The Roles Of Air-Sea Coupling and Atmospheric Weather Noise in Tropical Low Frequency Variability

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- What is the role of atmosphere-ocean coupling in climate simulations and predictions?
  - Investigate by comparing CGCM and AGCM simulations.

Some of the Results That Motivate This Work

1. An AGCM forced by observed SST does not reproduce the observed SST forced climate statistics (e.g. ENSO-monsoon).
2. A CGCM does not have the same climate statistics as the AGCM component of that CGCM forced by the CGCM SST.

Examples

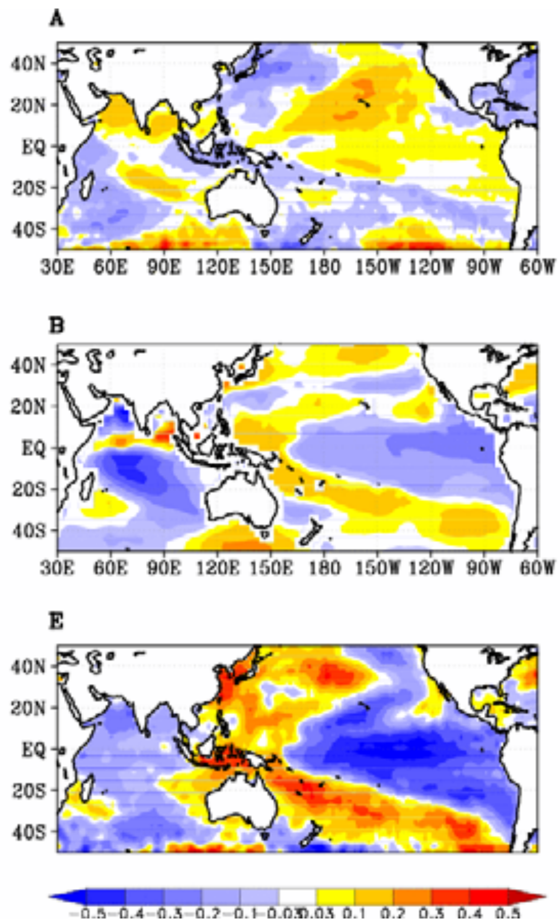
- Kumar et al. 2005, *GRL*
- Copsey et al. 2006, *GRL*

Kumar et al. 2005

AGCM+Obs SST

Pacemaker

Obs



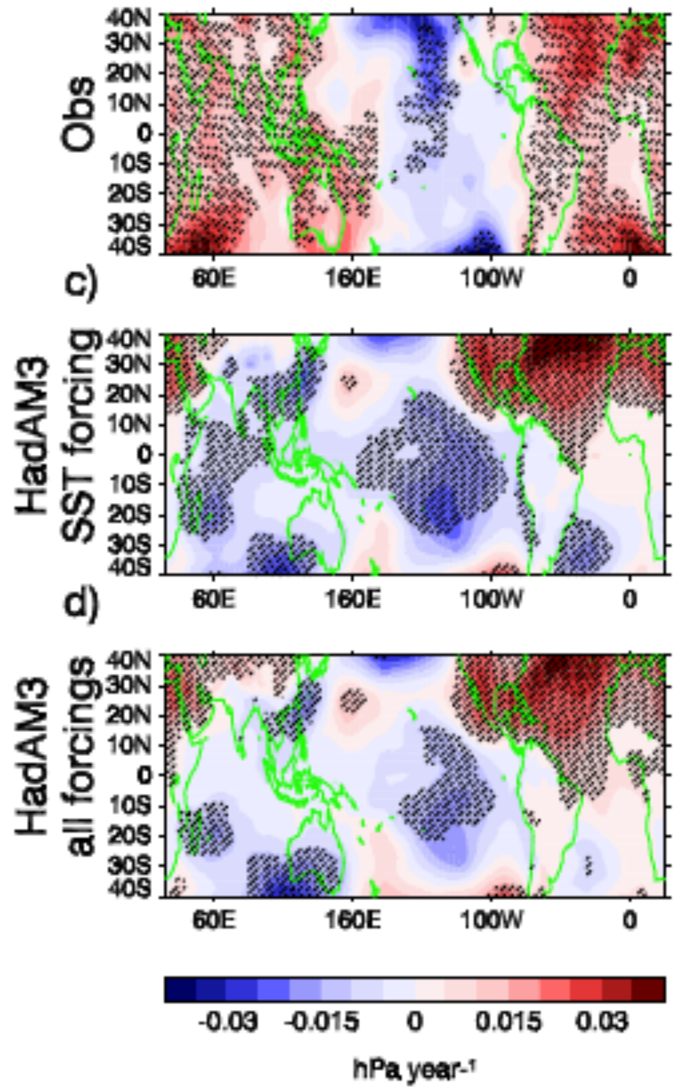
Simultaneous Correlations of IMR and SST

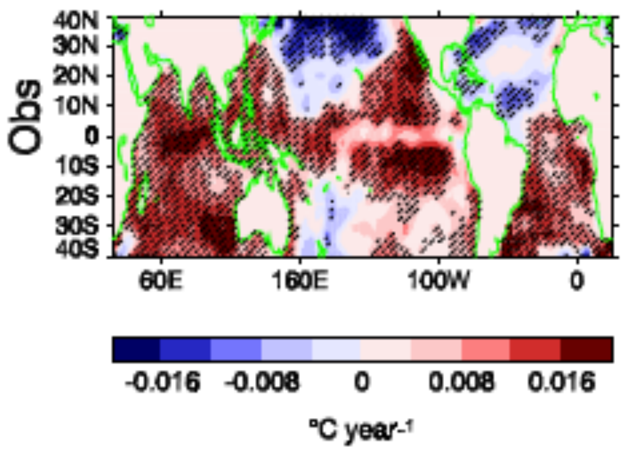
Copsey et al. 2006

Trends 1950-1996

SST observed (below)

SLP observed and simulated (right)





Possible Explanations

1. Coupled and uncoupled systems have intrinsically different SST forced responses.
2. Coupled and uncoupled system have the same SST forced response, except for model bias.
   – SST forced response would be the same in a perfect model framework.
   – Coupled and uncoupled system will differ due to the role of weather noise.

Weather Noise and SST

- Hasselmann (1976)
  - Null hypothesis for climate variability: SST variability is forced by weather noise.
- Barsugli and Battisti (1998)
  - Where SST is forced by weather noise, the weather noise is related to SST in CGCM but not AGCM.

Eliminate Model Bias: Perfect AMIP Experiment

- CCSM3 CGCM
  - 100 year current climate control simulation named **CONTROL**
  - T42 26 level atmosphere CAM3
  - Constant external forcing (GHG, solar, volcanic)
- CAM3 AGCM
  - Same AGCM as in **CONTROL**
  - 6 member ensemble of simulations, with each member forced by the same time-varying SST from **CONTROL**

References

- Chen, H., E. K. Schneider, B. P. Kirtman, and I. Colfescu, 2013: Evaluation of weather noise and its role in climate model simulations. *J. Climate*, **26**, 3766-3784, DOI: 10.1175/JCLI-D-12-00292.1.

- Colfescu, I., E. K. Schneider, and H. Chen, 2013: Consistency of 20th century sea level pressure trends as simulated by a coupled and uncoupled GCM. *Geophys. Res. Lett.*, **40**, 3276-3280, DOI: 10.1002/grl.50545.

- Chen, H. and E. K. Schneider, 2013: Comparison of the SST Forced Responses Between Coupled and Uncoupled Climate Simulations. *J. Climate*, accepted.

Evaluation of SST Forced Response

- For any field, the time-dependent SST forced response is the ensemble mean of the AMIP ensemble.
  - Ensemble mean filters out "weather noise"
  - SST forced response cannot be determined directly from CGCM or any single AGCM ensemble member.

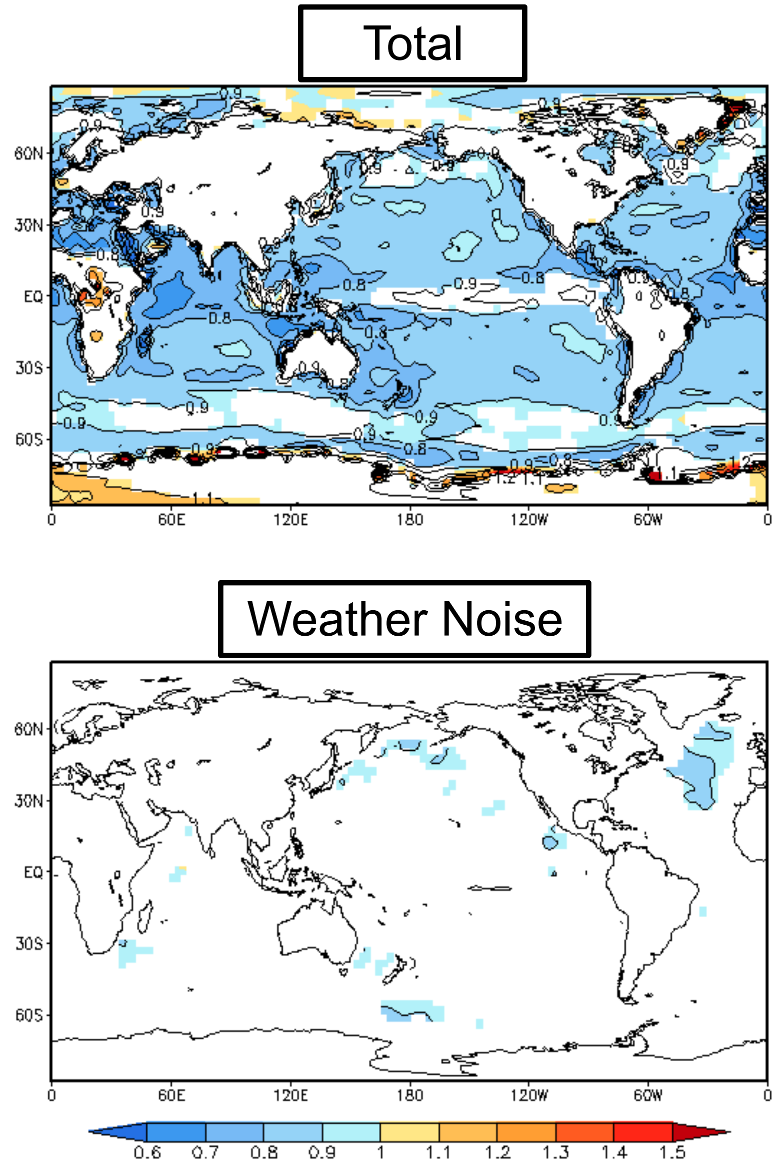
Evaluation of the Weather Noise

- Weather noise (noise in the following) is the residual after the SST forced response is removed.
  - Different noise for each member of the AGCM ensemble and for CGCM.

Compare CGCM and AGCM Statistics

- Ratio of variance CGCM:AGCM
  - Example: net surface heat flux (NHF)
  - Example: precipitation

Ratio of Standard Deviation of Monthly Mean Net Surface Heat Flux Variance CONTROL:AGCM$_i$



<1

≅1

Significance test:

In shaded regions the ratio is different from 1 at the 1% significance level

Explanation

Variance (total) =
    Variance (SST forced)
  + Variance (noise)
  + 2 × Covariance (SST forced, noise)

- **SST Forced variance is identical** in coupled and uncoupled by construction.
- **Noise variance is the same** in coupled and uncoupled.
- Covariance is different:
  - Zero in AGCM, because does not respond to the noise
  - Nonzero in CGCM, because noise forces SST.

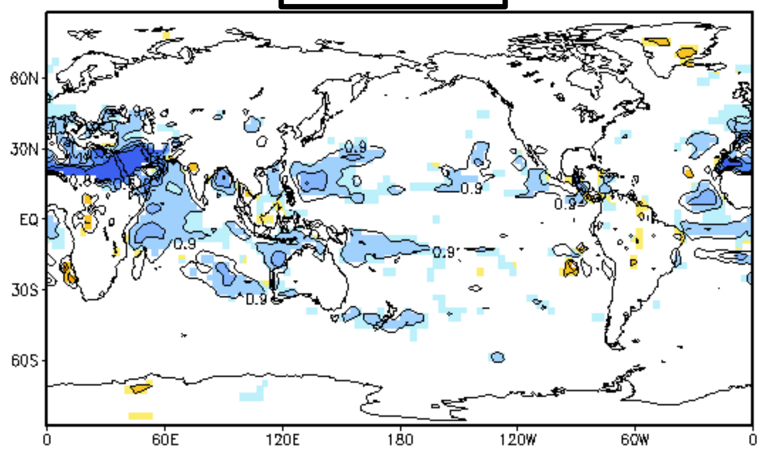
Net Heat Flux Variance Result

- Variance ratio of total NHF ≠1 is evidence that the SST variability is forced at least in part by noise.
- Variance ratio of noise = 1 is evidence that coupling does not affect the weather noise variance.

Ratio of Precipitation Anomaly Standard Deviations CGCM:AGCM

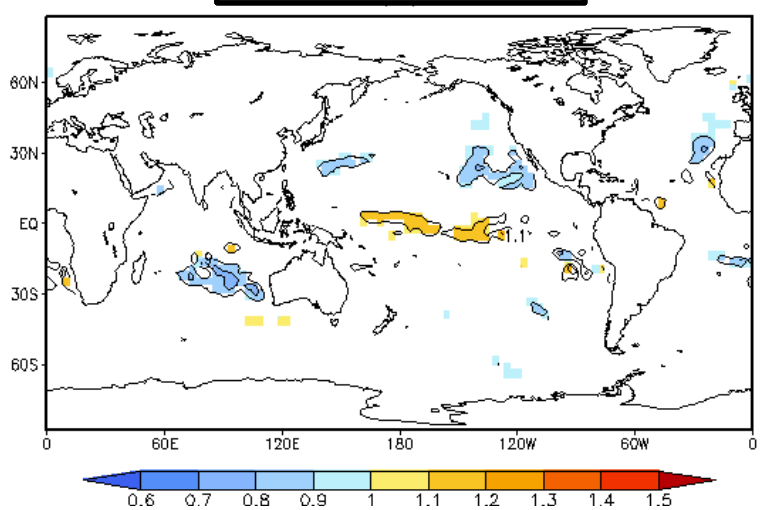
Total

<1



Weather Noise

≅1



Precipitation Statistics

- Uncoupled model produces excessive precipitation variance, mostly in tropical regions because:
    1. SST is the response to noise forcing associated with precipitation noise.
    2. Precipitation in these regions also responds strongly to SST.
  - Using uncoupled models to investigate precipitation extremes in the tropics is probably a bad idea.

How to Compare SST Forced Response in CGCM and AGCM?

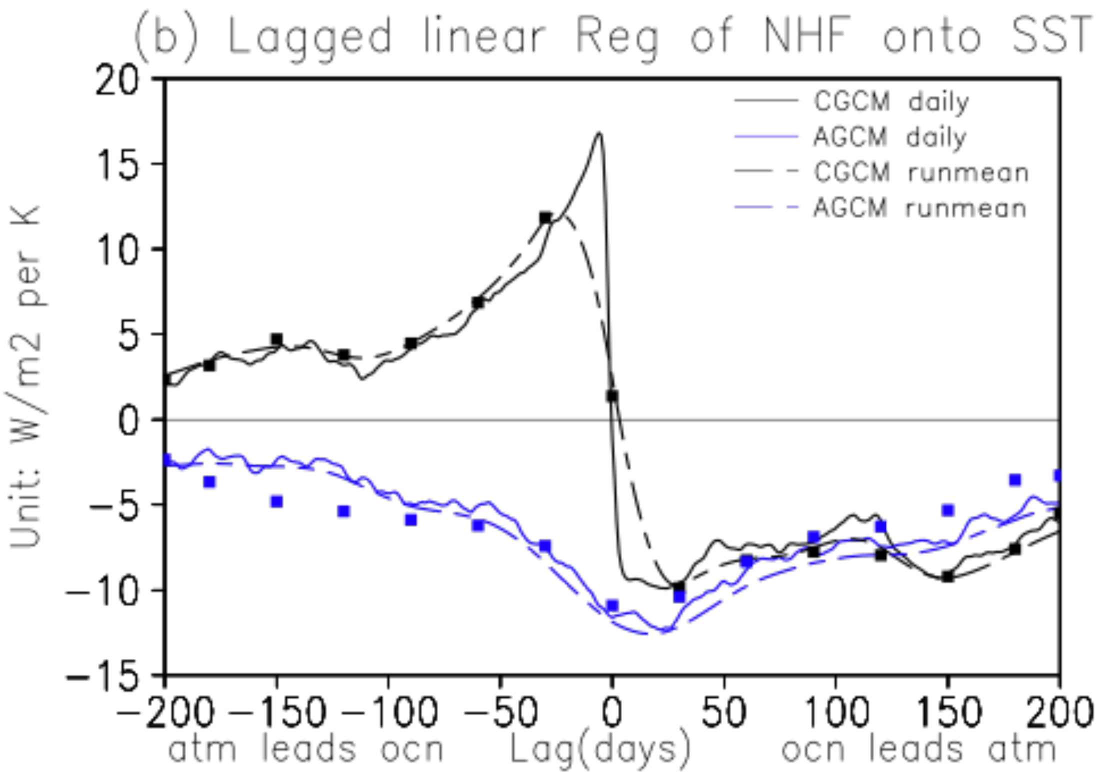
- Questions:
  - Is the SST forced response the same in CGCM and AGCM?
  - Is weather noise forcing the SST?

Test: Compare CGCM and AGCM Time Lagged Regressions

- Compare time lagged regressions between an atmospheric field *F* and SST (e.g. Wang et al. 2005).
  - If SST forced AGCM and CGCM fields are the same, then
    - When SST leads *F*, AGCM and CGCM correlations are the same.
  - If weather noise forcing of the SST is important, then:
    - When *F* leads SST, AGCM and CGCM correlations are different.

- Use indices to isolate teleconnections in the forced response, monthly mean data.

Monthly Mean vs. Daily Lag Regressions of NHF/SST in the AMV Region



Appendix

Here, we present a mathematical framework, following Compo and Sardeshmukh (2009), of a set of linear anomaly equations for the coupled and uncoupled systems. Since there is no external forcing considered, the coupled system is adapted as follows, using their notation:

$$\frac{dy}{dt} = L_{yy}y + L_{yx}x + B_y\eta_y \qquad \text{(A1)}$$

$$\frac{dx}{dt} = L_{xy}y + L_{xx}x + B_x\eta_x \qquad \text{(A2).}$$

The atmospheric state vector is y and the SST state vector is x. The atmospheric and oceanic dynamics and interactions are represented by the matrices $L_{\alpha\beta}$, the vectors η_α denote the atmospheric and oceanic stochastic forcing, and the matrices B_α transform the stochastic forcing into dynamic forcing.

The equation for the uncoupled atmospheric system forced by the time-varying x from the coupled system is

$$\frac{d\hat{y}}{dt} = L_{yy}\hat{y} + L_{yx}x + B_y\hat{\eta}_y \qquad \text{(A3).}$$

Structurally, Eqs. (A3) and (A1) are identical, but the realization of the stochastic forcing differs, but is taken to have the same statistics. For time scales longer than decorrelation time of the atmosphere, the *d/dt* terms on the LHS of Eqs. (A1) and (A3) are much smaller than the other terms on the RHS and can be neglected. The following applies for the magnitude of the time lag much longer than the atmospheric decorrelation time. Then the solution to Eq. (A1) is:

$$y = Ax + C\eta_y \qquad \text{(A4),}$$

where $A = -(L_{yy}^{-1}L_{yx})$ and $C = -(L_{yy}^{-1}B_y)$. Similarly, the solution to Eq. (A3) is:

$$\hat{y} = Ax + C\hat{\eta}_y \qquad \text{(A5),}$$

that is, as the sum of an SST-forced component (Ax) and a noise component. The linear transformation of the noise vector is also noise vector. The SST-forced component is identical for the coupled and uncoupled systems. Using Eq. (A4), Eq. (A2) can be written as:

$$\frac{dx}{dt} = Dx + B_x\eta_x + E\eta_y \qquad \text{(A6),}$$

where $D = L_{xy}A + L_{xx}$ and $E = L_{xy}C$.

The formal solution to Eq. (A6) is

$$x_t = x_0e^{Dt} + e^{Dt}\int_0^t e^{-Dt'}(B_x\eta_{x,t'} + E\eta_{y,t'})dt'$$

Then the CGCM/AGCM differences at a point of lagged covariances over time T of x and y *($\hat{y}$)* with a time lag of τ are:

$$\begin{aligned} < x_t, y_{t+\tau} > - < x_t, \hat{y}_{t+\tau} > &= \int_0^T x_t(Ax_{t+\tau} + C\eta_{y,t+\tau})dt - \int_0^T x_t(Ax_{t+\tau} + C\hat{\eta}_{y,t+\tau})dt \\ &= \int_0^T x_tC(\eta_{y,t+\tau} - \hat{\eta}_{y,t+\tau})dt \end{aligned} \qquad \text{(A7).}$$

Since the atmospheric noise from the uncoupled system ($\hat{\eta}_y$) is uncorrelated with ocean (x) and the atmospheric noise from the coupled system (η_y) is uncorrelated with oceanic noise (η_x) or with oceanic initial condition (x_0), Eq. (A7) is reduced to

$$\begin{aligned} < x_t, y_{t+\tau} > - < x_t, \hat{y}_{t+\tau} > &= \int_0^T x_tC\eta_{y,t+\tau}dt \\ &= \int_0^T \left[x_0e^{Dt} + e^{Dt}\int_0^t e^{-Dt'}(B_x\eta_{x,t'} + E\eta_{y,t'})dt'\right]C\eta_{y,t+\tau}dt \qquad \text{(A8).} \\ &= \int_0^T \int_0^t e^{D(t-t')}E\eta_{y,t'}C\eta_{y,t+\tau}dt'\,dt \end{aligned}$$

From the property of stochastic noise, contribution from the integral only occurs when $\tau < \tau_{atm}$, with the atmospheric decorrelation time (τ_{atm}) taken into account. The integral is not significantly different from zero when $\tau > \tau_{atm}$. Thus, when ocean leads the atmosphere by longer than the atmospheric decorelation time (i.e., $\tau > \tau_{atm}$), the RHS of Eq. (A8) is small, i.e., the difference of lagged covariances between coupled and uncoupled systems is small. However, when ocean leads the atmosphere by less than the atmospheric decorelation time (i.e., $\tau < \tau_{atm}$), which includes the ocean being simultaneous with the atmosphere ($\tau = 0$) and ocean lagging the atmosphere ($\tau < 0$), the difference is not negligible.

If the atmosphere is still modeled as a linear system plus fast noise, but with a nonlinear relationship of SST forcing the atmosphere (i.e., L_{yx} is nonlinear but L_{yy} is still linear), the solutions to Eqs. (A1) and (A3) can still be written as in the linear case in Eqs. (A4) and (A5). The nonlinear matrix A (due to L_{yx}) does not affect the CGCM/AGCM differences in Eq. (8), and the conclusions are the same as in preceding paragraph.

To examine the effect of state-dependent noise, such as depending on the SST (e.g., Weng and Neelin 1999, Majda et al. 2009, Sura and Sardeshmukh 2009), the operator B_y in Eqs. (A1) and (A3) is taken to depend on the x (i.e., SST). The solutions to Eqs. (A1) and (A3) are still written as Eqs. (A4) and (A5), but the matrix C in this case is x-dependent. Then the matrix E is also x-dependent. The dependence on x of C and E does not change the conclusions concerning the lag correlations.

If the coupled and uncoupled lag regressions with SST leading are the same, then the SST forced response is the same

1) even if the atmospheric response to the SST in nonlinear

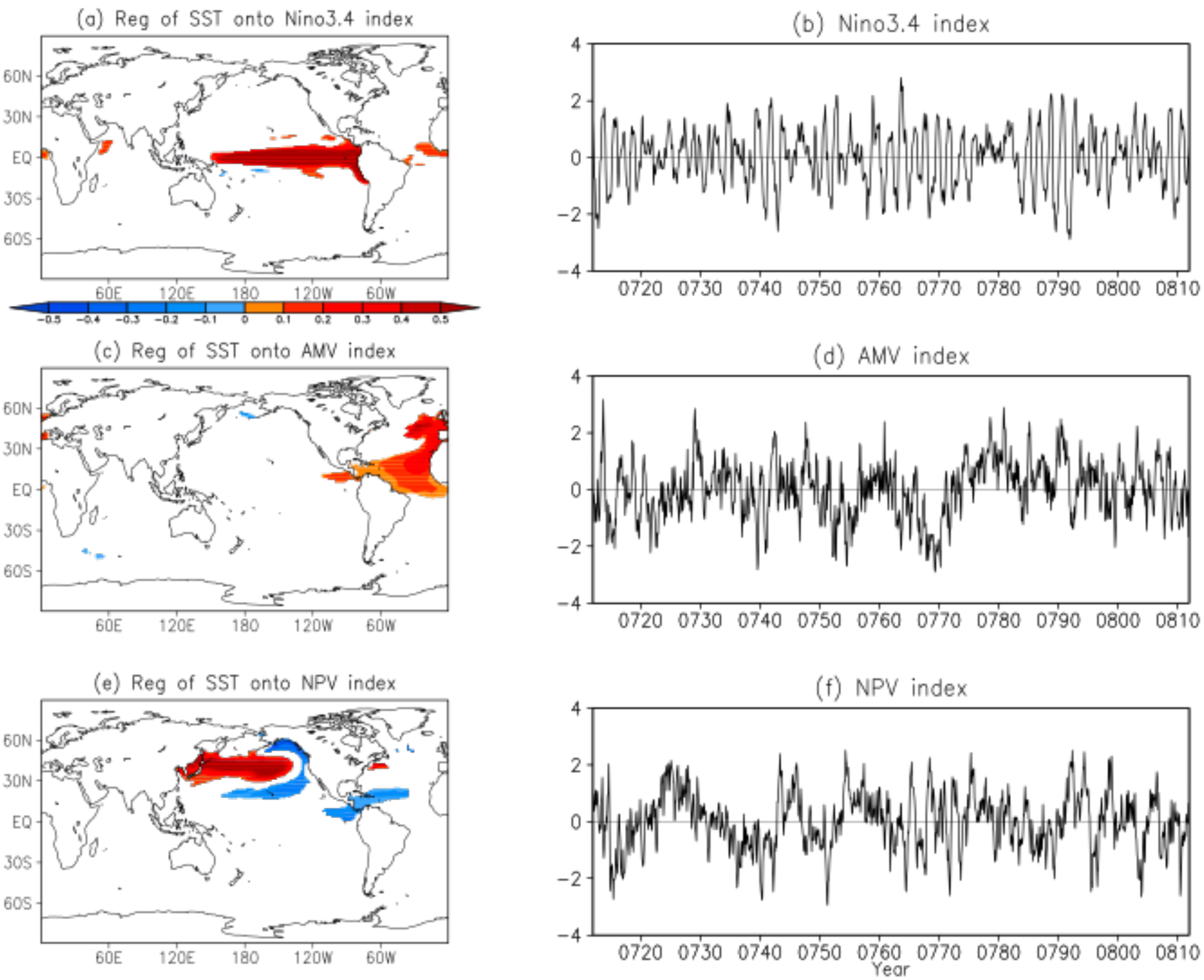
2) even if the noise is state (SST) dependent.

SST Indices (same for CGCM and AGCM)

NINO3.4

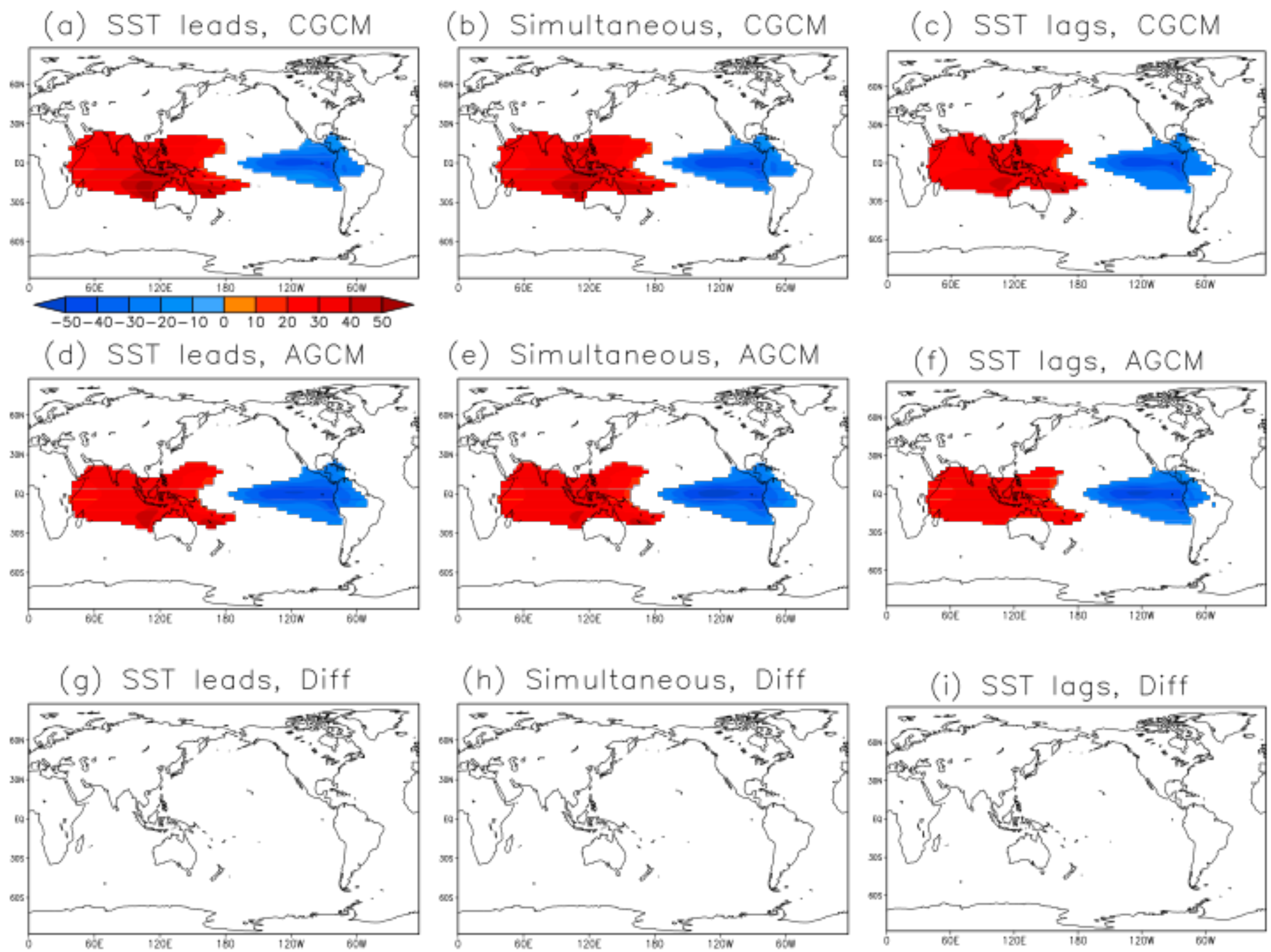
AMV

NPV



NINO3.4 vs. SLP

	SST Leads	Simultaneous	SST Lags
CGCM			
AGCM			
Difference			



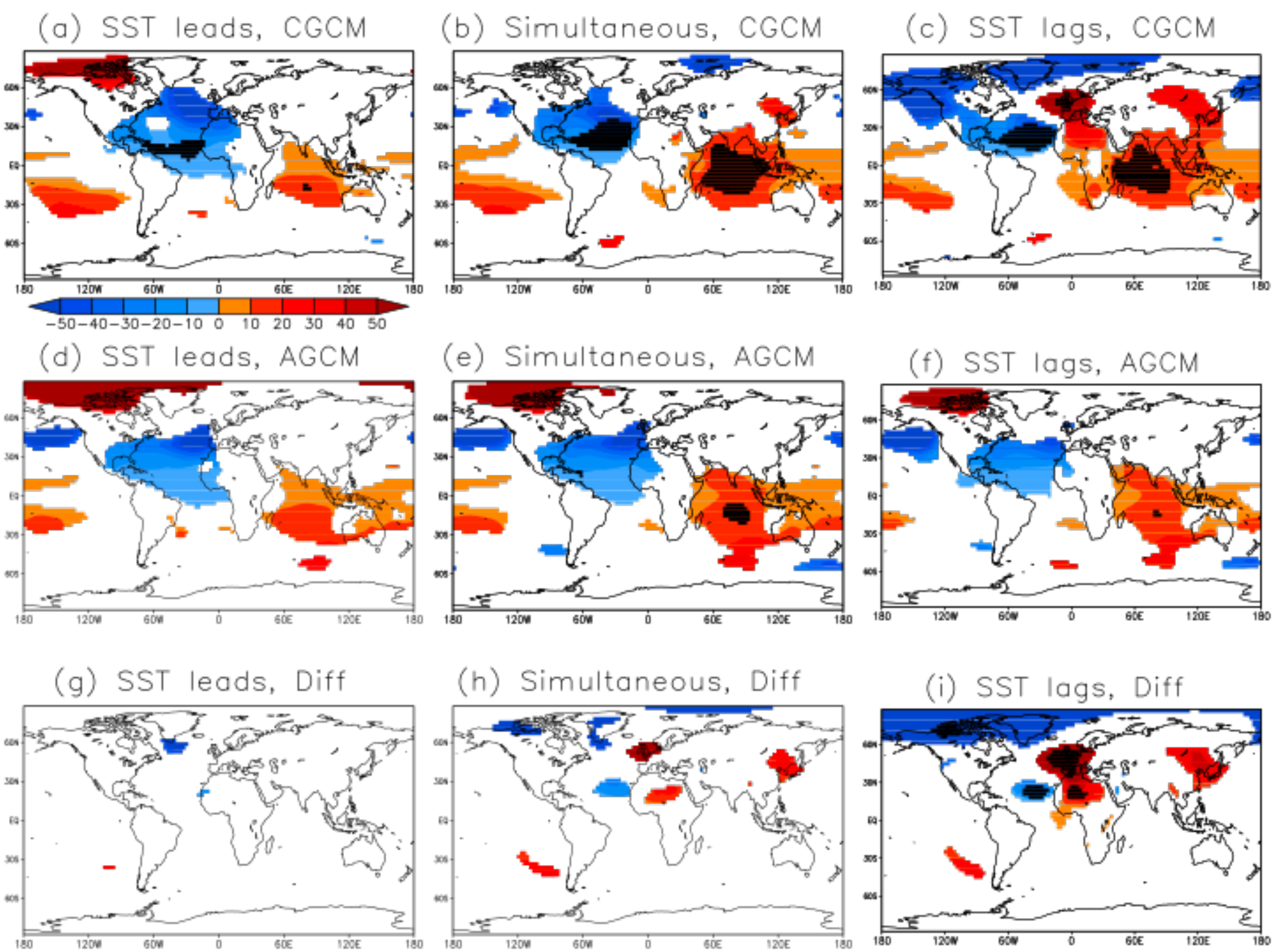
AMV vs. SLP

SST Leads | Simultaneous | SST Lags

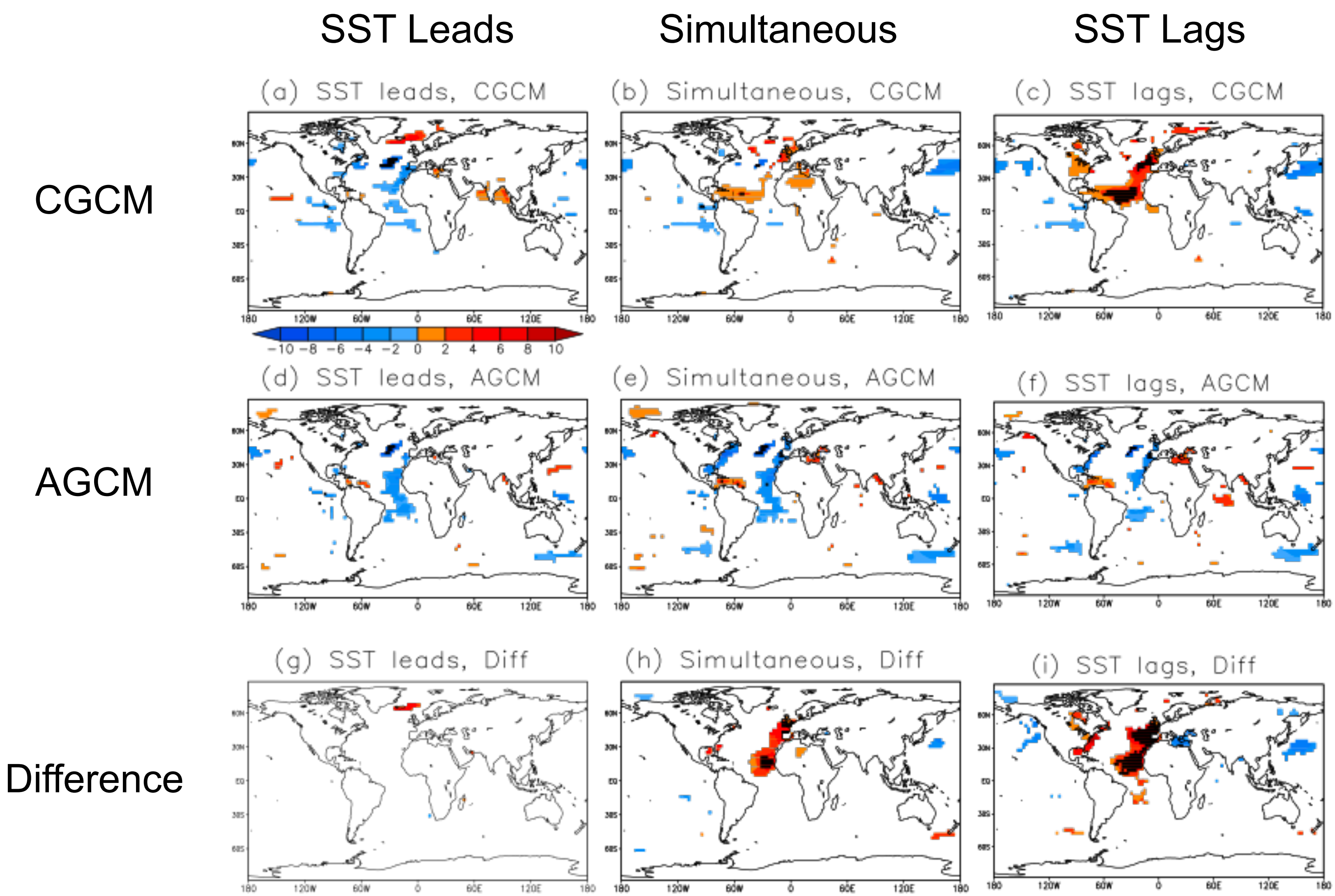
CGCM

AGCM

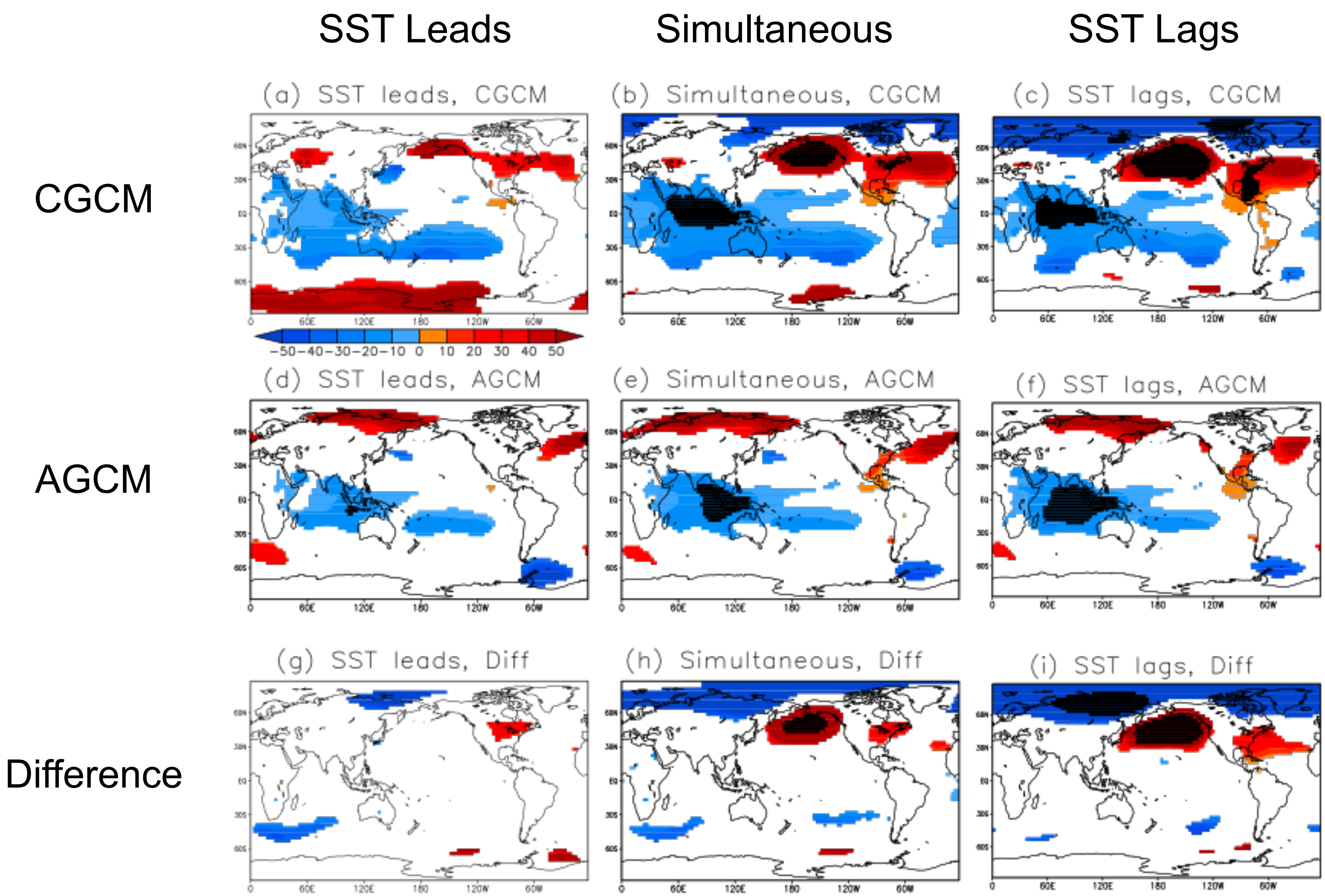
Difference



AMV vs. NHF


SST Leads
Simultaneous
SST Lags
CGCM
AGCM
Difference
(a) SST leads, CGCM
(b) Simultaneous, CGCM
(c) SST lags, CGCM
(d) SST leads, AGCM
(e) Simultaneous, AGCM
(f) SST lags, AGCM
(g) SST leads, Diff
(h) Simultaneous, Diff
(i) SST lags, Diff
-10 -8 -6 -4 -2 0 2 4 6 8 10
180 120W 60W 0 60E 120E 180

NPV vs. SLP



SST Leads
Simultaneous
SST Lags
CGCM
AGCM
Difference
(a) SST leads, CGCM
(b) Simultaneous, CGCM
(c) SST lags, CGCM
(d) SST leads, AGCM
(e) Simultaneous, AGCM
(f) SST lags, AGCM
(g) SST leads, Diff
(h) Simultaneous, Diff
(i) SST lags, Diff
−50 −40 −30 −20 −10 0 10 20 30 40 50

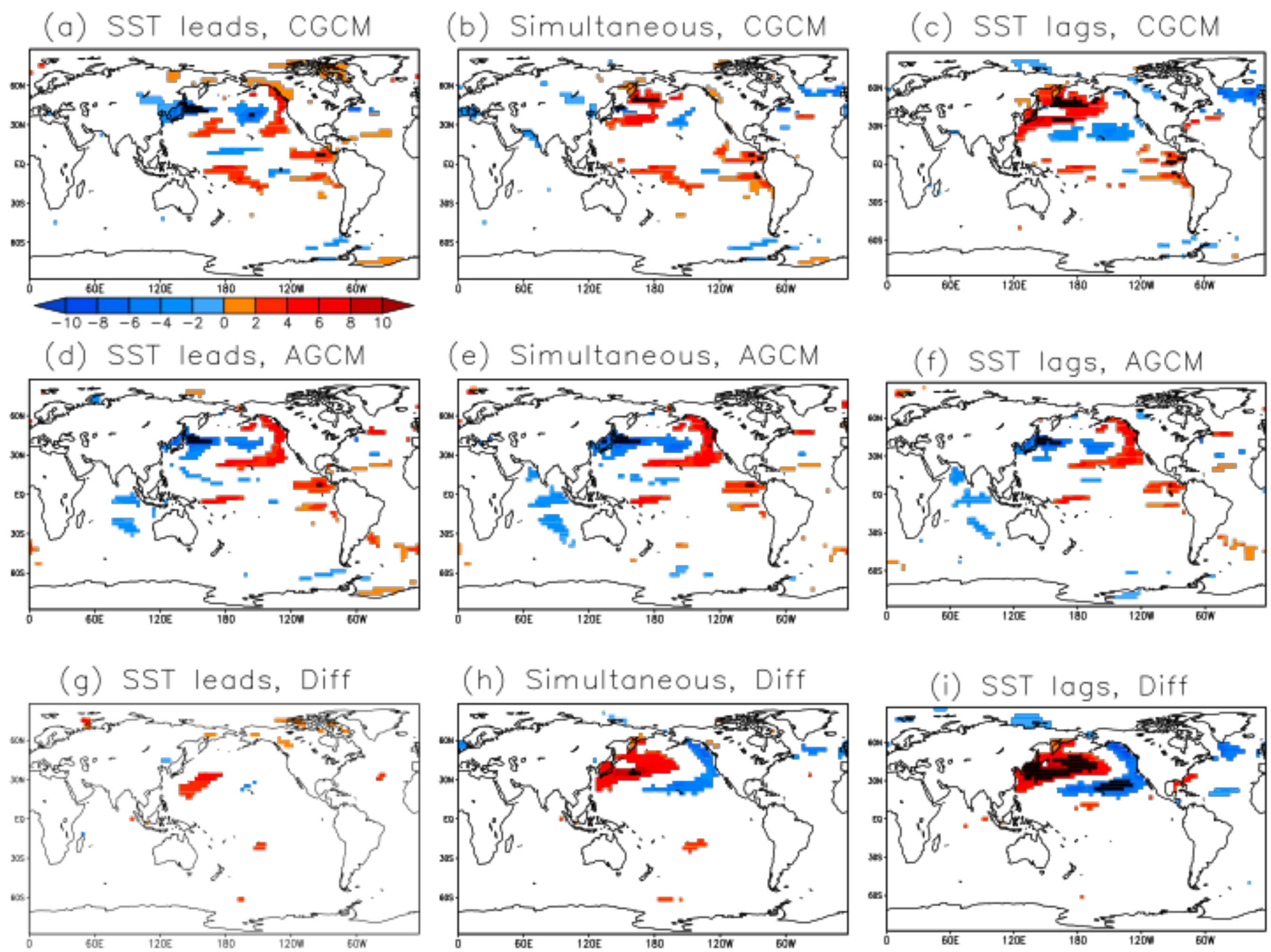
NPV vs. NHF

SST Leads | Simultaneous | SST Lags

CGCM

AGCM

Difference



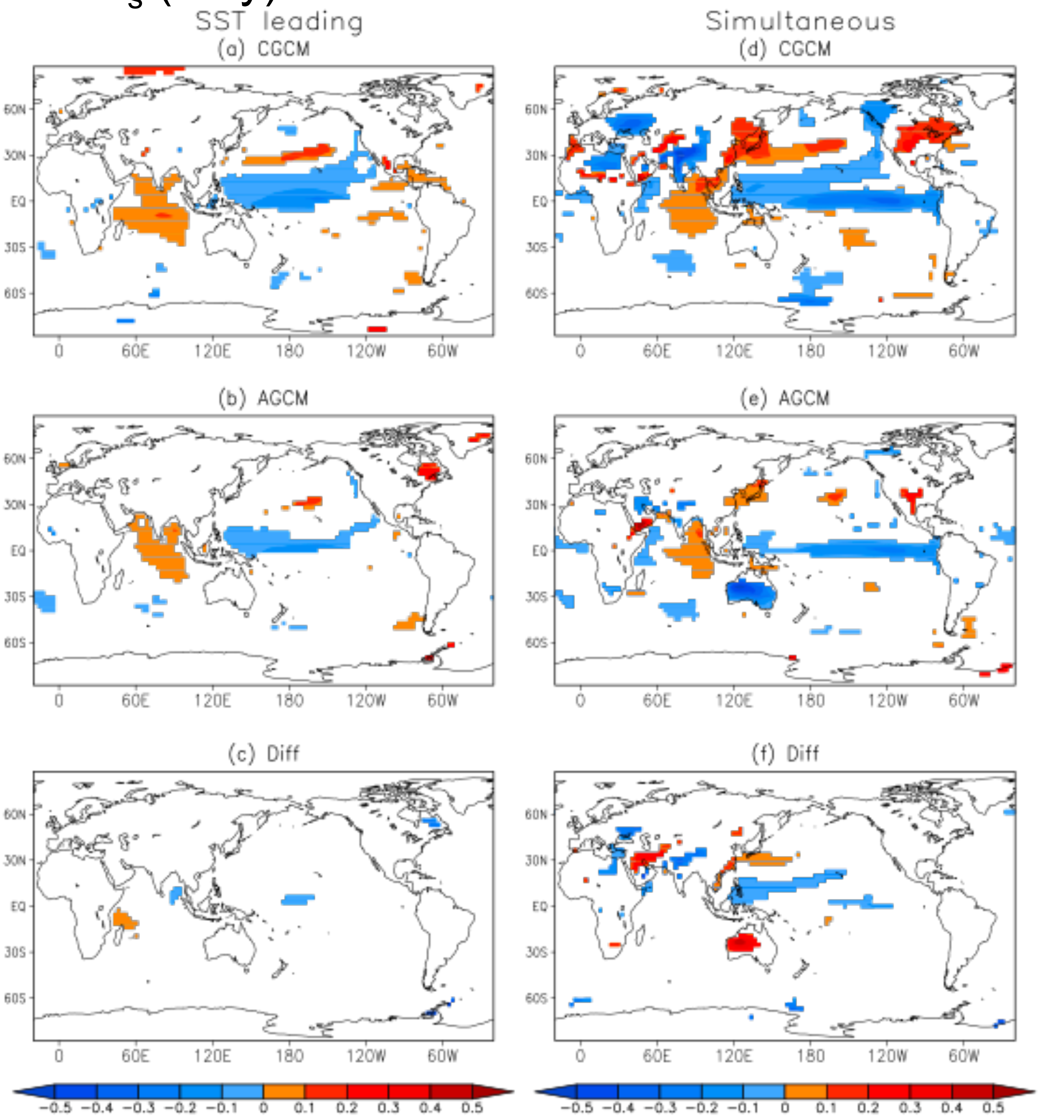
JJA IMR vs. T_s

T_s (May) Leads | Simultaneous

CGCM

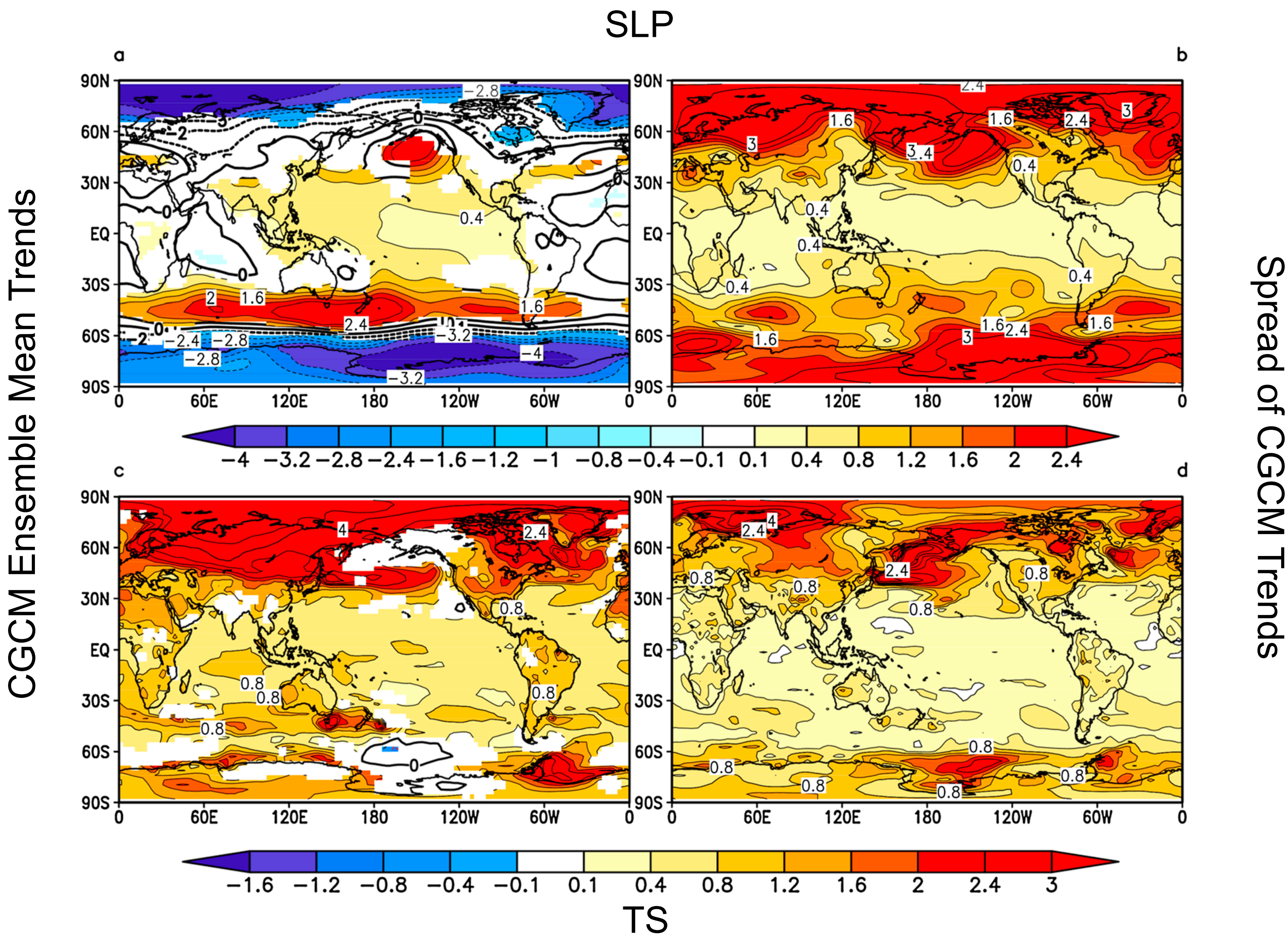
AGCM

Difference



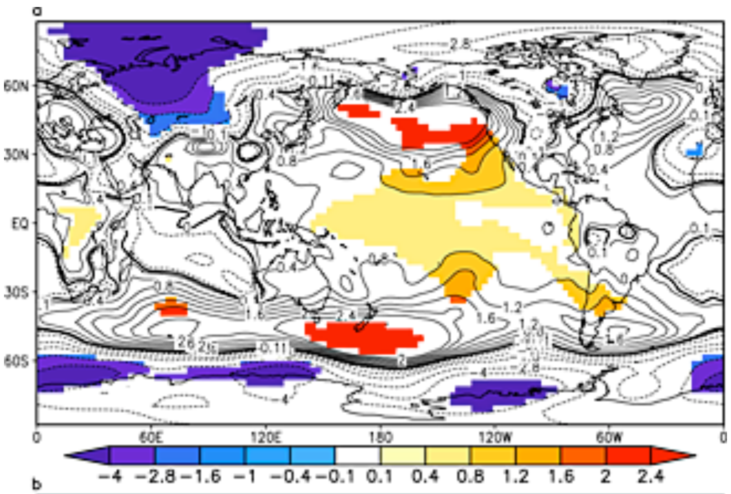
Perfect AMIP Experiment to Compare with Copsey et al.

- CCSM3 CGCM
  - 6 member ensemble of 1870-2000 simulations, one named **CONTROL**, each with the same "20C3M" historical external forcing (GHG, solar, volcanic)
  - T42 26 level atmosphere CAM3
- CAM3 AGCM
  - Same AGCM as in CCSM3
  - 6 member ensemble of simulations, with each member forced by the same historical external forcing and time-varying SST from **CONTROL**
- Analysis of 1950-1999 trends and spreads

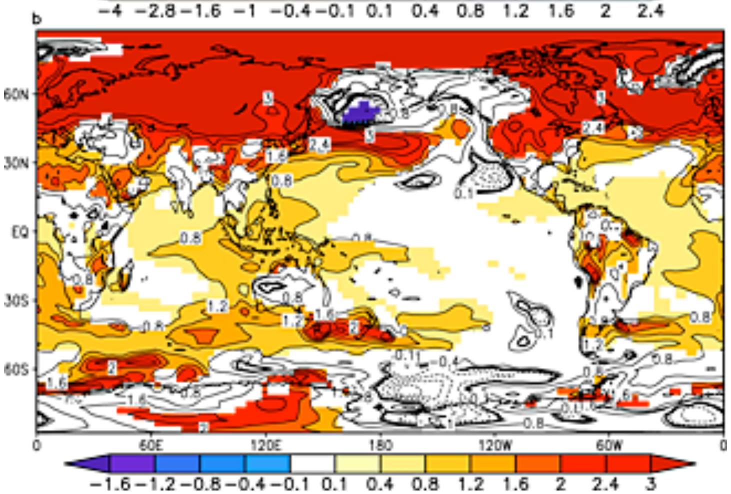

SLP
a
b
c
d
CGCM Ensemble Mean Trends
Spread of CGCM Trends
90N 60N 30N EQ 30S 60S 90S
0 60E 120E 180 120W 60W 0
−4 −3.2 −2.8 −2.4 −1.6 −1.2 −1 −0.8 −0.4 −0.1 0.1 0.4 0.8 1.2 1.6 2 2.4
−1.6 −1.2 −0.8 −0.4 −0.1 0.1 0.4 0.8 1.2 1.6 2 2.4 3
TS

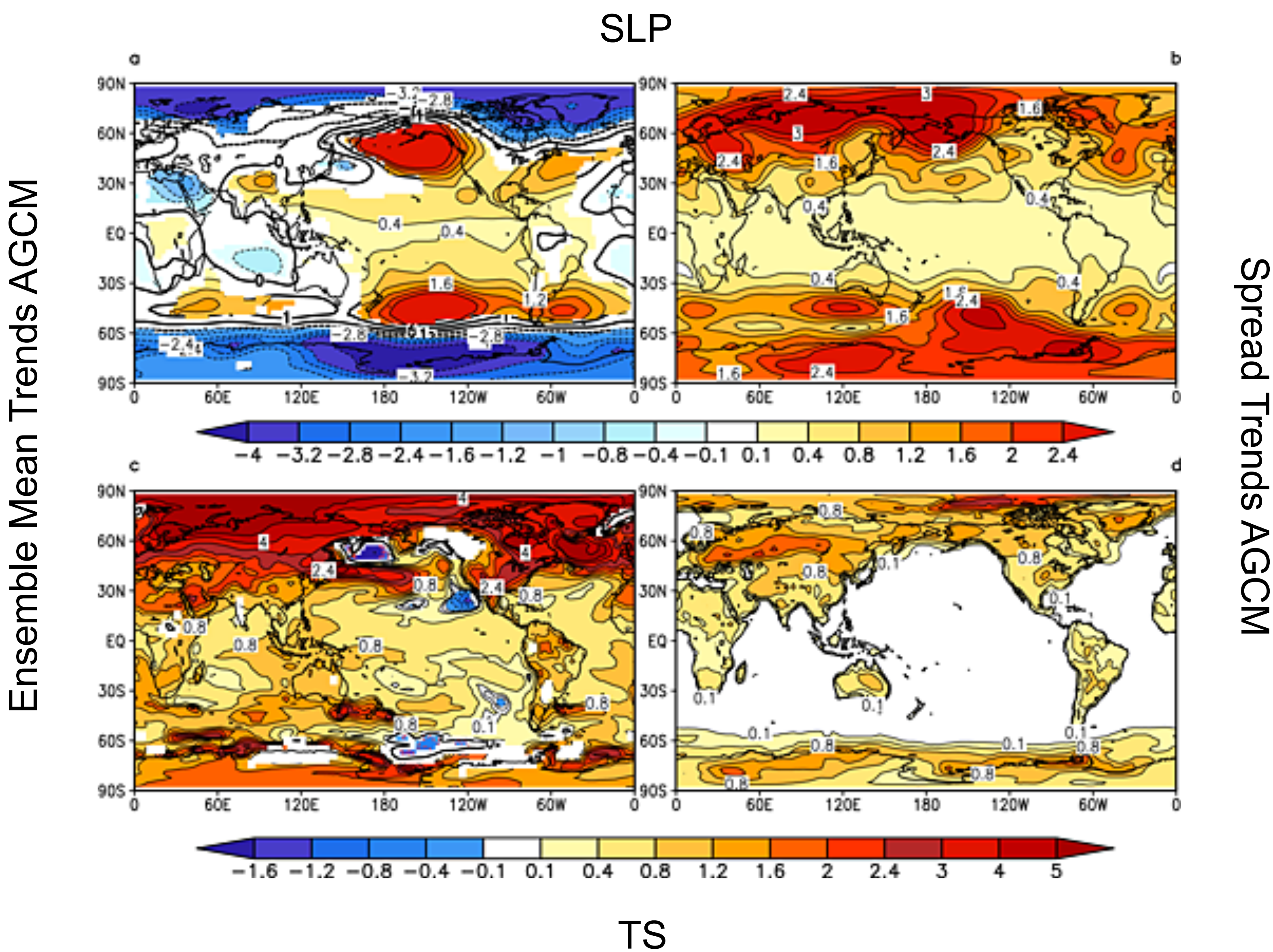
CGCM CONTROL Trends

SLP

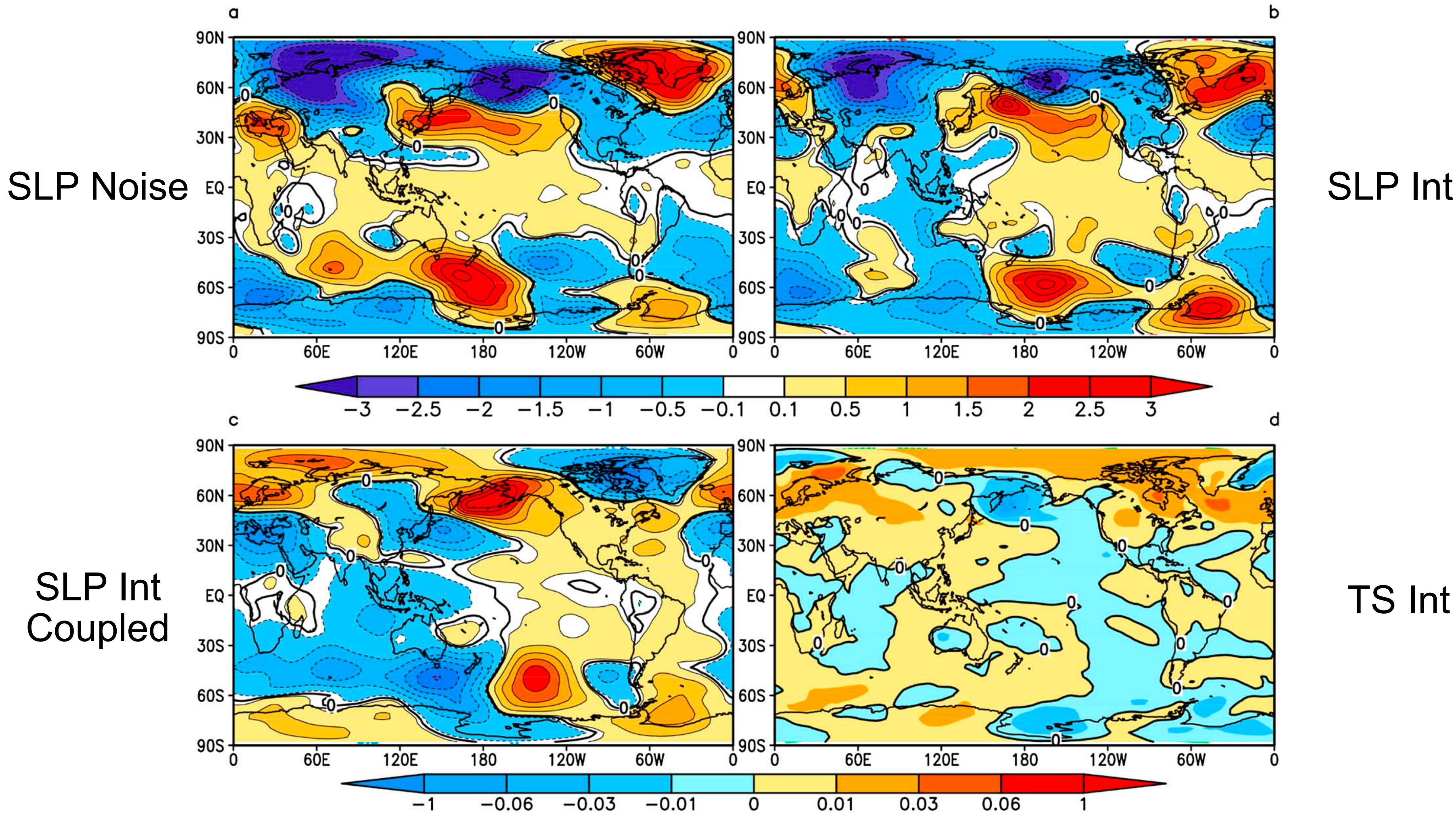


TS




SLP
Ensemble Mean Trends AGCM
Spread Trends AGCM
a
b
c
d
90N 60N 30N EQ 30S 60S 90S
0 60E 120E 180 120W 60W 0
−4 −3.2 −2.8 −2.4 −1.6 −1.2 −1 −0.8 −0.4 −0.1 0.1 0.4 0.8 1.2 1.6 2 2.4
−1.6 −1.2 −0.8 −0.4 −0.1 0.1 0.4 0.8 1.2 1.6 2 2.4 3 4 5
TS

CONTROL Trends Attribution



Trends Conclusion

- CGCM and AGCM appear to produce the same SST and externally forced atmospheric trends.
- Copsey et al. result may be due to model bias.

Examination of Kumar et al. Result?

- Perfect model version of this set of calculations is in progress:
  - Long control simulation AGCM + slab mixed layer ocean
  - AMIP-type ensemble: AGCM forced by SST from control
  - Pacemaker ensemble: AGCM forced by SST from control in tropical eastern, slab MLO elsewhere.

Summary

- The SST forced responses and noise variances are the same in this CGCM and AGCM.
- Uncoupled simulations will intrinsically produce misleading results for precipitation.
- Where/when the noise forcing of SST is important (e.g. the tropical western Pacific), the SST and its teleconnections are not predictable.

- *There are still some results that do not appear to fit this neat package.*

Relevant Result for C20C Noise Project

- The noise calculation and the tests to compare CGCM and AGCM can be applied to examine questions like:
  - Is the forced response of an AMIP-type simulation the same as the observed? Is the noise variance the same?
  - Is the forced response of one reanalysis the same as another?

Additional References

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