Recent Efforts to Alleviate Tropical Biases

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Thanks to Ben Kirtman for his help in preparing this talk

Abstract

- A recent ongoing organized effort to alleviate tropical biases in coupled GCMs, involving scientists from several institutions, is described. The bias that has received the most attention is the split-ITCZ problem in the tropical Pacific, although biases in the annual cycle of SST in the equatorial Pacific and ENSO variability are also of great interest. An overview of this effort is presented, including causal hypotheses that have been put forward and sensitivity tests that have been performed. Two competing hypotheses that will be explored are: one that the cause of the biases is due to errors in parameterizations in the atmospheric model, and the other that the causes are rooted in the ocean model. The problem of how to organize community efforts to accelerate progress in alleviating the biases will be addressed.

Outline

- Recent history of (a specific series of) tropical bias workshops and meetings
  - Motivation
  - Process
  - Content

Tropical Biases in CGCMs

- Biases in the Pacific
  - Equatorial cold tongue penetrates too far west; double ITCZ
  - Biennal component of annual cycle of SST at equator too strong
  - ENSO period too short; amplitude too strong or too weak; structure unrealistic
  - Too warm E. Pacific
  - Diffuse thermocline
  - Nonexistent or unrealistic MJO (West Pac./Indian Ocean)
  - Upper tropospheric equatorial easterlies too strong
- Biases in the Atlantic
  - ITCZ in the wrong place at the wrong time, thermocline slopes the wrong way
- Biases in the Indian Ocean
  - Climatological thermocline structure unrealistic
- Biases over land
  - Unrealistic precipitation distribution and variability

Documentation of Biases

- **Neelin, J. D., and and Coauthors, 1992**: Tropical air-sea interaction in general circulation models. Climate Dyn., 7, 73-104.
- **Mechoso, C. R., and and Coauthors„ 1995**: The seasonal cycle over the tropical Pacific in coupled ocean-atmosphere general circulation models. Mon. Wea. Rev., 123, 2825-2838.
- **Davey, M. K., and and Coauthors„ 2001: STOIC**: A study of coupled model climatology and variability in tropical ocean regions. Climate Dyn., 18, 403-420.
- **Latif, M., and and Coauthors„ 2001**: ENSIP: The El Niño Intercomparison Project. Climate Dyn., 18, 255-276.
- **AchutaRao, K. and K. Sperber, 2002**: Simulation of the El Niño Southern Oscillation: Results from the Coupled Model Intercomparison Project. Climate Dyn., 19, 191 - 209.
- Several for IPCC AR4 simulations

Status

- Many models, each with its own biases - some commonality, but always exceptions
- Model changes that lead to improvements in one model don’t work in others
- Progress is slow - is there a way to accelerate?

Recent Efforts to Stimulate Progress

- Tropical biases meetings (materials collected on Correcting Tropical Biases Project web page at grads.iges.org/ctbp)
  - **Princeton (GFDL) 2003**
    - Organized by Ping Chang and Chris Bretherton
    - Emphasis on double ITCZ in Pacific in AGCMs/CGCMs
    - Major results
      - Inclusion of cumulus momentum transport ("cumulus diffusion") in GFDL AGCM led to more realistic ENSO period (4 year instead of 2 year)
        - » Inclusion of CMT in CCSM did not lead to improvement in ENSO
        - » Inclusion of CMT in NASA made double ITCZ problem more severe
      - Biases sometimes are and sometimes aren't improved when resolution is increased
  - **Calverton (COLA) 2005**
    - Initiated by E. Sarachik (UWash), who enlisted J. Shukla (COLA) and Bill Collins (CCSM) because of concern about CCSM tropical biases
  - **Breckenridge (2006)** after CCSM workshop
    - Follow up to Calverton meeting

GFDL Meeting (2003)
Chris Bretherton's Summary
(complete summary by Ping Chang on CTBP web page)

Possible causes of biases

Atmosphere	• Deep convective feedbacks with PBL, SST wrong--> double ITCZ
Atmosphere	• Bad coastal winds (continental effect, resolution,…) --> bad coastal upwelling --> stratus region too warm --> double ITCZ
Atmosphere	• Solar and longwave cloud forcing wrong --> stratus region too warm --> double ITCZ
Ocean	• Ocean mixing wrong --> cold tongue too cold --> double ITCZ
Atmosphere	• Air-sea interaction wrong --> PBL not properly stabilized over cold tongue --> trades & upwelling too strong --> cold tongue too cold
Ocean	• Biology not included --> penetrative radiation too large --> cold tongue too cold

(Thanks, Meghan)

Calverton and Breckenridge Meetings

- Object
  - **Develop hypotheses** for the origin of tropical biases
  - Design and carry out experiments to **test these hypotheses**
- **Restrict** focus **to** improve chances of success
  - **Double ITCZ and ENSO in western and central equatorial Pacific**
  - Concentrate on improving biases **in CCSM3**
- Second meeting to report on results of experiments

Hypothesis driven model development

- Noble goal
- How did it work?

Calverton Meeting:

taken from a scanned transparency

2. The meeting will have a discussion or "brainstorming" format. There will be no formal presentations. However, some preparation may increase the chances for a productive outcome. In particular, you should bring visual materials appropriate to the discussion format of the meeting (e.g. transparencies, no PowerPoints) to concisely illustrate your ideas and suggestions.

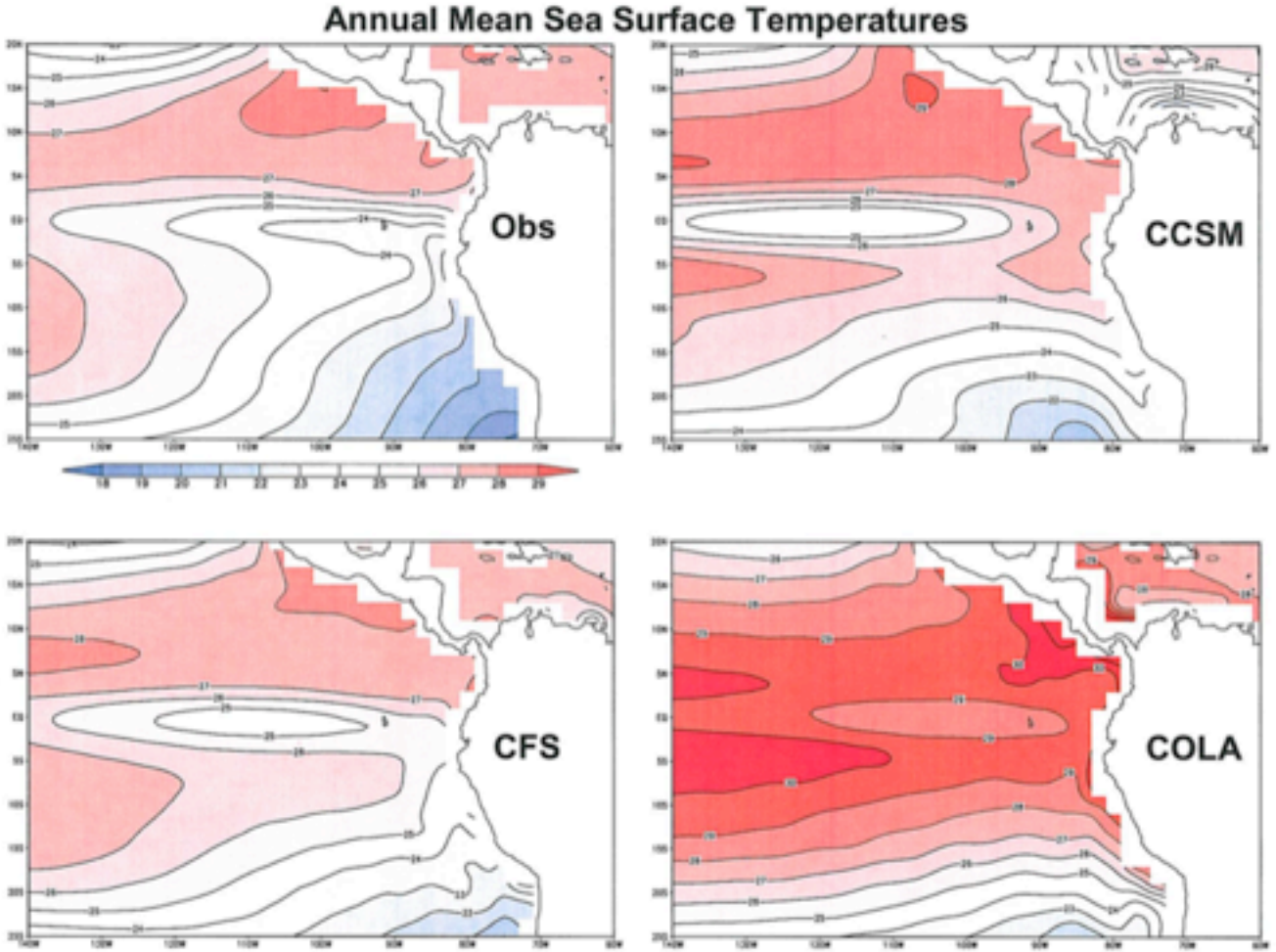
I strongly recommend against this restriction in future meetings)

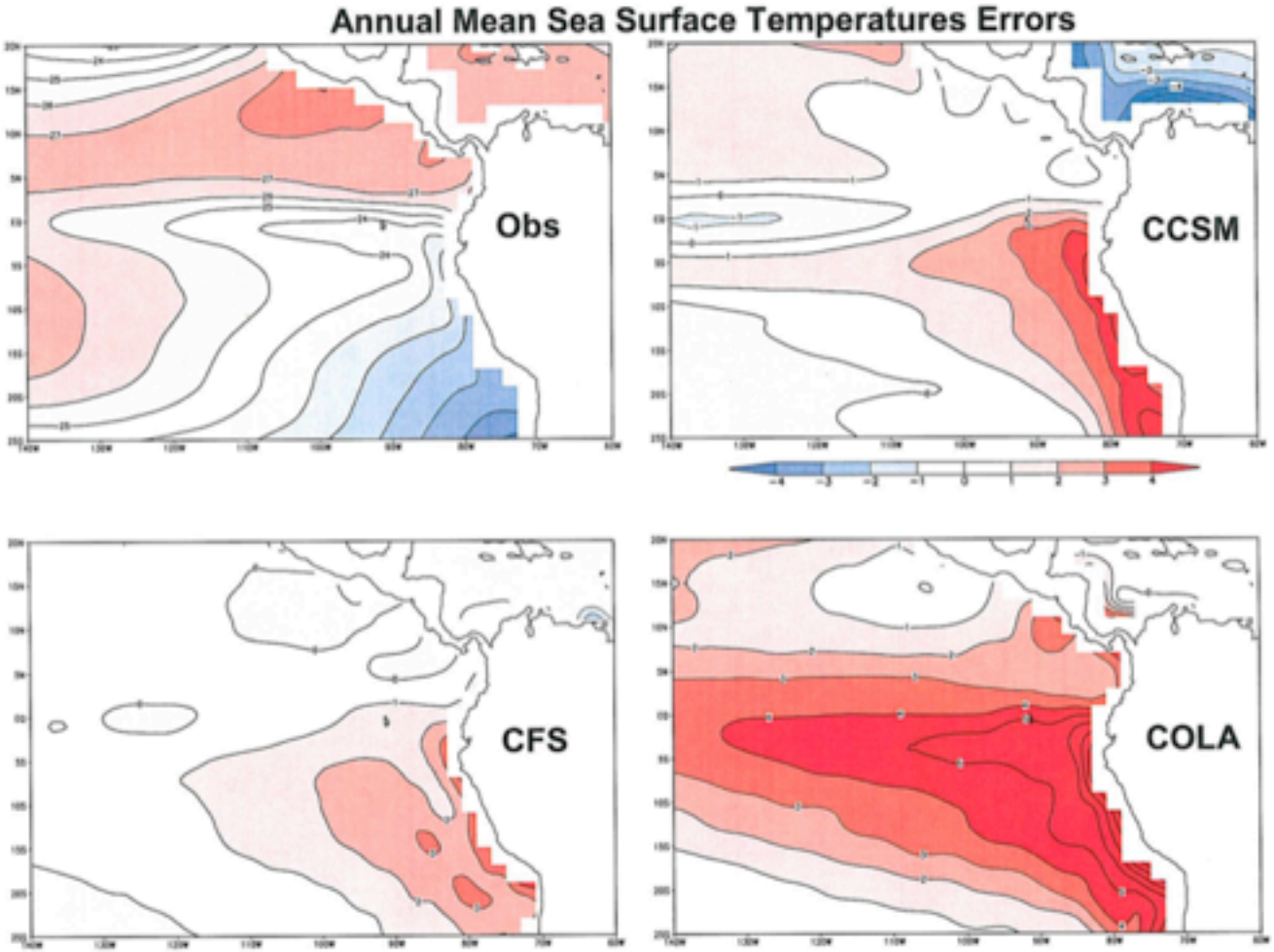
Double ITCZ

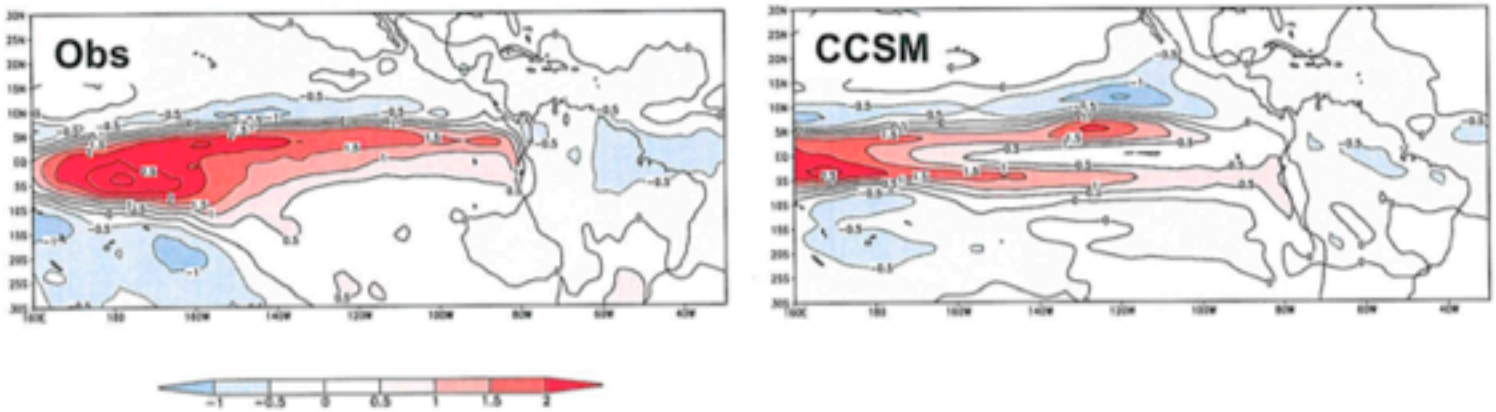
- Ed Sarachik's introduction to the Calverton meeting
  - In order to reduce the too-extensive westward extension of the cold tongue in equatorial Pacific SST, models have to be modified to do one of two things:
    1. Reduce the (easterly) atmospheric wind stress response to the SST
    2. Reduce the magnitude of the SST response (due to oceanic upwelling) to the wind stress

! (Ed applies Ekman layer theory to design CGCM experiments)

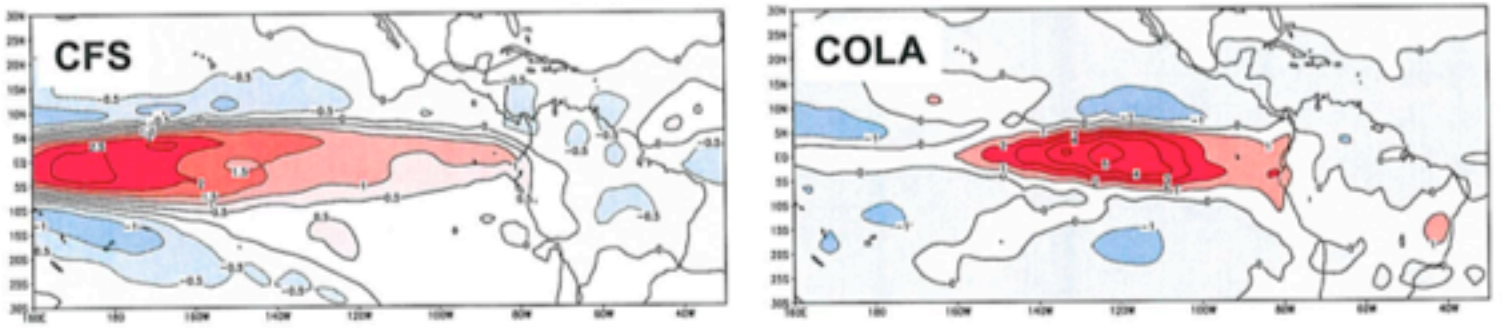
Documentation of Biases (brief review by Ben Kirtman)



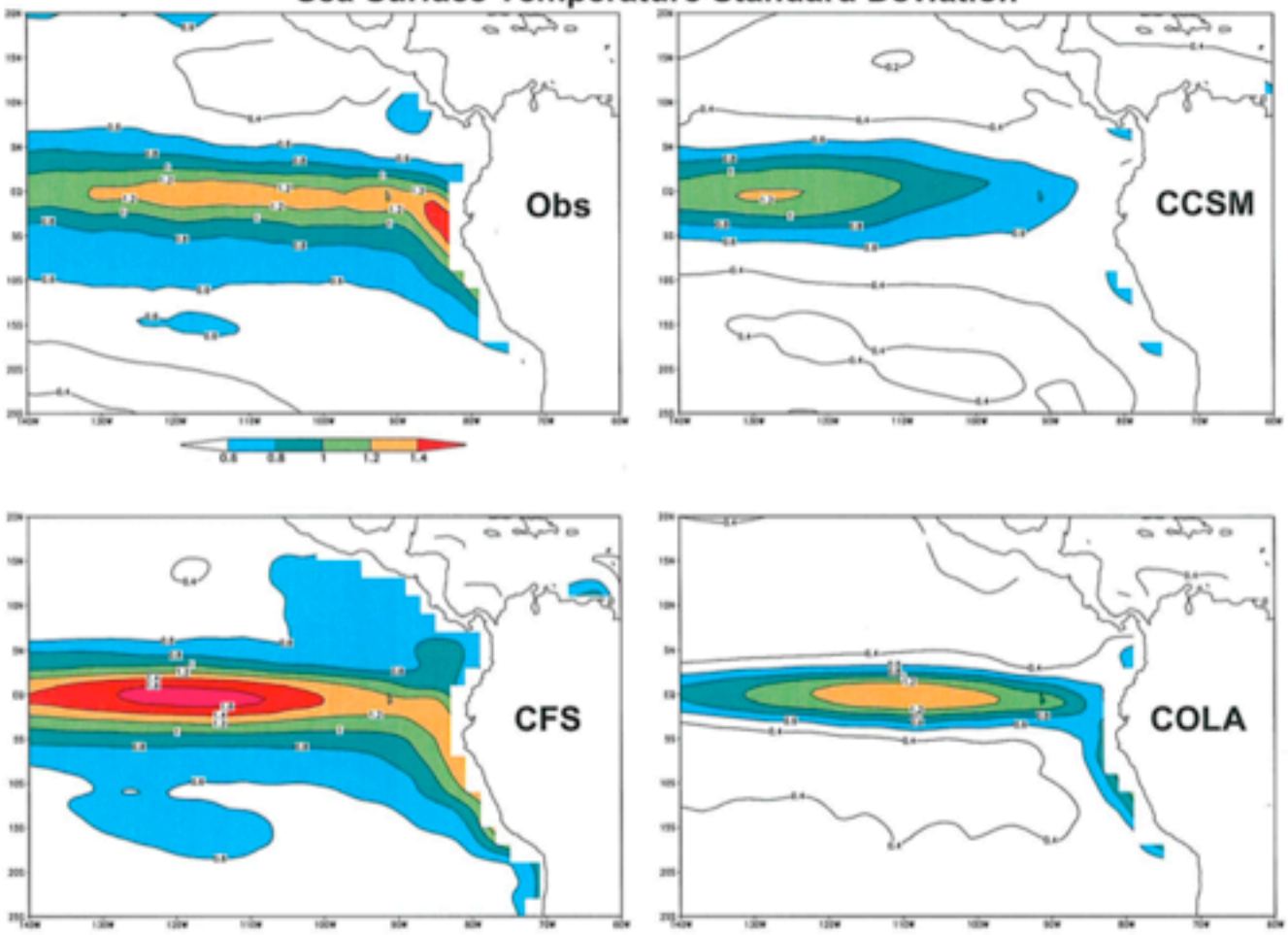

Annual Mean Sea Surface Temperatures Errors
Obs
CCSM
CFS
COLA



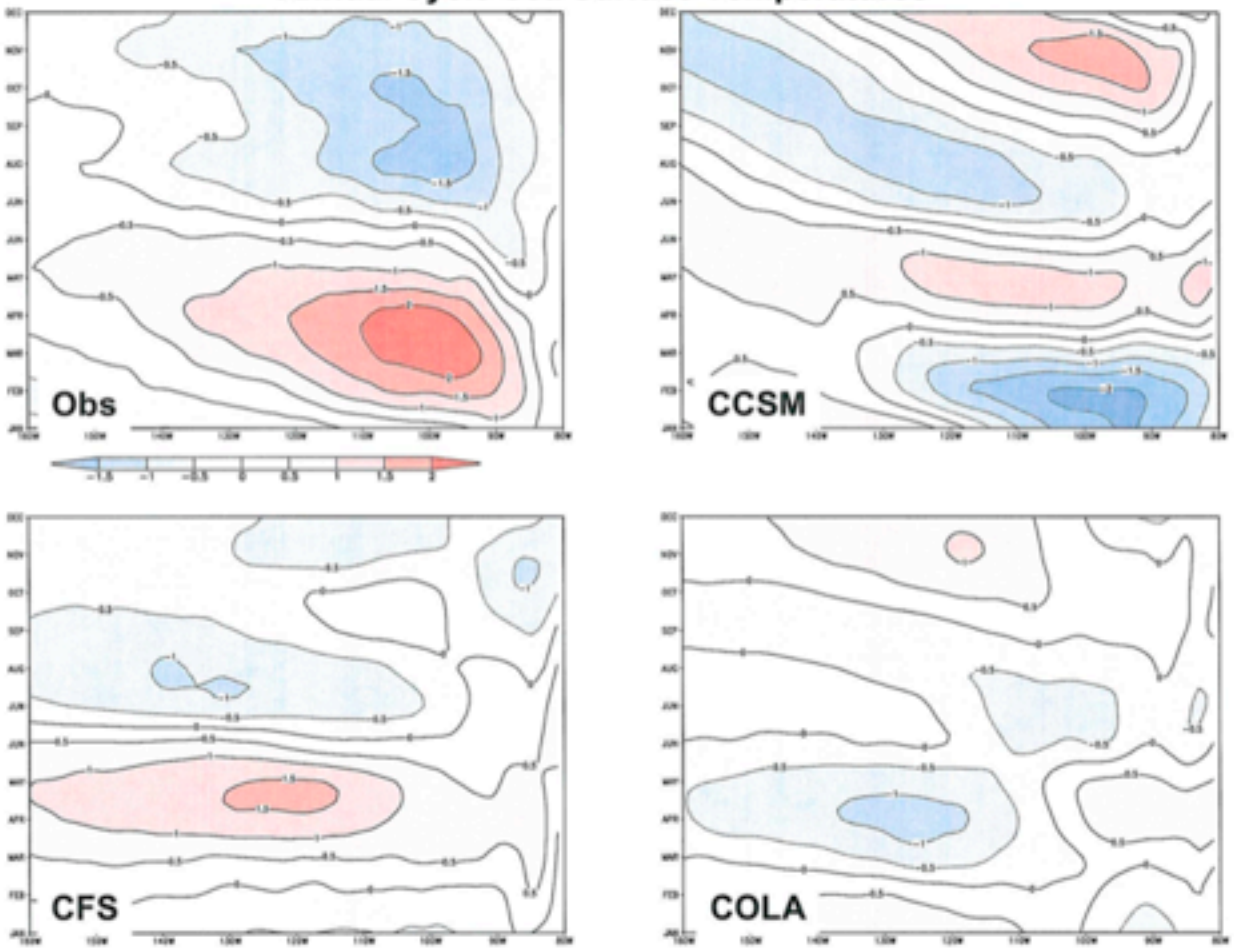
Regression of Nino3.4 SSTA onto Precipitation Anomalies



Sea Surface Temperature Standard Deviation



Annual Cycle Sea Surface Temperatures



Hypotheses

- Model based
  - Improve the model representation of specific processes and figure out why the tropical biases do/do not improve afterwards
    - Atmosphere
    - Ocean
    - Coupling
  - Business as usual
- Mechanism based
  - Perform experiments to understand the mechanisms and sensitivities of the biases
  - Use this understanding as input to the model based procedures
  - Not business as usual

Model Based Hypotheses (AGCM)

- **Numerics**
  - Increased vertical resolution needed in atmosphere
    - Increase throughout troposphere improves CFS annual mean SST, ENSO, MJO
    - Increase in lower atmosphere improves GFDL double ITCZ
  - Increased horizontal resolution in atmosphere improves E. Pacific (CCSM, GFDL)
- **Parameterizations**
  - Inclusion of convective momentum transport (cumulus friction) will lead to improvement in double ITCZ and ENSO
    - GFDL: improves ENSO period and structure, no effect on double ITCZ
    - NASA: degrades double ITCZ
    - CCSM: no effect first try
  - Improved convective heating distribution and closure will lead to improvement in double ITCZ and ENSO
    - GFDL: replacing RAS by MCA improves double ITCZ, MJO, increases ENSO amplitude
- **Rainfall reevaporation**
  - Rainfall reevaporation parameter is a useful tuning knob for double ITCZ
    - NASA: sensitive, can improve double ITCZ
    - GFDL: no sensitivity

Model Based Hypotheses (OGCM)

- Parameterizations
  - Reduced horizontal viscosity will improve currents (CCSM)
  - Reduced background diffusivity will sharpen thermocline and warm equatorial Pacific SST (IPRC)
- Non-uniform sunlight penetration due to phytoplankton necessary to correctly simulate SST (already taken into account: CCSM and GFDL)

Model Based Hypotheses (coupling)

- Need to resolve diurnal cycle (coupling several times a day) to warm SST (*)
  - Improves GFDL and CCSM
- Reduce surface wind stress bias by include ocean surface currents in surface bulk formula for surface wind stress (done already in CCSM and GFDL) (*)

Mechanism Based Hypotheses (I)

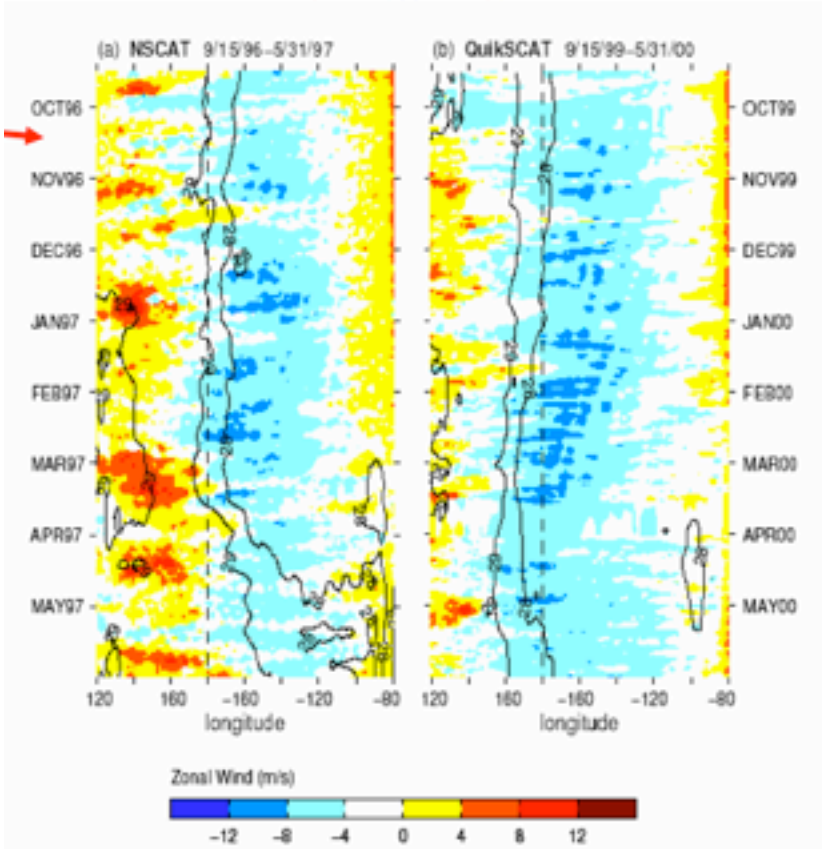
- Oceanic equatorial Ekman dynamics: wind stress is too strong or upwelling is too cold
- Vertical distribution of convective heating affects surface wind stress (how??)
- Wind stress response to low latitude convective heating too narrowly confined to equator causes short ENSO period.
- Too little stratus gives too much solar and warm bias in E. Pac.
- Too strong feedback between convection and moisture convergence is responsible for double ITCZ through transients in SH (to explain sensitivity to rainfall reevaporation)

Mechanism Level Hypotheses (II)

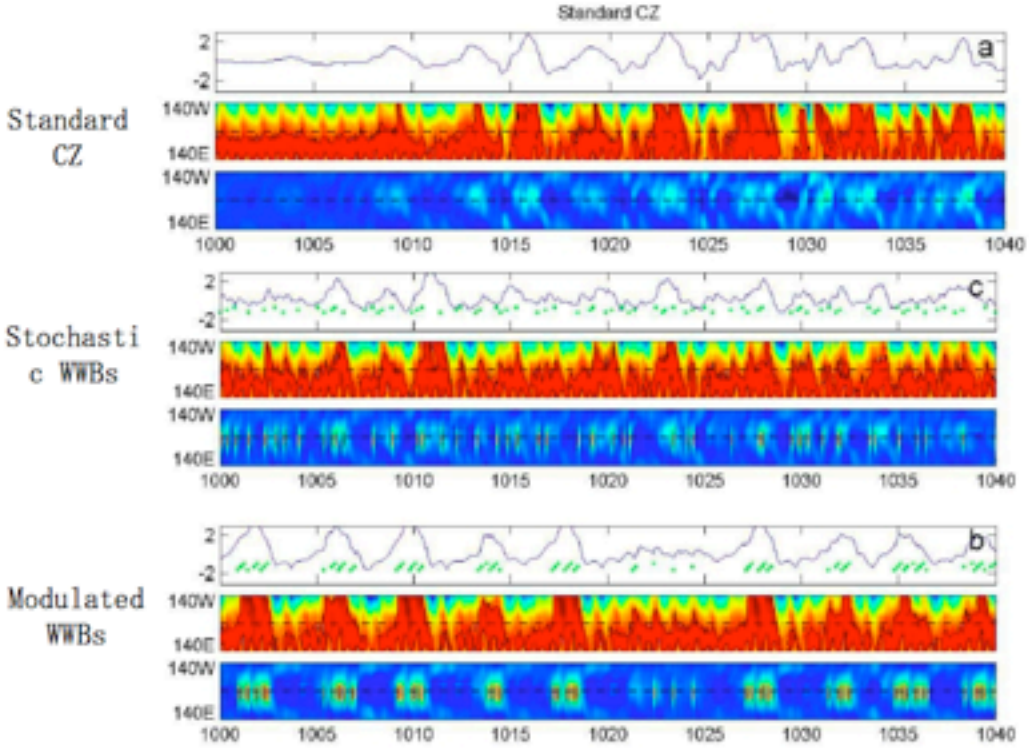
- Biases can affect ENSO
  - Mean state double ITCZ implies split precip. anomalies in response to a monopole SSTA
  - Too extensive cold tongue affects location of precip. anomalies and ENSO period
  - Incorrect annual cycle can affect phase locking (GFDL)
  - Poor simulation of westerly wind bursts (e.g. dependence on SST) can degrade ENSO simulation
    - Parameterized WWBs improve ECMWF predictions
  - Little understanding of why ENSO amplitude varies from weak to strong in various models.
- Poor annual cycle of SST in E. Pac may result from too strong dynamical influence

Westerly Wind Bursts (Tziperman)

Zonal winds and warm pool extension

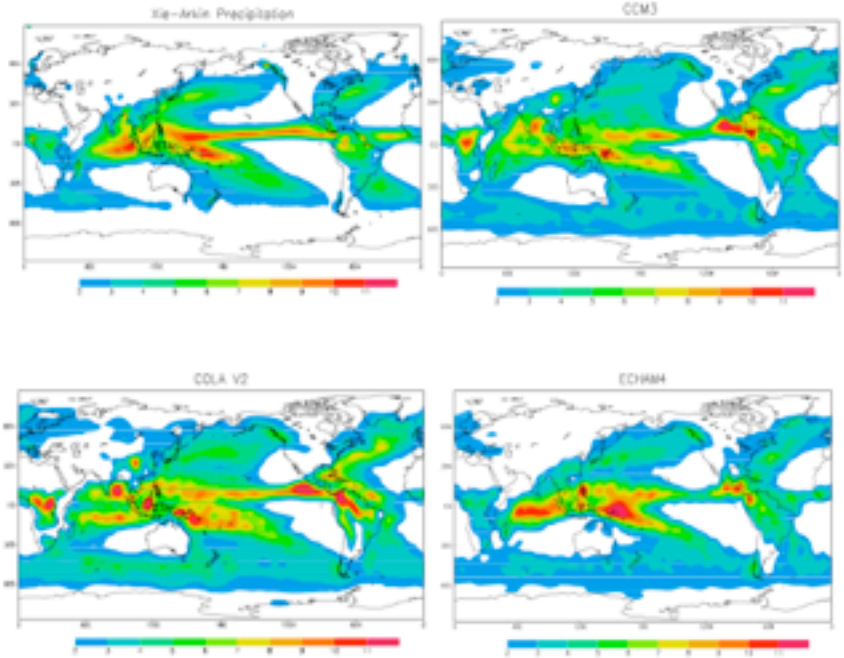


Results: stochastic vs modulated WWBs

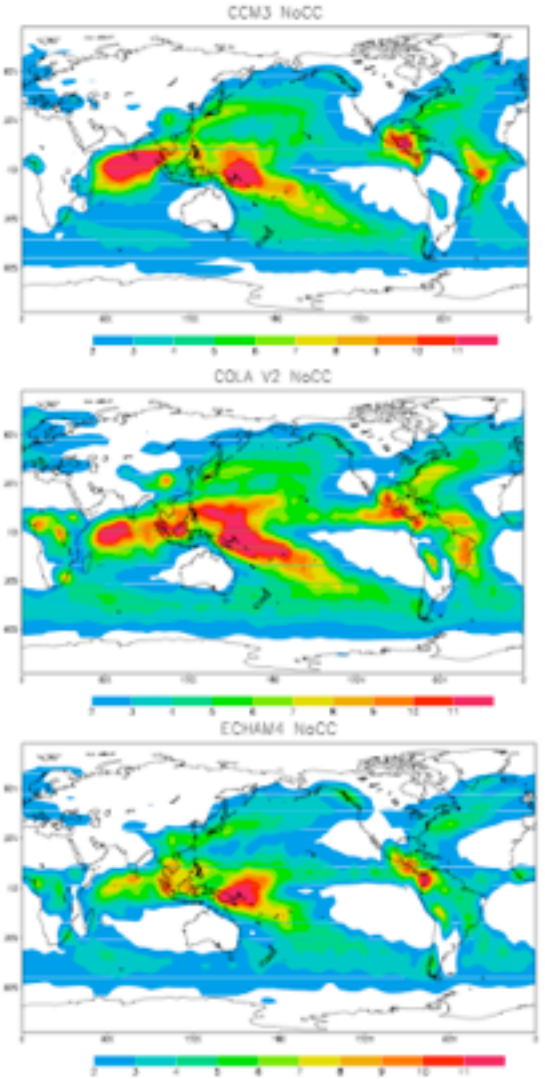


No Convection AGCM Experiments (Schneider)

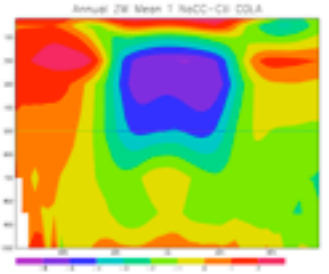
Annual Mean Precip



No Convection

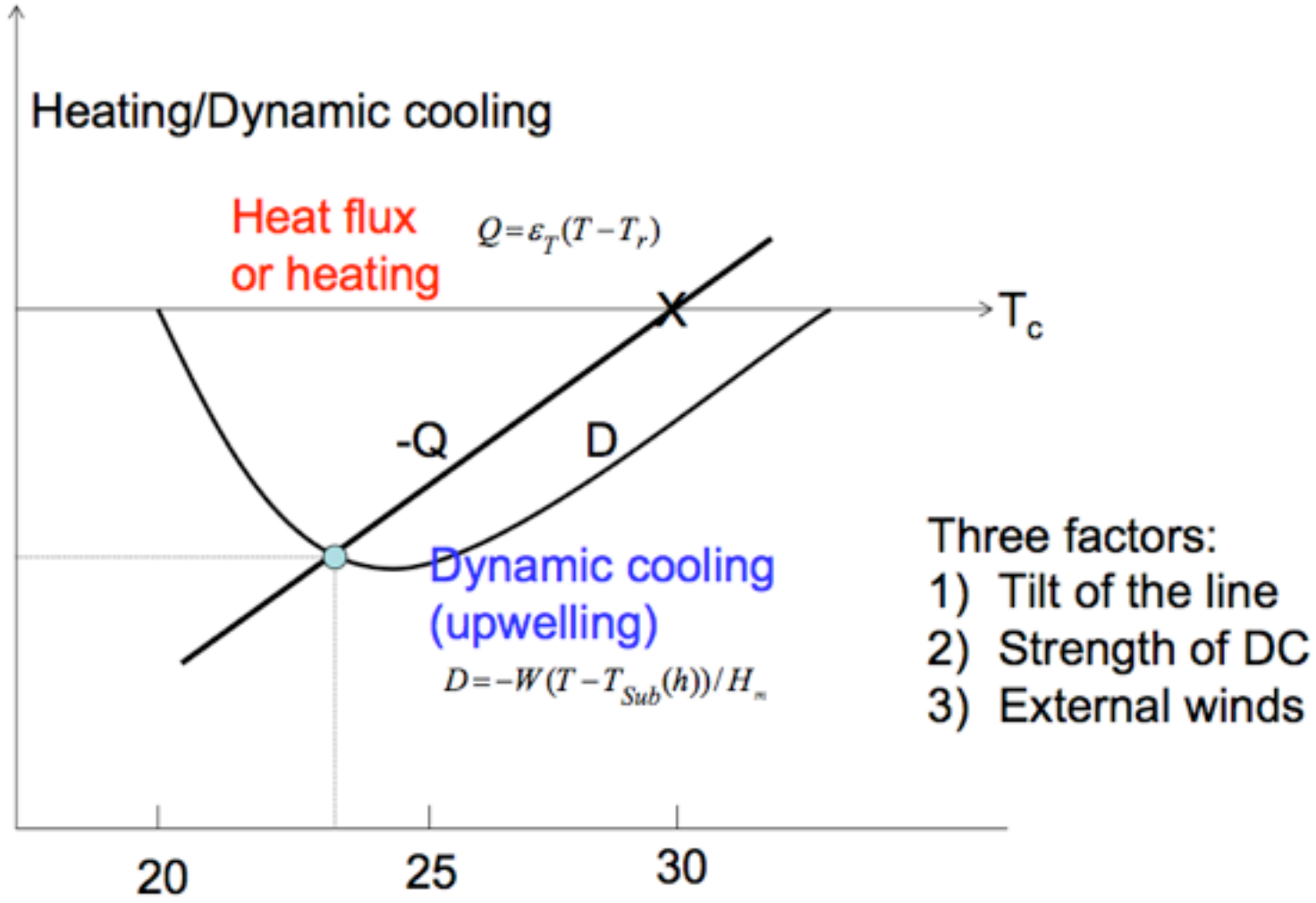


COLA Annual Zonal Mean T



Maintenance of the Cold Tongue Temperature (Jin)

A simple model for cold tongue temperature (Jin 1998)

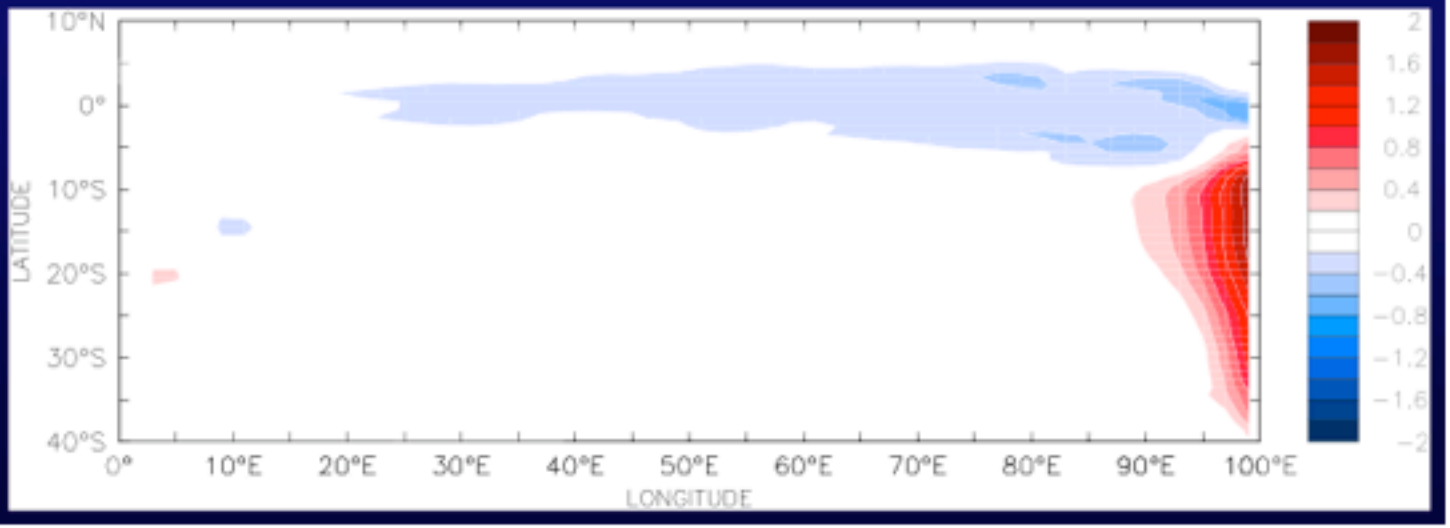


Three factors:
1) Tilt of the line
2) Strength of DC
3) External winds

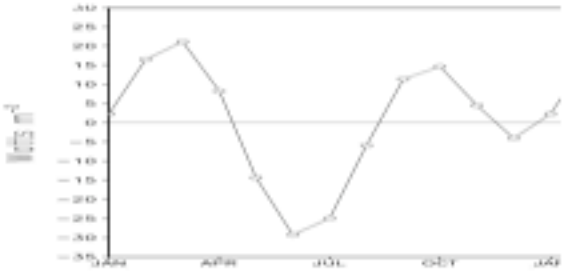
Upwelling Temperature, Thermocline Structure, and Background Diffusivity (Furue)

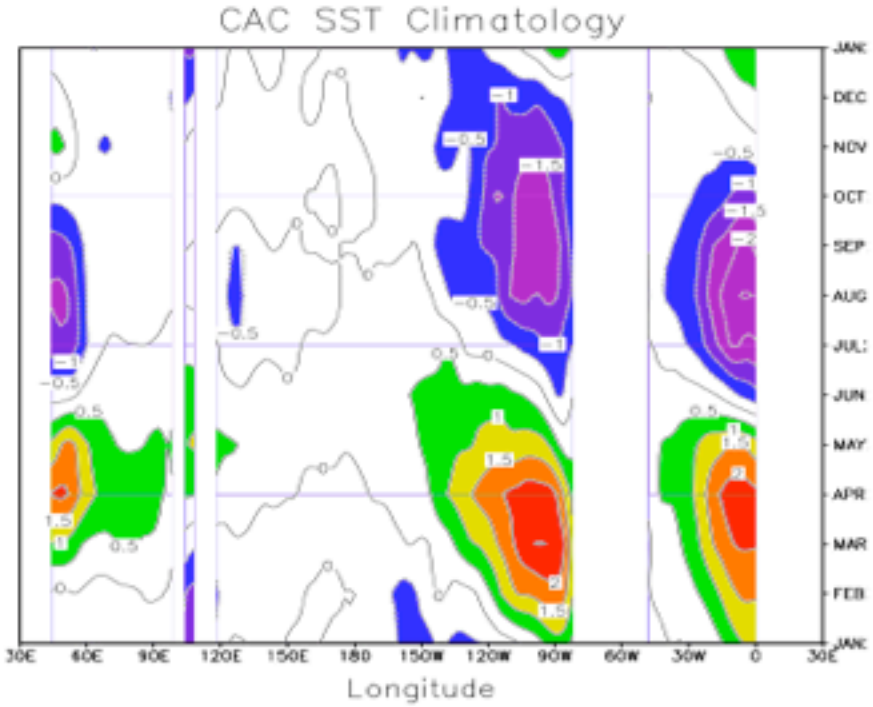
κ_b: vertical diffusivity [$cm^2\ s^{-1}$]

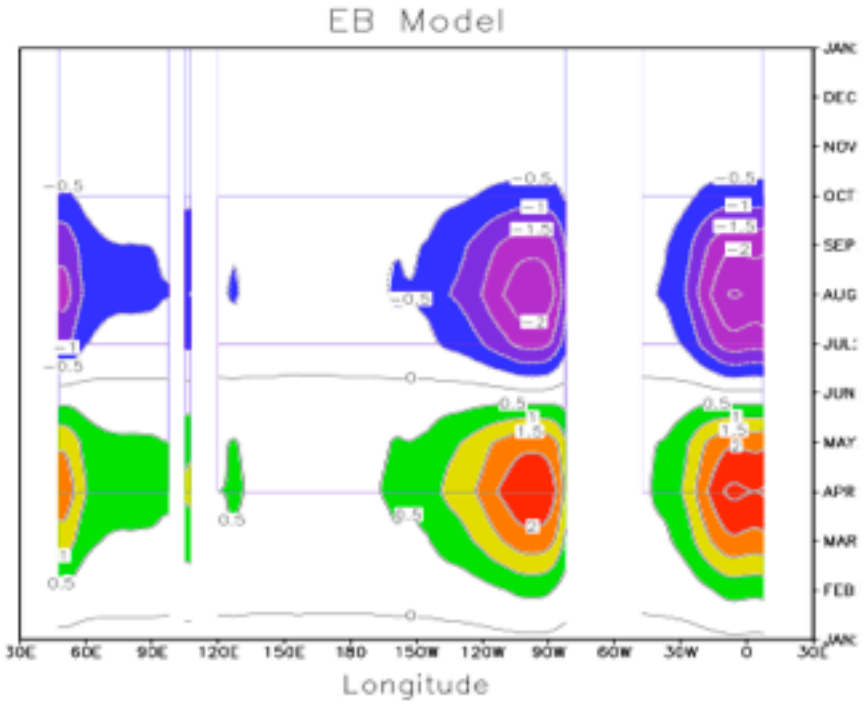
SST difference:
(κ_b = 0.1 run) minus (κ_b = 0 run)



Annual Cycle of SST at Equator Produced by Solar Forcing in Slab Atm/Ocean EBM (Schneider)







Calverton Principles

- Biases in the eastern and western Pacific probably have different causes and will require different cures.
- Coupled experiments at an early stage are crucial.
- Biases in the mean state and annual cycle develop quickly, so only relatively short coupled simulations are necessary to evaluate their sensitivities.

Agreed on Experiments

1. **Add estimated fluxes due to westerly wind bursts to fluxes provided to the ocean in the Western Pacific.**
   Lead: Tziperman
   Participants: CCSM (Large), GFDL (Rosati), Murtugudde, ECMWF(Balmaseda)
2. **Explore sensitivity of AGCM and coupled simulations of the ITCZ/SPCZ to rainfall re-evaporation.**
   Lead: GMAO (Bacmeister)
   Participants: COLA (Kirtman), CCSM (Rasch), GFDL (Rosati), PCMDI (Potter)
3. **"Correct" the temperature of upwelling waters in the ocean in coupled simulations.**
   3a) Equatorial Pacific (away from coasts)
   Lead: Schopf/Klinger
   Participants: CCSM (Danabasoglu), IPRC (Richards), GFDL (Wittenberg)
   3b) Equatorial Pacific near S. American coast
   Lead: Schopf/Klinger
   Participants: CCSM (Danabasoglu), GISS (Sun), IPRC (Richards)
4. **Suppress deep convection in regions of incorrect double ITCZ (SE Pacific).**
   Lead: CCSM (Bretherton)
   Participants: IPRC (Wang), COLA (Schneider), GMAO (Bacmeister)
5. **Increase low level (below 500m) vertical resolution in AGCM.**
   Lead: GFDL/CCSM (Rosati/Rasch)
   Participants: NCEP (Pan), ECMWF (Balmaseda), GMAO (Bacmeister), COLA (Misra)
6. **Examine AGCM response to warming of the tropical troposphere (without corresponding surface warming).**
   Lead: Neelin
   Participants: GMAO (Bacmeister, Suarez), CCSM (Rasch), IPRC (Richards), GFDL (?)
7. **Relate specific initial errors in AGCM/CGCM simulations to biases.**
   Lead: GMAO (Suarez)
   Participants: NCAR (?), IPRC (Potter), GFDL (Rosati), NCEP (Pan)
8. **Diagnostics**

Breckenridge Meeting

- Recognize tropical bias results presented at CCSM workshop
- Results from agreed-on experiments
- New material

Short Summary of Bias Discussion at CCSM Workshop

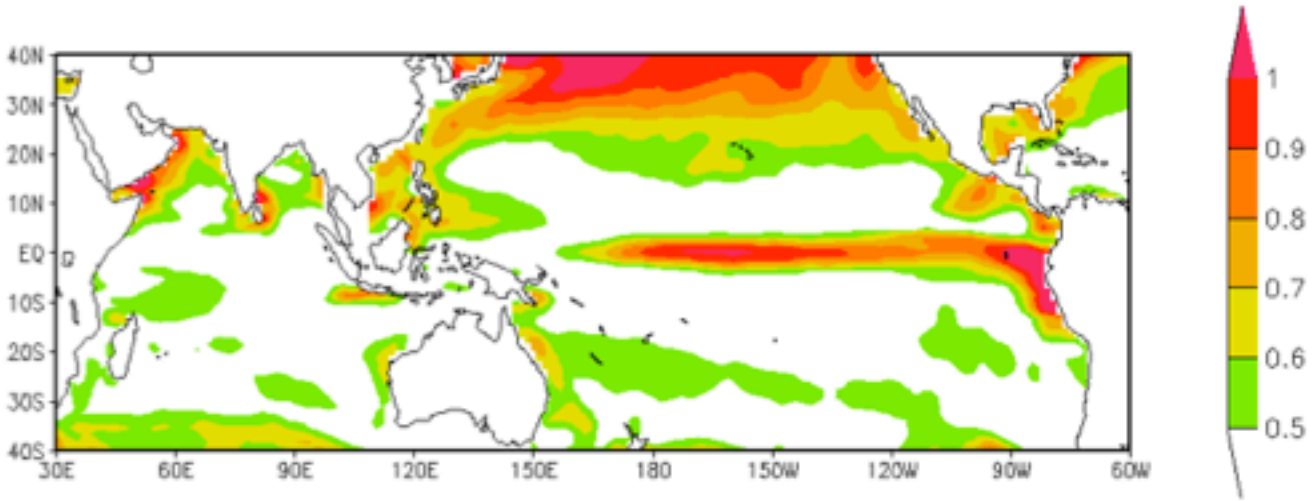
- Cumulus momentum transport produces positive effect (3 speakers)
- Better resolution needed in upper ocean when biology/sunlight coupling included
- Improve ocean by eliminating Smagorinsky horizontal diffusion
- Zonal wind stress needs to be improved
  - Rainfall reevaporation
  - Increase boundary layer height (contradictory results)
  - Better resolution PBL
  - Higher (x 20) horizontal viscosity in atmosphere (impressive improvements)
- Dilute ascent moist convection

Reports on Experiments and Diagnostics Agreed on at the Previous Meeting

1. Westerly wind bursts
   - Ben Kirtman (presented by Schneider)
2. Rainfall reevaporation
   - CCSM (described at CCSM Workshop)
   - Julio Bacmeister (presented by Schneider)
3. Ocean upwelling temperature
   - Paul Schopf et al. (presented by Schneider)
4. Improve mean precipitation distribution
   - CCSM (described at CCSM Workshop)
   - Ed Schneider and Ben Kirtman
5. Better low level resolution in AGCM
   - CCSM (described at CCSM Workshop)
6. Tropospheric but not surface warming
7. Diagnosis of biases from initial errors
8. Diagnostics
   - Matt Wyant et al. (convective heating distribution)
   - Ed Schneider (surface fluxes)

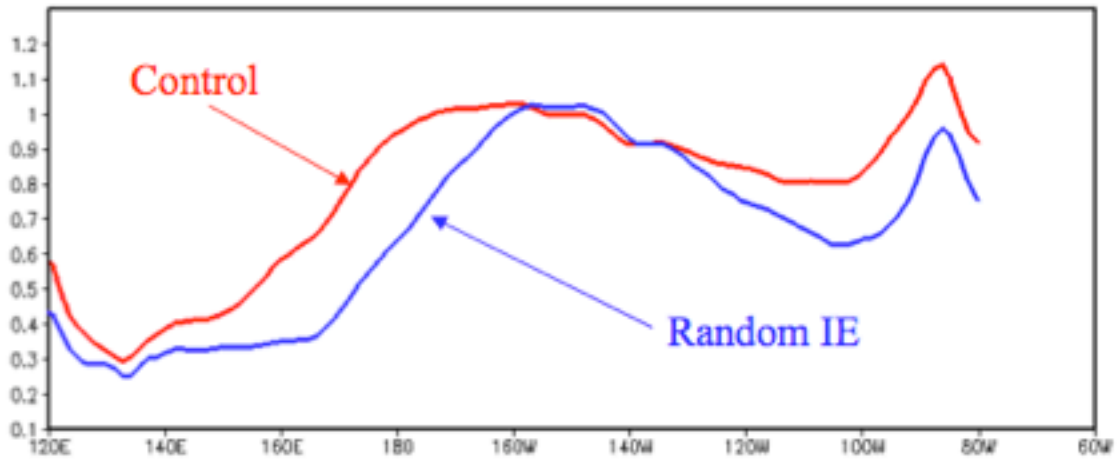
Excessive Westward Extension of ENSO Events

Control SST
Standard Deviation

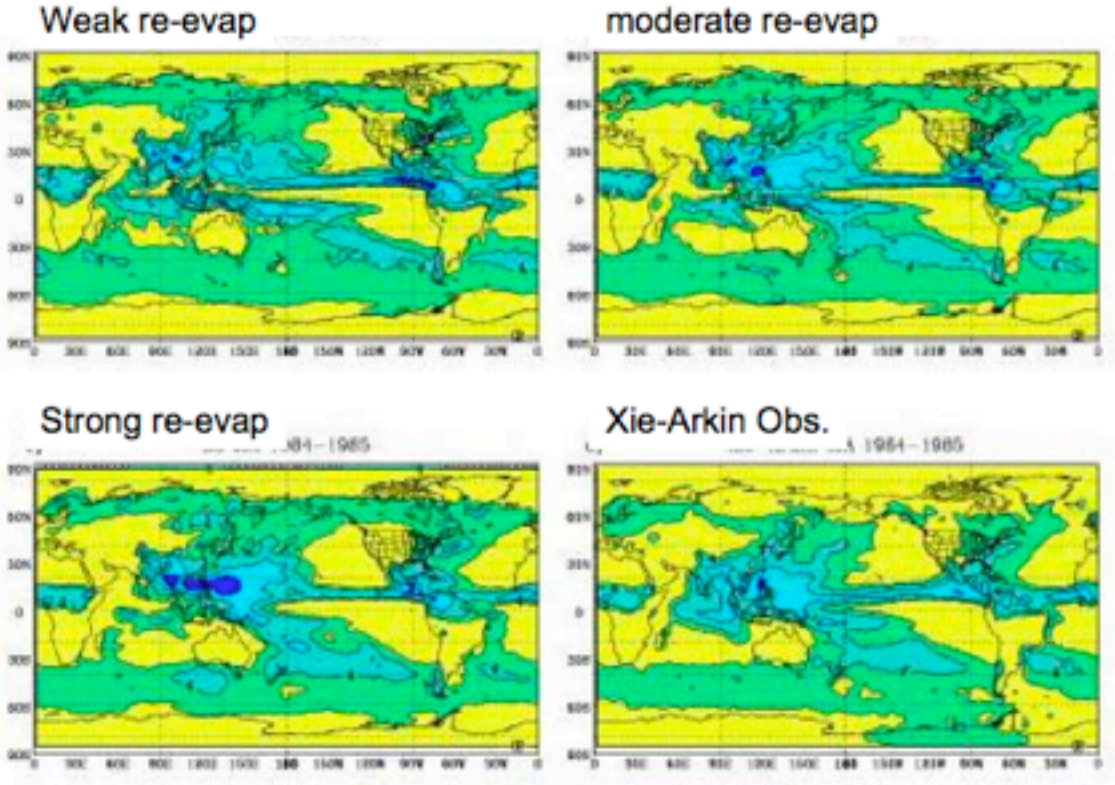


De-correlating Noise Statistics

Equatorial Pacific
SST Standard
Deviation



Kirtman



Mean precipitation for June-July-August (JJA) 1984-85 from 3 simulations compared with observations.

Strengthening parameterized rain-revaporation in the NSIPP/GMAO AGCM leads to reduction in the model's "double-ITCZ" bias.

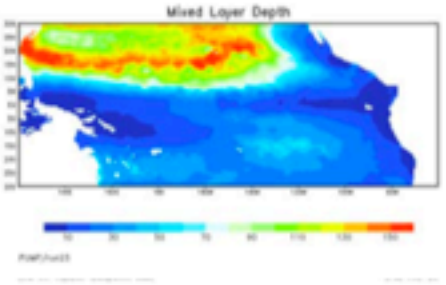
How does reevaporation eliminate the southern ITCZ?

Why doesn't it also eliminate the northern ITCZ?

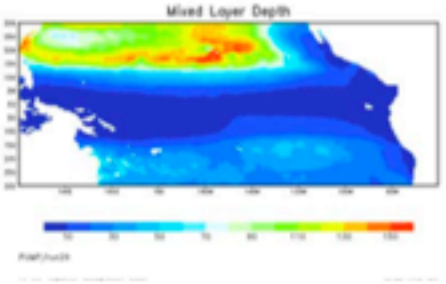
Bacmeister

Boreal Winter MLD

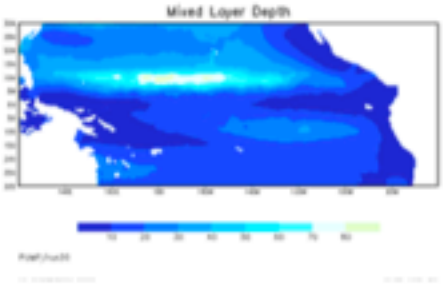
Lo dissip all



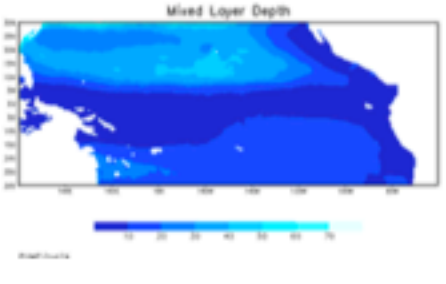
Lo dissip off eq



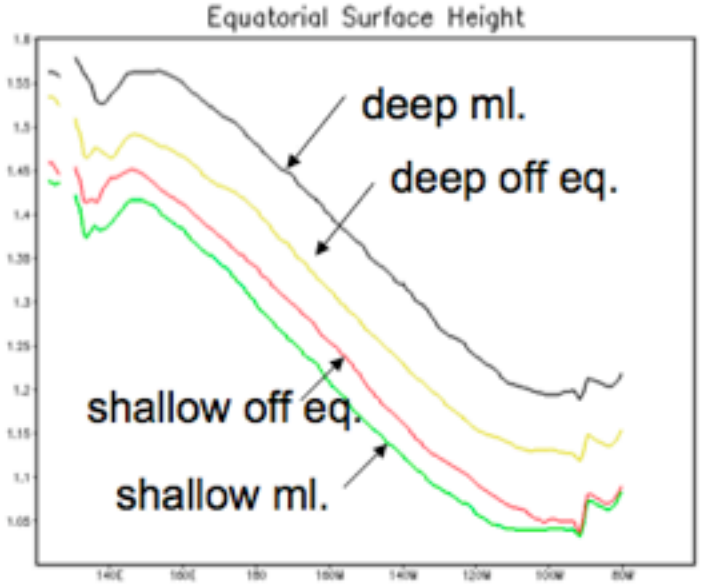
Hi dissip off eq



Hi dissip all

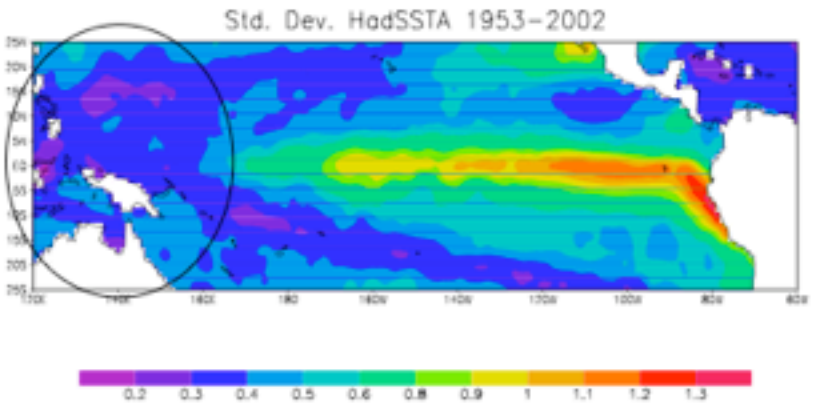


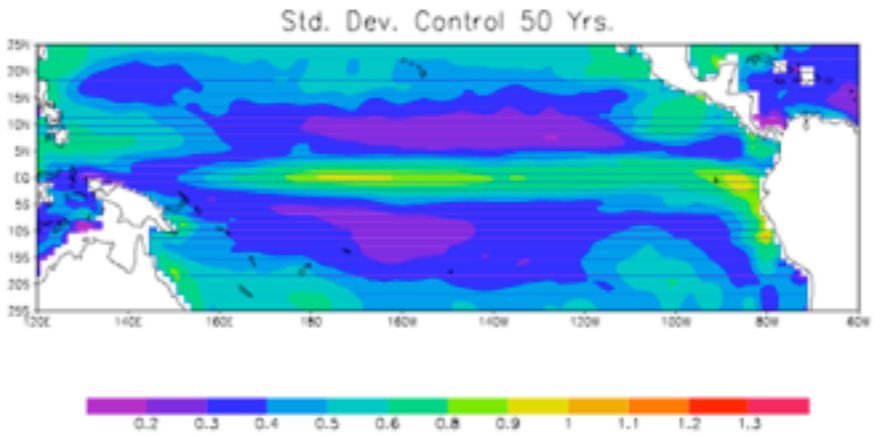
Deeper mixed layers near WBL bifurcation lead to warmer waters entering the STC to upwell at eq.

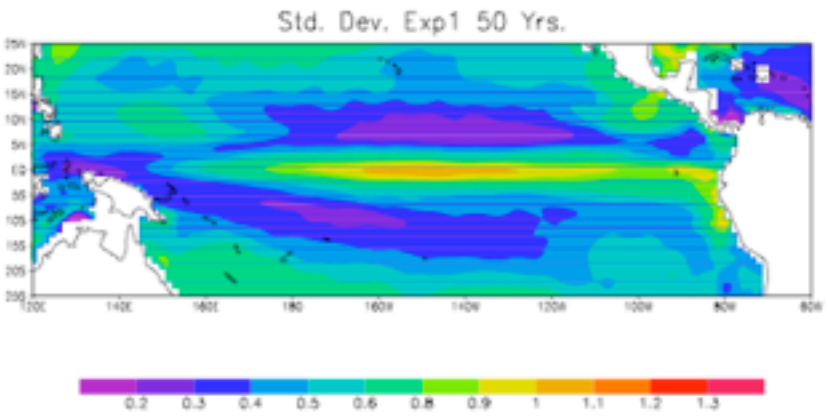


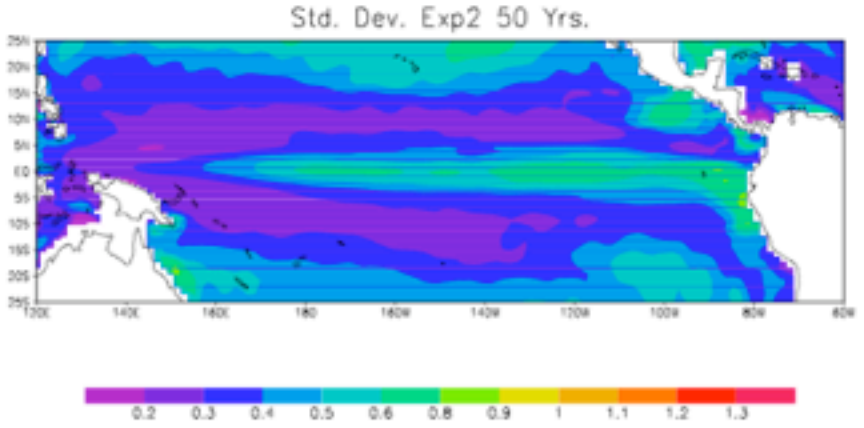
Results also show more heat transport by ocean with deeper mixed layers, loss of TIWs with shallow MLs

Schopf



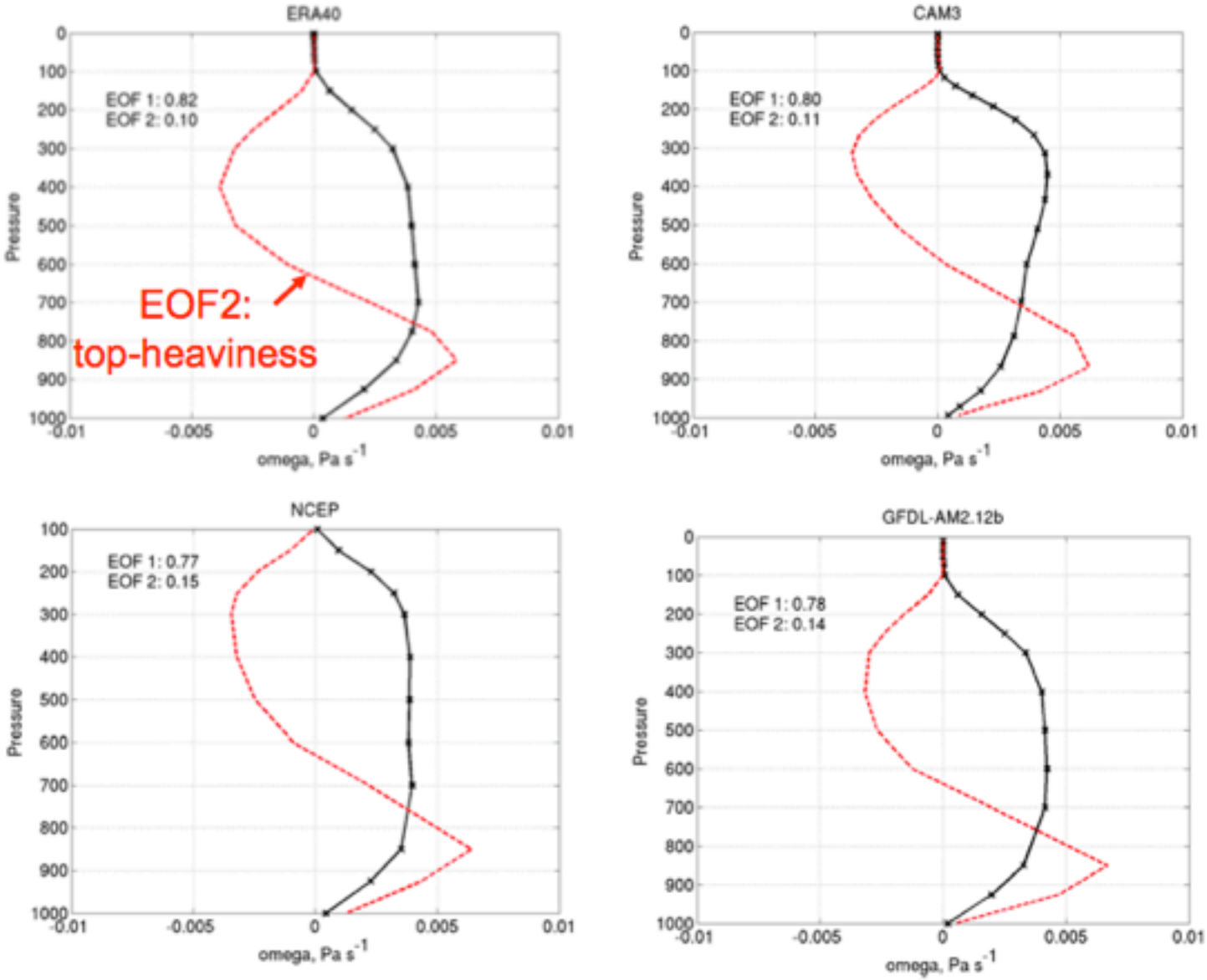






Schneider and Kirtman: Introduce SST Correction

EOFs 1 and 2 explain 92% of variance



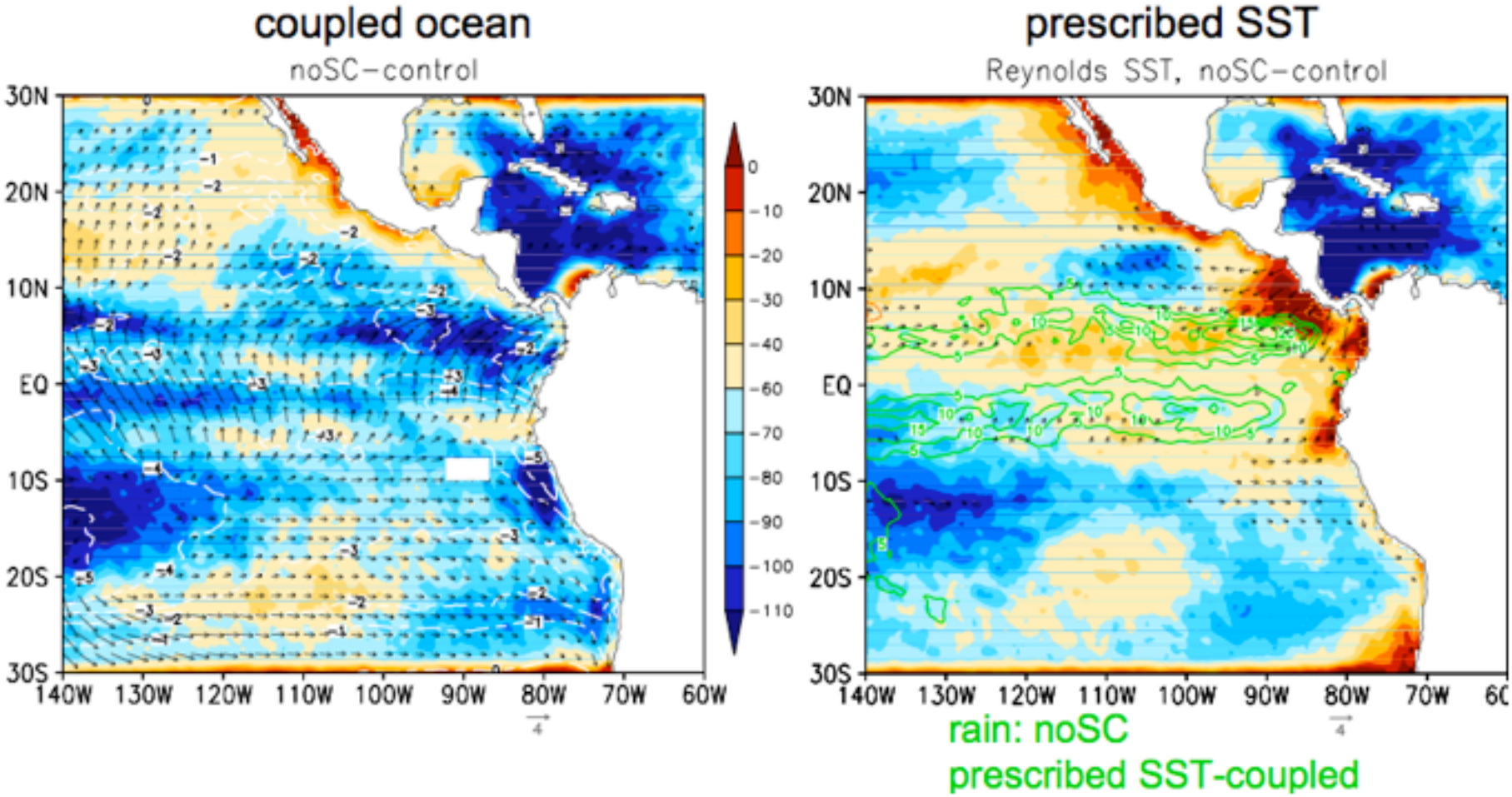
Wyant: Vertical structure of convective heating

Talks describing other topics

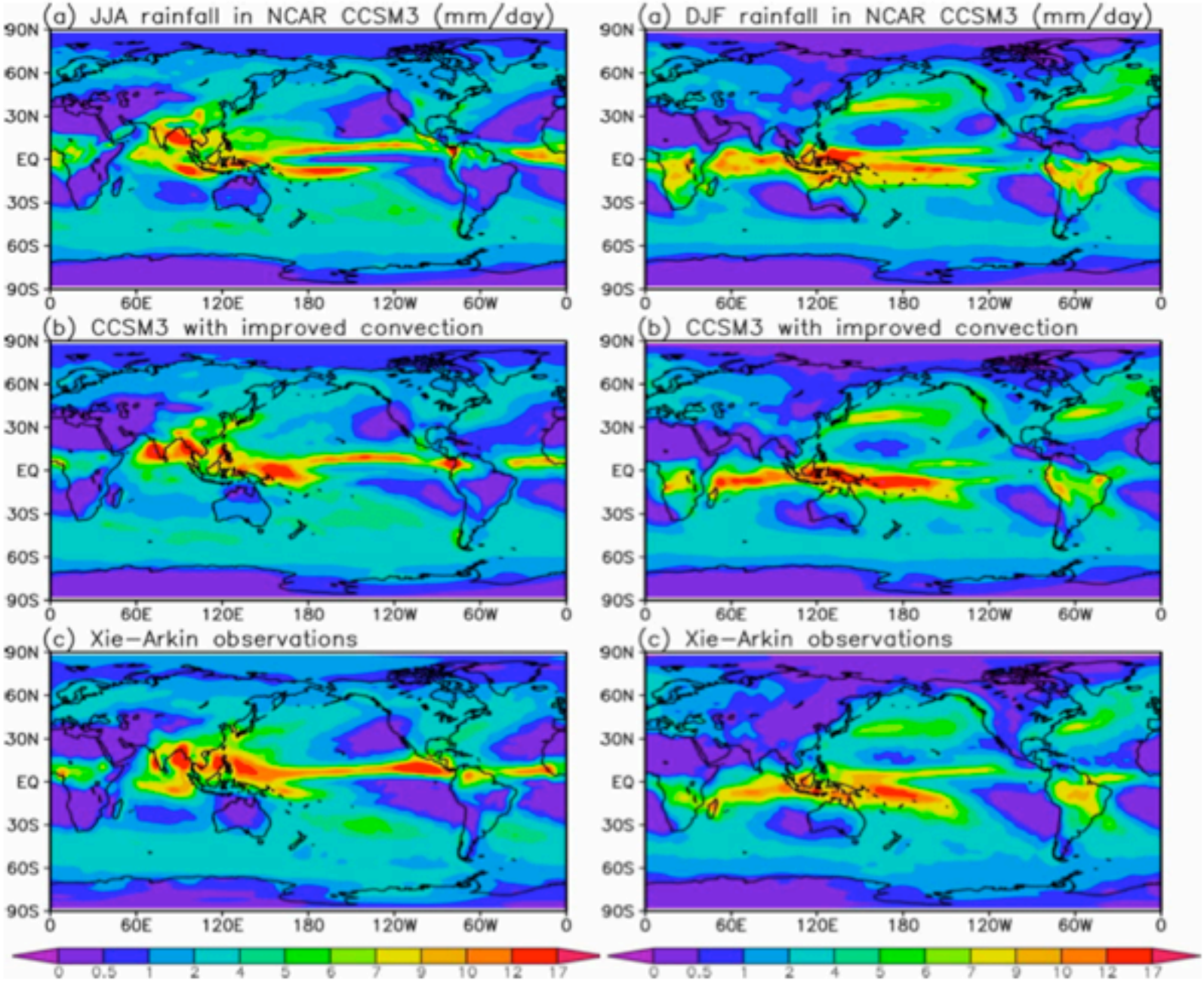
1. **Radiative/shallow convection feedbacks**
   - Simon de Szoeke
2. **Parameterization of convective heat and moisture fluxes**
   - Guang Zhang new heating closure
   - Xiaoqing Wu convective momentum transport
3. **Sunlight penetration**
   - Zhengu Liu
4. **Decoupled Indian Ocean with CCSM3**
   - Jin-Yi Yu (presented by Schneider)

Removing shallow cumulus convection (noSC) changes radiative forcing (W m^{-2}, color), SST, and winds dramatically in the coupled model; less so with prescribed SST.

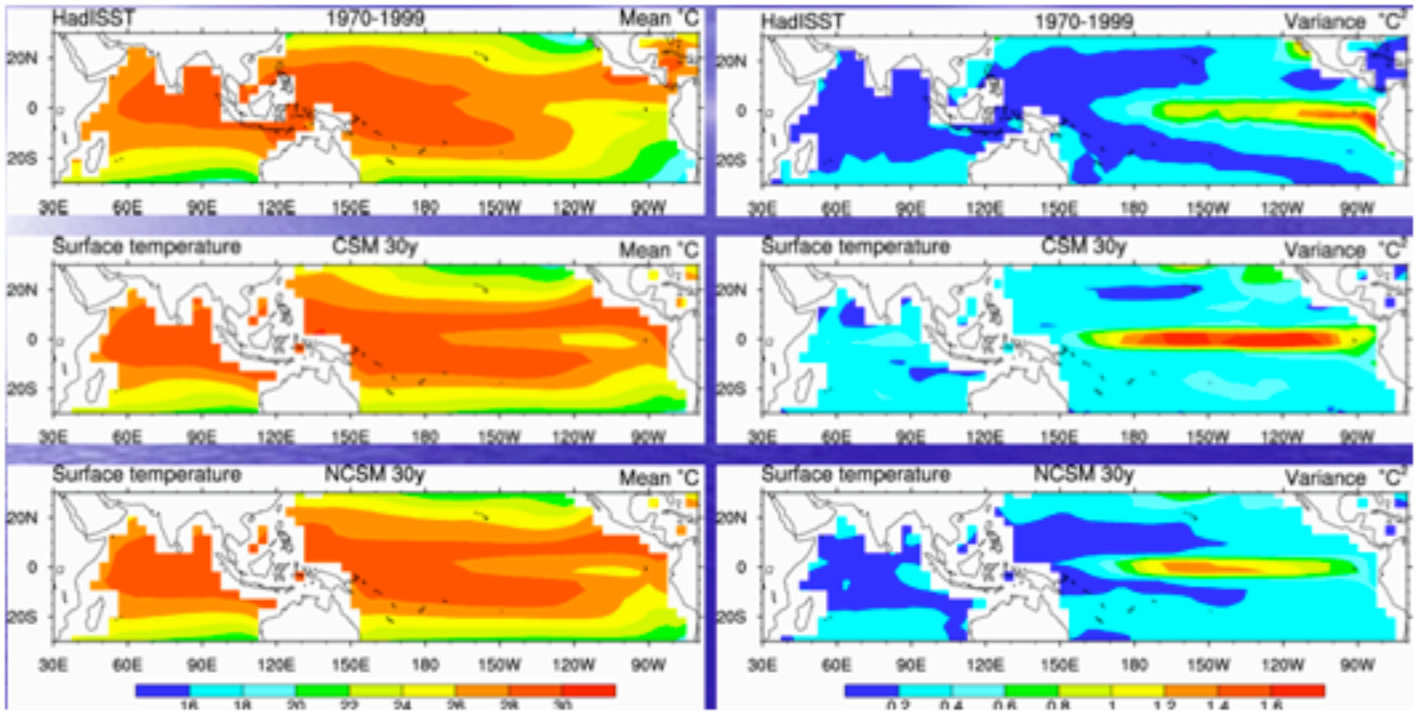
April differences

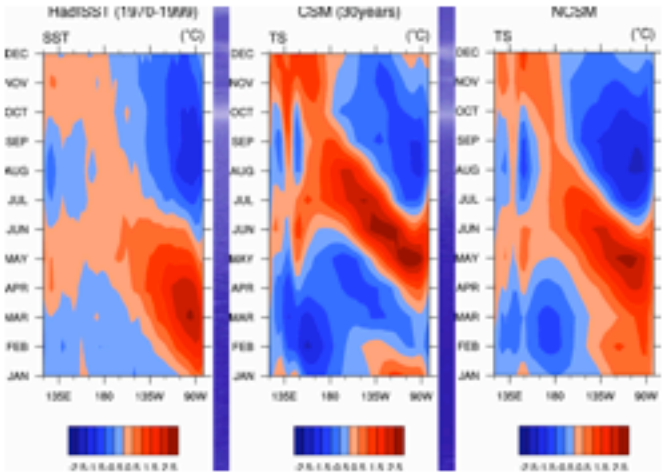


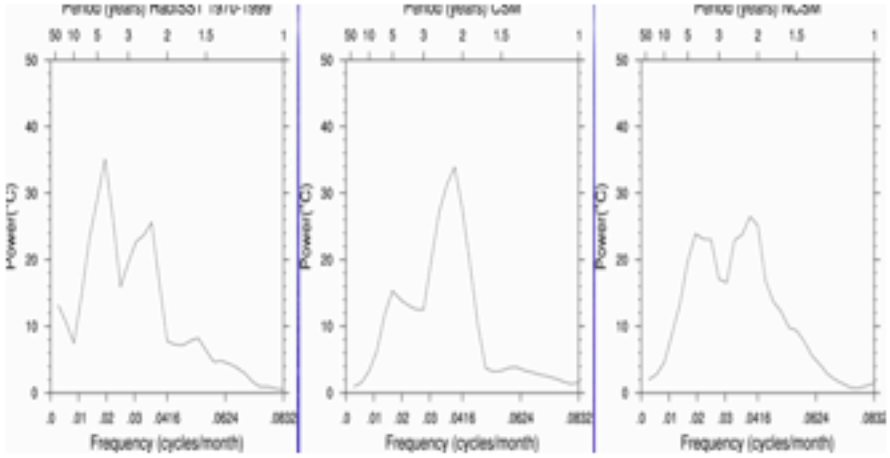
De Szoeke: regional coupled model


(a) JJA rainfall in NCAR CCSM3 (mm/day)
(a) DJF rainfall in NCAR CCSM3 (mm/day)
(b) CCSM3 with improved convection
(b) CCSM3 with improved convection
(c) Xie–Arkin observations
(c) Xie–Arkin observations
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0 0.5 1 2 4 5 6 7 9 10 12 17

Zhang







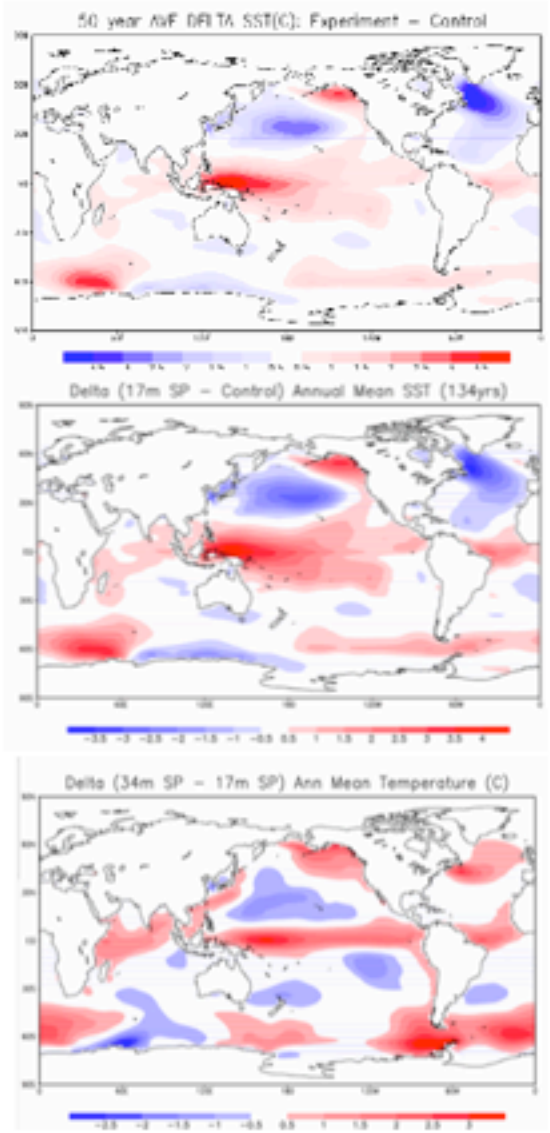
Wu: CCSM3 new closure, trigger, cmt

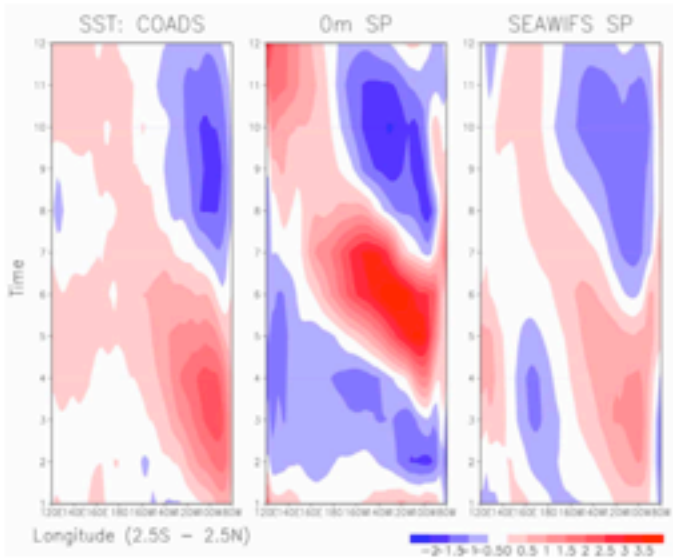
SST Changes

SeaWiFs - 0 m

17m - 0 m

34m - 17 m

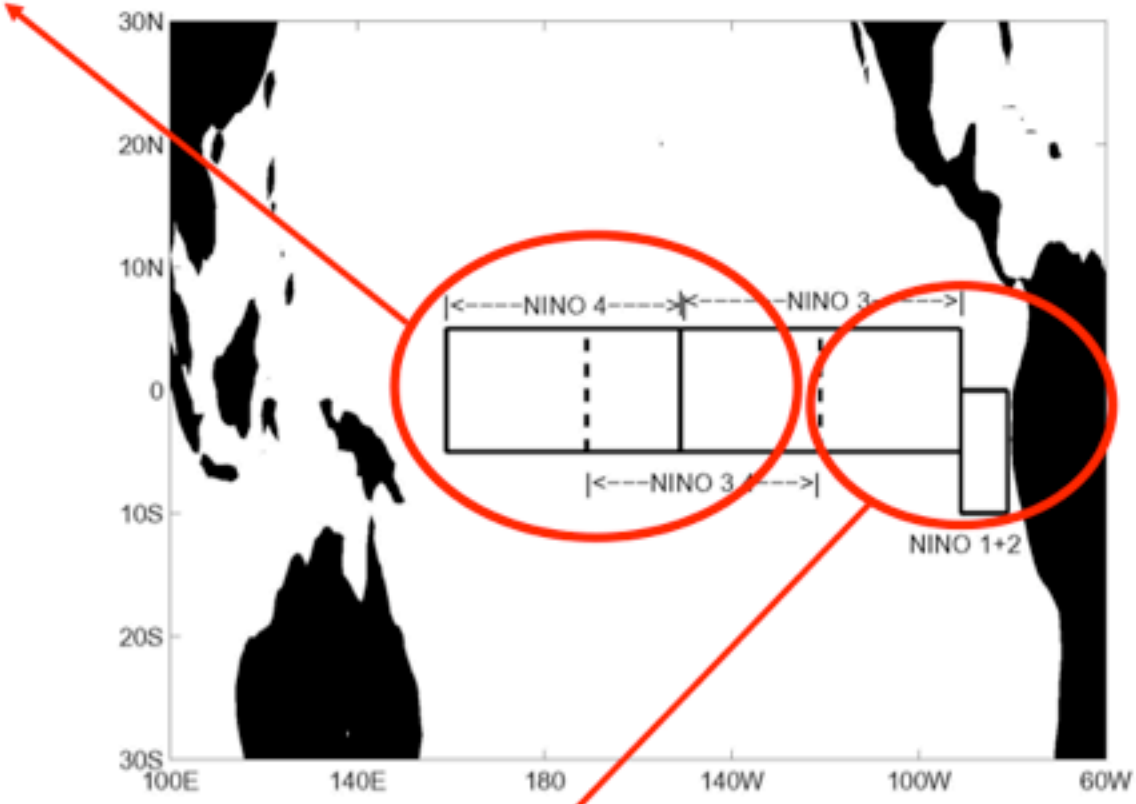




Liu: R15 FOAM sensitivity to sunlight penetration (counterintuitive - deeper penetration does not necessarily lead to cooling)

Two-Oscillator View of ENSO

Central Pacific Oscillator (forced by Indian Ocean-monsoon)

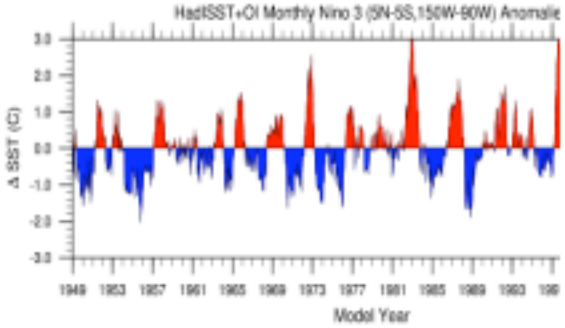


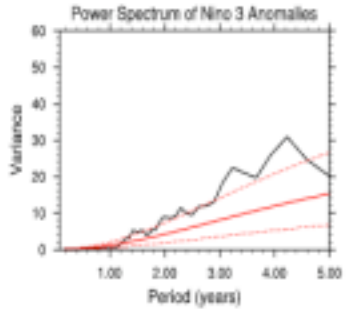
Eastern Pacific Oscillator (Onset controlled by thermocline depth)

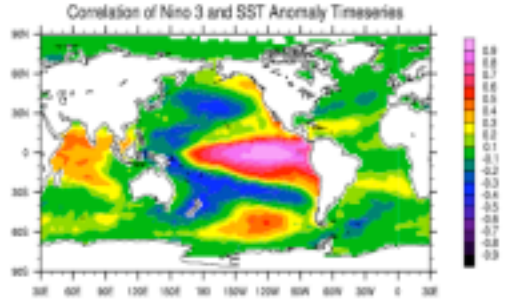
Yu

Post-Meeting Advances in CCSM3 (Pictures Courtesy of Peter Gent)

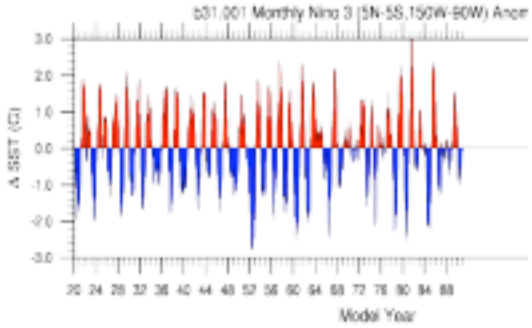
HadSST

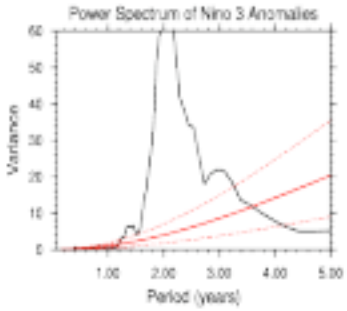


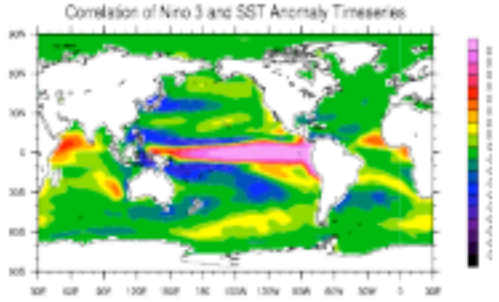




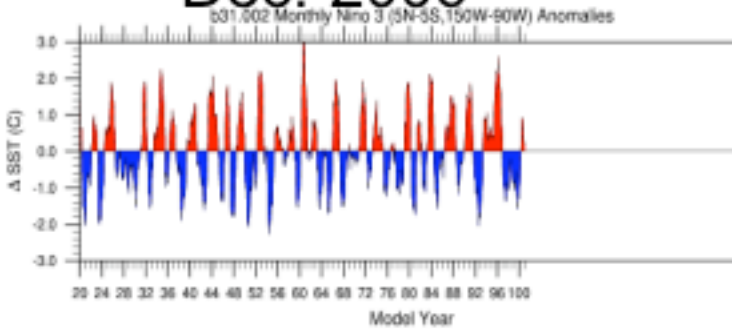
CCSM3 old

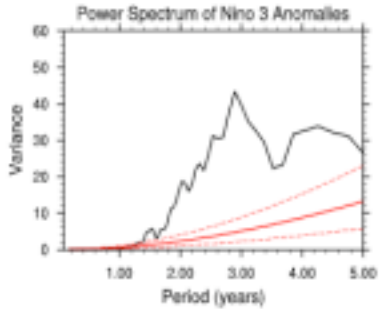


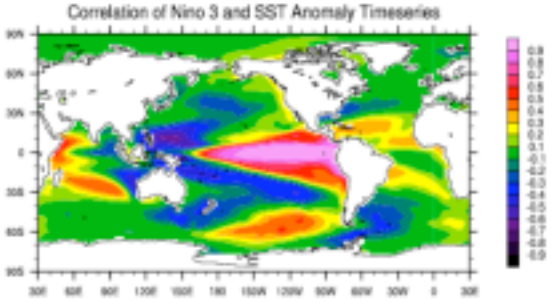




CCSM3 new (circa Dec. 2006







Summary of Results

- Are tropical biases due to inadequacies in the ocean or the atmosphere?
  - Support for both views
  - Certainly part of the problem is in the atmosphere, probably convection parameterization
  - Ocean is still a suspect (as is land)
- Each model appears to have unique problems and sensitivities to parameterization changes
  - The approach of our group, to focus on reducing specific related biases in a single model at a time, may have the best chance for success

Comments on the Process

- The connection between theoretical understanding of coupled tropical climate from simpler models and useful mechanistic experiments with CGCMs was not really made.
- The closest anyone came to this was Ed Sarachik with his introductory comments.
- Problem appears to be that the theory is not sufficiently well developed to make contact with the CGCMs.

My Personal Recommendations

- Keep trying hypothesis-driven approach
- Success will require better coordination between theoretical, diagnostic/mechanistic and CGCM modeling activities (*multi-scale intellectual interactions*)
- Restricting focus to a single bias syndrome and a single model (at a time) is the best way to help all models improve