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

Simultaneous Correlations of IMR and SST
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. 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$\_i$

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

<1

≅ 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:

\[
\frac{dy}{dt} = L_{yx}y + L_{yx}x + B_y \eta_y \tag{A1}
\]

\[
\frac{dx}{dt} = L_{xy}y + L_{xx}x + B_x \eta_x \tag{A2}.
\]

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 \(\eta_\alpha\) denote the atmospheric and oceanic stochastic forcing, and the matrices \(B_\alpha\) 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

\[
\frac{d\tilde{y}}{dt} = L_{yx}\tilde{y} + L_{yx}x + B_y \tilde{\eta}_y \tag{A3}.
\]

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:

\[
y = Ax + C\eta_y \tag{A4},
\]

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

\[
\tilde{y} = Ax + C\tilde{\eta}_y \tag{A5},
\]

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:

\[
\frac{dx}{dt} = Dx + B_x \eta_\xi + E\eta_x \tag{A6},
\]

where \(D = L_{yx}A + L_{xx}\) and \(E = L_{yx}C\).

The formal solution to Eq. (A6) is

\[
x_t = x_0 e^{Dt} + e^{Dt}\int_0^t e^{-D\tau} (B_x \eta_{\xi,\tau} + E\eta_{\xi,\tau}) d\tau.
\]

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

\[
< x_r, y_{r,xt} > - < x_r, \tilde{y}_{r,xt} > = \int_0^T x_r (Ax_{r,xt} + C\eta_{r,xt}) dt - \int_0^T x_r (Ax_{r,xt} + C\tilde{\eta}_{r,xt}) dt = \int_0^T x_r C(\eta_{r,xt} - \tilde{\eta}_{r,xt}) dt \tag{A7}.
\]

Since the atmospheric noise from the uncoupled system \((\tilde{\eta}_y)\) is uncorrelated with ocean \((x)\) and the atmospheric noise from the coupled system \((\eta_y)\) is uncorrelated with oceanic noise \((\eta_x)\) or with oceanic initial condition \((x_0)\). Eq. (A7) is reduced to

\[
< x_r, y_{r,xt} > - < x_r, \tilde{y}_{r,xt} > = \int_0^T x_r C\eta_{r,xt} dt = \int_0^T \left[ x_r e^{Dr} + e^{Dr} \int_0^t e^{-D\tau} (B_x \eta_{\xi,\tau} + E\eta_{\xi,\tau}) d\tau \right] C \eta_{r,xt} dt \tag{A8}.
\]

\[
= \int_0^T \int_0^t e^{D(t-\tau)} E \eta_{\xi,\tau} C \eta_{r,xt} d\tau dt.
\]
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

CGCM

(a) SST leads, CGCM
(b) Simultaneous, CGCM
(c) SST lags, CGCM

(d) SST leads, AGCM
(e) Simultaneous, AGCM
(f) SST lags, AGCM

AGCM

(g) SST leads, Diff
(h) Simultaneous, Diff
(i) SST lags, Diff

Difference
AMV vs. SLP

CGCM

(a) SST leads, CGCM
(b) Simultaneous, CGCM
(c) SST lags, CGCM

AGCM

(d) SST leads, AGCM
(e) Simultaneous, AGCM
(f) SST lags, AGCM

Difference

(g) SST leads, Diff
(h) Simultaneous, Diff
(i) SST lags, Diff
AMV vs. NHF

SST Leads
- (a) SST leads, CGCM
- (d) SST leads, AGCM
- (g) SST leads, Diff

Simultaneous
- (b) Simultaneous, CGCM
- (e) Simultaneous, AGCM
- (h) Simultaneous, Diff

SST Lags
- (c) SST lags, CGCM
- (f) SST lags, AGCM
- (i) SST lags, Diff
NPV vs. SLP

- CGCM
  - SST Leads
    - (a) SST leads, CGCM
  - Simultaneous
    - (b) Simultaneous, CGCM
  - SST Lags
    - (c) SST lags, CGCM

- AGCM
  - SST Leads
    - (d) SST leads, AGCM
  - Simultaneous
    - (e) Simultaneous, AGCM
  - SST Lags
    - (f) SST lags, AGCM

- Difference
  - SST Leads
    - (g) SST leads, Diff
  - Simultaneous
    - (h) Simultaneous, Diff
  - SST Lags
    - (i) SST lags, Diff
NPV vs. NHF

SST Leads

CGCM

SST Leads, CGCM

Simultaneous

Simultaneous, CGCM

SST Lags

SST Lags, CGCM

AGCM

SST Leads, AGCM

Simultaneous, AGCM

SST Lags, AGCM

Difference

SST Leads, Diff

Simultaneous, Diff

SST Lags, Diff
JJA IMR vs. $T_s$
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
CGCM Ensemble Mean Trends

Spread of CGCM Trends

SLP

TS
CGCM CONTROL Trends

SLP

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.

  o 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


