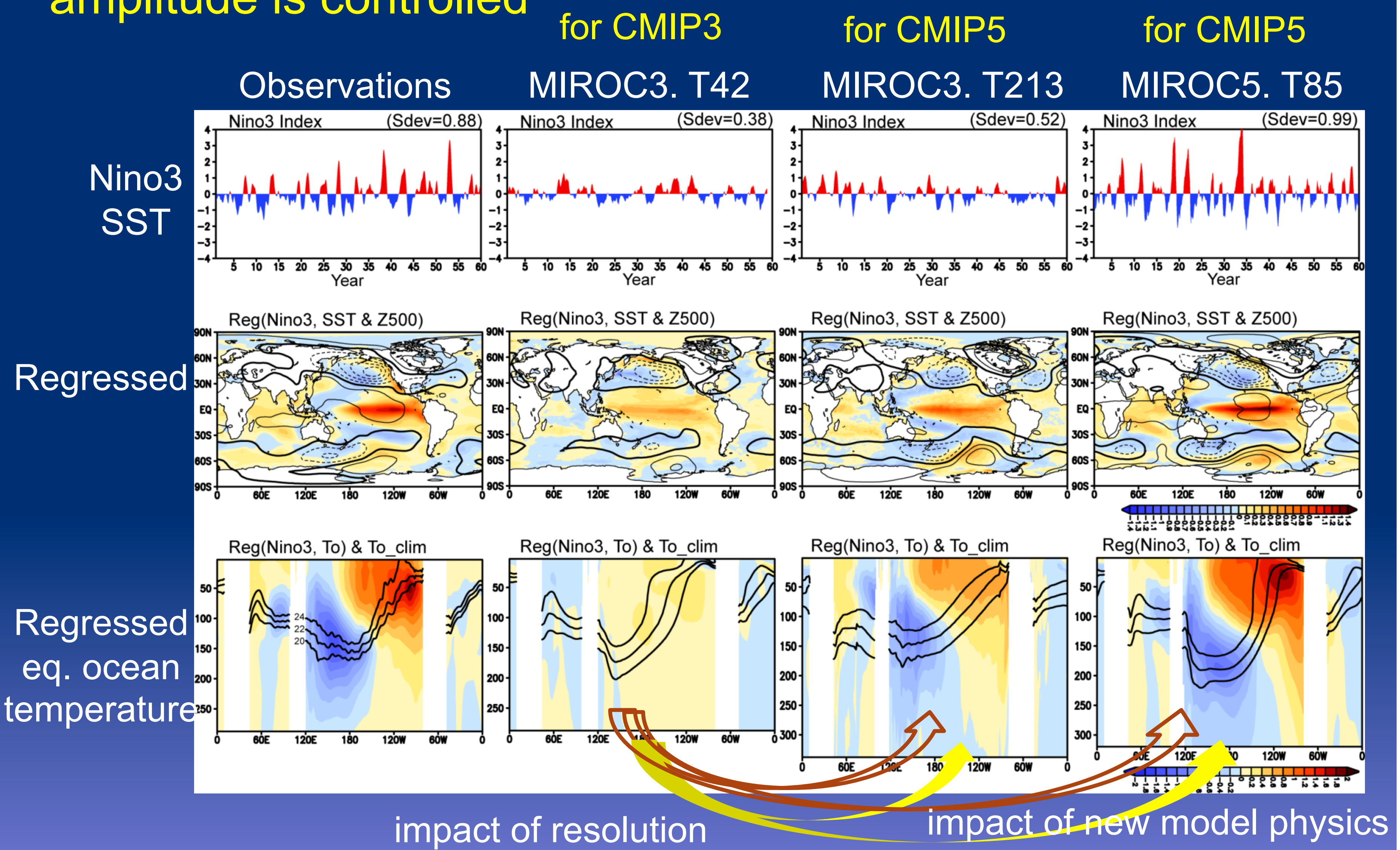
Model #

Guilyardi et al. (2009)

✓ Error? But, large uncertainty for the ‘true’ ENSO amplitude in records < 100y (Wittenberg 2009)

ENSO in MIROC3/MIROC5

A 'better' model should be used to examine how ENSO amplitude is controlled



ENSO in GCMs: Recent progress

✓ENSO diversity in CGCMs is likely due to the atm. component

- Schneider 2002, Guilyardi et al. 2004, 2009

✓In particular, convection scheme potentially has a great impact

- CMT - Wittenberg et al. 2003, Kim et al. 2008, Neale et al. 2008
- Entrainment - Wu et al. 2007, Neale et al. 2008, Watanabe et al. 2011
- Low clouds - Toniazzo et al. 2008, Lloyd et al. 2009

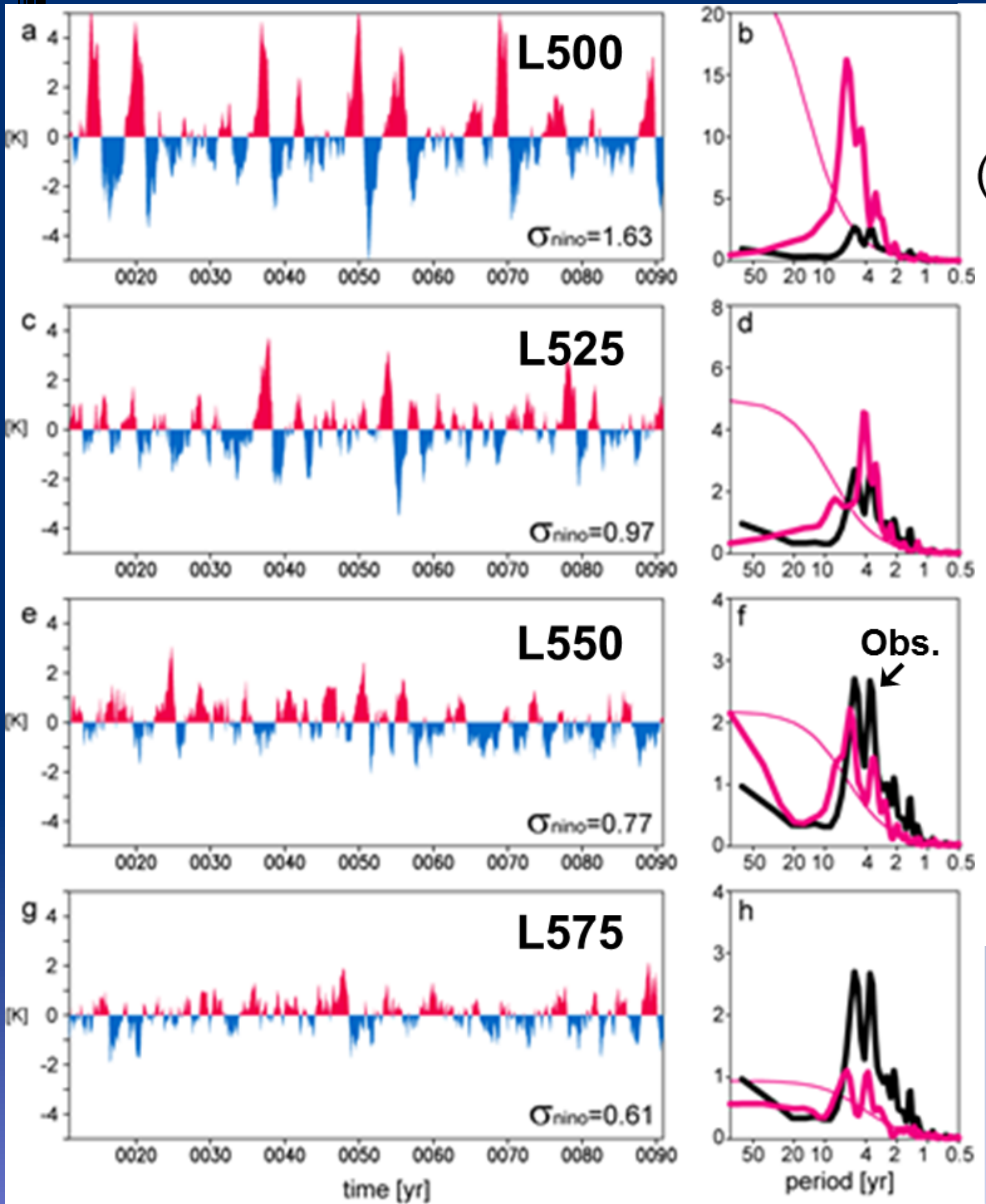
Entrainment rate ε & updraft velocity w (Gregory 2001, Chikira & Sugiyama 2010)

Parameter sweep experiments using MIROC5

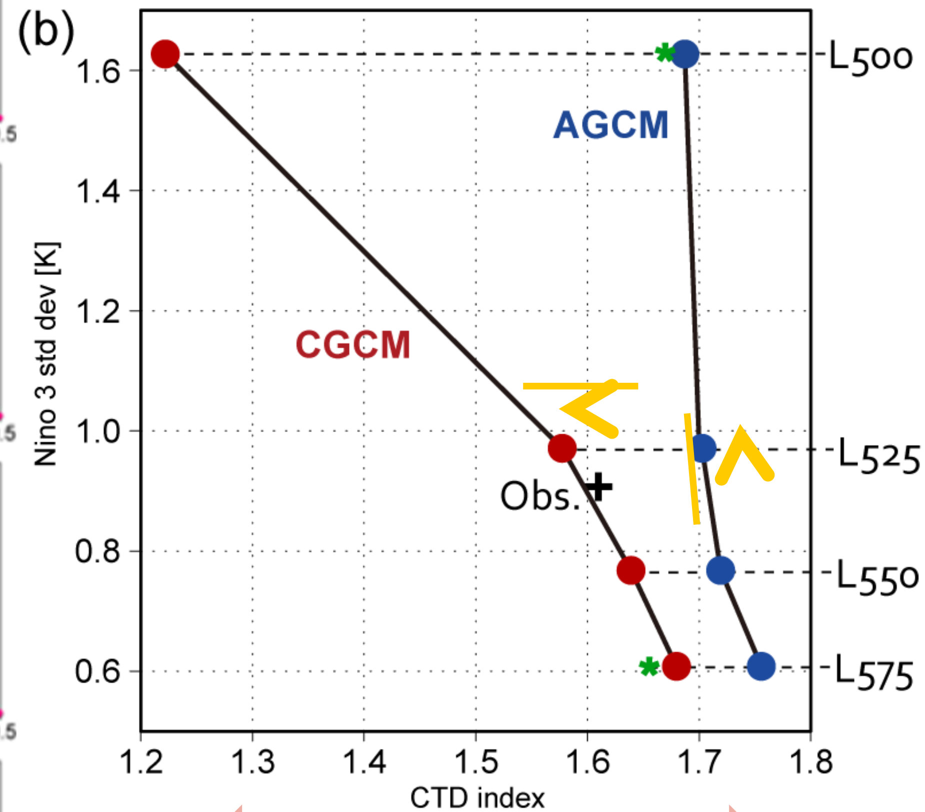
Perturbation to λ: λ =0.5 (L500), 0.525 (L525), 0.55 (L550), 0.575 (L575)
CTL & 2xCO2 runs: 100 yrs x 4 cases x 2 runs

Large λ -> suppress deep clouds

ENSO control mechanism in MIROC5



ENSO & mean state error



wet cold tongue dry

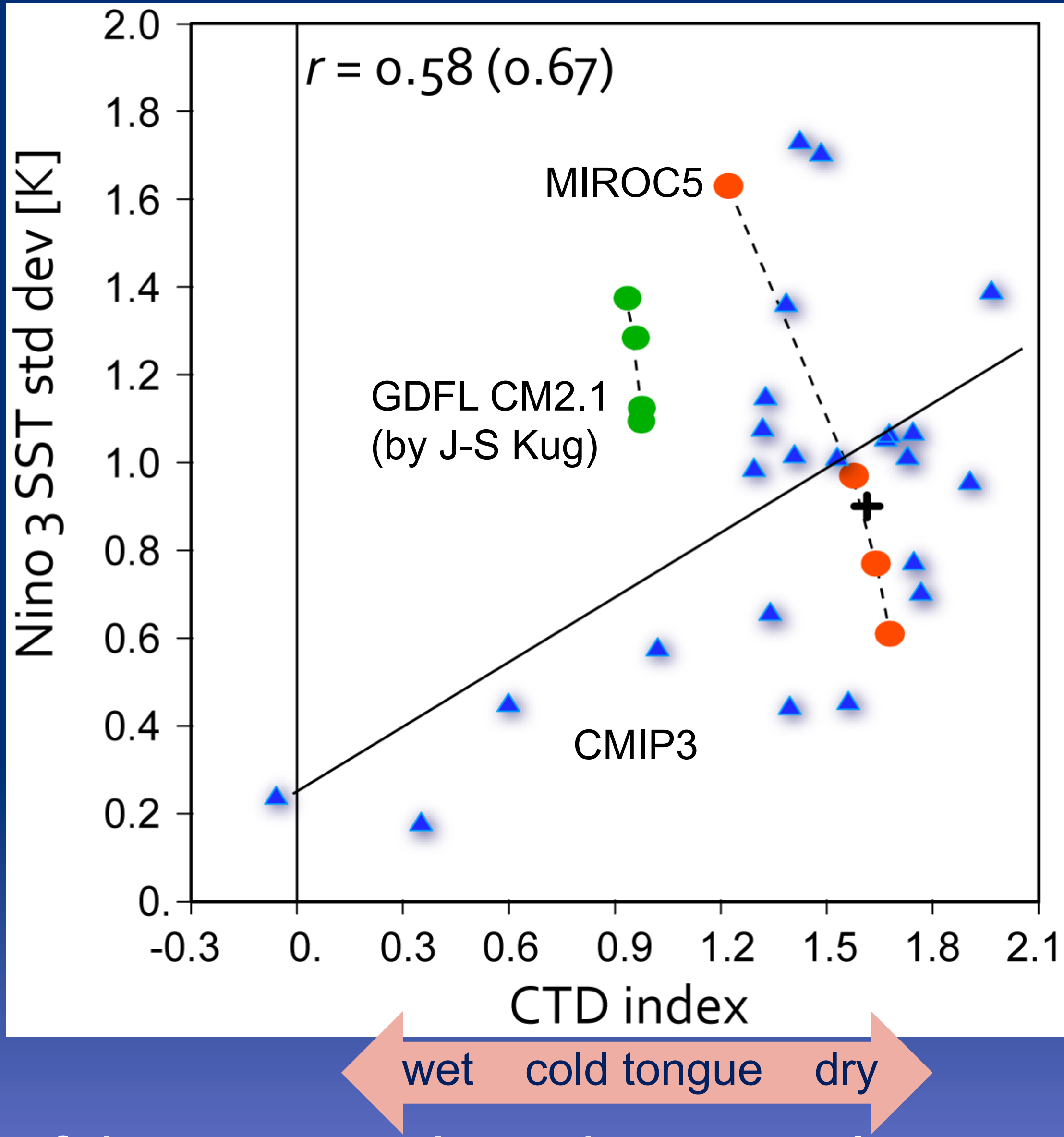
Direct effect of convection

Coupled feedbacks

Watanabe et al. (2011, JC)

Mean precip-ENSO in CMIP3 models

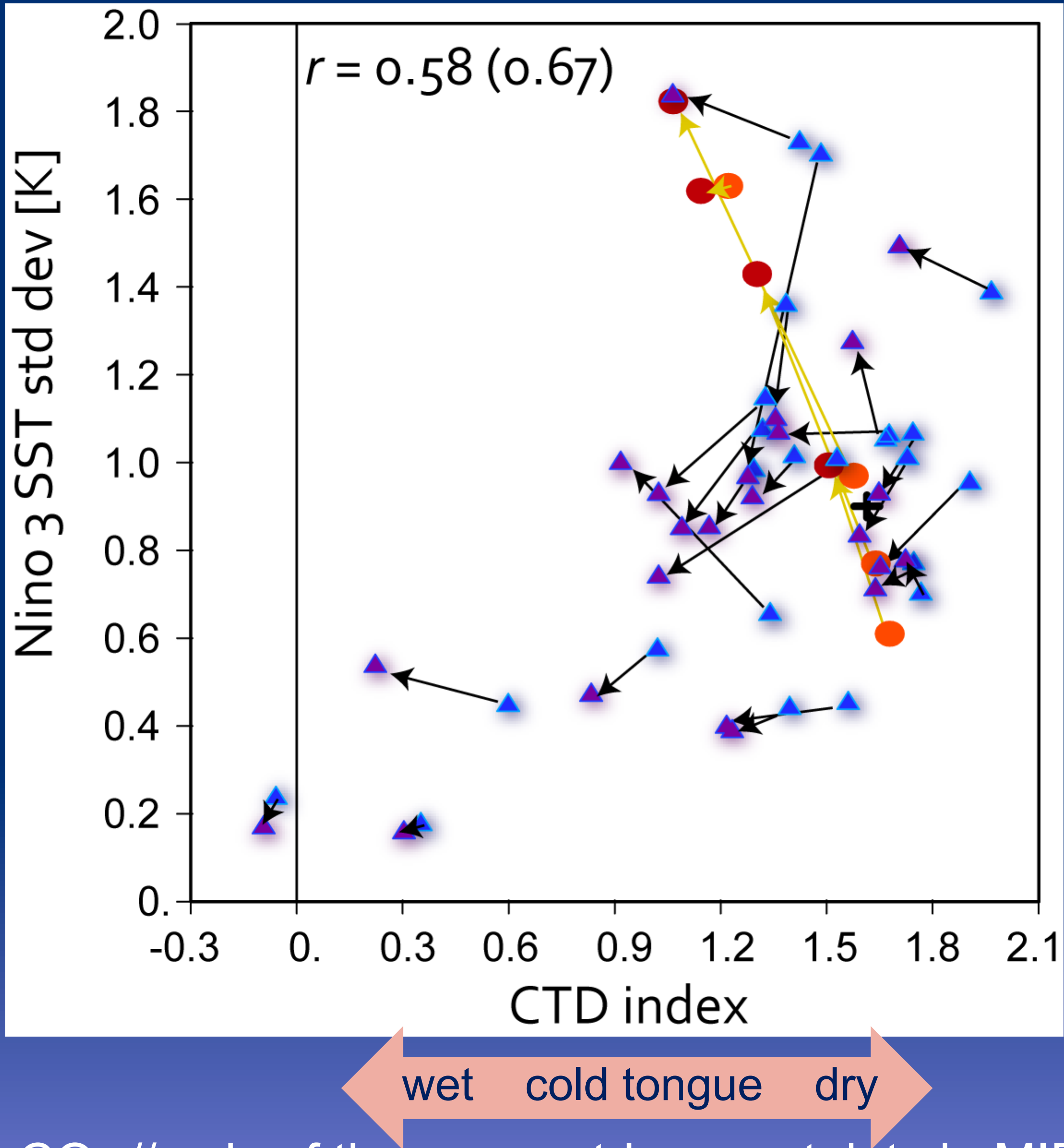
CTL or 20C
(present)



Different axes of the parametric and structural uncertainties !!

Mean precip-ENSO in CMIP3 models

$2xCO_2$ or A1b (future)

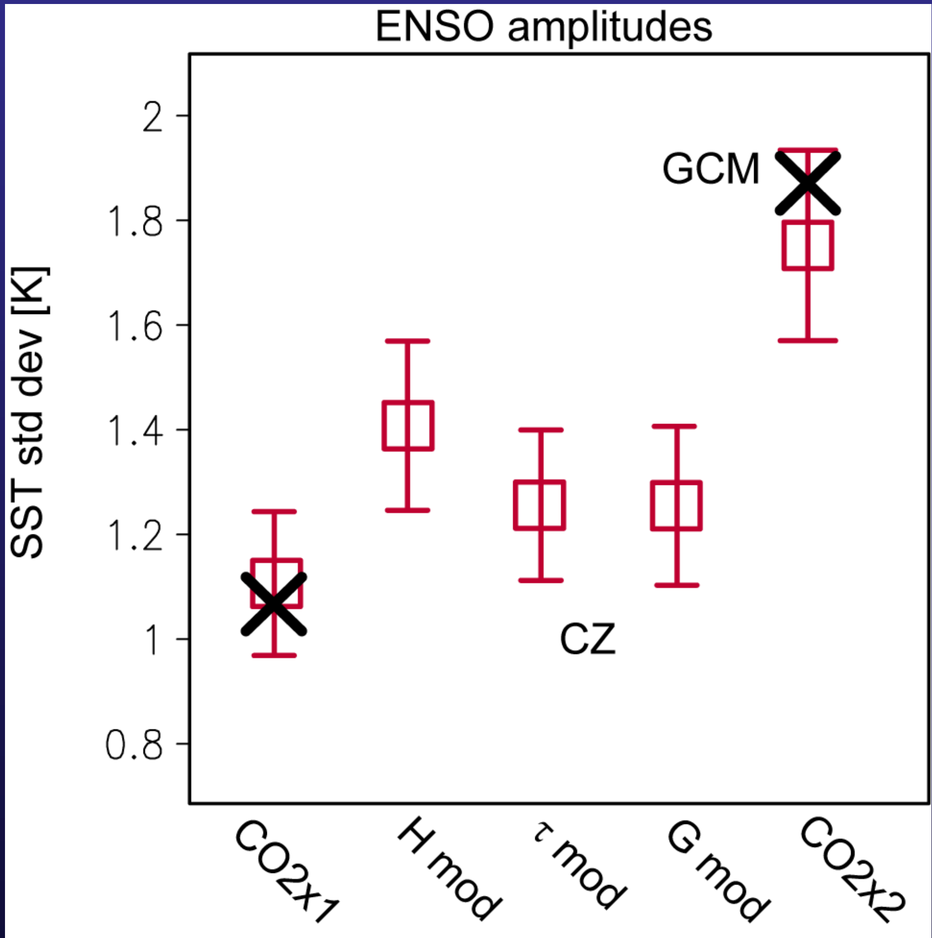


Sensitivity to $2xCO_2$ // axis of the parametric uncertainty in MIROC5

Causes for ENSO amplitude change

CZ model w/
empirical atmosphere

$$\tau(x,y,t) = \underbrace{R(x,y)T_n}_{\tau_{\text{signal}}} + \underbrace{\sum_i G_i(x,y)(1+BT_n)w_i(t)}_{\text{multiplicative } \tau_{\text{noise}}}$$



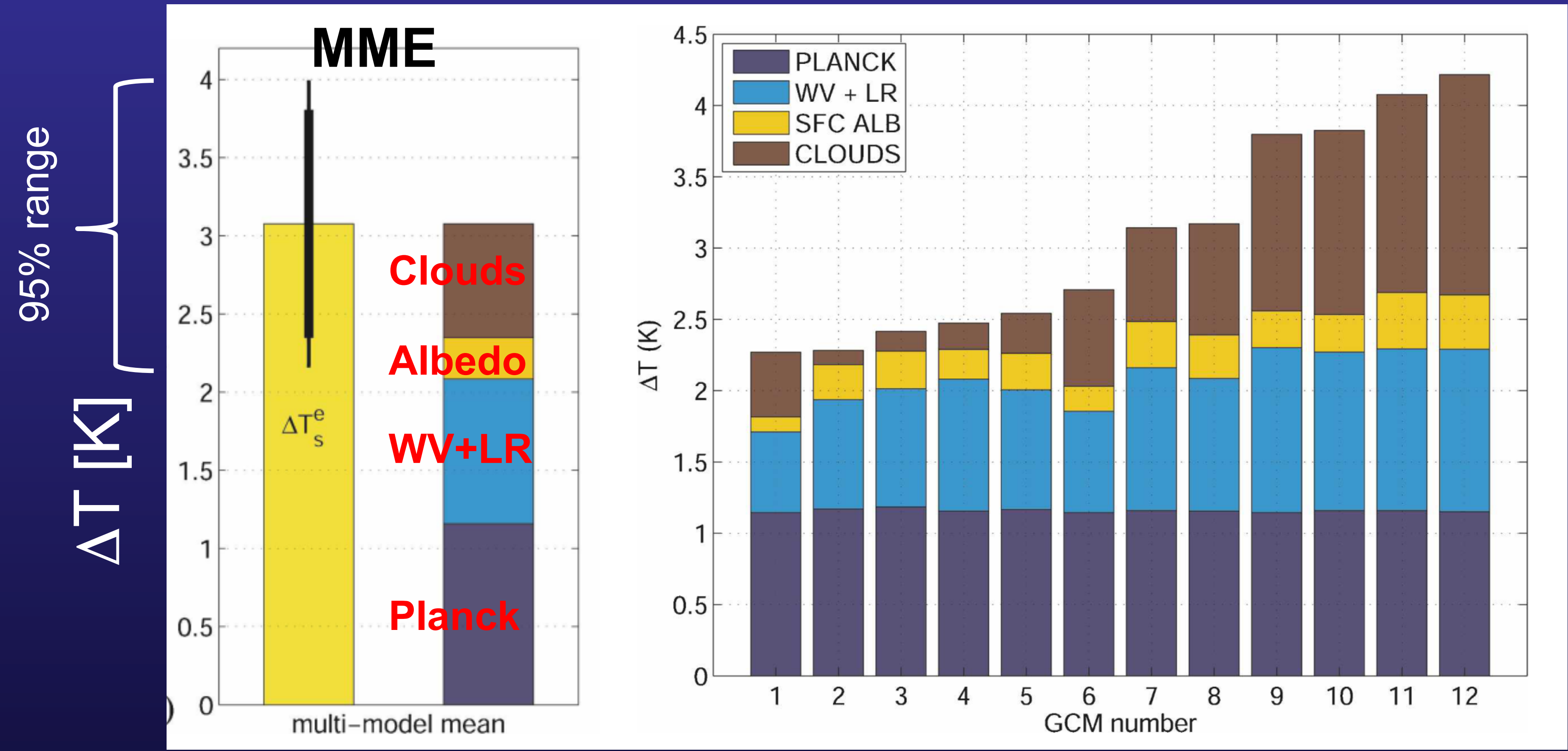
Positive contribution
to amplified ENSO:

- ✓ Shoaling of mean H
- ✓ Eastward shift of τ_{signal}
- ✓ Eastward shift of τ_{noise}
- ✓ Change in noise-coherence?

Uncertainty in climate sensitivity and feedbacks

Diversity in CFMIP1 models

Equilibrium climate sensitivity and feedbacks

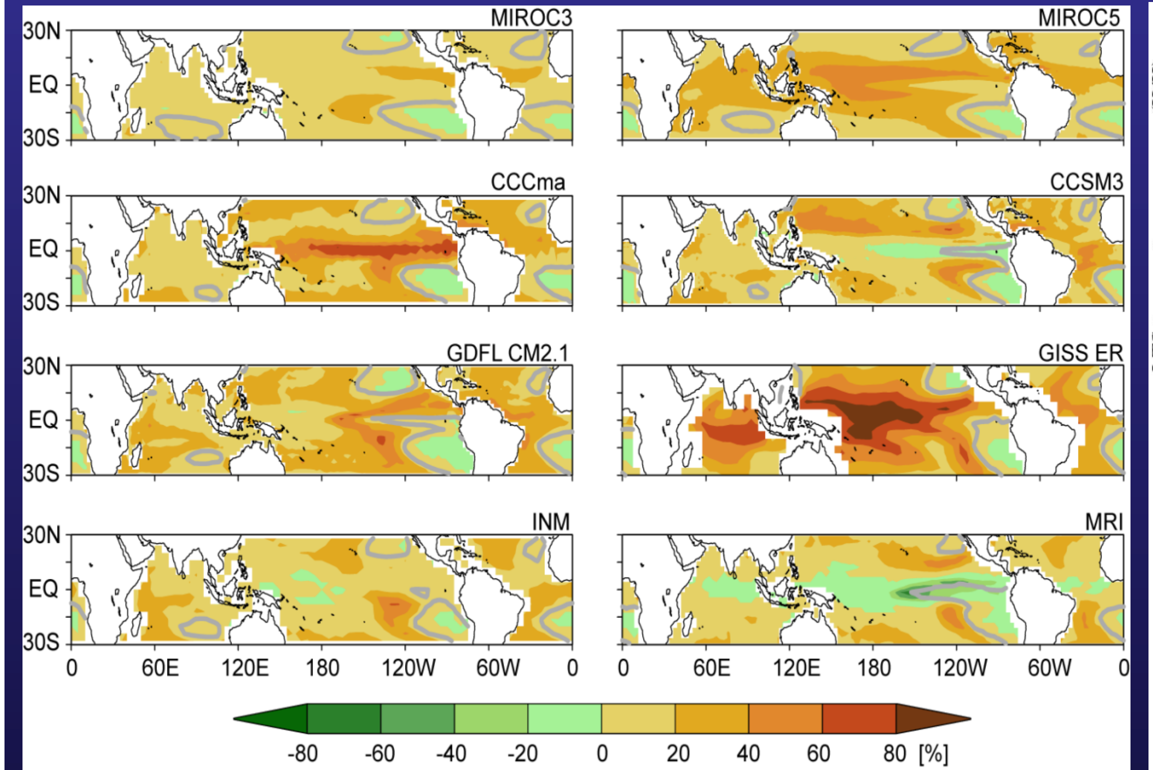


Dufresne & Bony (2008)

Well-known fact: uncertainty in climate sensitivity largely explained by different sign/magnitude of the cloud feedback

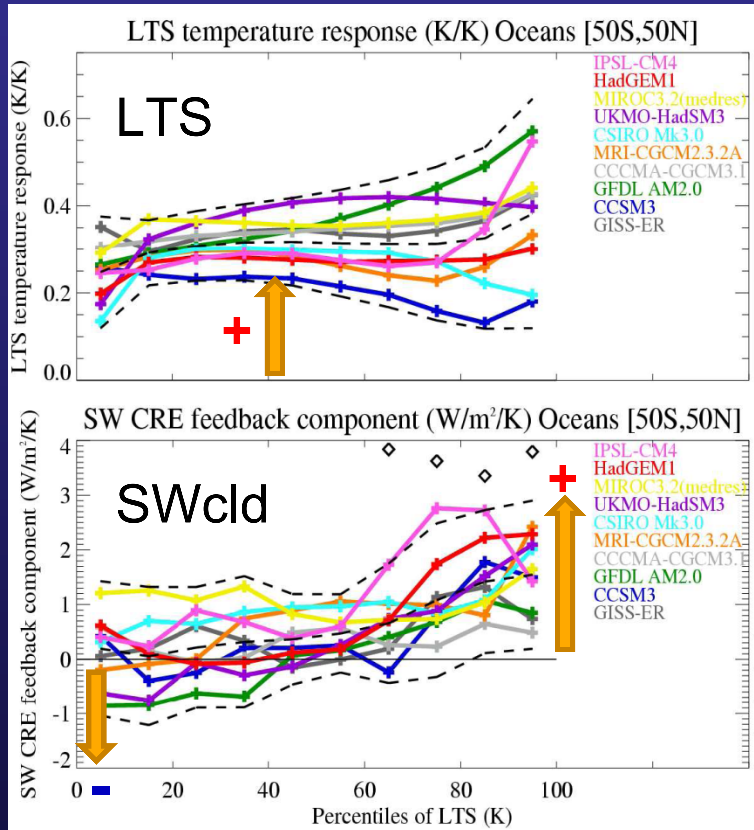
Importance to isolate robust and fragile parts of the cloud feedback

Change in stable regime frequency in CFMIP1



Watanabe et al. (2011, submitted to CD)

Sorted responses in CFMIP1



Unstable ⟷ Stable

Courtesy of M Webb

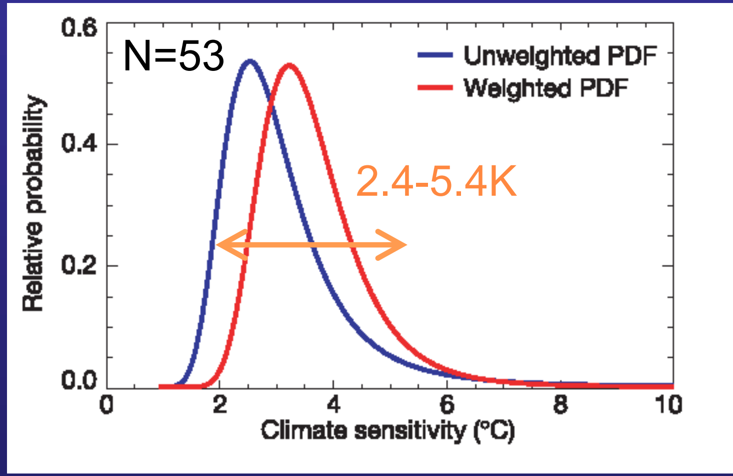
- ✓ Increasing LTS: sign robust (but not magnitude)
- ✓ Change in SWcld: fragile even sign

Parametric uncertainty

Perturbed Physics Ensemble (PPE)

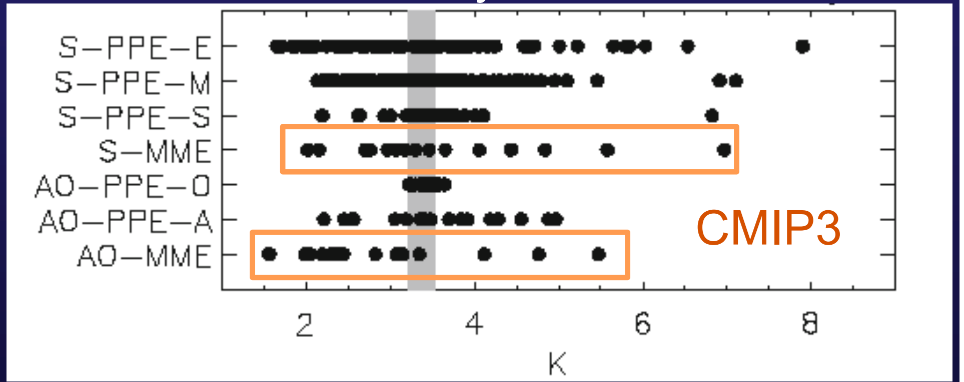
- ✓ Designed for systematic sampling of uncertainty in a single model framework
- ✓ Complementary ensemble to CMIP MME
- ✓ Some advantages over the "ensemble of opportunity"
- ✓ PPEs have been done with
    - HadCM3/HadSM
    - NCAR CAM3.x/4
    - MIROC3.2/5
    - ECHAM5
- ✓ Difference in parameter sets & perturbation strategy

Climate sensitivity in HadSM PPE



Murphy et al. (2004)

Climate sensitivity in QUMP & CMIP3



Collins et al. (2010)

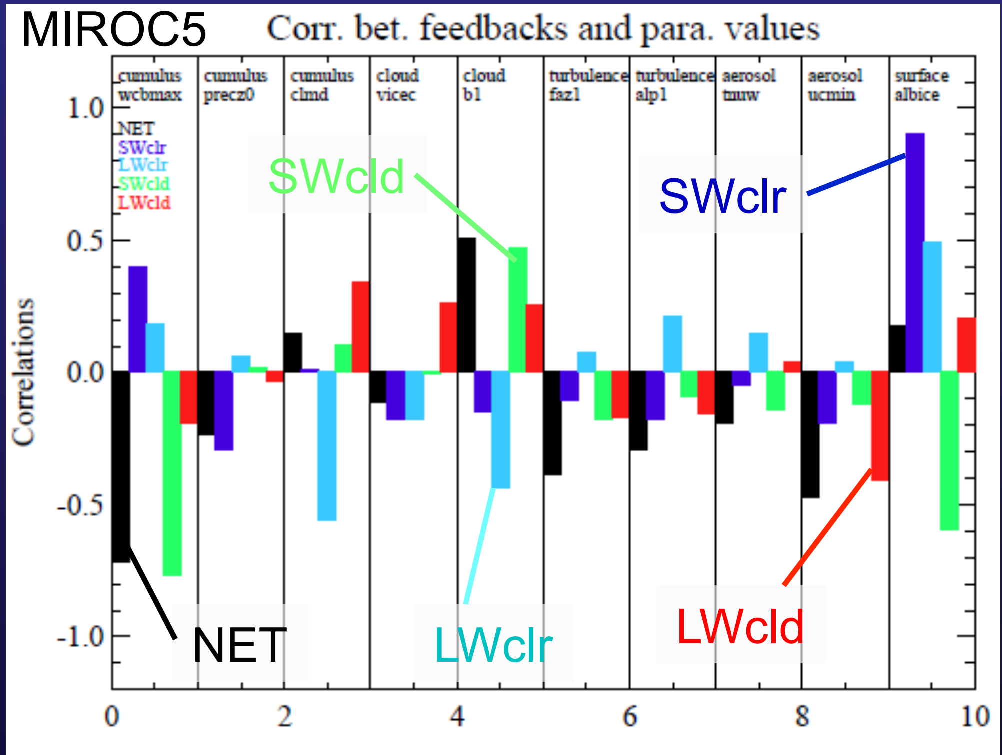
MIROC PPEs

- ☐ MIROC3.2 PPE (JUMP project, Annan et al. 2005)
- ✓ T20L20 slab model
- ✓ 13 parameters
- ✓ Perturbation w/ EnKF

- ☐ MIROC5 PPE

  (Shiogama et al. 20011, in prep.)
- ✓ T42L40 full CGCM
- ✓ 10 parameters
- ✓ Perturbation w/ Latin hypercube + emulator

Corr. between feedbacks and



# of parameter

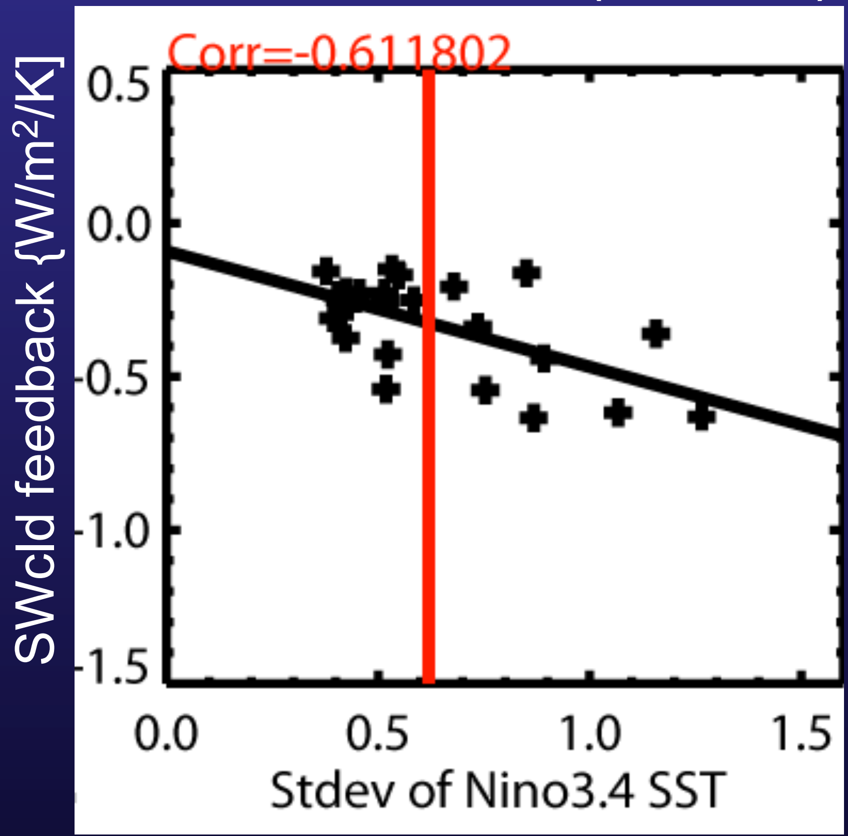
Courtesy of H Shiogama

ENSO and climate sensitivity?

Japan Uncertainty Modelling Project

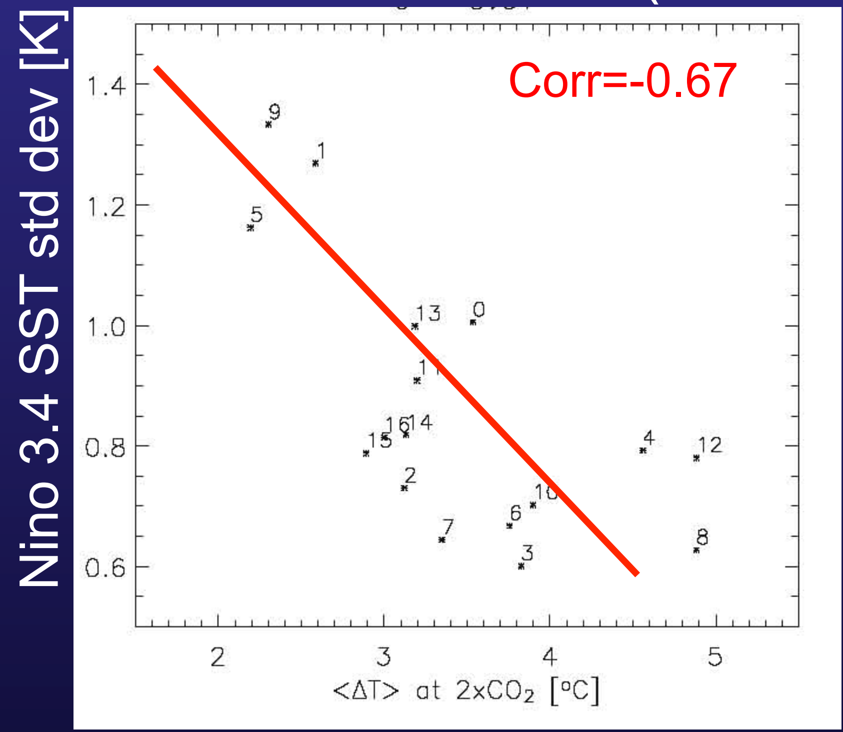
Reasons are not clear and may be different in different models, but a common feature of strong ENSO <-> low CS

MIROC5 PPE (JUMP2)



Courtesy of H Shiogama

HadCM3 AO PPE-A (QUMP)



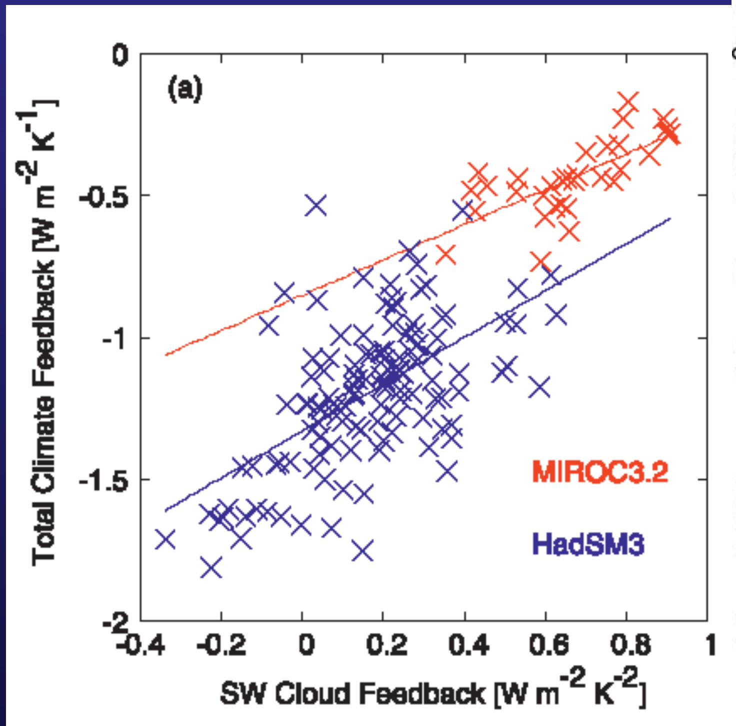
Equilibrium climate sensitivity [K]

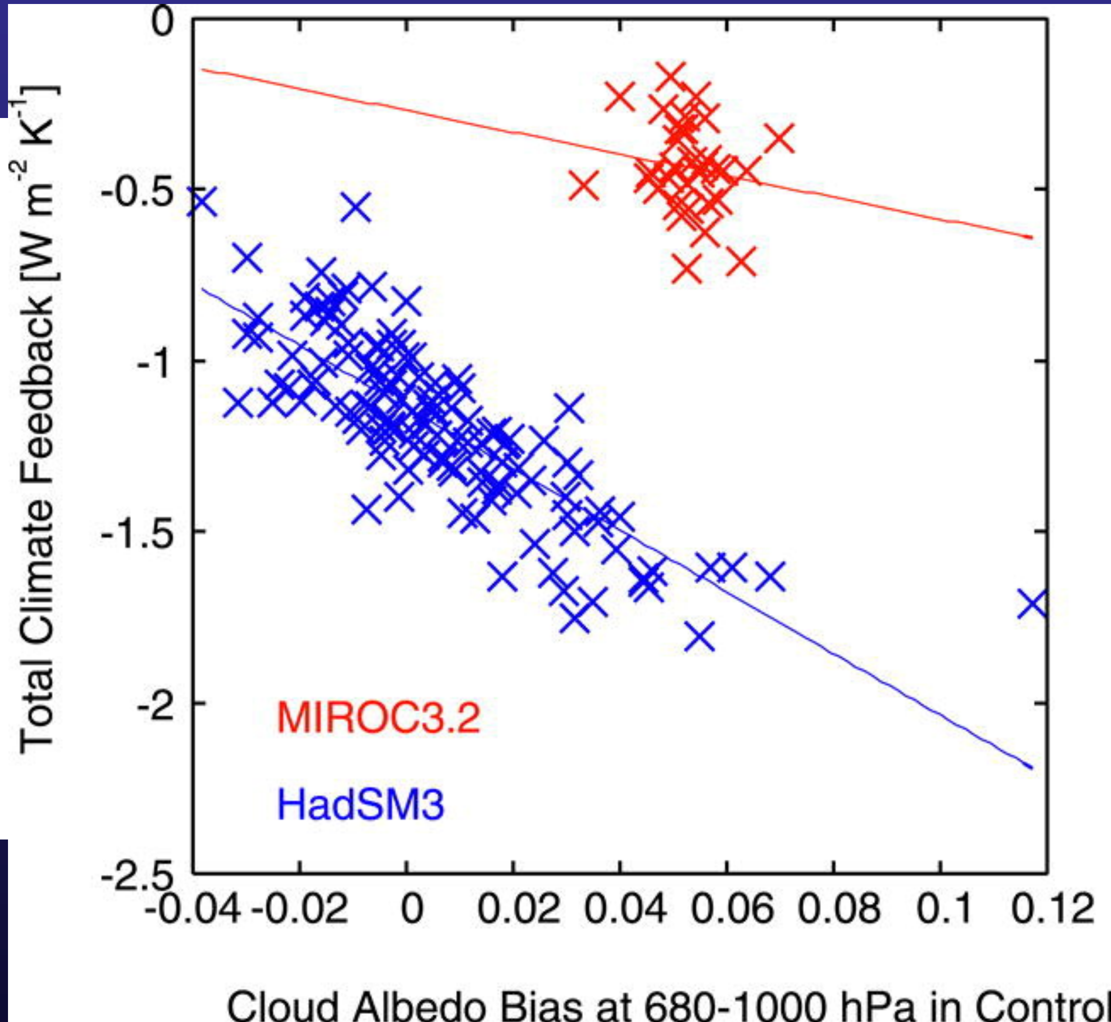
Toniazzo et al. (2008)

Combined structural/parametric uncertainty

Understanding how parameter-driven uncertainties in PPEs depend on structural properties of the model

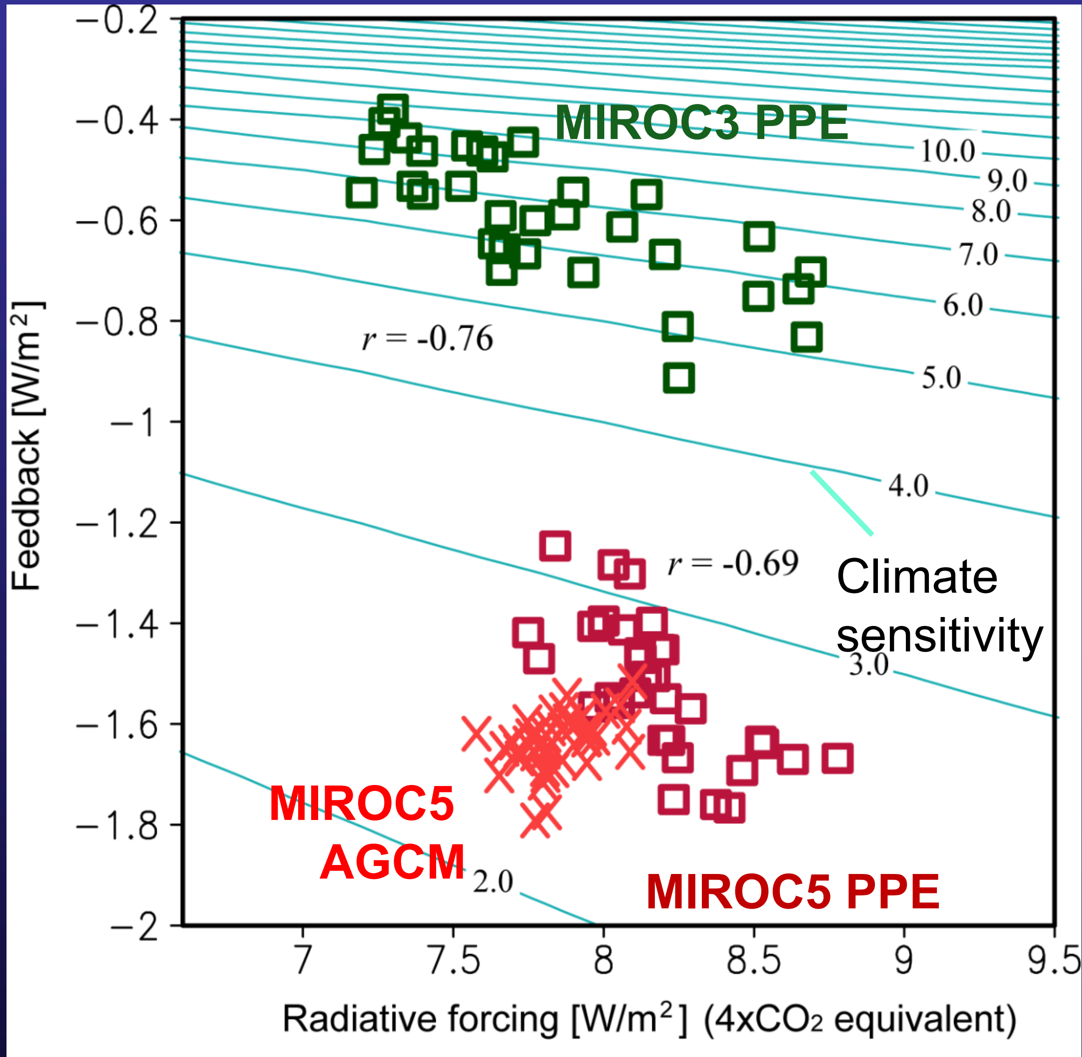
MIROC PPE vs HadCM3 PPE





Yokohata et al. (2011)

Forcing-Feedback in two PPEs



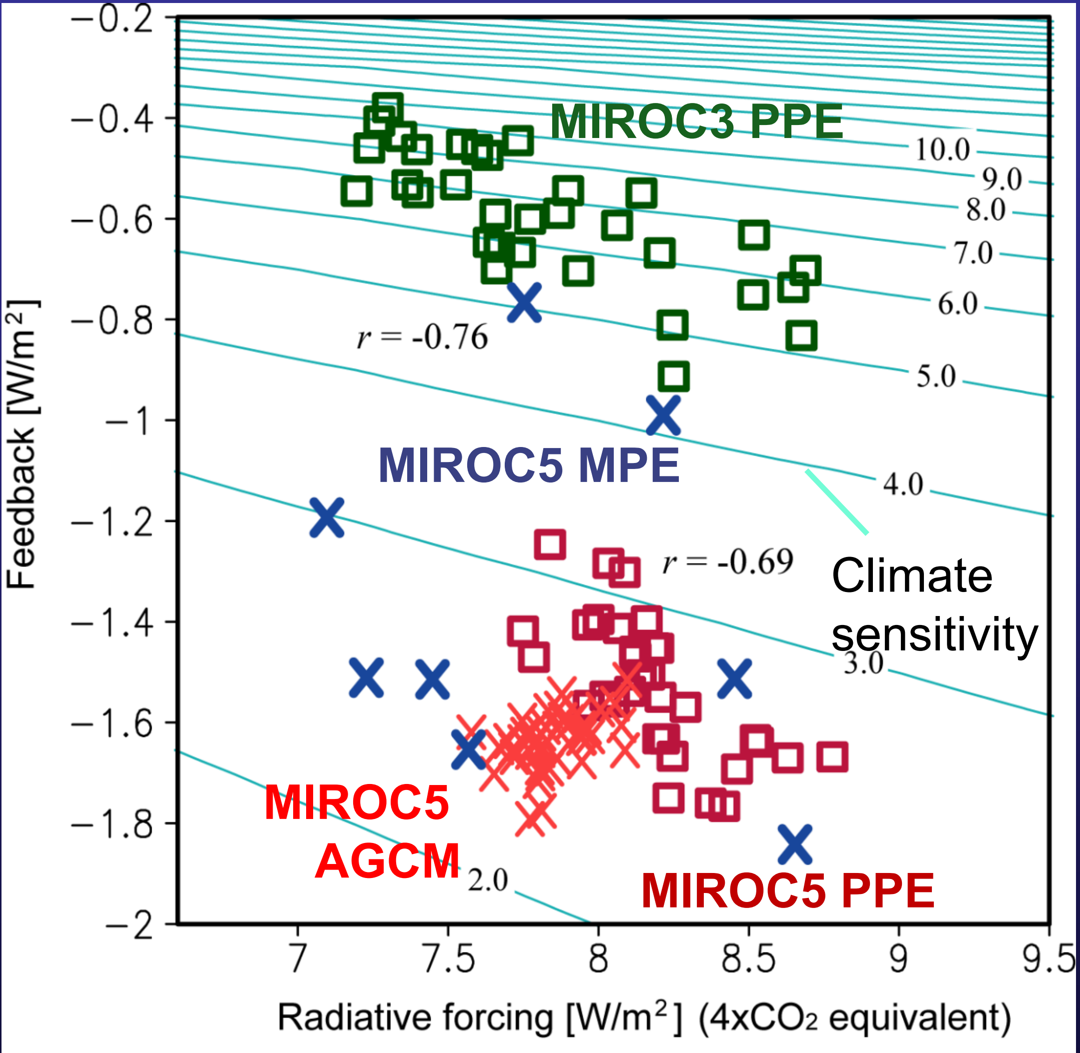
Multi-Physics Ensemble (MPE)

Replacing one or more schemes in MIROC5 w/ old ones:

- ✓ Std
- ✓ Oldcld
- ✓ Oldcum
- ✓ Oldvdf
- ✓ Oldcld+cum
- ✓ Oldcum+vdf
- ✓ Oldcld+vdf
- ✓ Oldcld+cum+vdf

- ✓ Structural difference > Parametric difference
- ✓ Any strategy to link them each other ?

Forcing-Feedback in two PPEs



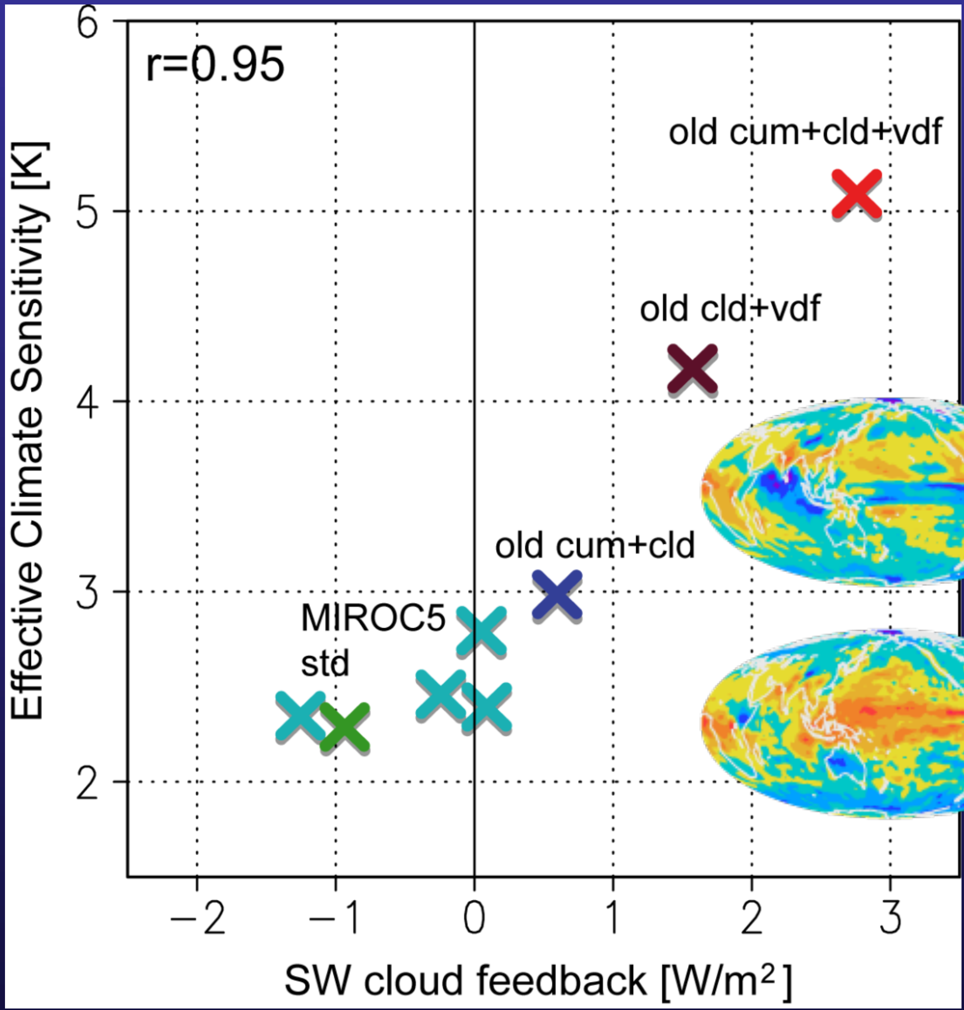
Multi-Physics Ensemble (MPE)

Replacing one or more schemes in MIROC5 w/ old ones:

- ✓ Std
- ✓ Oldcld
- ✓ Oldcum
- ✓ Oldvdf
- ✓ Oldcld+cum
- ✓ Oldcum+vdf
- ✓ Oldcld+vdf
- ✓ Oldcld+cum+vdf

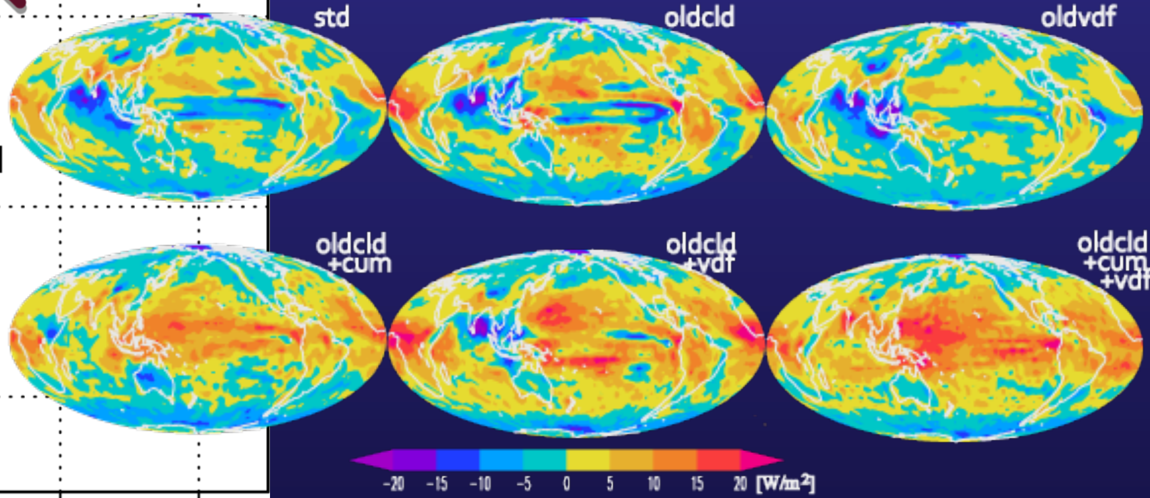
- ✓ Structural difference > Parametric difference
- ✓ Any strategy to link them each other ?

MPE: Filling the gap between PPEs



Oldcld -> small impact
Oldvdf -> small impact
Oldcld+vdf -> large impact!!

SWcld feedbacks



'Feedback occurs thru the interaction of a suite of parameterized processes rather than from any single process' (Zhang & Bretherton 2008)

Reducing error -> reducing uncertainty

"NWP methods show promise for improving parameterizations in climate GCMs" (Phillips et al. 2004)

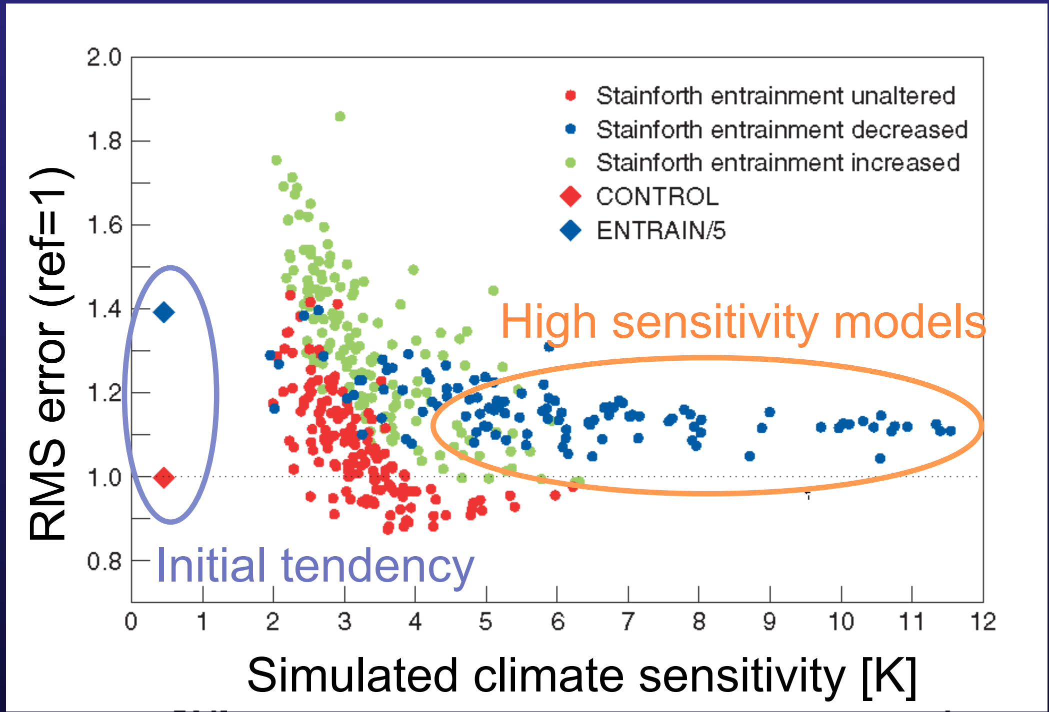
Climate sensitivity & model error (analysis increments)

- Initial tendency analysis

  can weight the models in MME/PPE (Rodwl & Palmer 2007)

- Transpose AMIP II (e.g. Boyle et al. 2005, Martin et al. 2010)

→ "seamless model assessment"



Rodwel and Palmer (2007)

Summary

- One of the ultimate goals for climate modeling: eliminating error-induced uncertainty

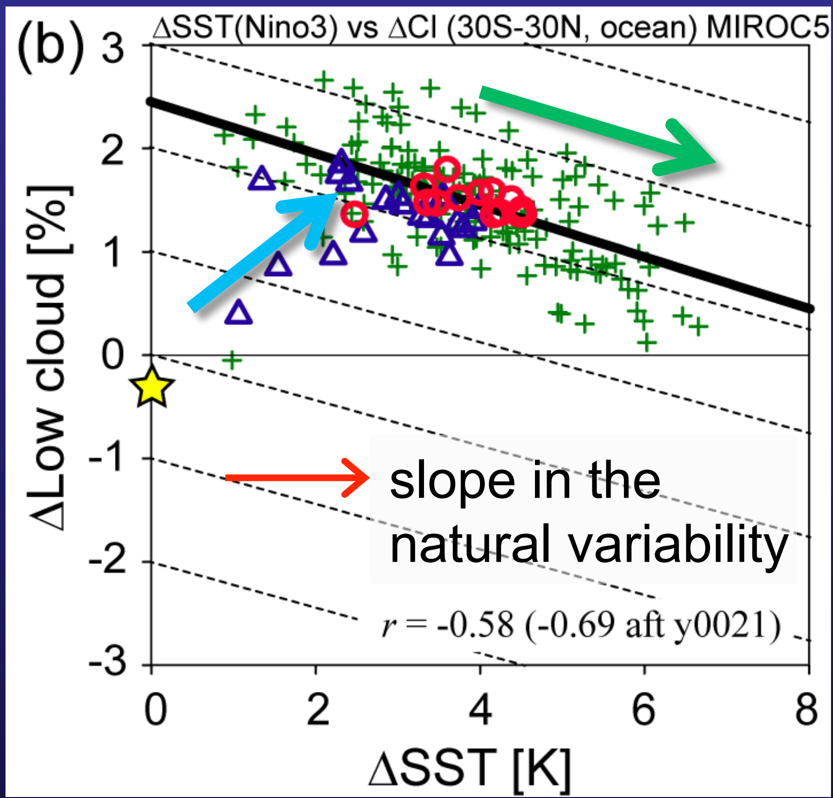
- MME can/should not necessarily be converged

- Importance of:
  - ✓ Identifying robust/fragile parts & timescales of climate response/feedback
  - ✓ Attributing the diversity of GCMs to individual processes/interactions

- Extensive use of various ensembles & methods (MME/PPE/MPE/NWP ……)

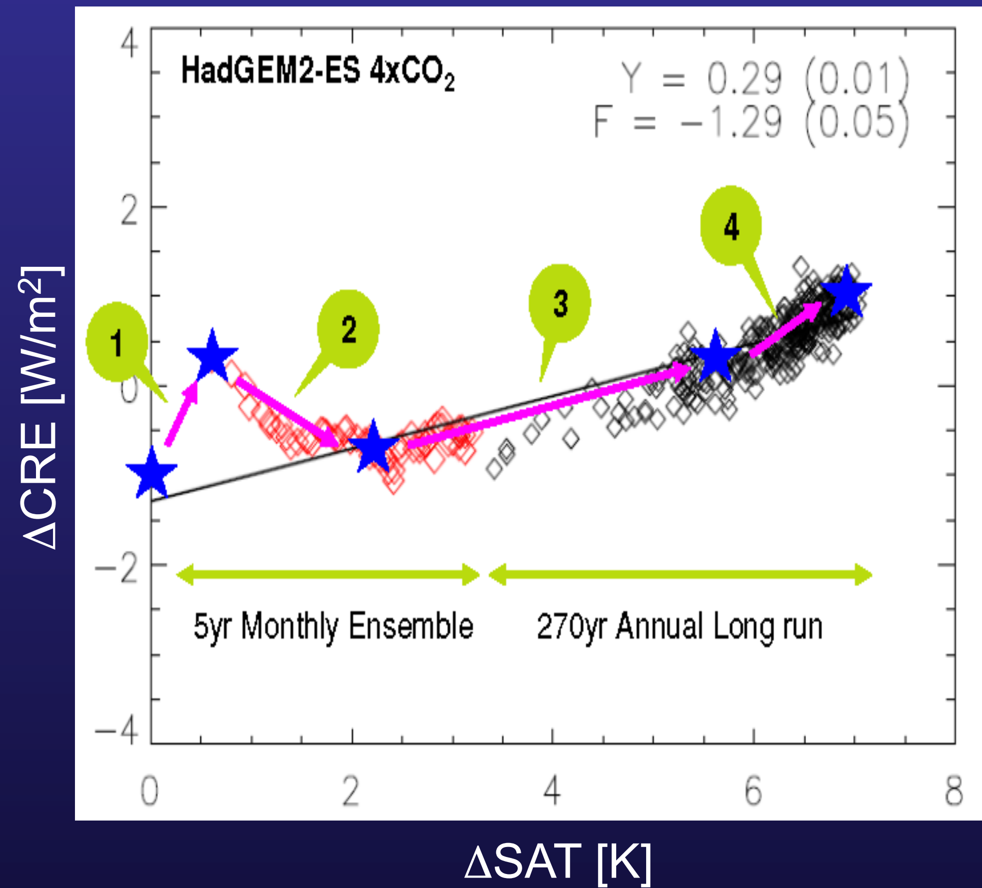
Importance to understand response/feedback on different timescales

MIROC5 4xCO2



Watanabe et al. (2011, submitted to CD)

HadGEM2-ES 4xCO2



＋ ann. mean, single run (150y)
○ decadal mean, single run
△ ann. mean, ensemble avg (20y)
★ initial month of △

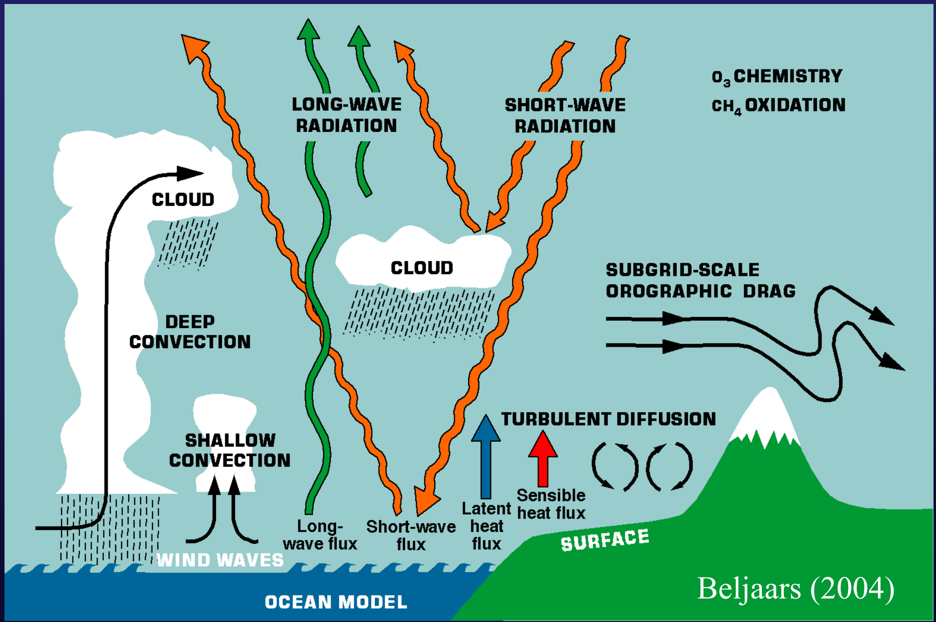
Courtesy of T Andrews

backup

What can we do for the uncertainty?

- ✓ Reducing uncertainty – Use of observations (reanalysis / satellites / palaeo)
- ✓ Quantifying uncertainty
- ✓ Understanding sources of uncertainty

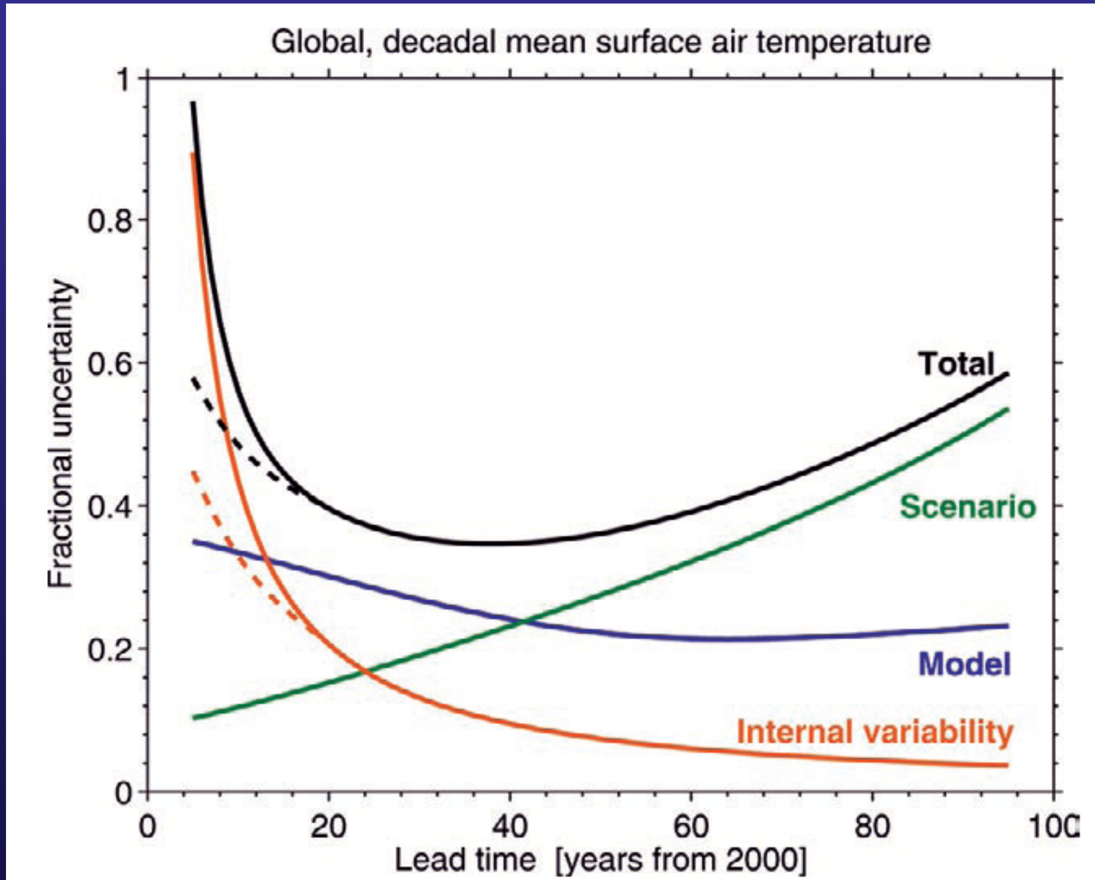
≈ Understanding model's behavior associated with parameterized physical processes



- Radiation
- Convections
- Clouds
- Turbulence
- Aerosols
- …….

Attributing uncertainty

Sources of climate projection uncertainty wrt the lead time

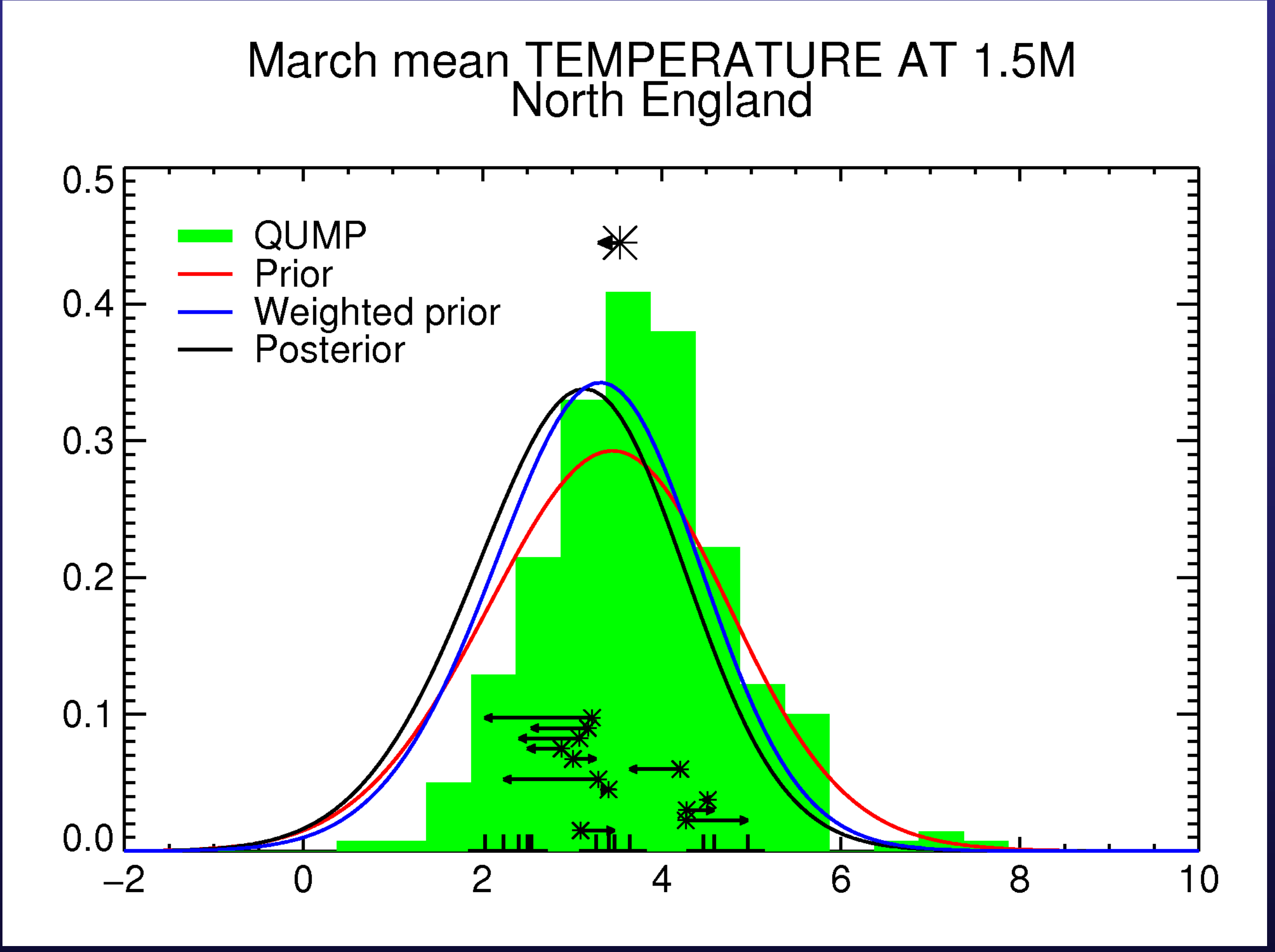


Hawkins and Sutton (2008)

Uncertainty due to model ----- where does it come from?

Combined structural/parametric uncertainty

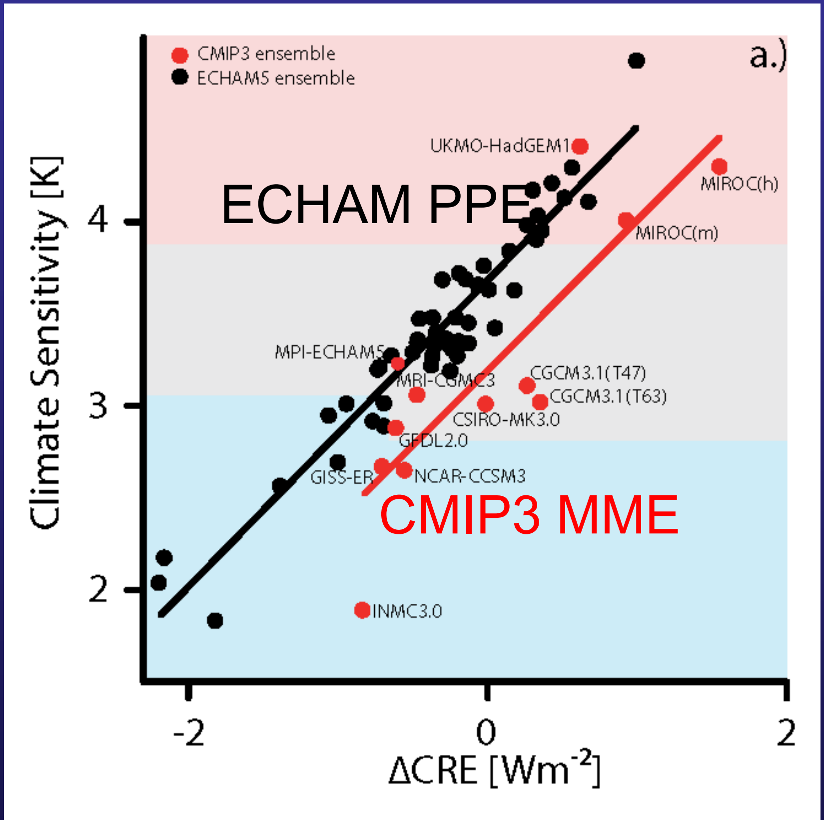
Combining perturbed parameter ensembles, multi-model ensembles and observational constraints



Harris et al. (2010) [Courtesy of J Murphy]

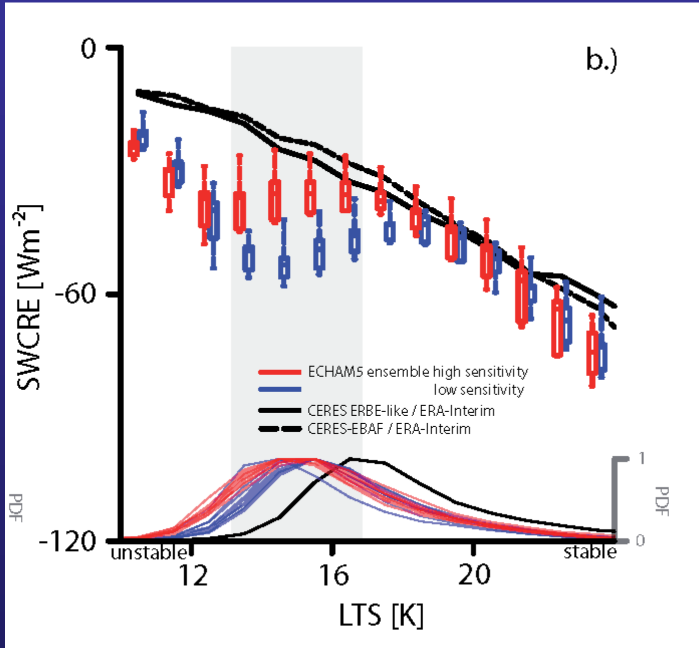
Combined structural/parametric uncertainty

ECHAM5+slab PPE N=50

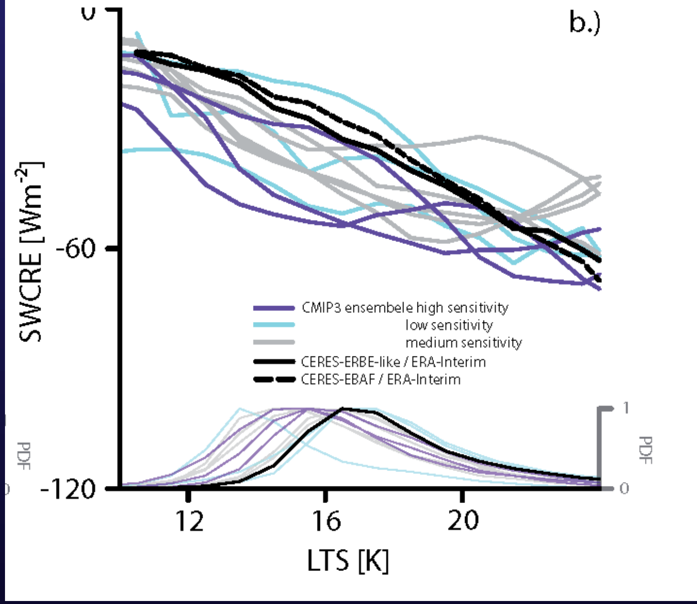


Klocke et al. (2011)

PPE



MME

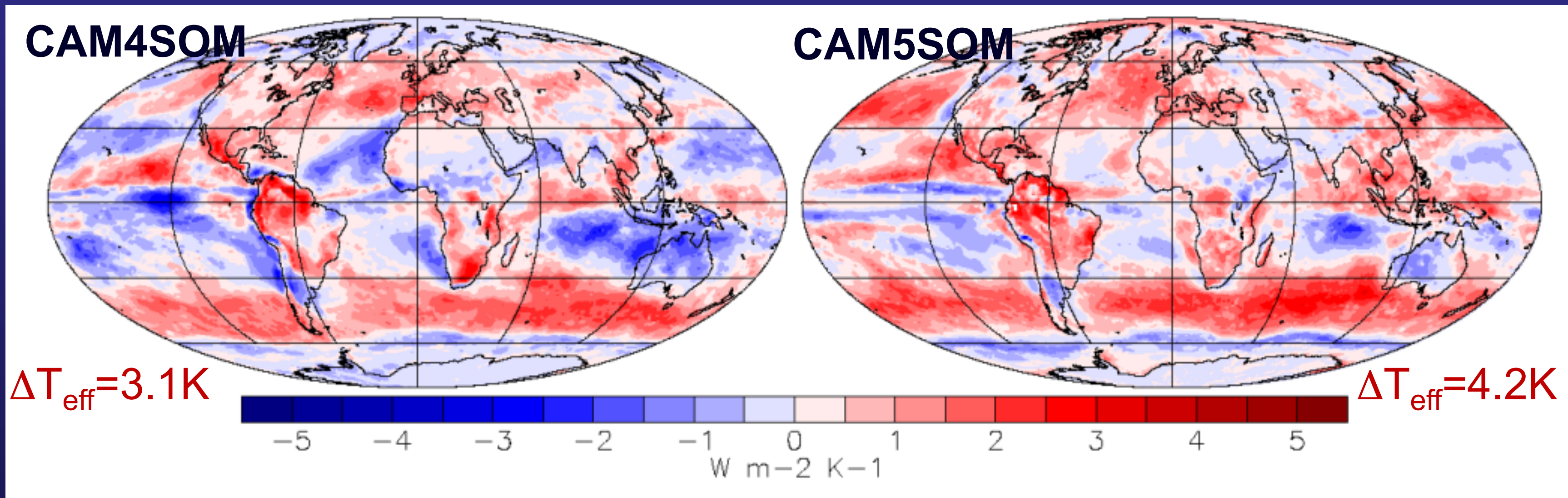


Error-feedback relationship is model-dependent

MPE: Filling the gap between PPEs

MPE enables to systematically explore the processes generating different feedbacks

Adjusted SCRF in 2xCO_2 runs



Impacts of individual parameterization schemes

Run	CAM4	+cloud	+rad	+aero	+PBL	+ShCu	CAM5
ΔT_{eff}	2.8	2.9	3.7	3.5	2.9	**4.4**	4.4

New shallow cumulus scheme works toward positive SCRF in CAM5

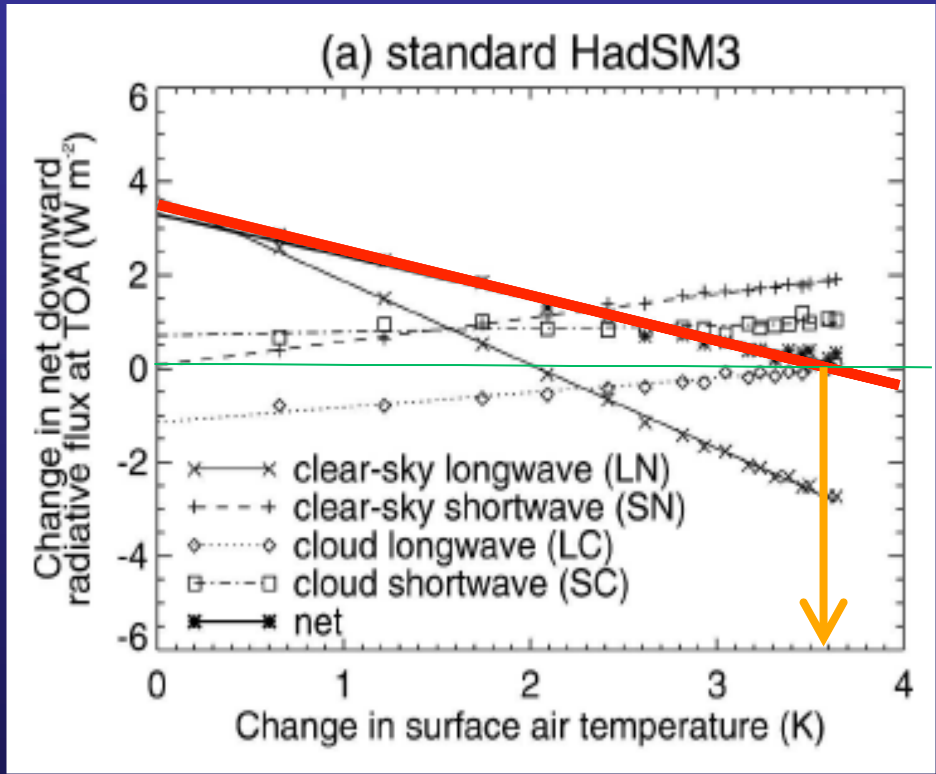
Gettleman et al. (2011, submitted to JC)

How to evaluate climate sensitivity?

- In a CGCM 2xCO_2 experiment (=>20y),

  $N = F + \alpha \Delta T$

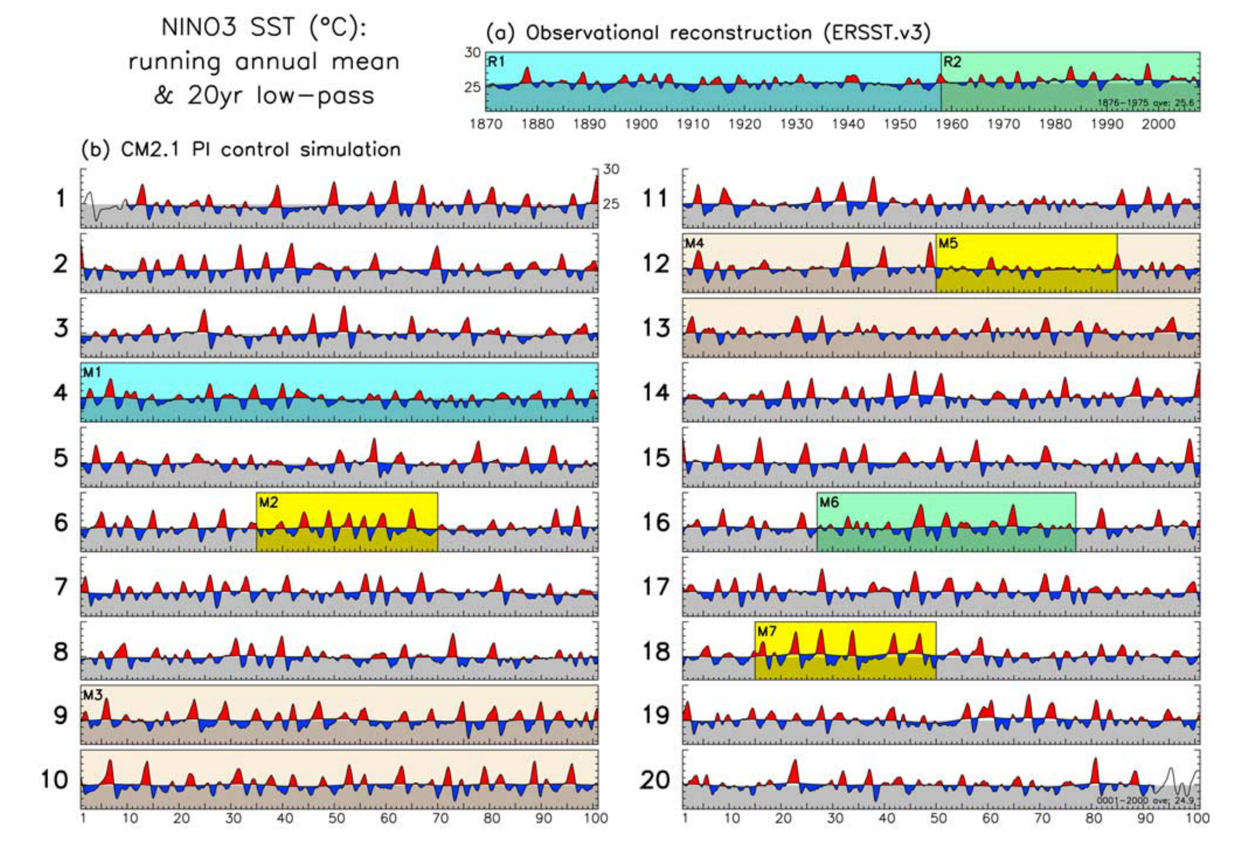
  and plot N against ΔT
- Assuming constant F and α on short timescale
- N can be decomposed into SW, LW and their clear-sky, cloud components



Gregory and Webb (2008)

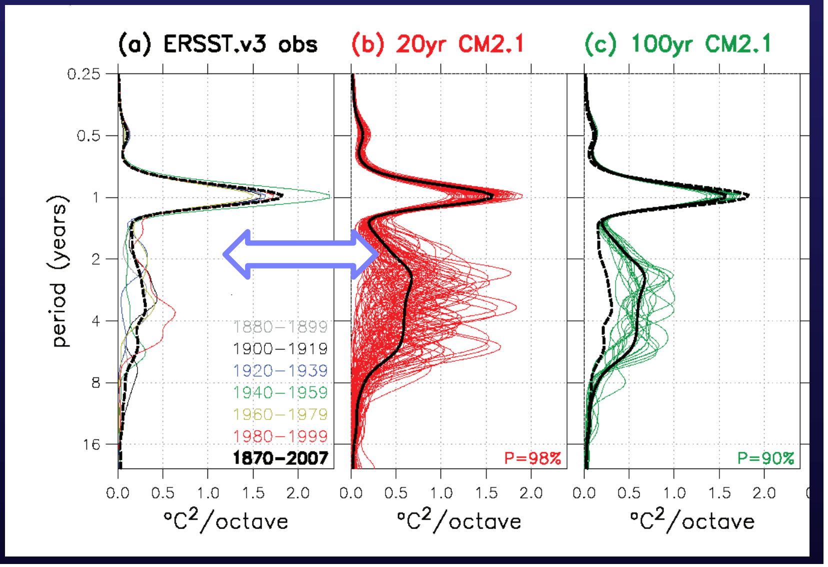
- **Cloud component is surprising: F_{LC} and F_{SC} are non-zero!**
- This caused by rapid local changes to the vertical temperature profile due to the altered radiative heating, with consequent changes to stability, vertical mixing, and the moisture profile.
- Cloud contribution to F = “tropospheric adjustment” of CO2 forcing

Uncertainty in ENSO amplitude



ENSO timescale

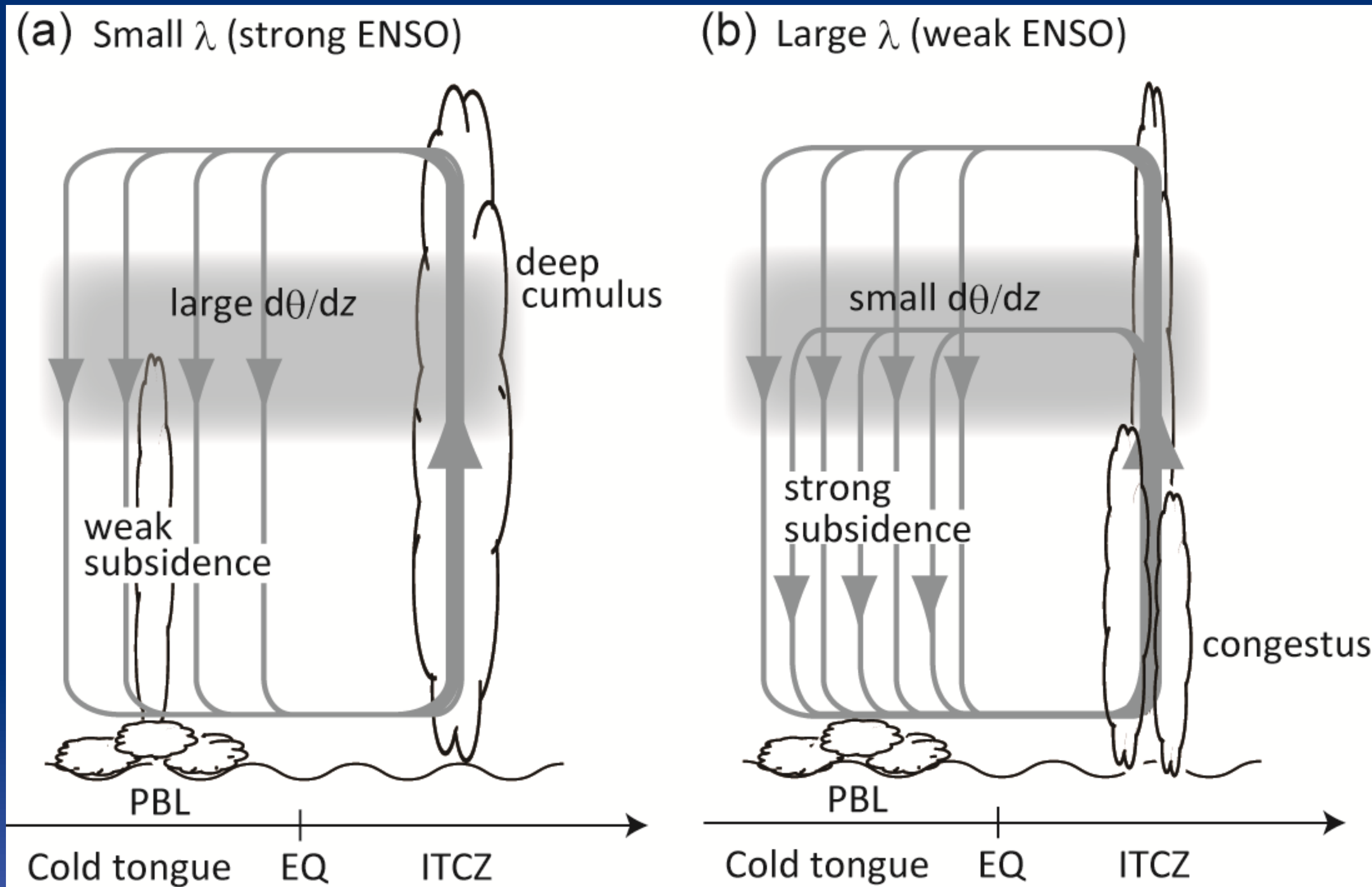
Wittenberg (2009)



Large uncertainty for the 'true' ENSO amplitude in records < 100y

Mechanism of convective control

Subsidence region (cold tongue) is controlled by the convective region (ITCZ)



Wet cold tongue
-> enhanced effective
Bjerknes feedback

Dry cold tongue
-> reduced effective
Bjerknes feedback

Question

Small but cooler cold tongue (=larger zonal SST gradient) for large λ: is it consistent with weaker ENSO?

A simple tropical climate model (Jin 1996, Watanabe 2008)

$$\dot{T}_e = -\varepsilon_T (T_e - T_r) - \theta(w)\frac{T_e - T_{se}}{H_m}$$

$$\dot{h}_w = -r h_w - \frac{r b L \tau}{2}$$

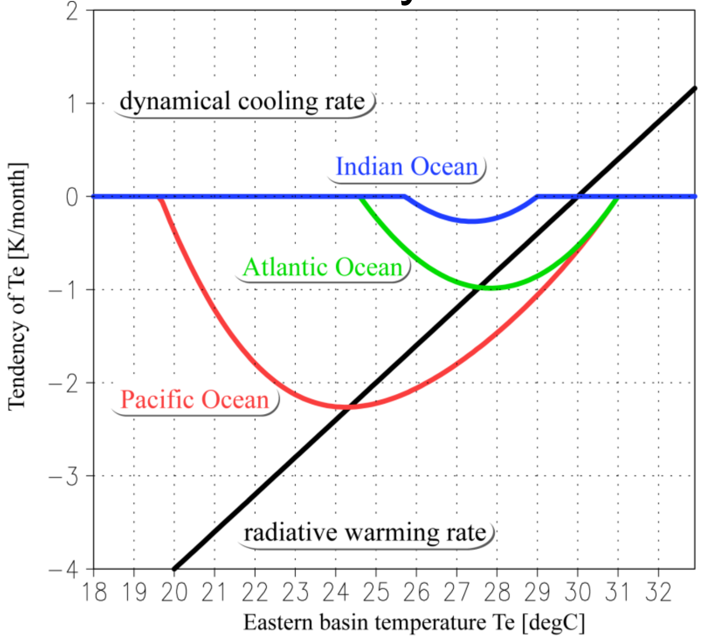
$$w = -\alpha_d \tau$$

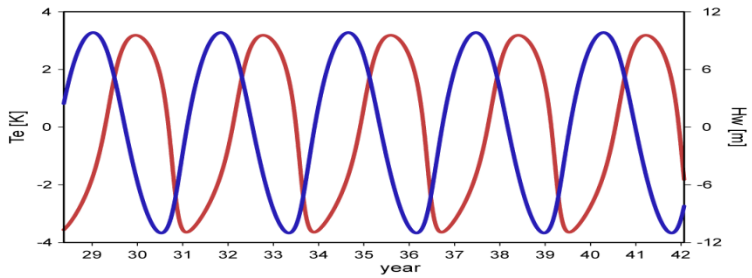
$$\tau = \tau_0 - \mu(T_r - T_e)$$

$$h_e = h_w + bL\tau$$

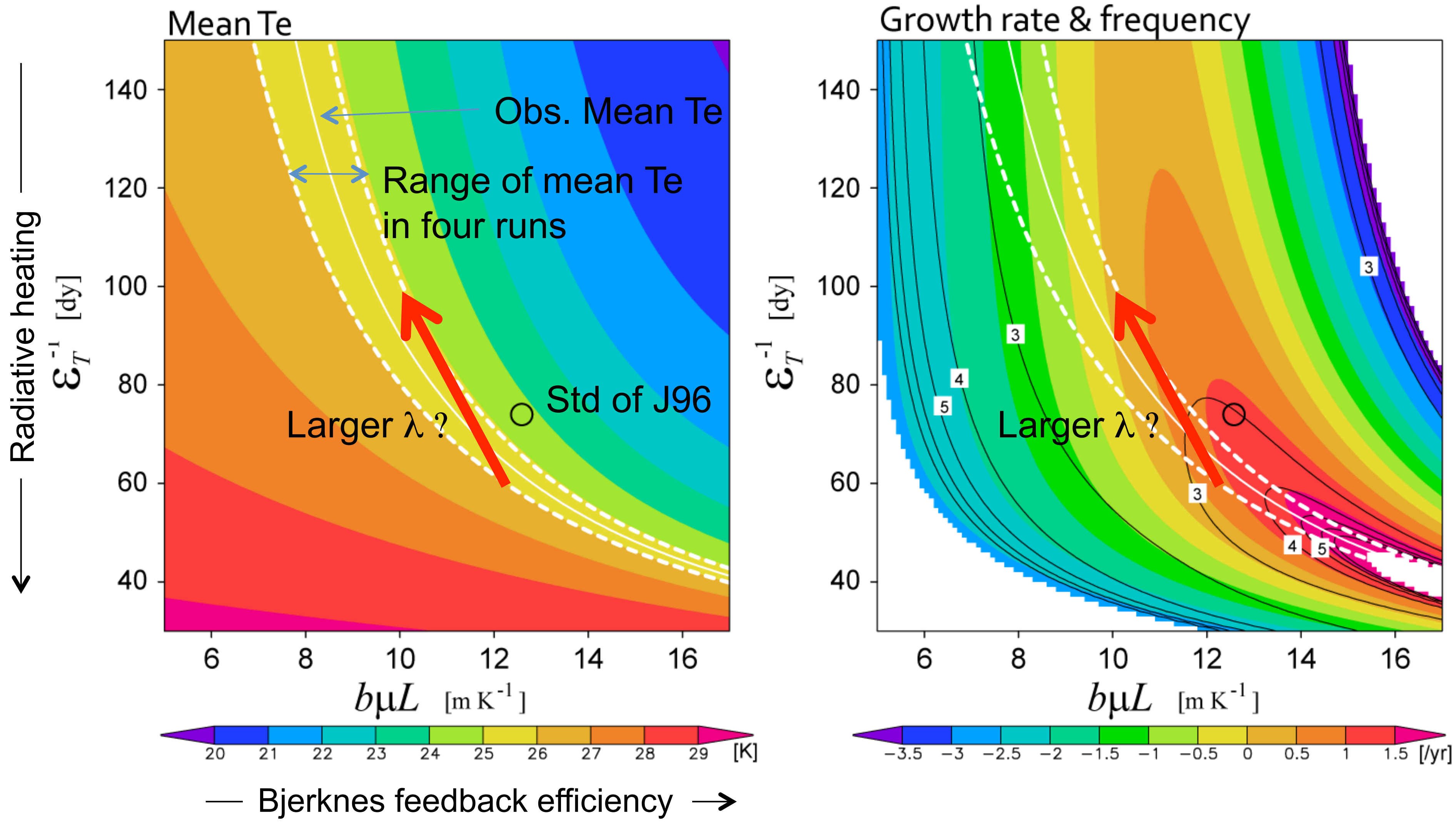
$$T_{se} = T_r - (T_r - T_{r0})\frac{1 - \tanh\left[(H + h_e - z_0)/h^*\right]}{2}$$

Stationary solutions





Question



Cooler cold tongue & weaker ENSO can coexist if $\lambda^{-1} \propto bL$

What can we do for the uncertainty?

✓ Reducing uncertainty – Use of observations (reanalysis / satellites / palaeo)

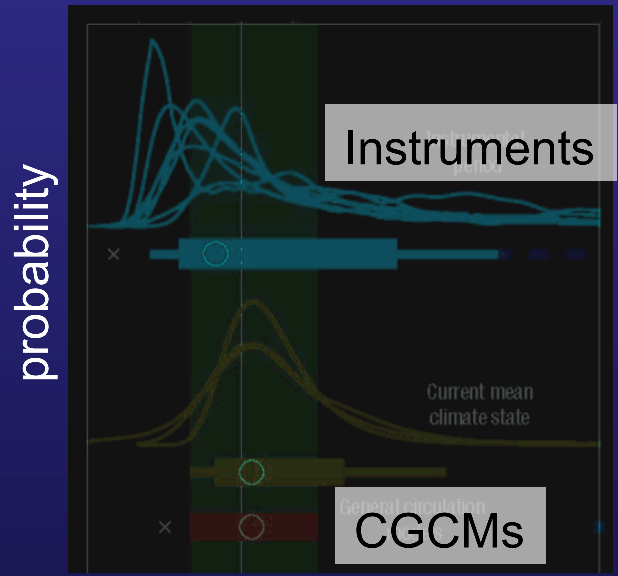
Constraining:

*Modify PDF by using observations

*Weighting models using a metric

*Difficulty due to error/uncertainty in observations, too!

Climate sensitivity



Knutti and Hegerl (2008)

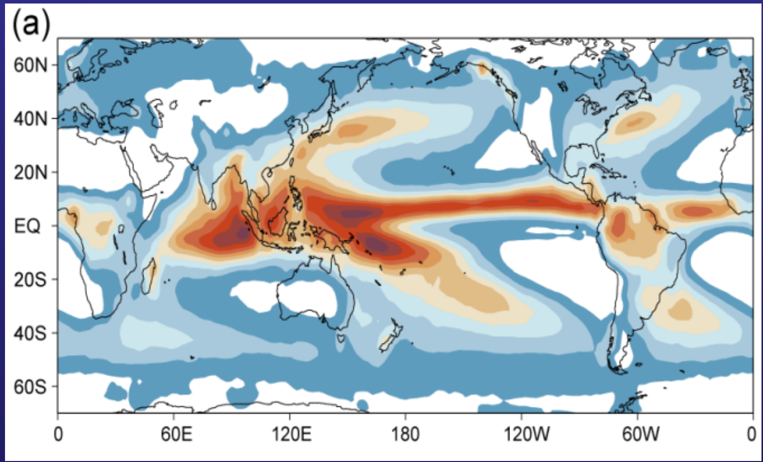
MIROC updates after AR4

		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

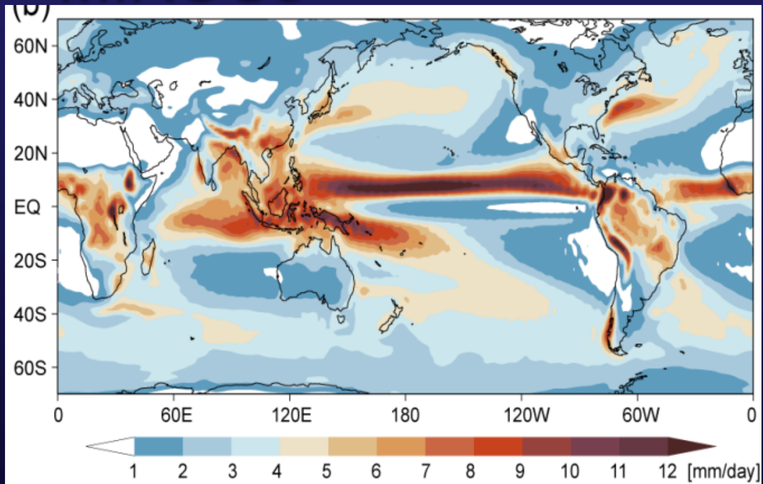
Mean climatology

Annual mean precipitation

CMAP

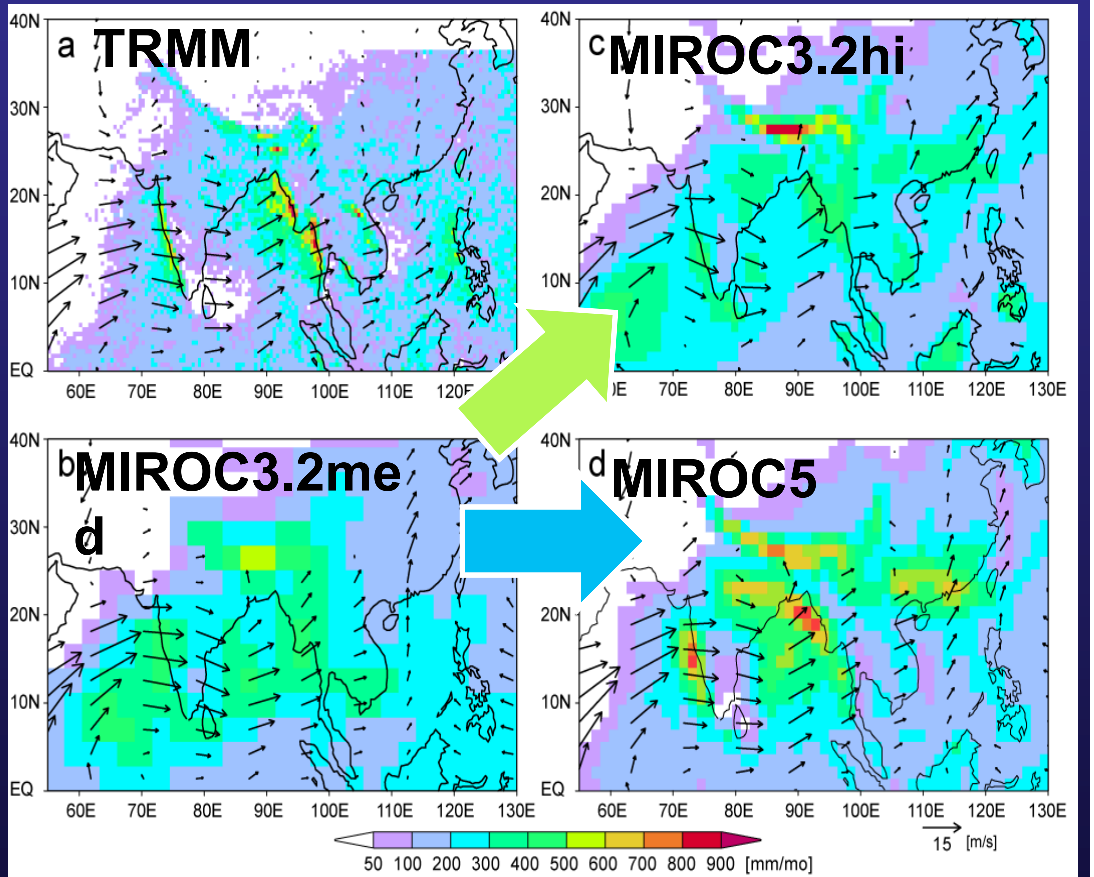


MIROC5



Watanabe et al. (2010, JC)

JJA precipitation



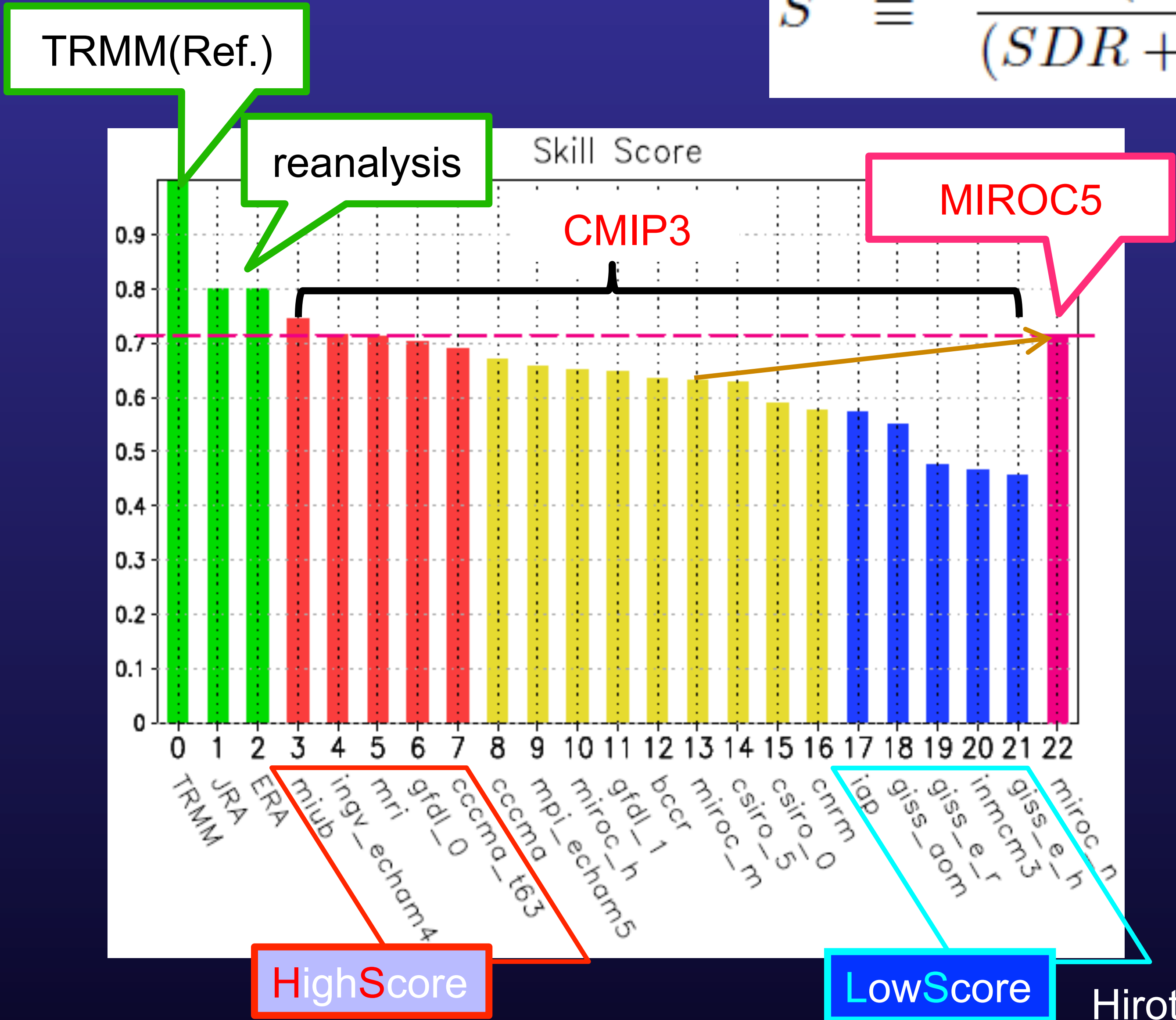
✓Effect of increased resolution

✓Effect of the new model physics

Precipitation metric over the tropical oceans

$$S \equiv \frac{4(1+R)^4}{(SDR + 1/SDR)^2}$$

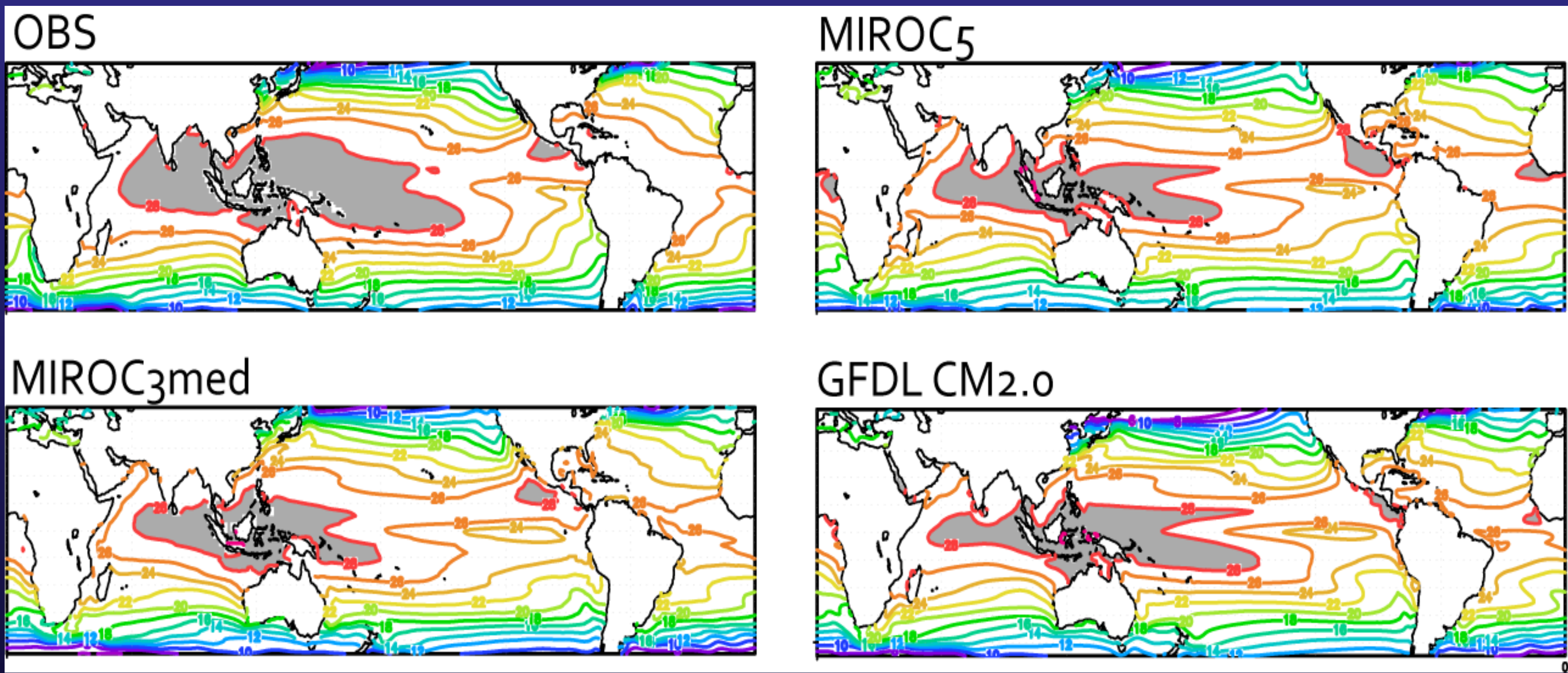
(Taylor, 2001)



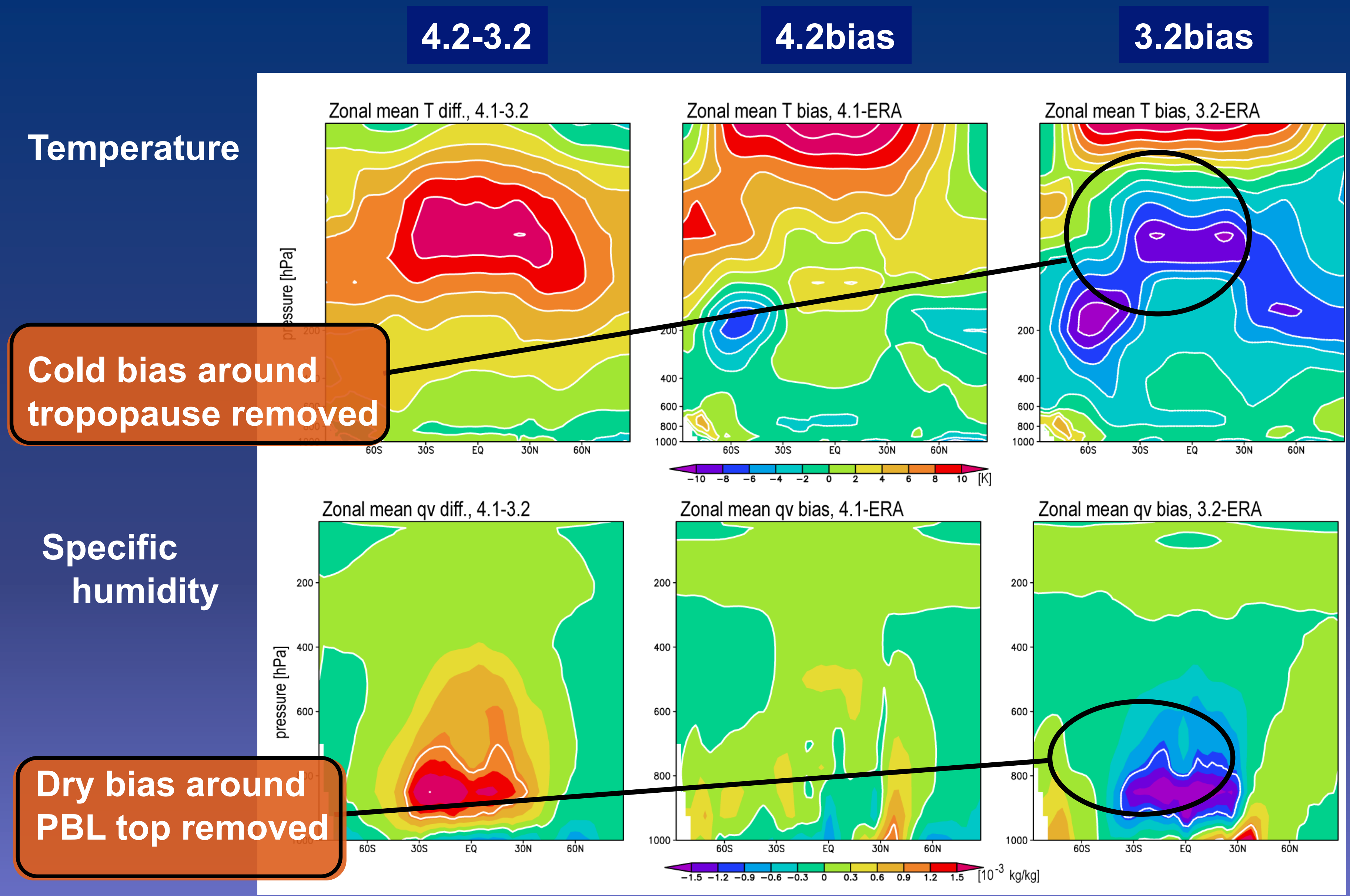
Hirota et al. (2011, JC)

20C mean SST

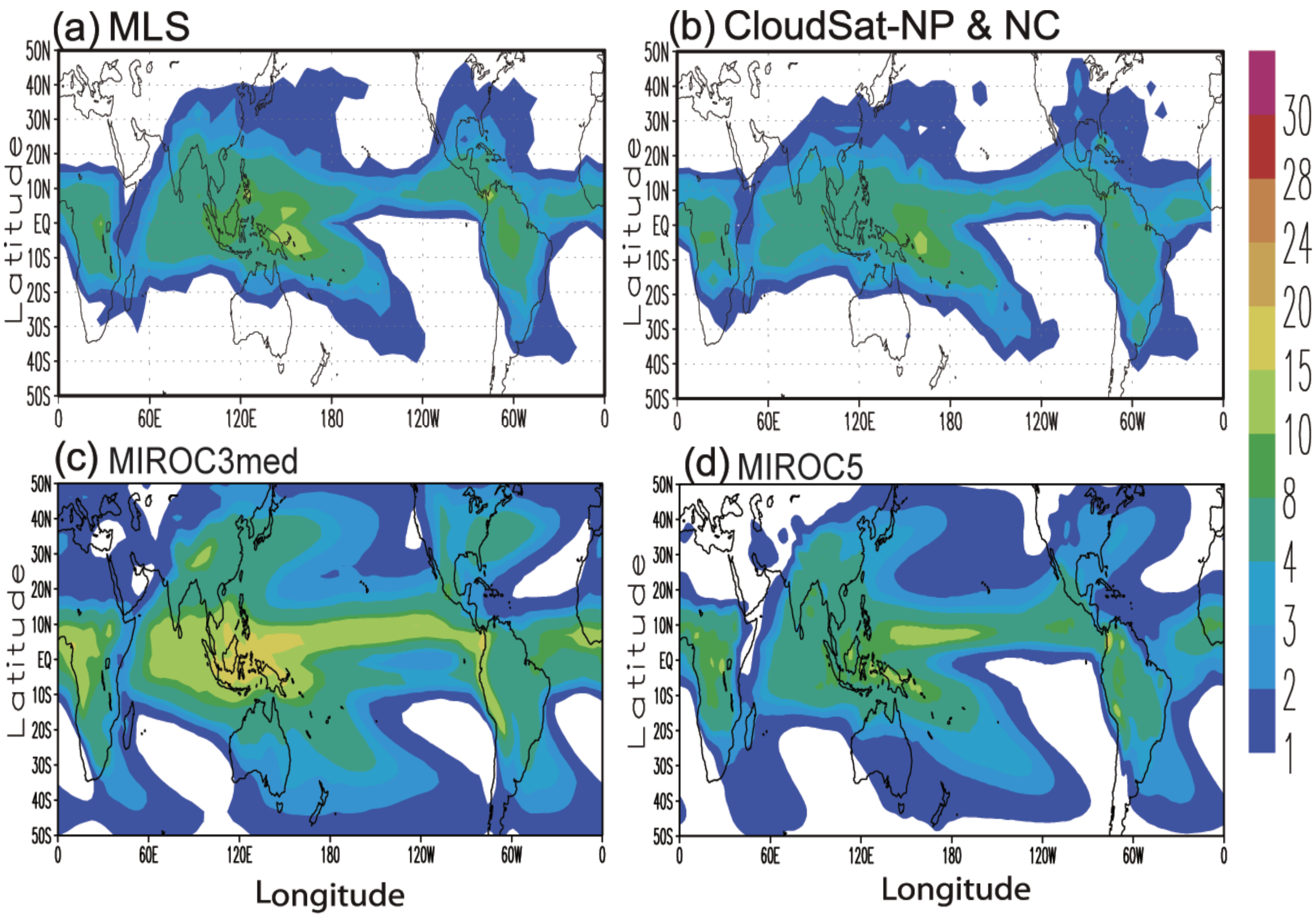
1961-1990 annual avg. from 20C run



Model performance: zonal-mean states



Property of MIROC5 215 hPa cloud ice



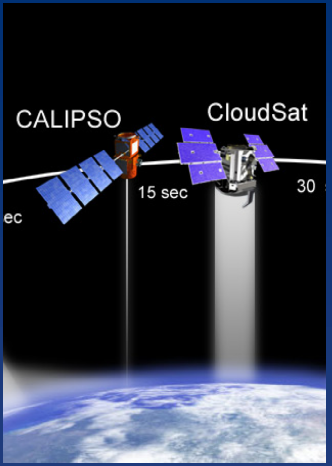
After Waliser et al. (2009)

Property of MIROC5

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

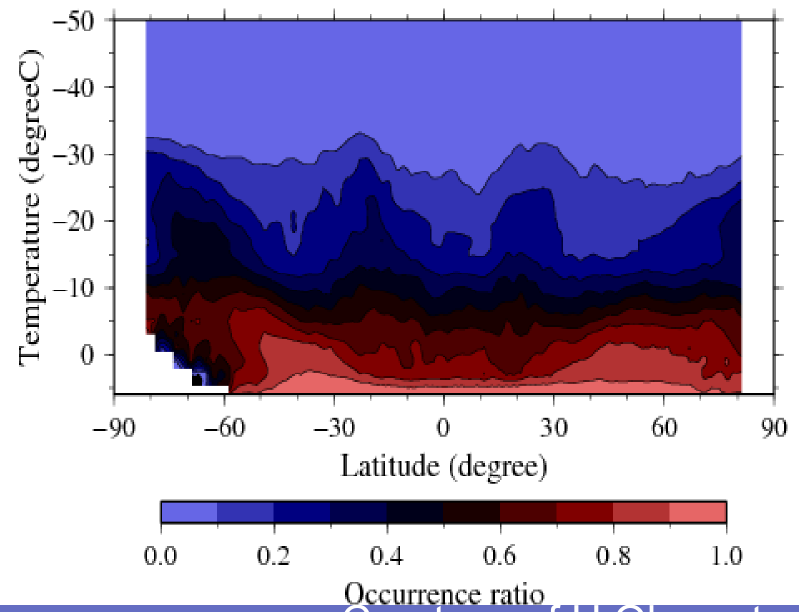
CloudSAT and CALIPSO

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

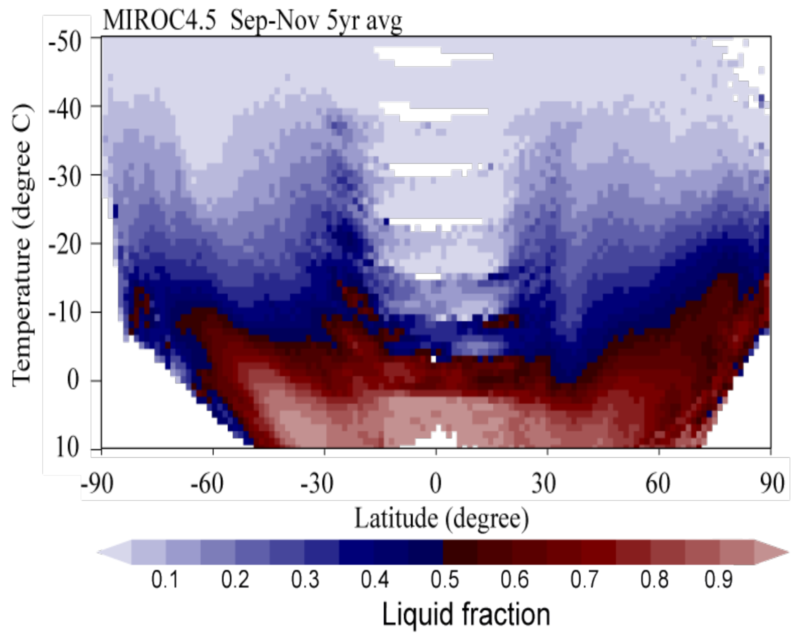


Latitude - temperature cross section of the ratio of cloud particle type

Sep-Nov 2006, CloudSAT/CALIPSO



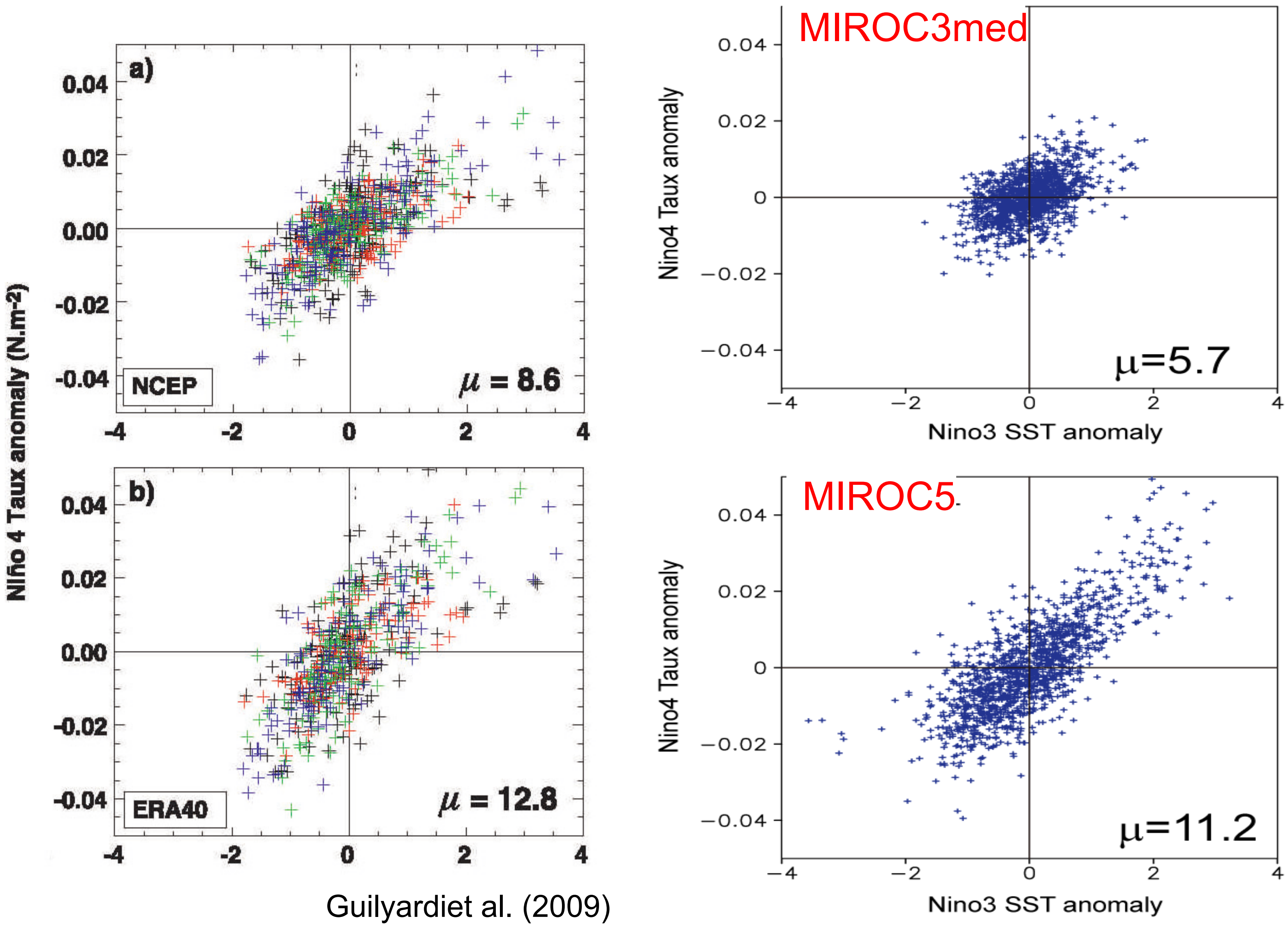
Sep-Nov climatology, MIROC4.5



Courtesy of H Okamoto

ENSO in MIROC5

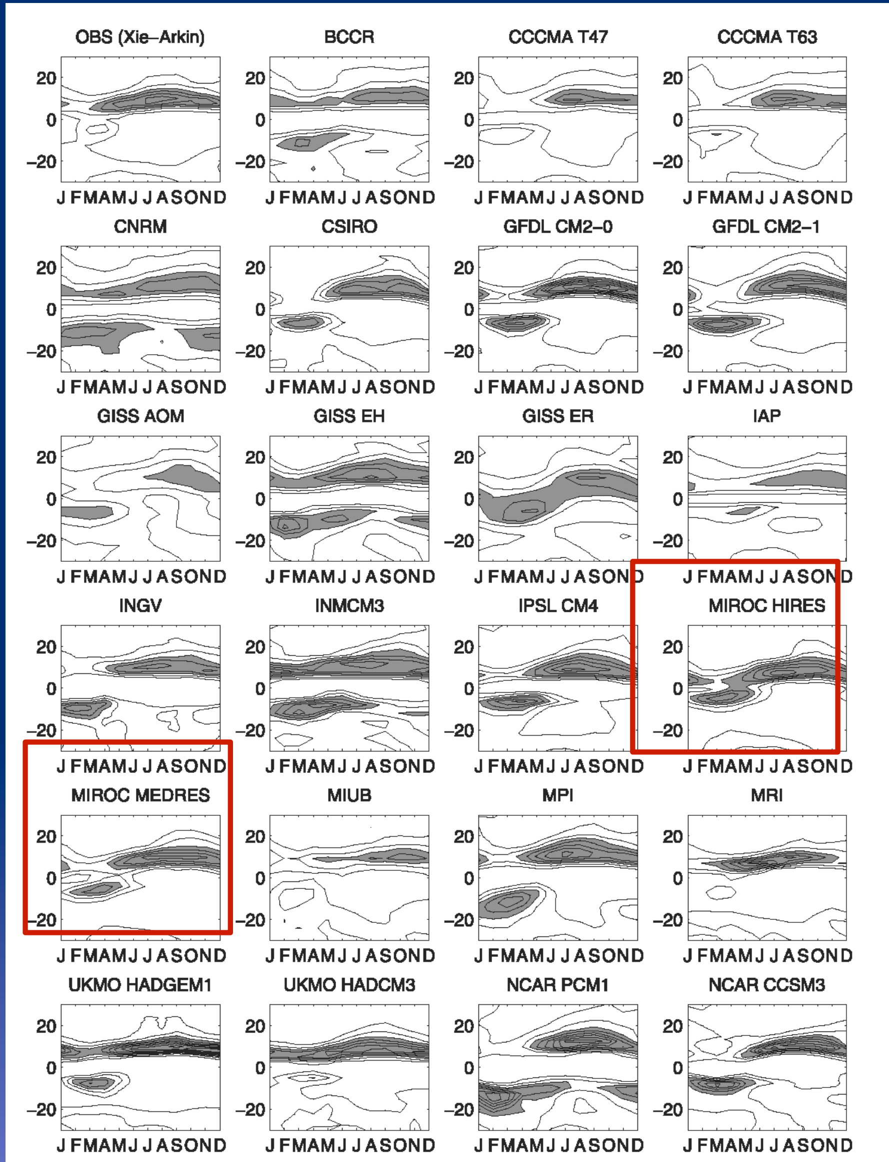
A-O coupling strength

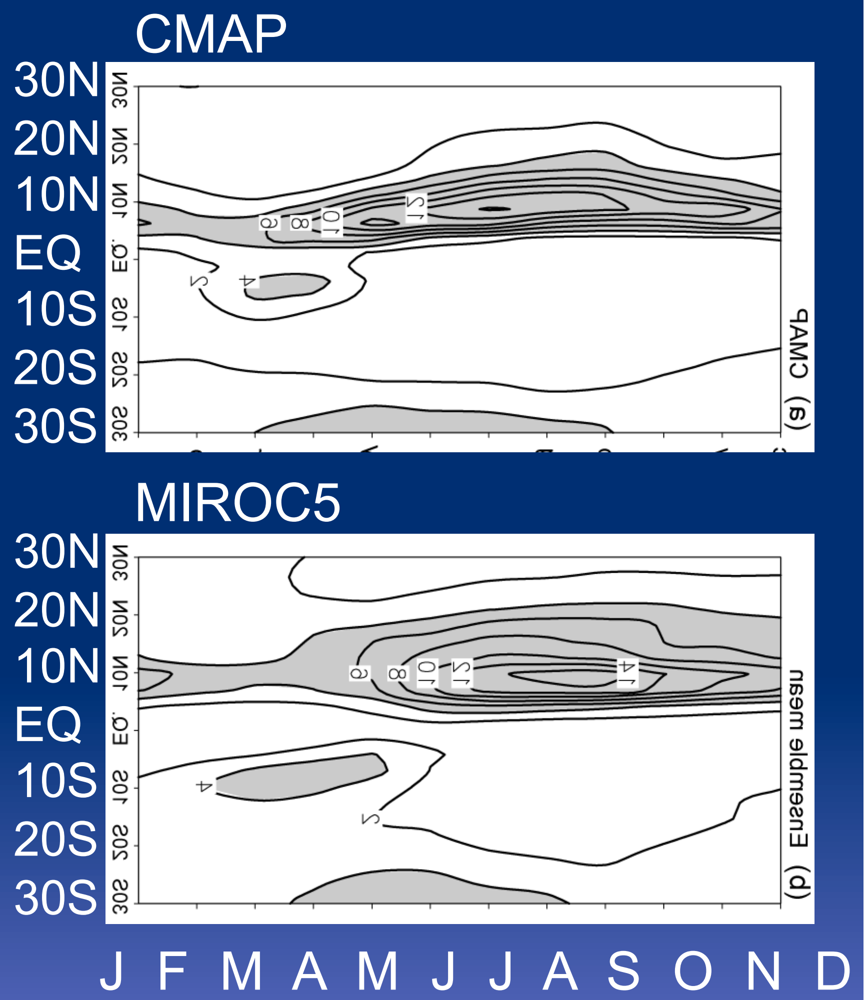


Guilyardiet al. (2009)

Double ITCZ problem

Precipitation seasonal cycle over the E. Pacific





Bellucci et al. (2010)

Perturbing cumulus convections

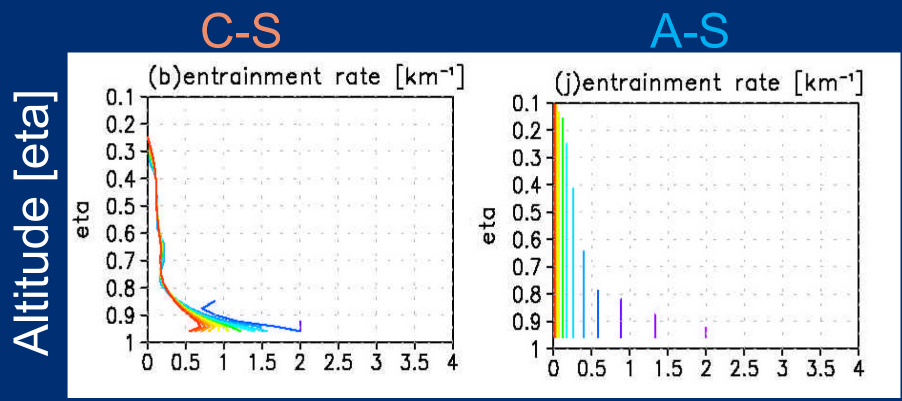
Chikira-Sugiyama convection scheme:
Mixture of A-S and Gregory schemes

Entrainment rate (ε)

- Conventional A-S scheme: prescribed
- C-S scheme: state dependent

$$\varepsilon = \lambda \frac{aB}{w^2} \quad , \quad \frac{\partial w^2}{\partial z} = 2a(1-\lambda)B - \frac{w^2}{\tau}$$

Vertical profiles of ε in a single column model



Cloud type

Chikira and Sugiyama (2010, JAS)

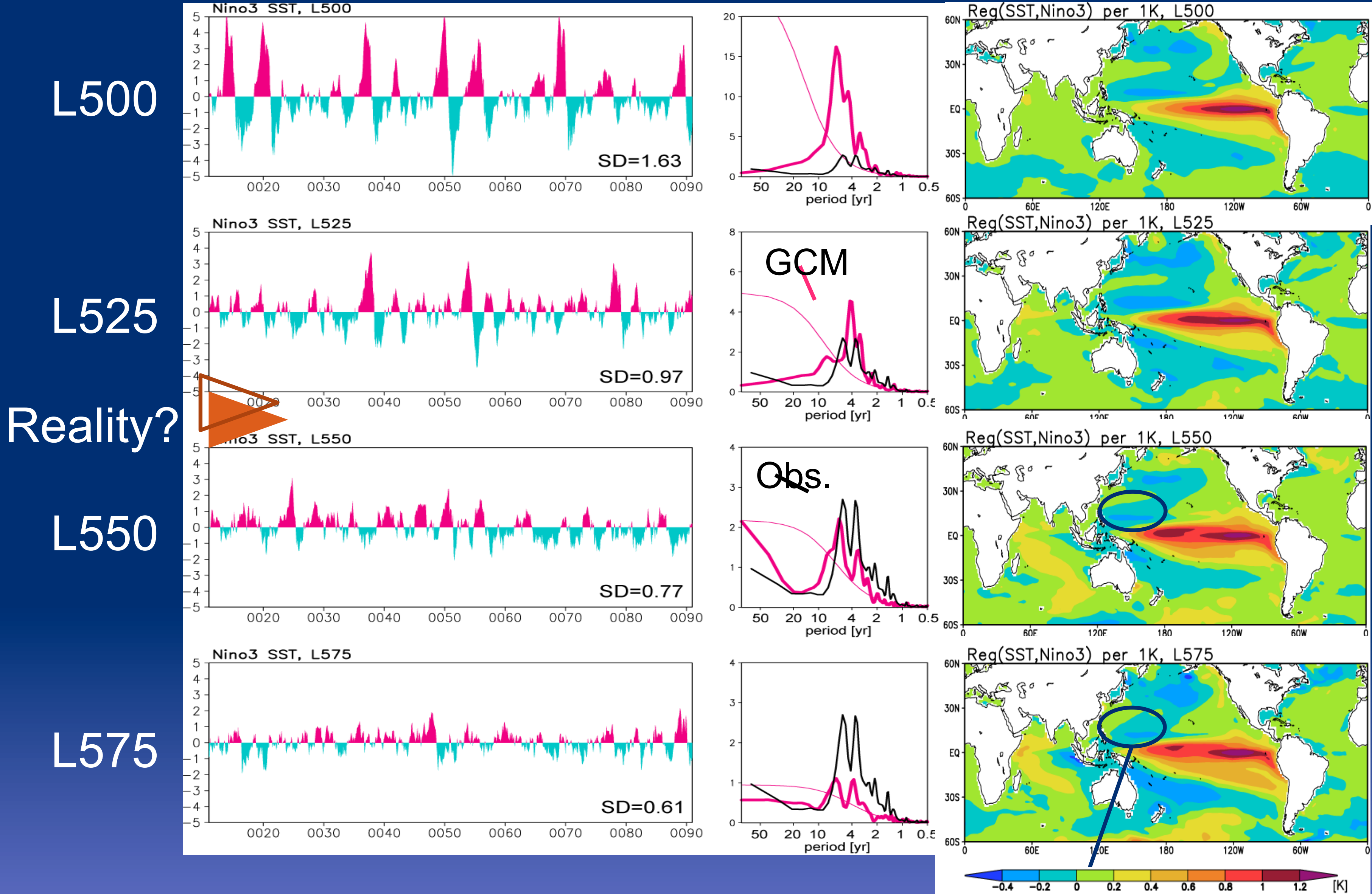
Efficiency of the entrainment controlled by λ
(large λ -> suppress deep clouds)

Sensitivity experiments w/ T42 MIROC5

exp	λ	Length
L500	0.5	85
L525	0.525	85
L550	0.55	85
L575	0.575	85

* λ=0.53 is the default value in the official T85 CTL

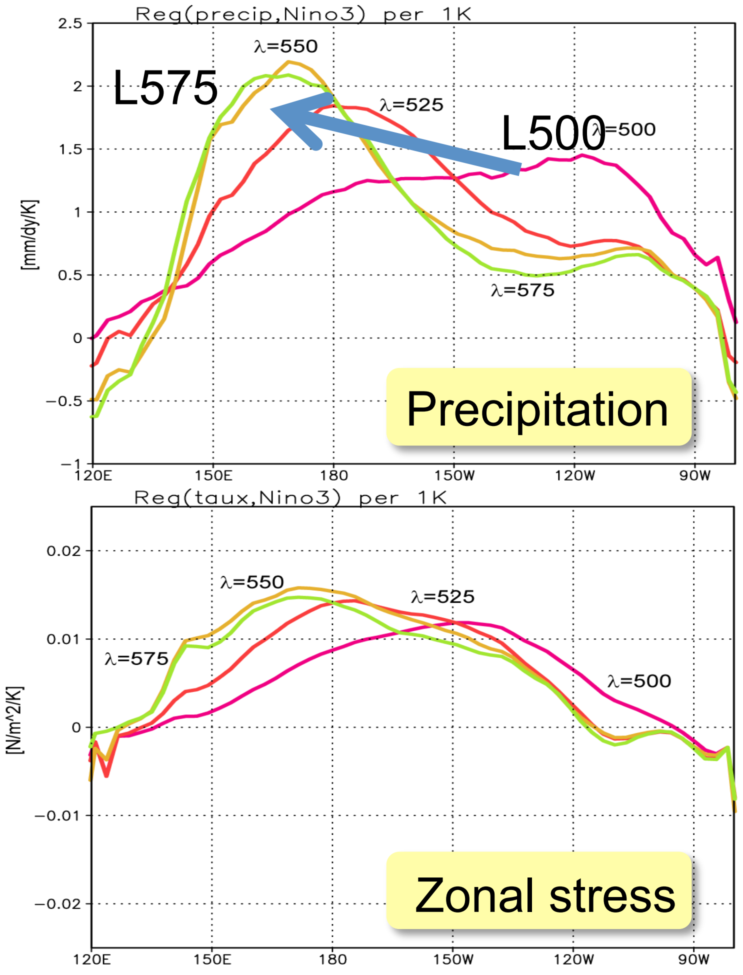
ENSO in MIROC5

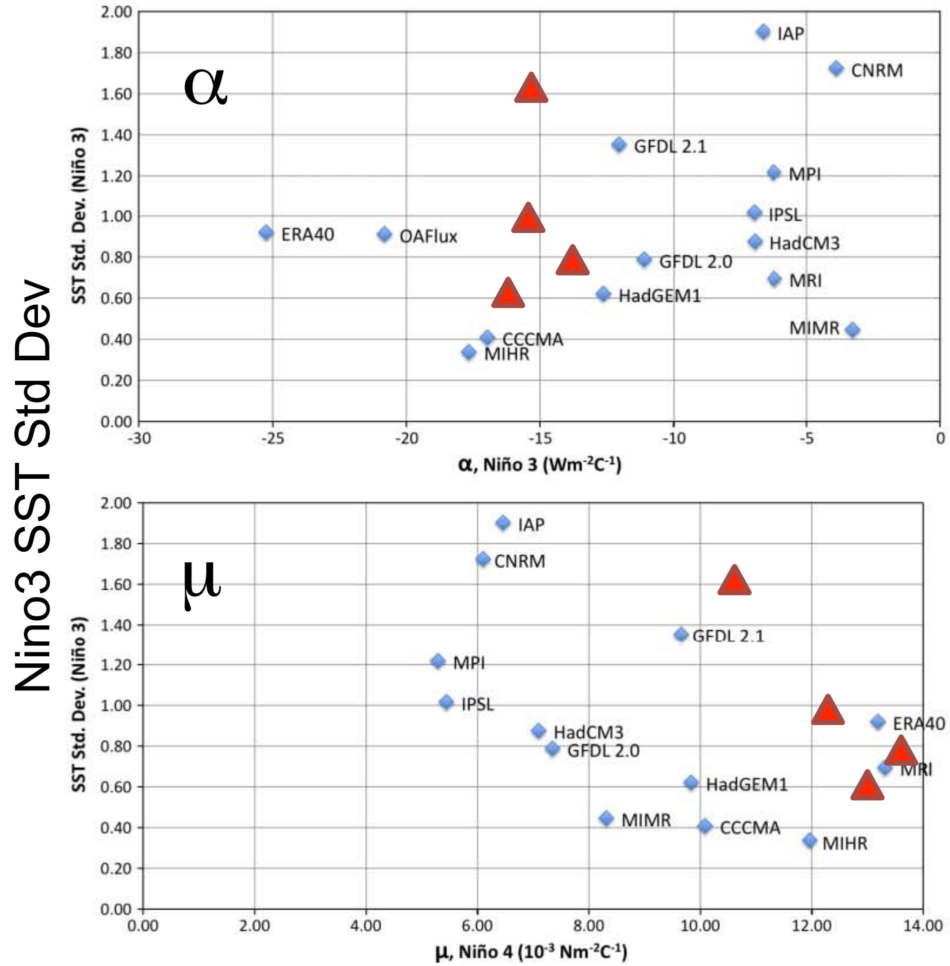


artificial? CP El Niño?

Comparison of the ENSO structure

Nino3-regression along EQ





Lloyd et al. (2009)

As ENSO amplifies, maximum in both precipitation and τ_x anomalies be stronger but shifted to the western Pacific -> **reduction in the effective Bjerknes feedback**

Mean state differences

Deviations from the ensemble mean

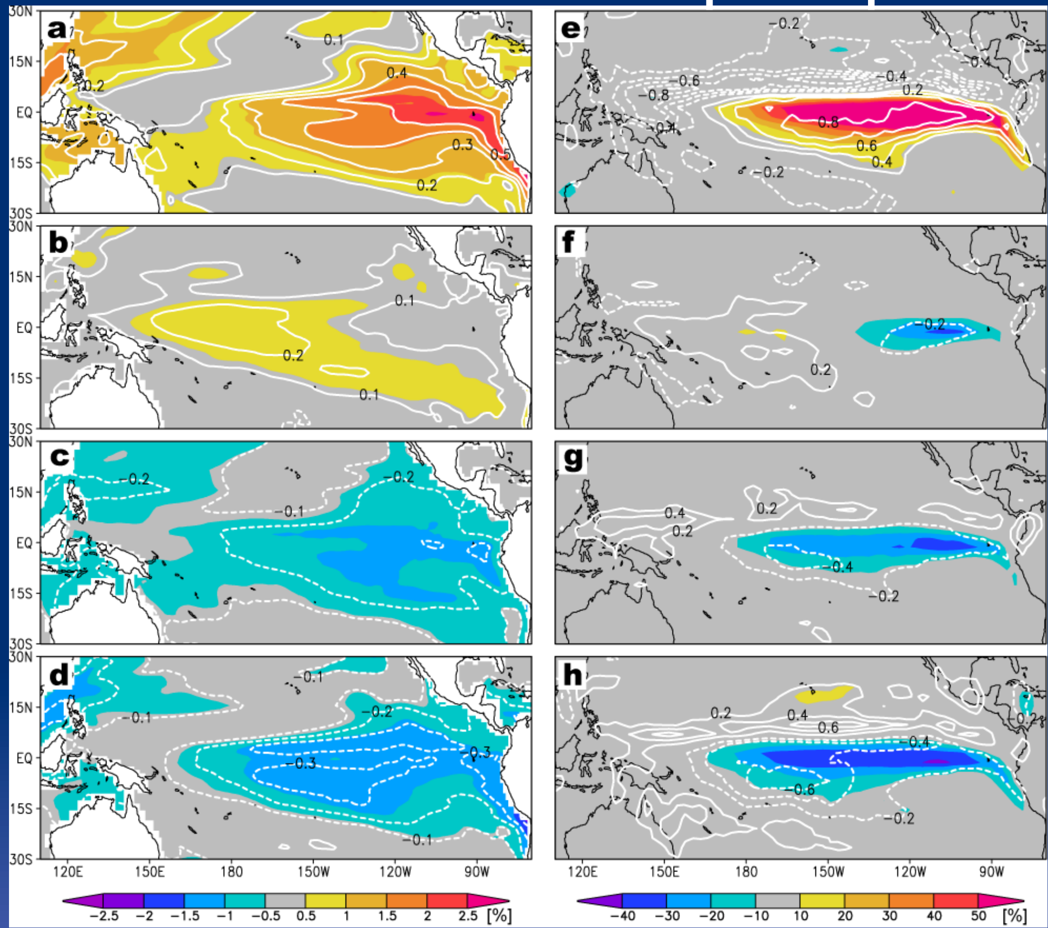
SST precip.

L500

L525

L550

L575



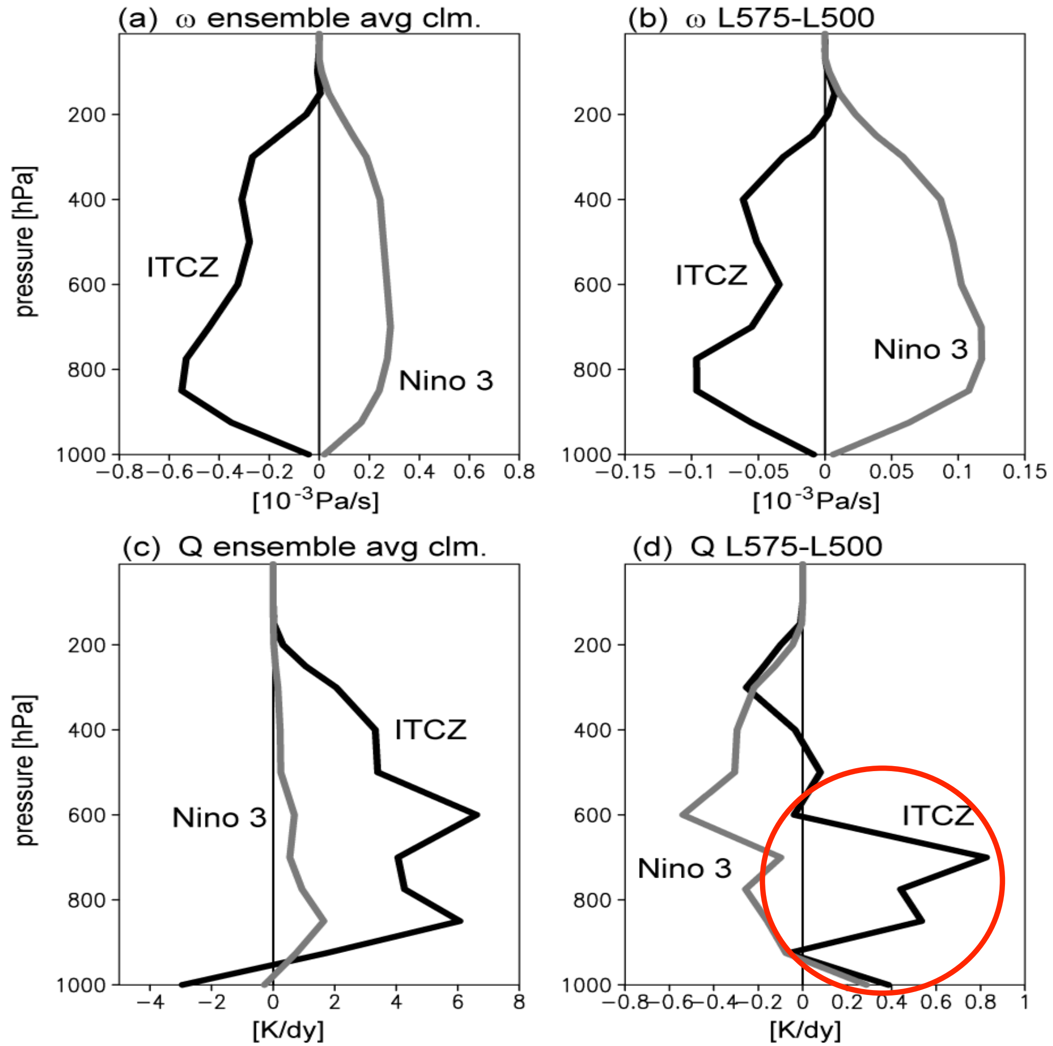
^ ENSO amplitude

Larger λ (efficient cumulus entrainment)
-> drier & colder mean state in E. Pacific <-> weaker ENSO

Mean state differences

Model clim. L575-L500

ω



Q_{cum}

More congestus?