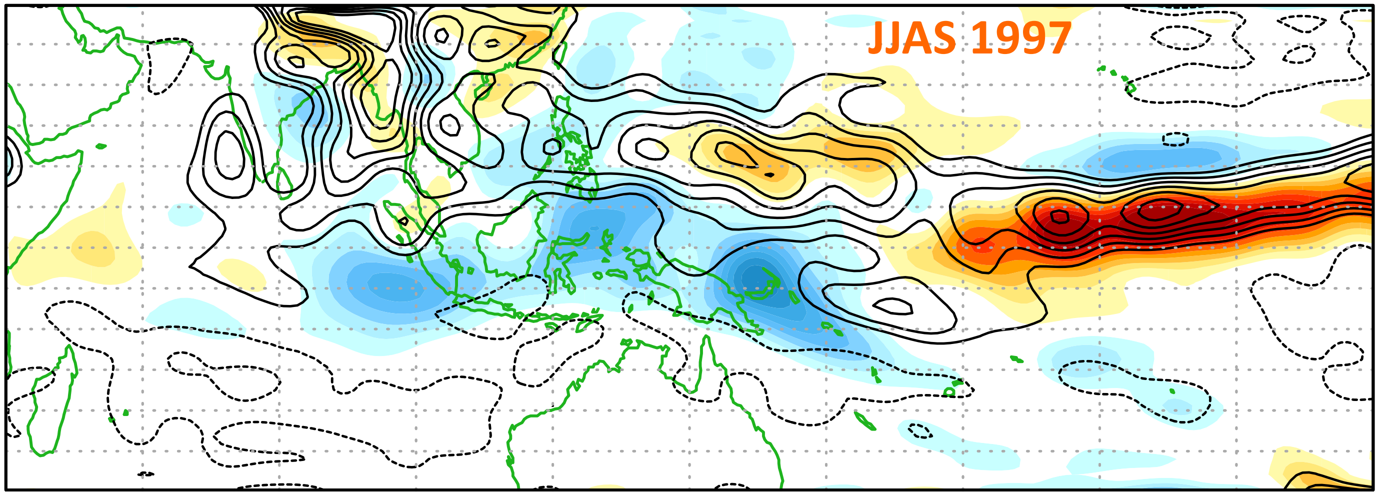
Correcting tropical diabatic heating in CFSv2

David M. Straus, Erik T. Swenson and Laurie Trenary



shading – anomalies (interval of 0.3°K/day)

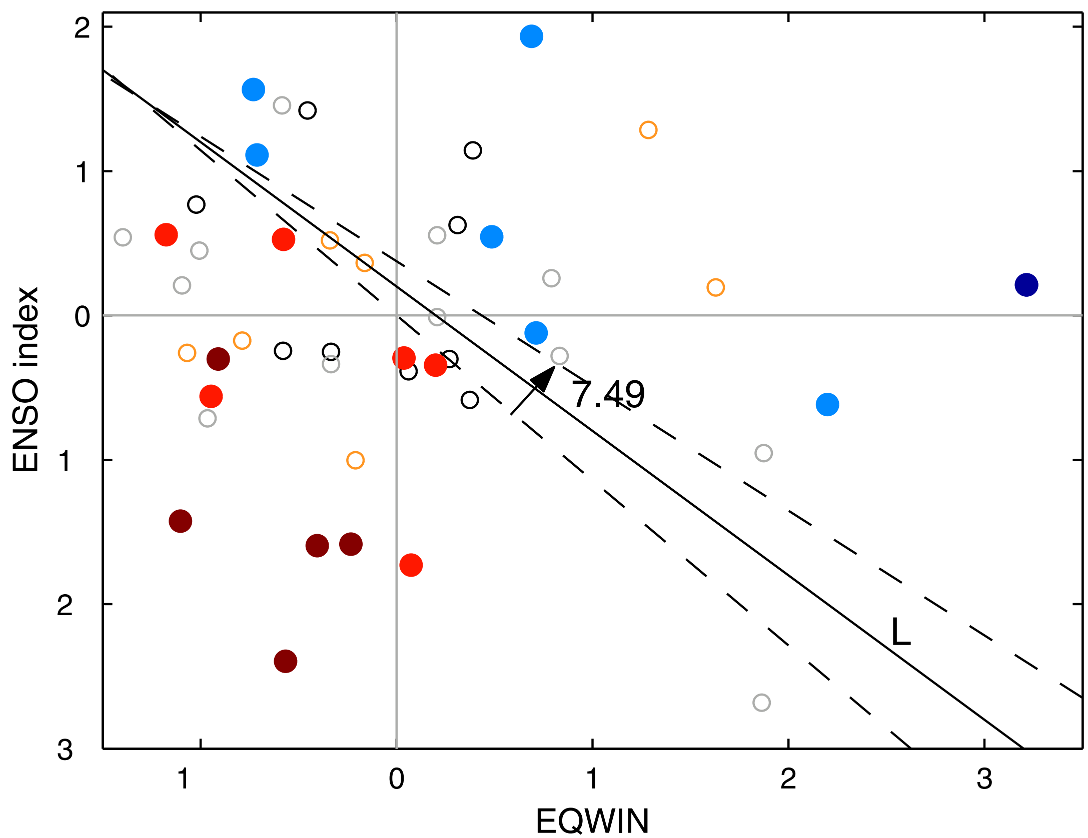
contours – total (interval of 0.5°K/day)

Monsoon Mission Dec 4-5, 2019

Scientific Goal:
Identify, understand (and predict) the component of the inter-annual variability of summer mean Monsoon rainfall over India that is forced from the tropics.

- Since SST is relatively predictable on a time scale of a few months, a traditional path has been to try to use tropical SST to predict the Indian Monsoon rainfall.
- **Tropical SST** (→ Tropical Atmos.Circ → Circ. over India) → **Monsoon Rainfall**
- This implicitly assumes that the ocean forces the atmosphere on seasonal time scales, which is reasonable for the Tropical Pacific (e.g. ENSO)
- However, in the Indian Ocean, the atmosphere also forces the ocean (e.g. Wu and Kirtman 2004).
- **Tropical SST** ← → **Atmos.Circ** (→ Circ. over India) → **Monsoon Rainfall**
- **We need a set of combined SST/Circulation Indices for statistical prediction!**

The **EQWIN** is the negative of the (normalized) anomaly of the zonal component of the surface wind at the equator (60°E – 90°E, 2.5°S – 2.5°N). EQWIN is highly correlated (coefficient 0.81) with the difference between OLR of WEIO and EEIO.



Each season during 1958–2003 is shown on the phase plane of the June to September average of the **ENSO index** (negative of Nino 3.4 index) and EQWIN. The corresponding ISMR anomaly (normalized by the standard deviation) is represented with different symbols: large dark blue (red) closed circles for values above (below) 1.5 (- 1.5), blue (red) closed circles for values between 1 (-1) and 1.5 (-1.5), small black (orange) open circles for values between 0.25 (- 0.25) and 1 (- 1) and small gray open circles for values between - 0.25 and 0.25.
(From Gadgil et al. 2004)

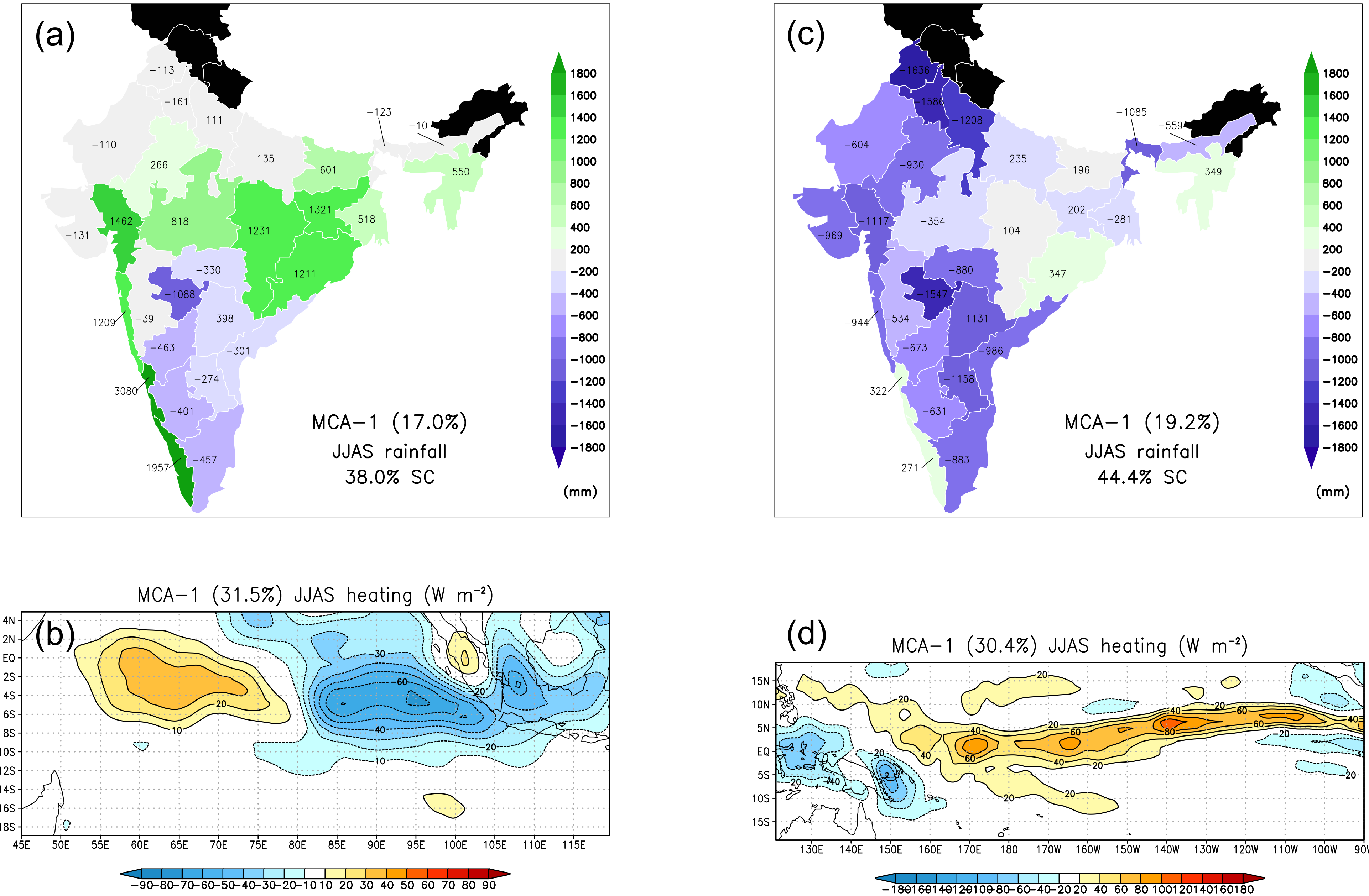
- **Tropical SST ← → Atmos.Circ** **(→** Circ. over India) **→ Monsoon Rainfall**

- For modeling and prediction, the effects of the tropical SST anomalies on the tropical circulation will depend on the resulting ***three-dimensional diabatic heating*** anomalies in the tropical atmosphere.

- **Tropical SST ← → [Tropical Q + Atmos.Circ] … → Monsoon Rainfall**

- The Tropical Heating gives us a more direct link both to the tropical and extratropical circulation, and hence ultimately to the Monsoon Rainfall.

Maximum Covariance Analysis: Tropical Heating (Vertically Integrated) vs. Rainfall



Inter-Annual Variability of JJAS Means

- The Tropical Heating gives us a more direct link both to the tropical and extratropical circulation, and hence ultimately to the Monsoon Rainfall.

- Two approaches to making use of Tropical Diabatic Heating:

  - Diagnosis of Model Errors may guide improvements in model parameterizations

  - **Empirical correction: If the tropical diabatic heating can be empirically corrected in selective ways, we have a tool to probe its influence on the Monsoon**

Possible approaches to empirical diabatic heating correction:

1) **Replace the model's parameterized heating with a specified external diabatic heating at every time step**

2) **"Nudge" the tropical circulation fields towards observations at every time step & hope that the model parameterizations will do the right thing.**

3) **ADD a heating correction to the model's parameterized diabatic heating at each time step.**

Potential Problems with these approaches:

1) The feedback from the circulation to the heating is disabled, so the heating and the SST (which does respond to the circulation) will be inconsistent

2) Even given the correct circulation, the model may not produce the desired heating. Also, nudging introduces an unwanted damping

3) The model's circulation will respond to the added heating in such a way as to amplify it via a positive feedback between heating and circulation. But this can be controlled by making the added heating small. ***Note that no model feedbacks are disabled in this approach!!***

A Short History of Using the Added-Heating Approach:

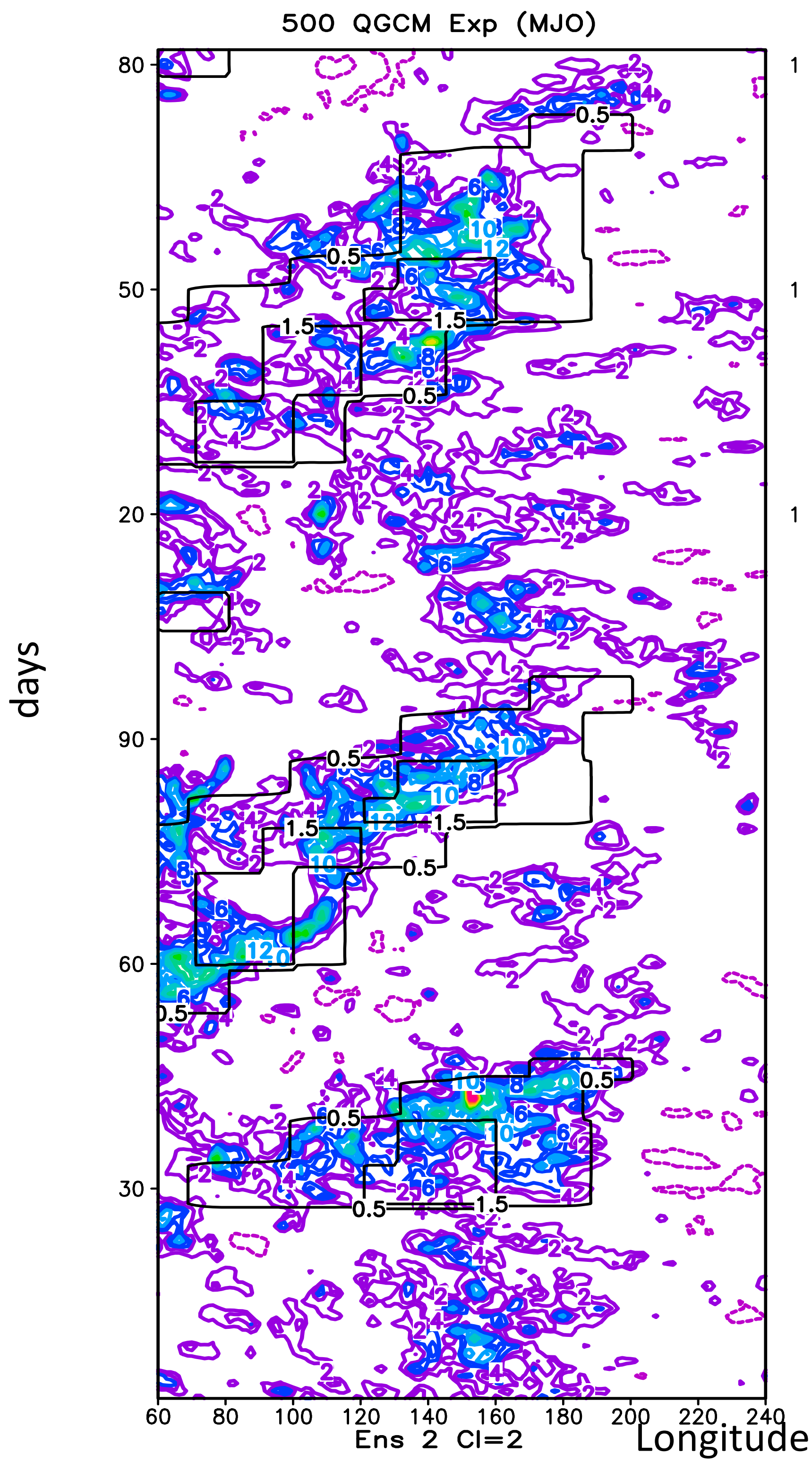
- Idealized, local diabatic heating added at many individual tropical locations to study the **forced Indian Monsoon circulation** (Jang and Straus, 2012)

- Observed estimates of (vertically integrated) tropical heating added in the Pacific (alone), Indian Ocean (alone) and the two basins together to study **the El-Nino response of the Monsoon circulation, particularly during 1997** (Jang and Straus 2013)

- Time-dependent (4d) tropical MJO-cycle heating added in the Indian and Pacific Oceans in large ensemble simulations (CESM) in order to study the **extra-tropical dynamical response to MJO** (Straus, Swenson and Lappen, 2015)

- Same as above (but in CFSv2), but for **fast and slow cycles of the MJO** (Yadav, Straus and Swenson 2019)

- Observed heating added to boreal winter 2015/16 and 2016/17 in the tropical Pacific and Indian Oceans in large ensemble experiments to determine **whether the anomalous 2015/16 North American response was forced** (Swenson, Straus, Snide, and al Fahad, 2019).



500 hPa temperature tendency due to diabatic heating (model parameterized + small added heating) for one CESM simulation for 80 days (in color, interval of 2 deg/day).

Added heating alone (black contours) (interval of 0.5 deg/day).

From Straus Swenson and Lappen, 2015

Monsoon Mission Strategy

1. Correct climatological Heating in tropical Pacific & Indian Ocean Basins together: Determine the improvement in Monsoon circulation and rainfall due to bias correction. *

2. Correction climatological heating in Tropical Pacific alone – this may correct the bias in the Indian Ocean

3. Correct climatological heating in the Indian Ocean alone

4. Correct Heating in both ocean basins for all years individually – how much of the Monsoon is tropically forced? (BUT some of this heating may not be predictable)

5. Further Mechanistic Added Heating studies

Correcting the Climatological Heating Bias

CFSv2 re-forecasts

- NCEP Climate Forecast System, version 2 (CFSv2)
- 1^{o} horizontal resolution (T126), 64 vertical layers (Higher resolution T382 model work under day – Laurie Trenary)
- Summer re-forecasts made each year for 20 years (1997-2016)
- Initialized from CFSR on May 1^{st}-10^{th} (10 ensemble members)
- Analyze June – September (JJAS)

Added heating experiments

- *Control*: Control set of re-forecasts with no added heating

- *Added Heating*: Re-forecasts repeated in same manner, but with an additional temperature tendency applied over the tropical Indo-Pacific such that the total diabatic heating rate is much closer to estimate from ERA-Interim

- Domain: Indian Ocean (60°E–120°E, 15°S–5°N) and Pacific Ocean (120°E–100°W, 15°S–20°N) decaying outside boundaries (5° e-folding scale); all vertical variation at and above 850 hPa level ($p < 850$ hPa)

- Target: Full JJAS seasonal cycle at each grid point: seasonal mean + trend + parabolic fit during season

- 10-day turn-on period prior to 00Z01Jun

ERA-Interim diabatic heating estimate

- Observational estimate taken as residual to thermodynamic eqn. for potential temperature θ using 6-hourly ERA-Interim winds, temperature and vertical velocity at 37 levels:

$$c_p \Pi \left(\frac{\partial \theta}{\partial t} + \vec{\nabla} \cdot (\vec{v}\theta) - \theta(\vec{\nabla} \cdot \vec{v}) + \omega \frac{\partial \theta}{\partial p} \right) = Q$$

$$\text{with} \quad \Pi = \left(\frac{p}{p_0} \right)^{R/c_p}$$

- The instantaneous heating rates, computed at 37 levels were integrated over 9 layers and then fit to a smooth function in the vertical pressure coordinate that maintains layer integrals.

Iterative approach for correcting heating

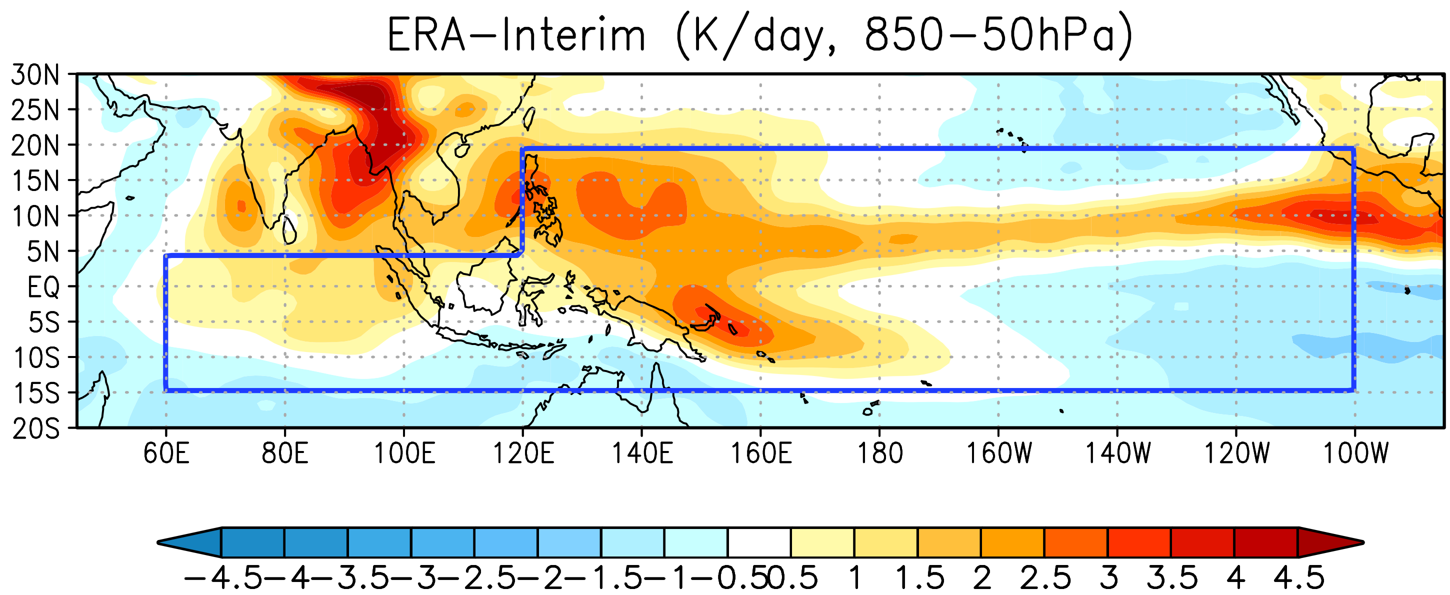
- Begin with difference between ensemble mean (e=10) diabatic heating rate in Control (Q_0) and ERA-Interim estimate (Q_{ERA}):

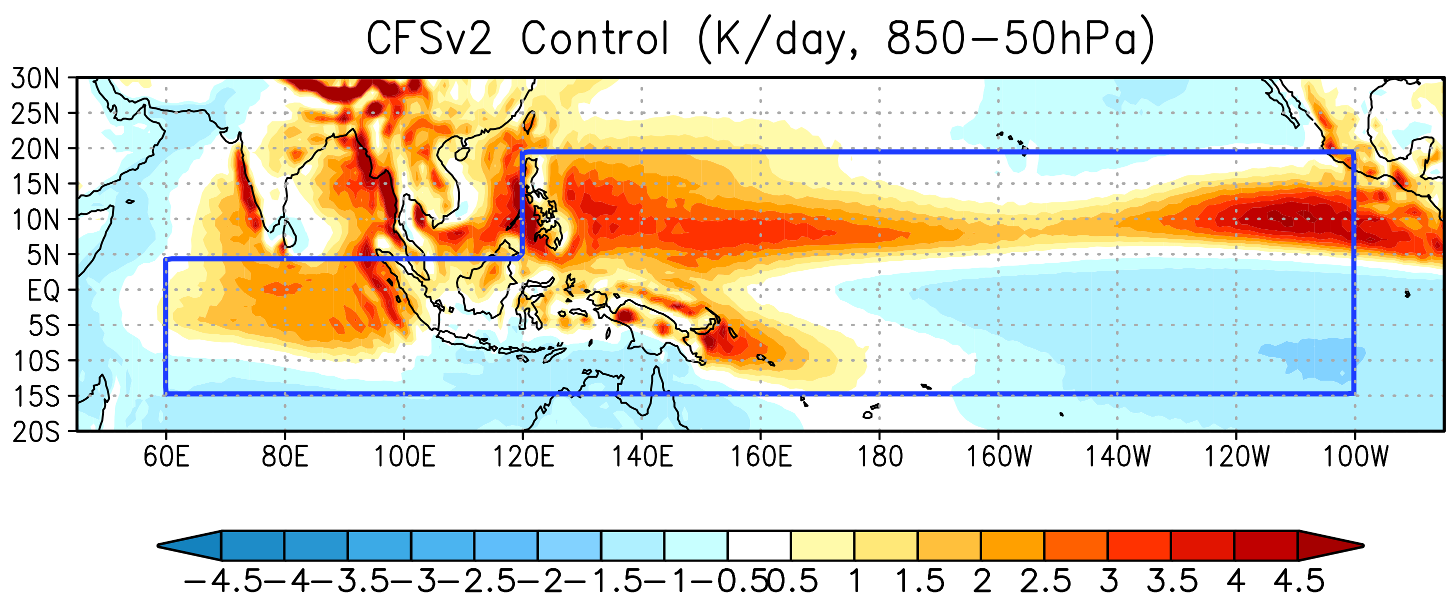
$$Q_{ERA} - Q_0$$

- Produce new set of runs adding in 10% of this difference, yielding new ensemble mean diabatic heating rate (Q_1):

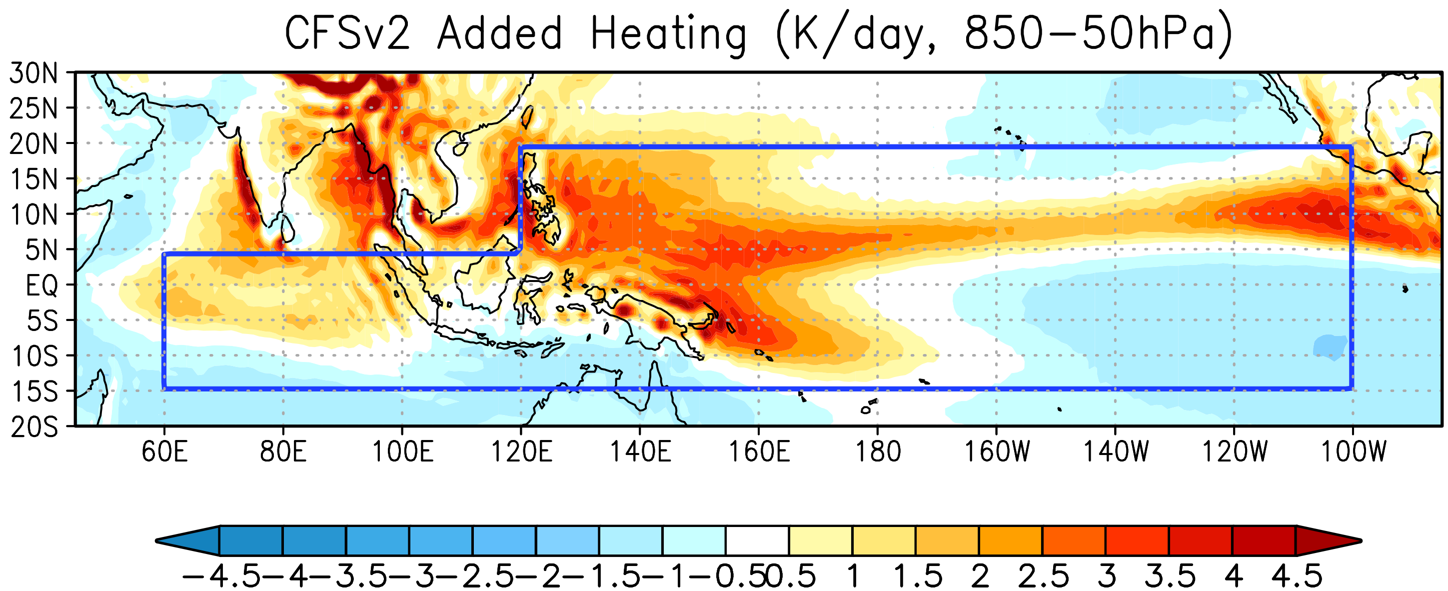
$$dT/dt + 0.1 * (Q_{ERA} - Q_0) \rightarrow Q_1$$

where the left hand side shows how we run the GMC (dT/dt comes from model itself), and the right hand side is the heating diagnosed after the ensemble is run


ERA−Interim (K/day, 850−50hPa)
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
60E
80E
100E
120E
140E
160E
180
160W
140W
120W
100W
−4.5 −4 −3.5 −3 −2.5 −2 −1.5 −1 −0.5 0.5 1 1.5 2 2.5 3 3.5 4 4.5


CFSv2 Control (K/day, 850−50hPa)
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
60E
80E
100E
120E
140E
160E
180
160W
140W
120W
100W
−4.5 −4 −3.5 −3 −2.5 −2 −1.5 −1 −0.5 0.5 1 1.5 2 2.5 3 3.5 4 4.5

Total climatological mean heating in the runs where added heating is applied ("Added Heating Runs").



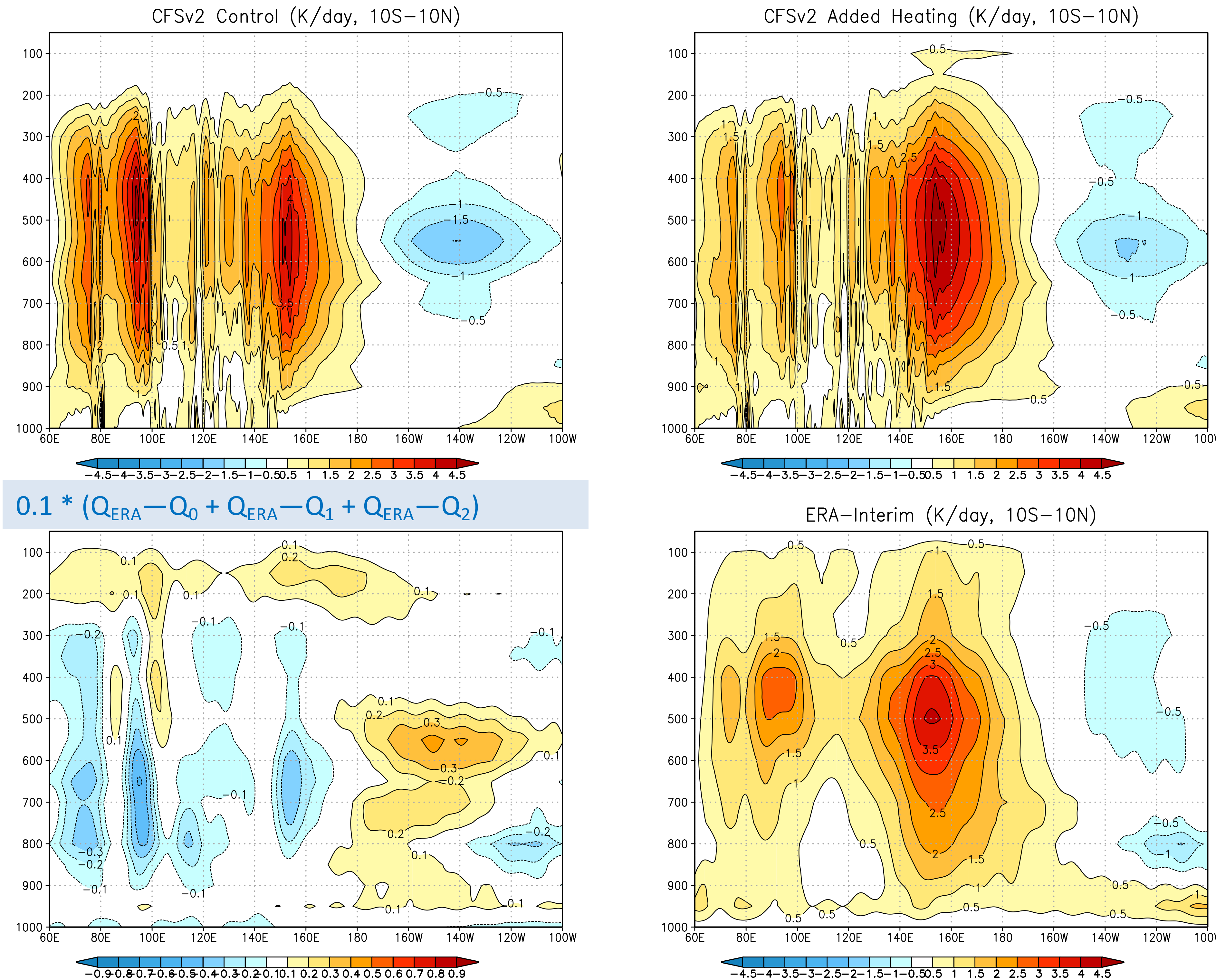
Iterative approach for correcting heating (continued)

- Repeat this process twice more for a total of n=3 times:

$$dT/dt + 0.1 * (Q_{ERA} - Q_0 + Q_{ERA} - Q_1) \rightarrow Q_2$$

$$dT/dt + 0.1 * (Q_{ERA} - Q_0 + Q_{ERA} - Q_1 + Q_{ERA} - Q_2) \rightarrow Q_3$$

In each case the left-hand side shows how we run the GCM (dT/dt comes from the model itself) and the right hand side is the heating diagnosed after the ensemble is run.


CFSv2 Control (K/day, 10S–10N)
CFSv2 Added Heating (K/day, 10S–10N)
0.1 * (Q_ERA—Q_0 + Q_ERA—Q_1 + Q_ERA—Q_2)
ERA–Interim (K/day, 10S–10N)

Iterative approach for correcting heating

- The resultant heating rate Q_3 is much closer to Q_{ERA} than Q_0, i.e. the mean-squared error, integrating over all relevant grid points, is much smaller:

$$||Q_{ERA} - Q_3||^2_F << ||Q_{ERA} - Q_0||^2_F$$

- Minimizing the mean-squared error is equivalent to maximizing the fraction of variance of Q_{ERA} explained by Q_n (FVE), given by:

$$FVE(n) = 1 - ||Q_{ERA} - Q_n||^2_F / ||Q_{ERA}||^2_F$$

- This is done for the JJAS mean, for the seasonal trend, and for the seasonal parabolic fit for each year over a 20 year period (1997-2016)

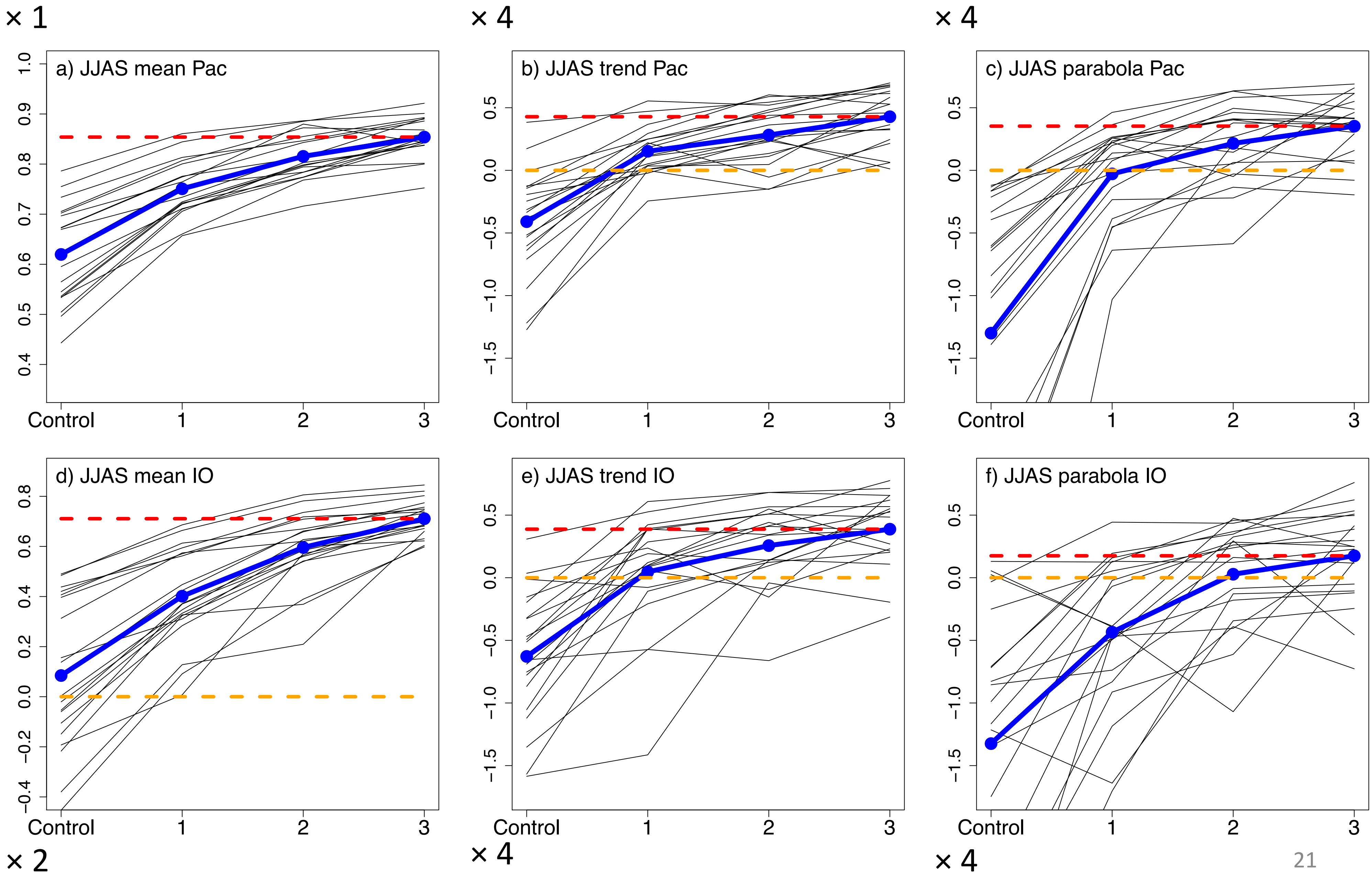
Sensitivity of iterative procedure

- Technique recently applied to both CFSv2 and CESM by Swenson et al. (2019), J. Atmos. Sci. - tropical heating corrected for two winter seasons:
- CFSv2 is *much more* sensitive compared to CESM with convergence requiring only 2 iterations adding in 10% of difference compared to 5 iterations adding in 20-40% of difference required for CESM

- Necessary sensitivity testing made using fewer ensemble members (i.e., e=5), adding in larger fraction of difference with ERA-Interim, and performing more iterations

- Choice of 10 members with 3 iterations of 10% yields adequate estimate of ensemble mean with significant error reduction for each iteration (to a much lesser extent for last iteration)

Iterative approach for correcting heating



References

Gadgil, S., P. N. Vinayachandran, P. A. Francis and S. Gadgil, 2004: Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophys. Res. Lett*., **31**, L12213, doi:10.1029/2004GL019733.

Jang, Y., and D. M. Straus, 2012: The Indian Monsoon Circulation Response to El Nino Diabatic Heating. *J. Climate,* **25,** 7487-7508. doi: http://dx.doi.org/10.1175/JCLI-D-11-00637.1

Jang, Y., and D. M. Straus, 2013: Tropical Stationary Wave Response to ENSO: Diabatic Heating Influence on the Indian summer monsoon, *J. Atmos. Sci.*, 70, 193-222. doi: http://dx.doi.org/10.1175/JAS-D-12-036.1

Straus, D. M., E. Swenson and C.-L. Lappen, 2015: The MJO Cycle Forcing of the North Atlantic Circulation: Intervention Experiments with the Community Earth System Model. *J. Atmos. Sci.,* **72**, No. 2: pp. 660-681.

Swenson, E., D. M. Straus, C. E. Snide and A. al Fahad, 2019: The Role of Tropical Heating and Internal Variability in the California Response to the 2015/16 ENSO Event. *J. Atmos. Sci.*, **76**, 3115-3128.

Wu, R., and B. P. Kirtman, 2004: Impact of the Indian Ocean on the Indian Summer Monsoon-ENSO Relationship. *J. Climate*, **17,** 3037-3054.

Yadav, P., D. Straus and E. Swenson, 2019: The Euro-Atlantic Response to the Madden-Julian Oscillation Cycle of Tropical Heating: Coupled GCM Intervention Experiments. *Atmos. – Ocean*, **57,** 161-181. DOI: 10.1080/07055900.2019.1626214.

Technical details – heating truncation

- Need to minimize size of input data for computational efficiency for reading and storing data

- Need also to represent heating analytically in space and time – for fast local construction of heating during model integration and for interpolation (e.g. forcing both low and high resolution CFSv2)

- Spatial truncation: 30 harmonics in longitude, 20 Hermite polynomials in latitude, 20 pressure levels (with linear interpolation in between)
- Corresponding heating coefficients represent about 90% of spatial variation on original grid while storage is 0.8% the original size on model grid

- Temporal truncation: 3 Legendre polynomials (mean+trend+parabola)

Technical details – CFSv2 source code

- During model initialization, read in all added heating coefficients once (*GFS_Initialize_ESMFMod.f* calls new subroutine)

- At each time step, additional temperature tendency introduced immediately prior to tendencies applied to U, V, T and Q (*gbphys_v.f* calls new subroutine)

***heating.f*:**
- Contains relevant subroutines for reading in heating coefficients, reconstructing heating, and updating temperature tendency
- Reconstructs heating based on coefficients and adds to temperature tendency within regional domain – determined based on longitude, latitude and pressure of current chunk of data that is being handled by particular processor

- CFSv2 run on Pleiades - NASA High-End Computing (HEC) Program

Technical details – outputting total diabatic heating

- In CFSv2 configure file (parm directory), turn on 3-D diagnostics:

ldiag3d=${ldiag3d:-.true.}

- Set output frequency to every 6 hours
- Results in output of tendencies (d3df* files) that include six components that sum to the total model diabatic heating rate:

latent heating from convective (CNVHR) and large-scale (LRGHR) moist processes, heating from longwave (LWHR) and shortwave (SWHR) radiation, heating from vertical diffusion (VDFHR) and sensible heating (SHAHR)

- Sum up components and interpolate in vertical from hybrid to pressure levels

- Model heating is quite consistent with residual estimate (computed using model winds, temperature and humidity)