CLIM 670 Earth System Modeling
George Mason University

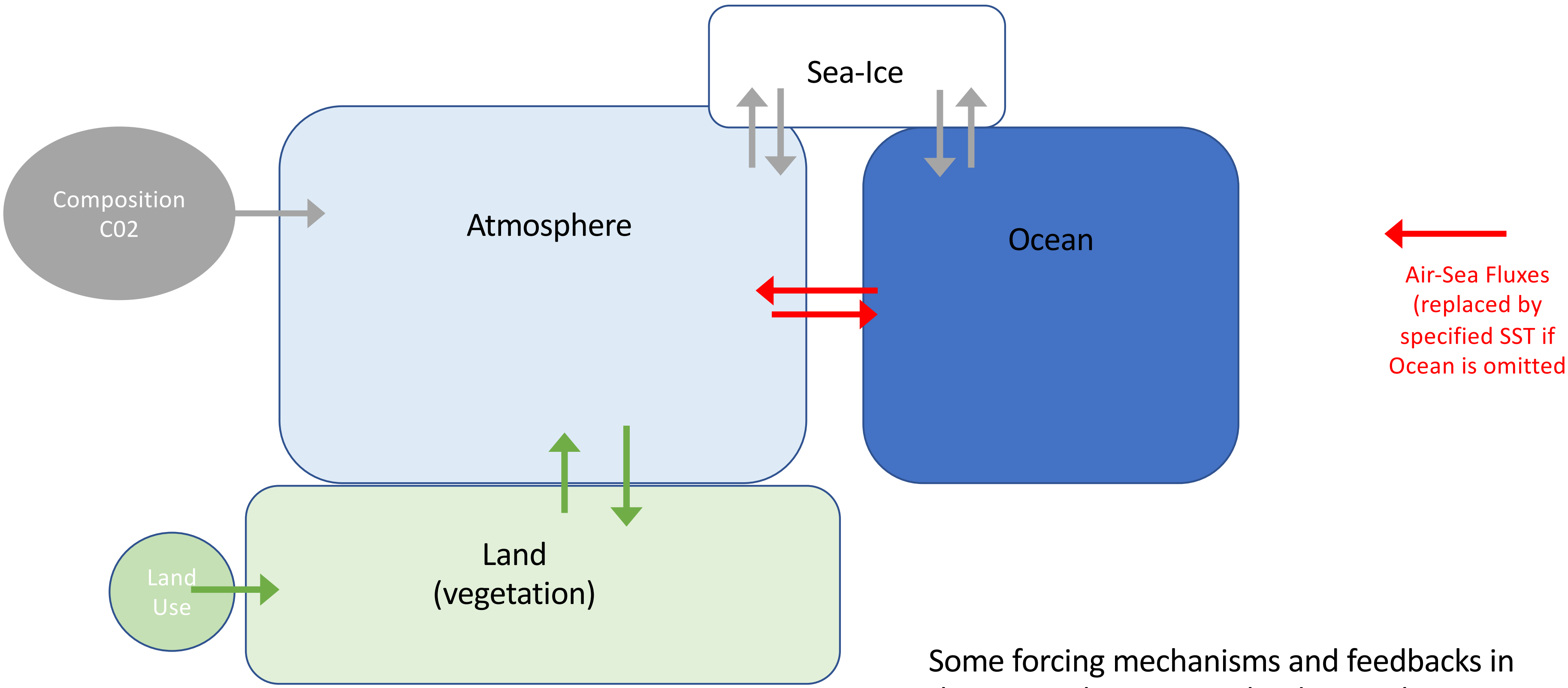
Intervention Experiments

David M. Straus

1. Introduction To Feedbacks in the Atmosphere-Ocean-Land-Cryosphere System

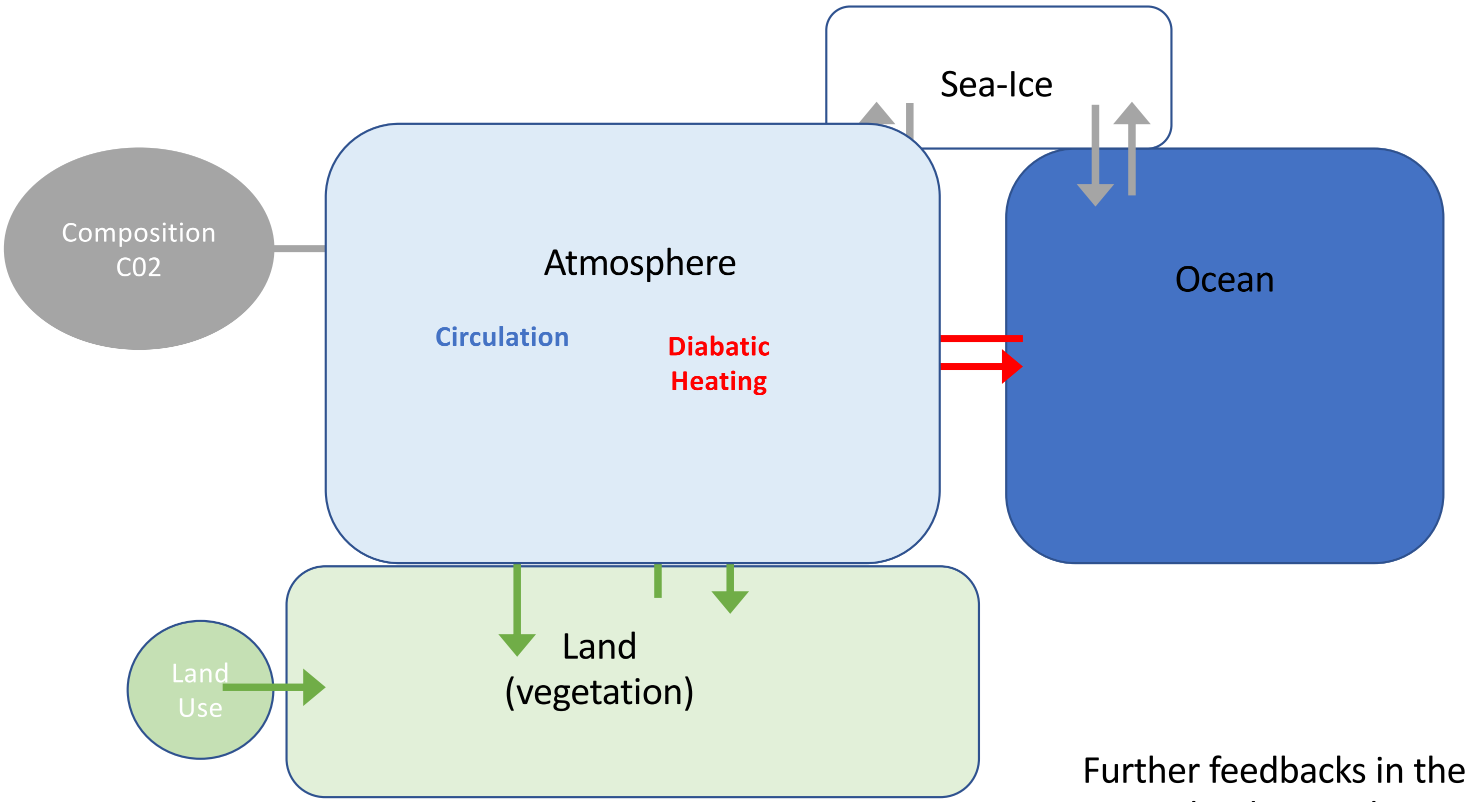
2. Experiments to Specify atmospheric diabatic heating

3. Experiments to Guide the atmosphere diabatic heating with added heating



Some forcing mechanisms and feedbacks in the atmosphere-ocean-land cryosphere system

1. Introduction To Feedbacks in the Atmosphere-Ocean-Land-Cryosphere System

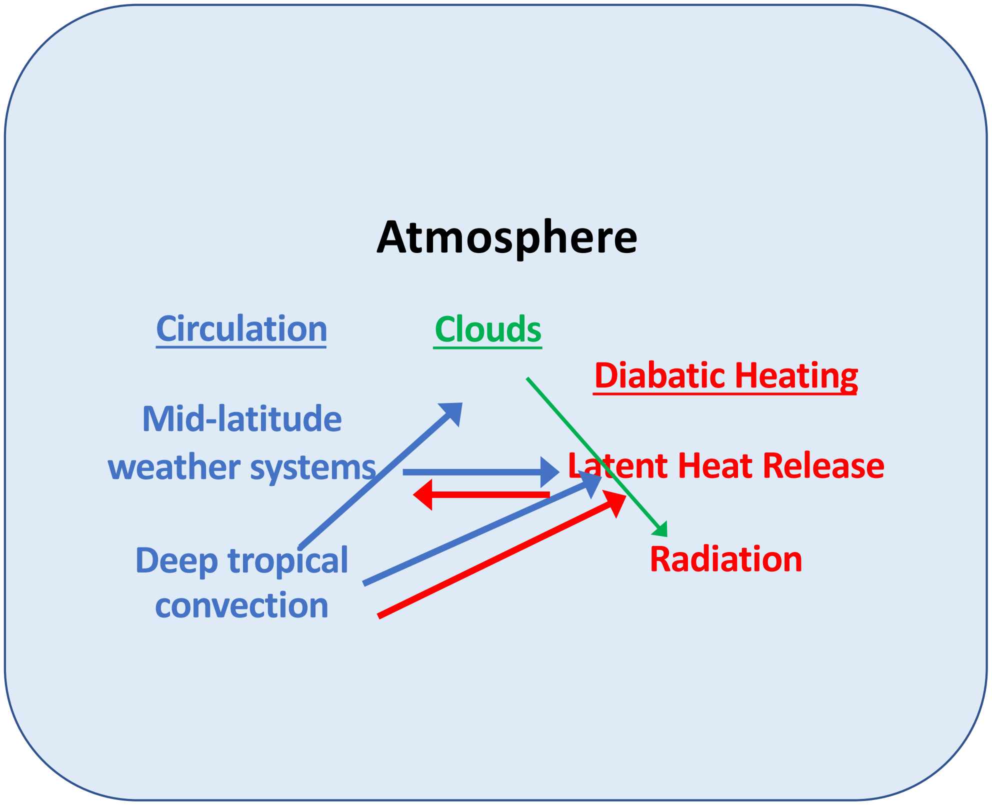


Air-Sea Fluxes
(replaced by
specified SST if
Ocean is omitted)

Application: ENSO

Further feedbacks in the atmosphere-ocean-land cryosphere system

1. Introduction To Feedbacks in the Atmosphere-Ocean-Land-Cryosphere System

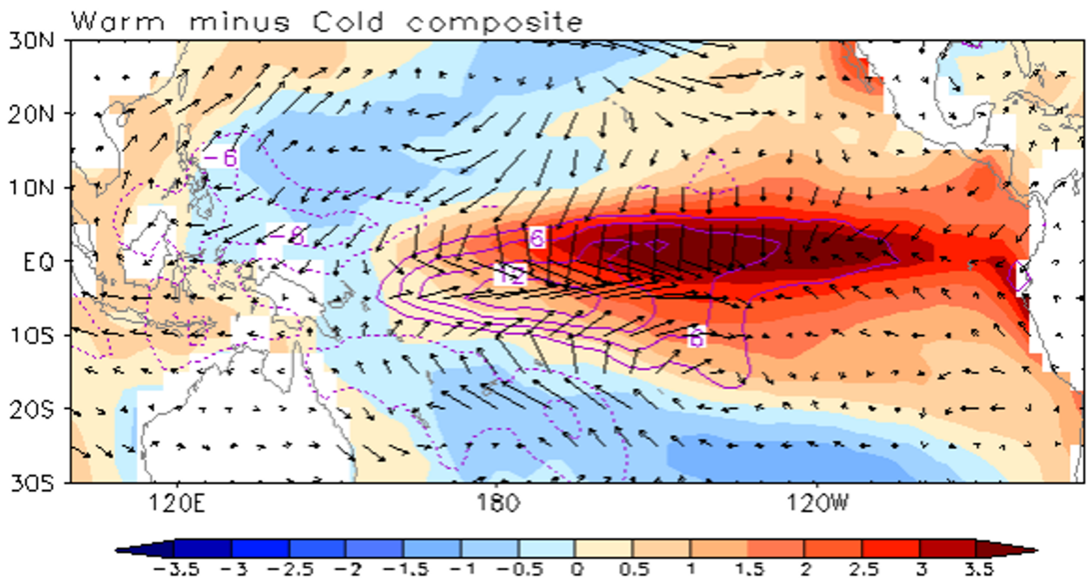


Heating + Clouds + Circulation feedbacks; Madden-Julian Oscillation

Introduction To Feedbacks in the Atmosphere System

2. Experiments to Specify atmospheric diabatic heating

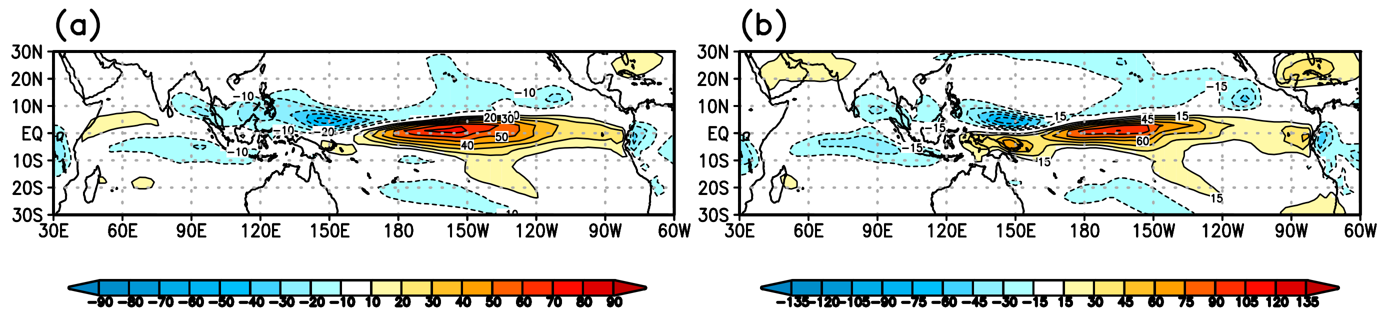
Understanding the Response to The El-Nino Southern Oscillation



During an El-Niño, the eastern Pacific SST is unusually warm.
The plot shows the difference between the El-Niño phase and its opposite (La-Niña)

2. Experiments to Specify atmospheric diabatic heating

Understanding the Response to The El-Nino Southern Oscillation



$$\frac{\partial \theta}{\partial t} + \vec{u} \cdot \overrightarrow{\nabla\theta} + \frac{\partial \theta}{\partial p} = \frac{1}{c_p}\left(\frac{p_0}{p}\right)^{\kappa} Q$$

Note that Q is computed by the model's parameterizations

Difference between DJFM mean vertically integrated **diabatic heating Q** for 3 warm events and Climatology, in Wm^{-2}, from ERAI.

Large anomaly of heating due to SST anomalies: The Warm Pacific Ocean persists throughout the winter, and can be considered a forcing on the atmosphere.
What is the remote seasonal mean response?

The atmospheric response to the warm ocean surface temperature anomalies depends on the atmospheric circulation:

(1) – in the presence of low-level tropical convergence, warm ocean surface leads to increasing rising motion.

(2) – an increase in rising motion of moist air leads to condensation of water, and release of latent heat, which further increases the rate at which air rises. This is deep convection in the tropics

(3) – this leads to high-level clouds, which then affects the radiative heating

(4) - The heating and rising motion produces upper level divergence and vorticity anomalies, which form a source for the propagation of stationary Rossby waves.

The top panel shows the DJFM 200 hPa Z for the 3 warm events, minus climatology.

“ENSO SIGNAL”

The bottom panel shows the anomaly for the storm tracks as measured by the DJFM mean of v’v’ at 300 hPa, where v’ is the meridional wind filtered to retain periods of less than 10 days

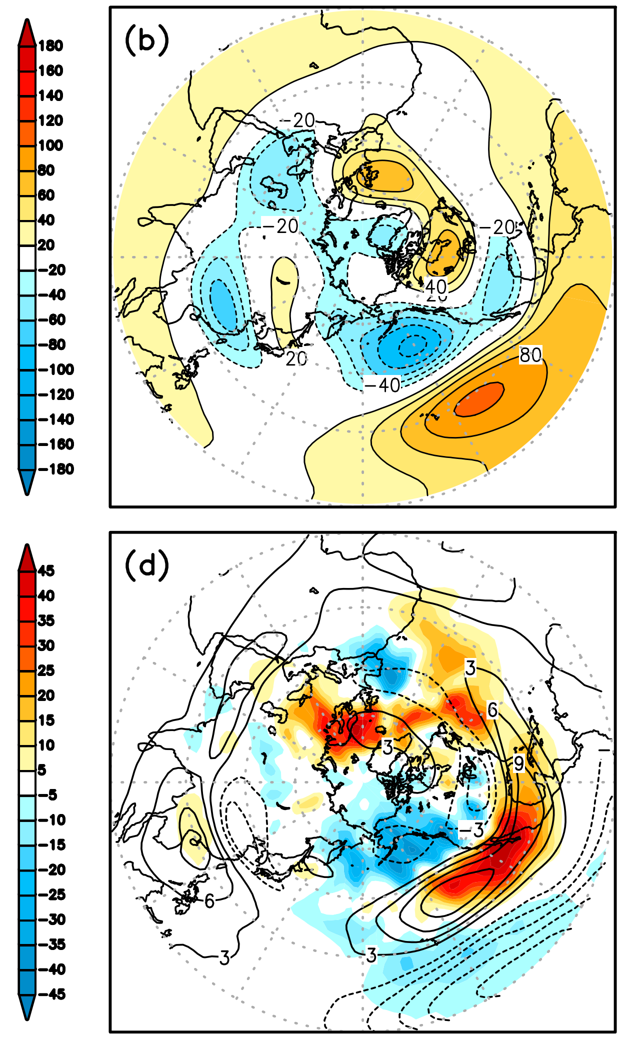


FIG. 4. (a) (b) Seasonal-mean 200-hPa geopotential height (interval of 20 m) and (c) (d) seasonal-mean 300-hPa

Two interesting questions that relate to the predictability of the mid-latitude response:

(1) The observed seasonal mean response to the El-Nino SSTs can be captured by AGCMs with specified (observed) SST, *but only if an ensemble mean is taken!* The response to a single seasonal integration of an AGCM seems to vary just by changing the initial condition, so in order to get what we think is the "true" forced SST signal we use many such integrations (an "ensemble") and take the average anomaly

WHY do we need to take the ensemble mean to get the signal that nature gets in only one realization?

→

(2) Does the nature of the time mean response remote depend only on the time mean heating? *Convection, and hence diabatic heating, in the tropics is very intermittent (or sporadic).* Do the statistics of the heating (beyond just its seasonal mean) matter at all?

Strategy: Capture the evolution of diabatic heating produced by the model's parameterizations in 50 AGCM ensemble members made for each of 3 observed El-Nino events. (**EXPERIMENT CTL**)

Compute the seasonal and ensemble **DJFM mean of that heating (in 3 dimensions) → Q_0**

Compute the **deviation of the DJFM mean heating of each ensemble member about Q_0 → Q_1**

Compute **the fluctuations of the heating about the seasonal mean with low frequencies (periods of 30-120 days) → Q_{low}**

Re-run these 3 x 50 seasonal integrations in which the diabatic heating coming out of the parameterizations is replaced before it is added to the temperature tendency by:

(a) **Q_0** - all ensemble members see the same fixed heating QFIX at all times EXPERIMENT FIX

(b) **Q_0 + Q_1** – each ensemble member sees its own seasonal mean at all times EXPERIMENT EFIX

(c) **Q_0 + Q_{1+} + Q_{low}** – each ensemble member sees its low frequency total heating. EXPERIMENT ESUBFIX

IN EACH EXPERIMENT THE SEASONAL ENEMBLE MEAN HEATING IS THE SAME !
(however we have totally disabled the feedbacks from the circulation to the heating)

Results of ENSO SIGNAL for ***CTL***

Z200 seasonal ensemble mean (top)

Storm tracks (bottom)

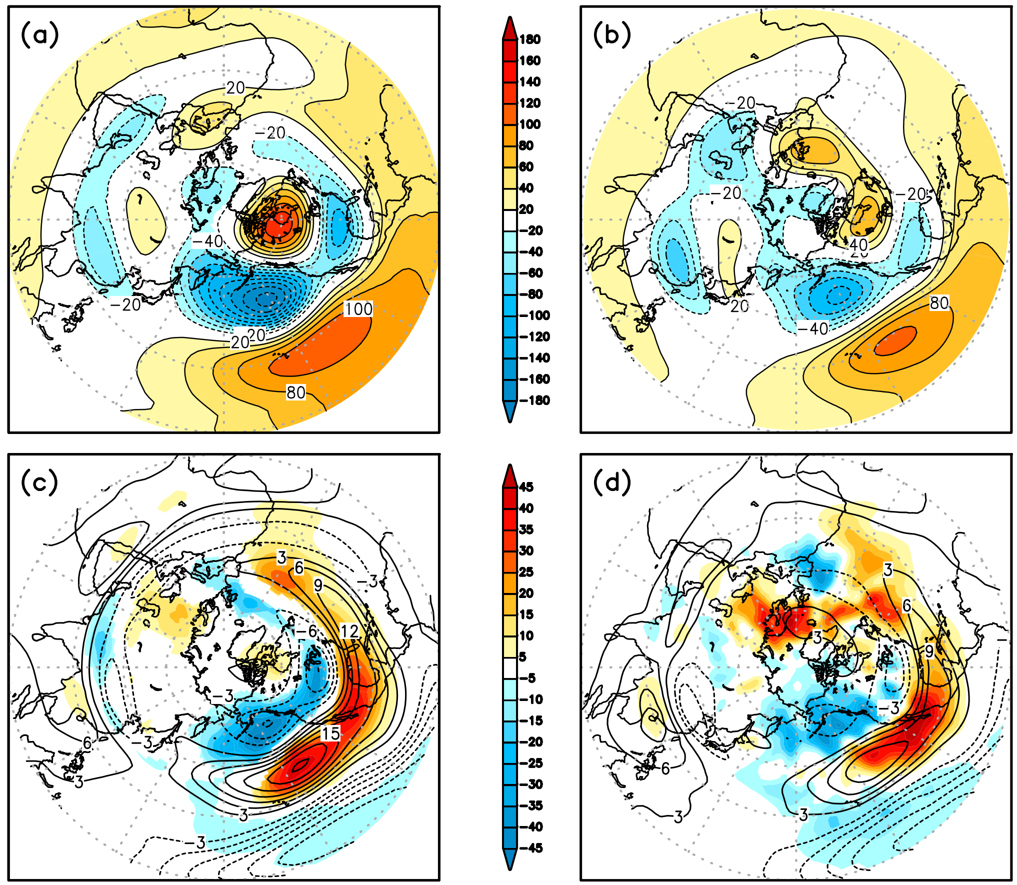


FIG. 4. (a),(b) Seasonal-mean 200-hPa geopotential height (interval of 20 m) and (c),(d) seasonal-mean 300-hPa $\overline{v'v'}$ (shaded, interval of 5 $m^2 s^{-2}$) with 200-hPa zonal wind (contours, interval of 3 $m s^{-1}$) for (left) CAM4.0 El Niño CTL minus CLIM ensemble mean and (right) ERA-40 (DJFM composite minus 23-yr climatological average, spanning 1979/80–2001/02). Domains span the Northern Hemisphere (centered on the North Pole). Shading for CAM4.0 El Niño CTL minus CLIM ensemble-mean 200-hPa height and 300-hPa $\overline{v'v'}$ represents significance at 5% level beginning at ± 20 m and ± 5 $m^2 s^{-2}$, respectively.

Transient Tropical Diabatic Heating and the Seasonal-Mean Response to ENSO

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DAVID M. STRAUS
George Mason University, Fairfax, Virginia

We generate ensembles of seasonal simulations (CTL) under the framework of the Atmospheric Model Intercomparison Project (AMIP) constrained by the observationally based SST and sea ice. Spanning boreal winter [November–March (NDJFM)], the simulations are forced with boundary conditions corresponding to a few significant observed warm ENSO episodes: 1982/83, 1991/92, and 1997/98.

$$\mathbf{Q_c(t, e) = Q_0(t) + Q_1(e) + Q_{low}(t, e) + Q_{high}(t, e)}$$

where t and e are discrete indices denoting time step and ensemble member, respectively.

The variable Qc is partitioned into the smoothed ensemble-mean signal Q_0, the seasonal-mean ensemble deviation about that signal Q_1, the 30–120-day low-frequency variability Q_{low}, and the high-frequency (less than 30-day period) variability Q_{high}.
The component Q_0 is essentially a smooth seasonally evolving ensemble mean.
The component Q1 is constructed by taking the seasonal mean of Q - Q_0 for each ensemble member.

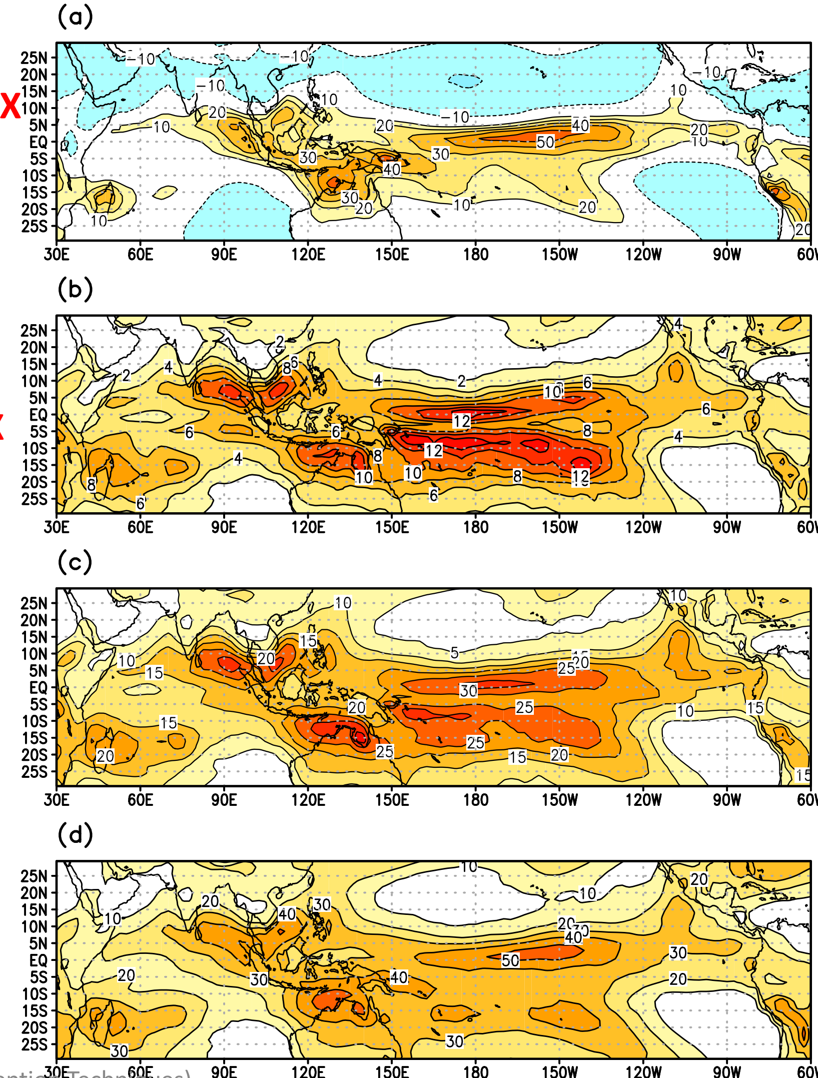
Vertical integral of Heating seen by FIX

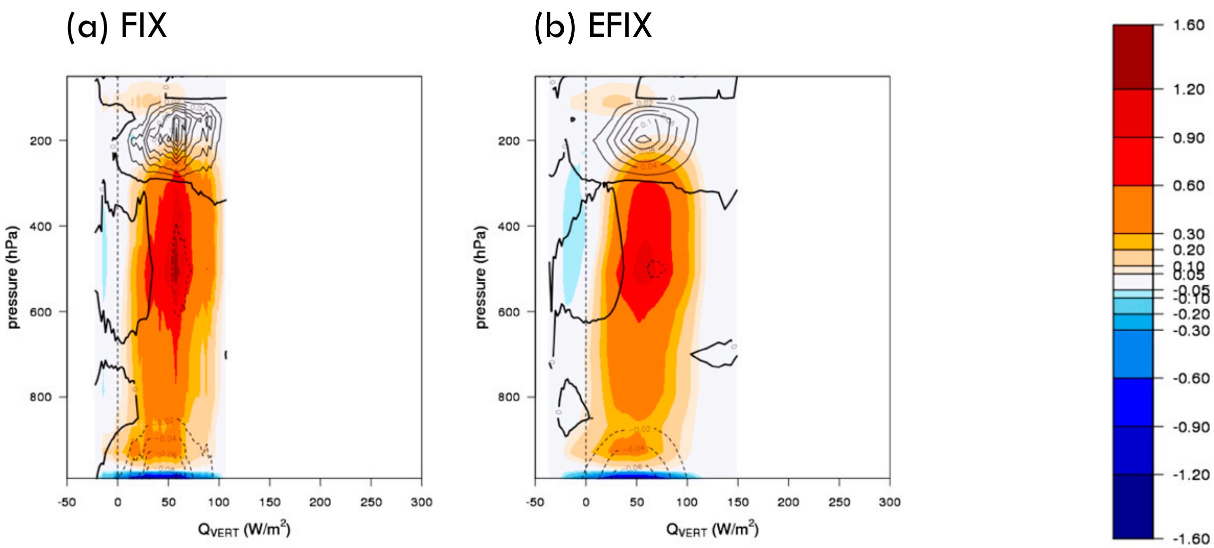
TABLE 1 . Experimental simulations and prescribed Q varying in time t and ensemble member e at every grid point across the tropical Indo-Pacific.

FIX	$Q(t, e) = Q_0(t, e)$
EFIX	$Q(t, e) = Q_0(t, e) + Q_1(t, e)$
ESUBFIX	$Q(t, e) = Q_0(t, e) + Q_1(t, e) + Q_{\mathrm{low}}(t, e)$

Std of Heating seen by EFIX

Std of Heating seen by ESUBFIX

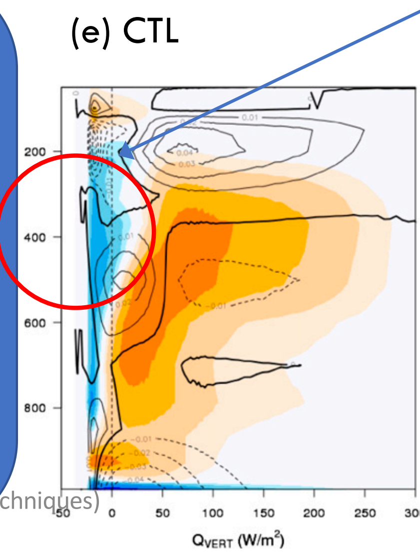




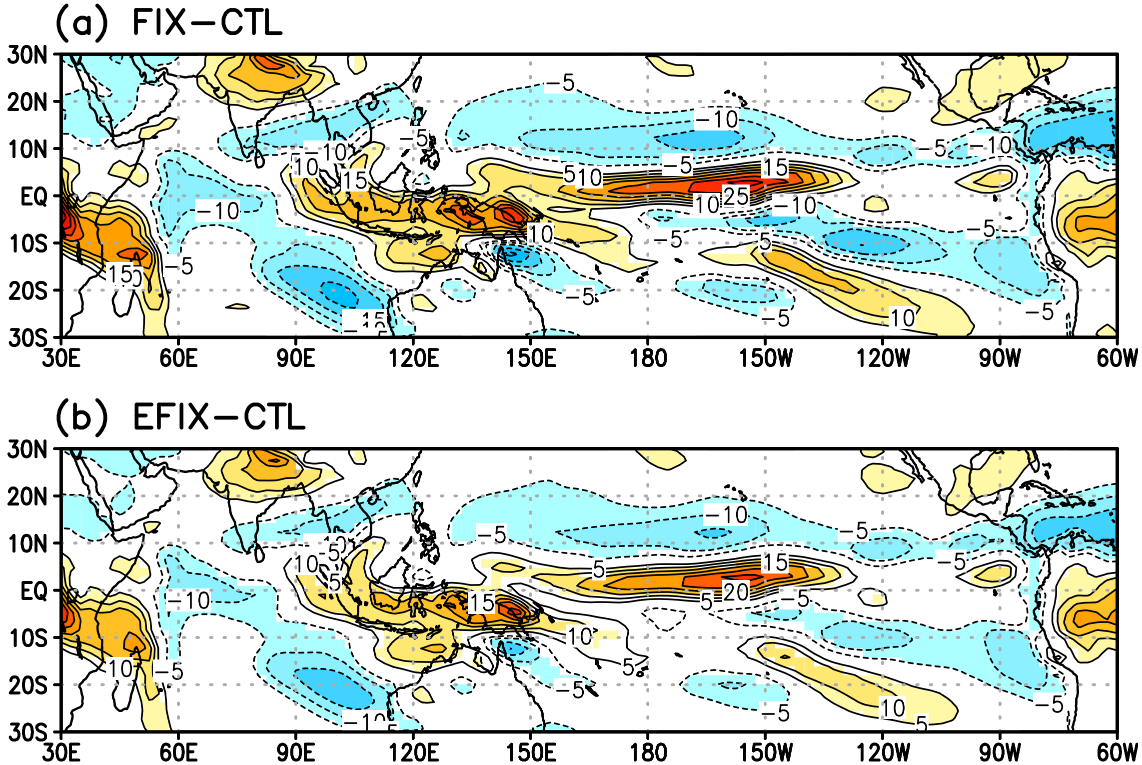
Main points:

Notice the presence of larger values of heating at 400 hPa in CTL than in FIX or EFIX, compensated for by much greater cooling in CTL than in FIX or EFIX

Histograms of diabatic heating as a function of pressure (y-axis) &
vertical integral (x-axis)
Histograms are weighted by their contribution to the seasonal ensemble mean



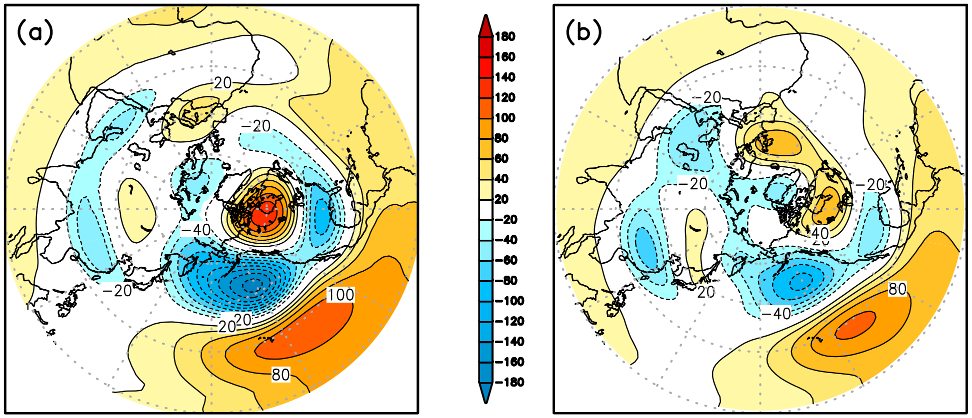
CTL run has the natural intermittent heating acting in it.



Using time-mean heating produces a larger upper tropospheric Rossby wave source !

200 hPa DIVERGENCE
TOP: FIX minus CTL
BOTTOM: EFIX minus CTL

May 2015 SWENSON AND STRAUS 1897

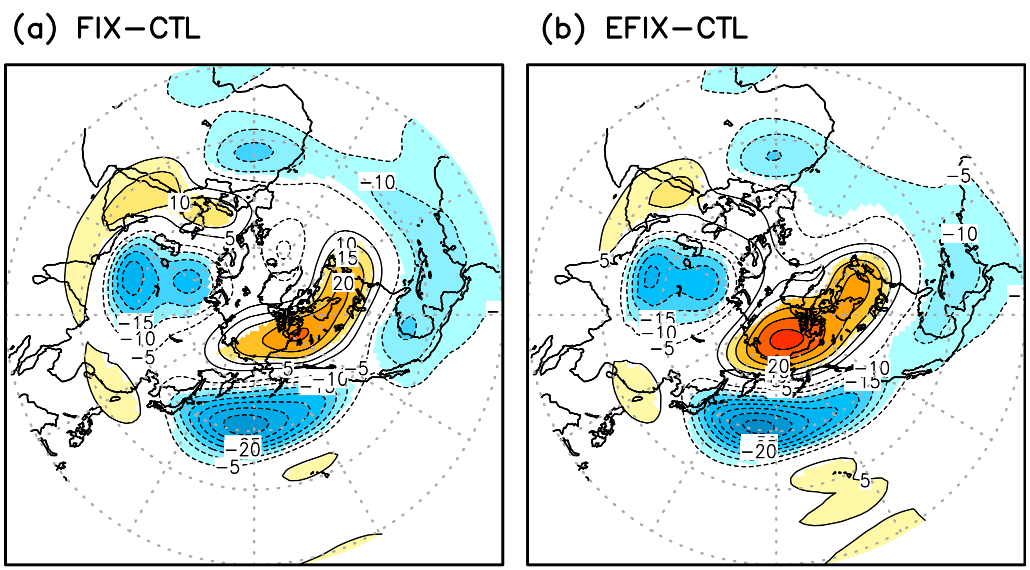


ENSO SIGNAL

200 hPa GEOPOTENTIAL HT.

LEFT: CTL

RIGHT: ERAI



ENSO SIGNAL

200 hPa GEOPOTENTIAL HT.

LEFT: FIX minus CTL

RIGHT: EFIX minus CTL

Using time-mean heating produces a larger ENSO signal !

3. Experiments to Guide the atmosphere diabatic heating with added heating

Background:

The Madden-Julian Oscillation: Organization of tropical convection on intra-seasonal time scales (30 to 60 days).

It is defined using *highly-filtered* near-equatorial fields of zonal winds and OLR (as a proxy for diabatic heating)*

*Low tropical OLR means very high (& cold) cloud tops, since OLR ~ σT^4

Of great interest is the remote mid-latitude *Euro-Atlantic* response to the MJO heating.

Warnings:

(A) Individual MJO episodes involve moving heating/cooling anomalies at different phase speeds

(B) The remote response will not be as straightforward to model as with ENSO because there will be wave interference.

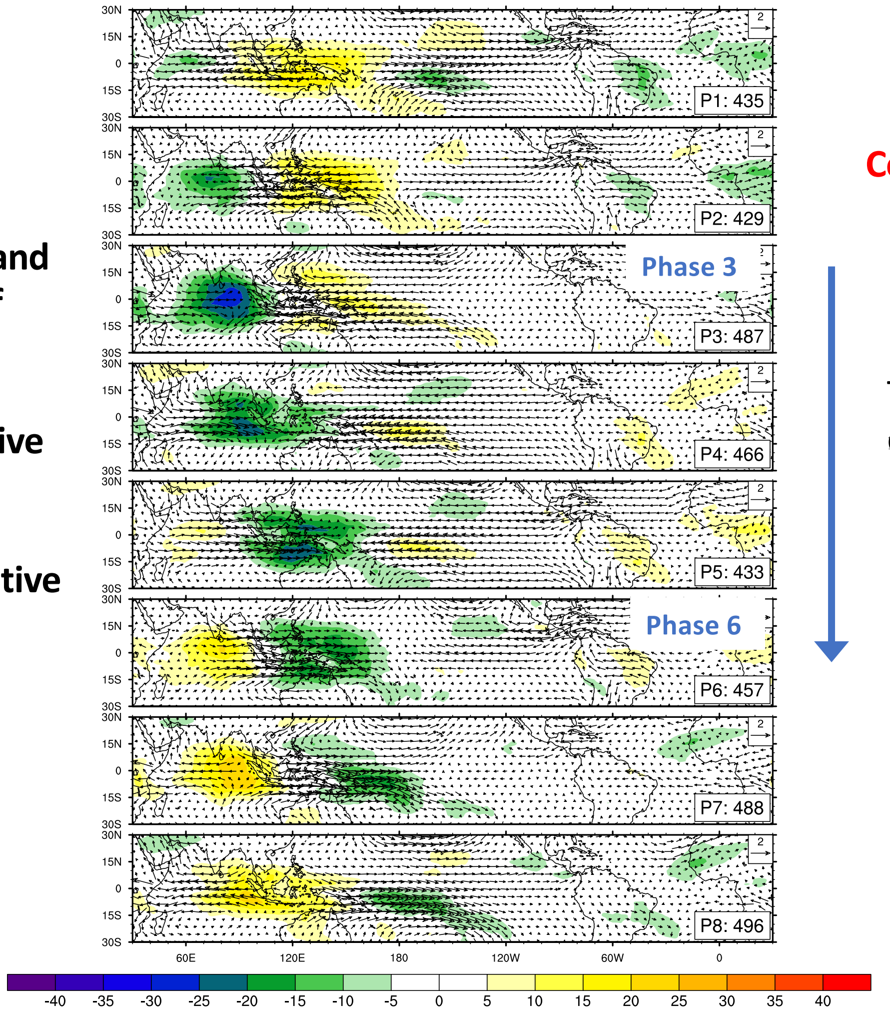
Yadav, P. and D. M. Straus, 2016

1980-2012: Oct to March

Composites of OLR and u850 for 8 phases of the MJO.

Green colors – positive heating anomalies

Yellow colors – negative heating anomalies



Composite of tropical OLR for *all* MJO episodes

Time increases downward

MONTHLY WEA

FIG. 3. Histogram of propagation time from phases 3 to 6.

Warning A

Wave Interference

2-day pulse at 0°N,135°E

2-day pulse at 0°N, 120°W

Model responses to 2-day pulses of tropical heating (*very* large ensemble)

Pulses turned off after days but response keeps growing

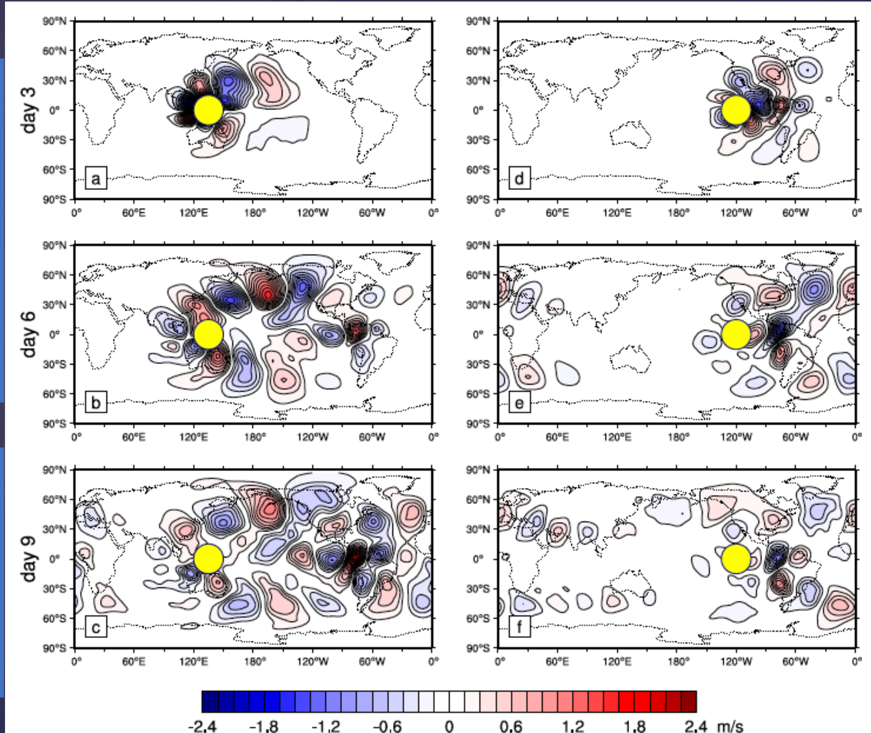


FIG. 3. Ensemble mean $v300$ response in CAM3 to a 2-day pulse of heat at 0°N, 135°E (a) 3, (b) 6, and (c) 9 days after the pulse begins. (d)–(f) As in (a)–(c), but for a pulse at 0°N, 120°W.

Response after 6 days resembles stationary response to long-term mean heating

Warning B Interference

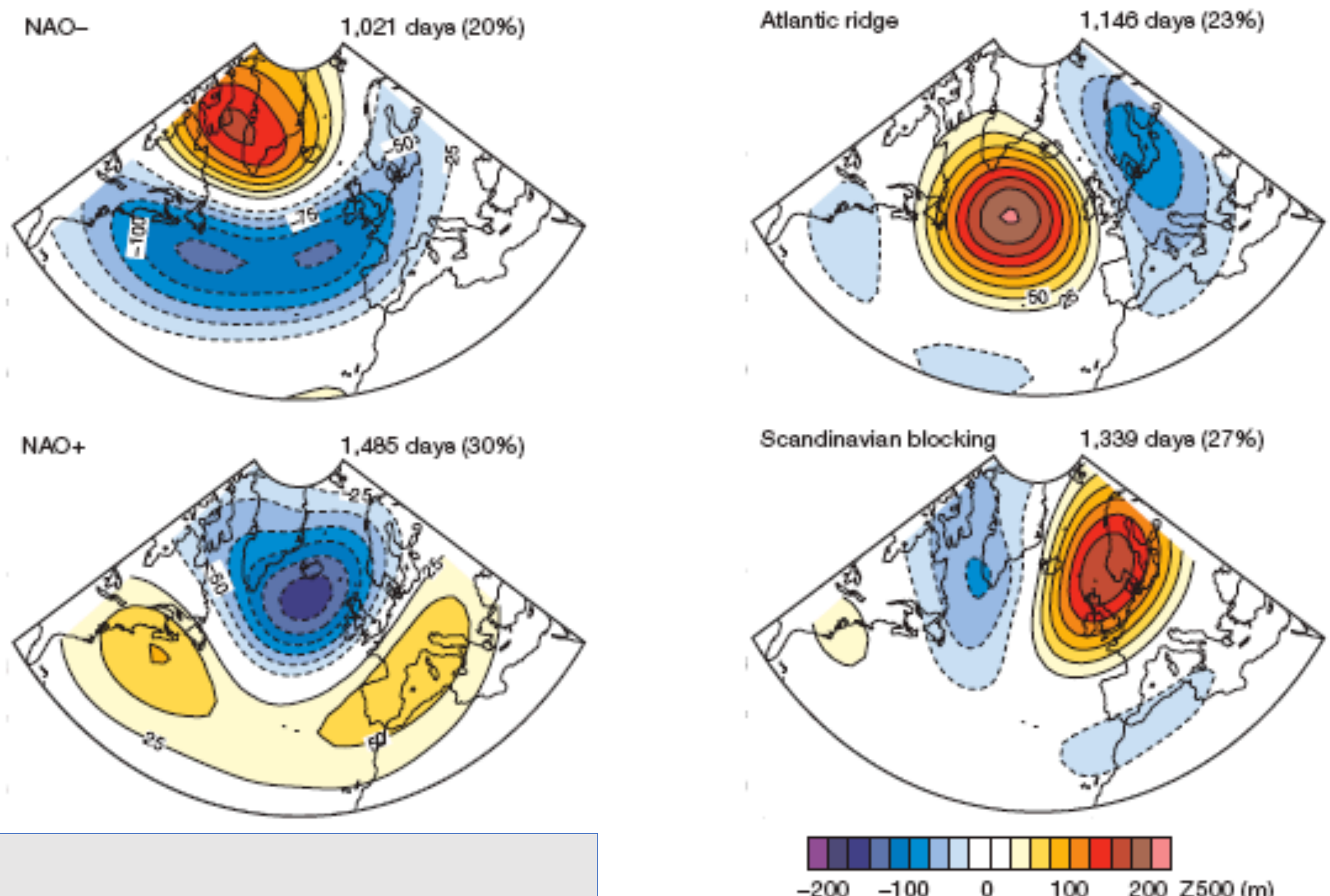
Ensemble mean v300 response in CAM3 to a 2-day pulse of heat at 0°N,135°E (a) 3, (b) 6, and (c) 9 days after the pulse begins. (d) – (f) as in (a) – (c), but for a pulse at 0°N, 120°W.

Grant Branstator, 2014: Long-Lived Response of the Midlatitude Circulation and Storm Tracks to Pulses of Tropical Heating. *J. Climate*, **27**, 8809–8826.

1

MJO has a measurable effect on the Euro-Atlantic circulation

Characteristic daily circulation regimes in 500 hPa geop. ht for boreal winter.

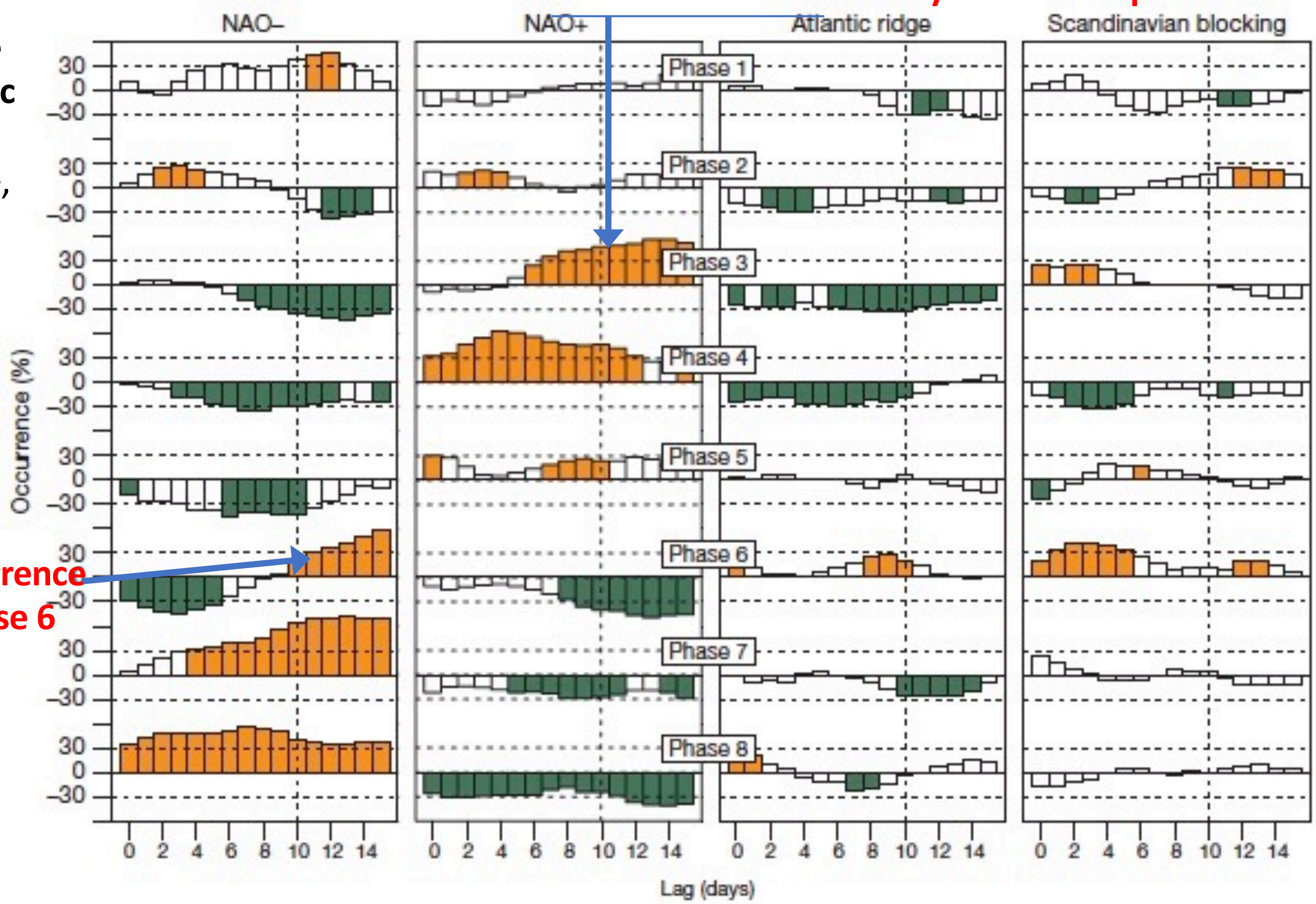


Cassou 2008

Figure 1 | Wintertime North Atlantic weather regimes. Centroids of the four weather regimes obtained from daily anomalous geopotential height at

Increase in NAO+ occurrence 10 days after MJO phase 3

columns are Euro-Atlantic patterns:
NAO-, NAO+, Atl Ridge & Scan Block



Rows are MJO phases

Increase in NAO- occurrence 10 days after MJO phase 6

Figure 3 | Lagge … change in the **the four North A** … on the basis of χ^2 MJO phases (ro … anomalous each MJO phase, I plot the anomalous percentage occurrence of a given … frequency of occurrence is lower than the minimum significant threshold

Time axis (x-axis) is time after MJO in a particular phase

Does this picture change if we distinguish fast from slow episodes?

3. Experiments to Guide the atmosphere diabatic heating with added heating

Does the remote response to the Madden-Julian Oscillation diabatic heating depend on the phase speed of MJO episodes?

Challenge in this problem: Most GCMs do not simulate the MJO very well.

Thus we need to guide the model to produce the oscillation we want, *without interfering with the delicate feedbacks between heating, circulation and radiation* that are important for the MJO.

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.

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

Added heating guiding the model to produce a series of MJO episodes !

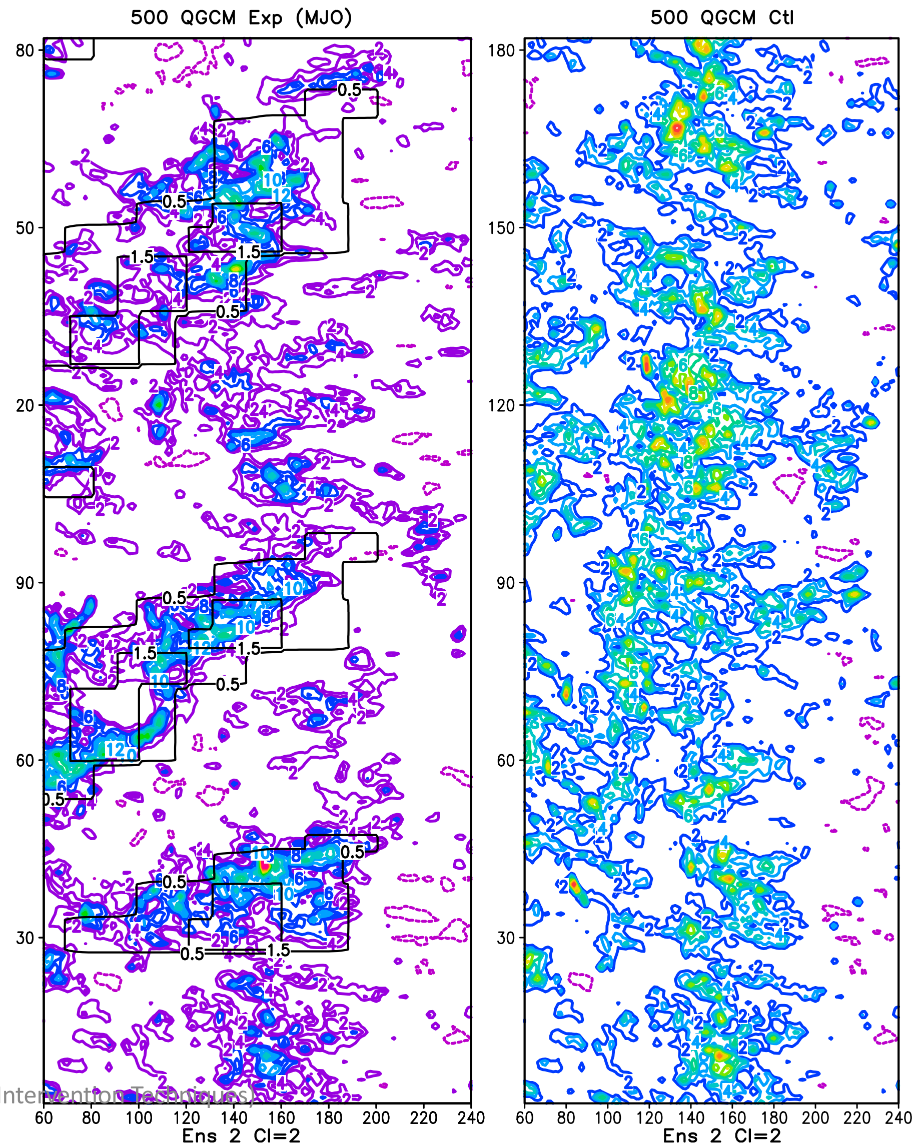
The Solution is to add a heating evolution ***Q(x,y,z,t)*** to the diabatic heating produced by the model's parameterizations – the total (model + added) heating is what acts on the temperature.

In the presence of all model feedbacks (none of which have been tampered with), added heating → more vertical motion → further surface convergence & rainfall → more latent heat release and heating !!!

So this positive feedback means we have to add a *very small* amount of heating - but it should have the right space-time properties.

Left panel shows total heating (at 500 hPa) for one DJF simulation of CESM (coupled model) with added heating in block contours (avg. 10S-10N) longitude is x-axis, time is y-axis.

Right panel shows model heating without added heating. (all heating in K/day)



Now we have the tool to distinguish:
(a) the Euro-Atlantic signal propagating from the "fast" episode heating
from
(b) the Euro-Atlantic signal propagating from the "slow" episode heating

- **Add one or more slow episode MJO heating evolutions to an ensemble of 50 seasonal simulations**

- **Repeat but with fast episode MJO heating evolutions.**

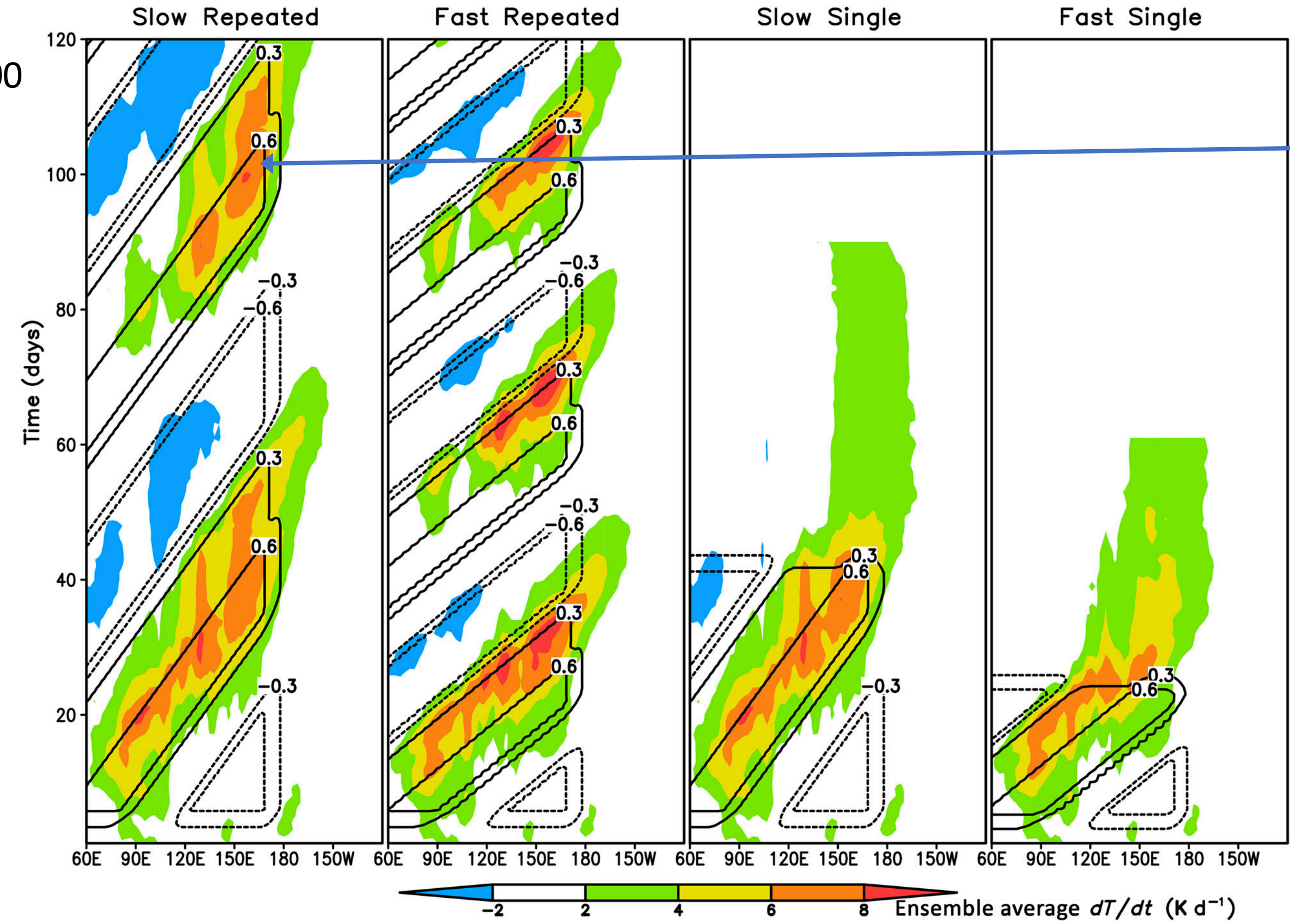
(Note that the identical heating evolution is added to each ensemble member)

Evolution of Q at 500 hPa (10S-10N)

Contours:
Added heating
(0.3 K/day contour)

Shading:
Ensemble mean total heating

Total heating >>
added heating

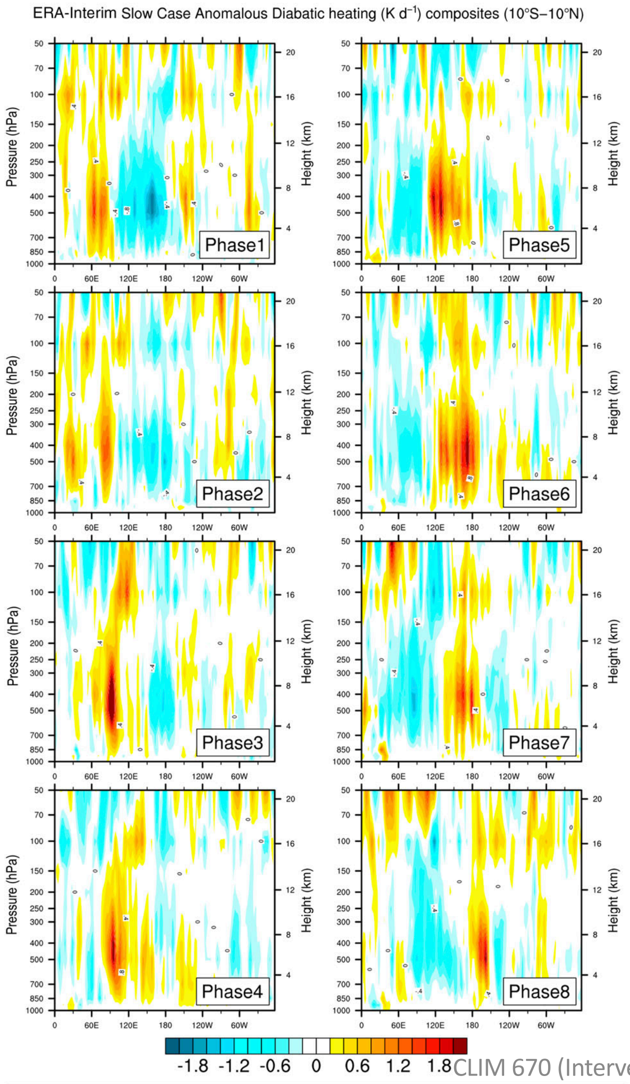


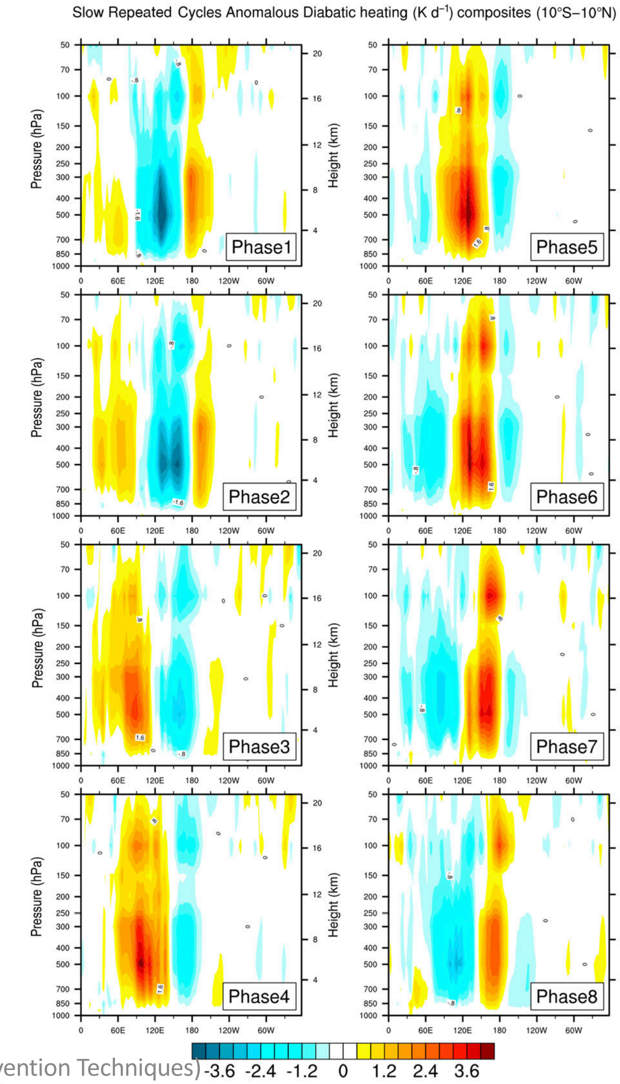
Note that in repeated episodes, the model responds more slowly in the 2nd episode. This is possibly a result of *wave interference*.

The shaded region shows ensemble average temperature tendencies due to all diabatic heating processes (including model-generated heating) at 500 hPa averaged from 10°S to 10°N for Slow Repeated Cycles, Fast Repeated Cycles, Slow Single Cycle, and Fast Single Cycle. The ordinate is forecast time up to 120 days starting from 1 December. Black contours show added heating with contour intervals of 0.3 K d−1.

ERA-I Slow Case Diabatic Heating Anomaly 10S-10N

Pressure longitude sections for each of 8 MJO phases





Model Slow Case Repeated Cycles Diabatic Heating Anomaly 10S-10N

Pressure longitude sections for each of 8 MJO phases

One important added benefit to the experimental design !

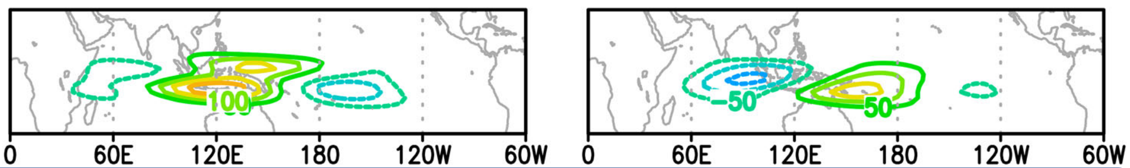
Since each of the 50 ensemble members has something in common day-by-day (namely that the added heating is identical across members for each day), we can use the technique called:

"Signal-to-Noise" Optimizing EOFs"
or
"*Predictable Component Analysis*"

While regular EOF analysis yields modes which explain the most space-time variance,
Predictable Component Analysis yields modes which have the greatest *signal-to-noise ratio*, which is defined as the ratio of the ensemble mean to the ensemble spread.

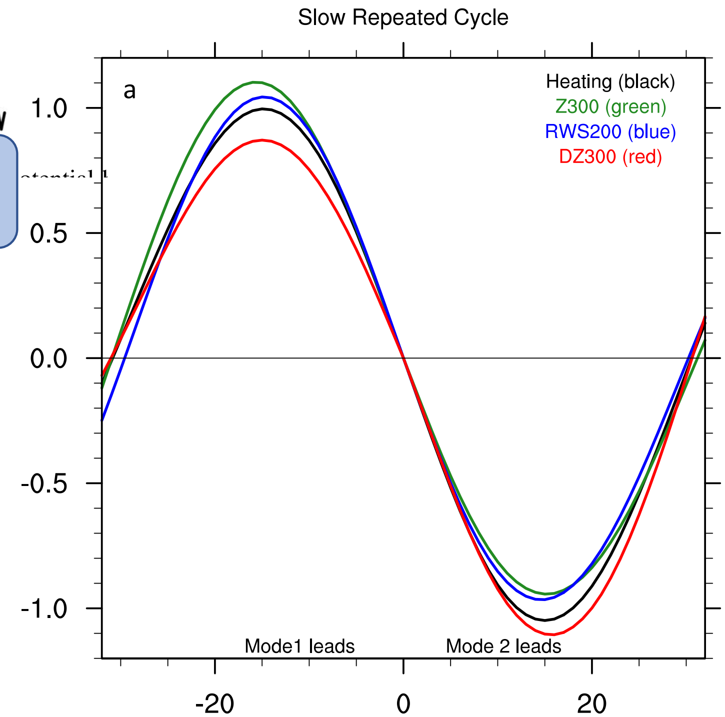
Leading Two modes of Planetary Wave Tropical Diabatic Heating in the [Slow Repeated Cycles Experiment] have space-time structure showing beautiful eastward propagation, with periods consistent with slow episodes

(e) Heating Optimal EOF 1 (f) Heating Optimal EOF 2



Spatial structure of leading two modes

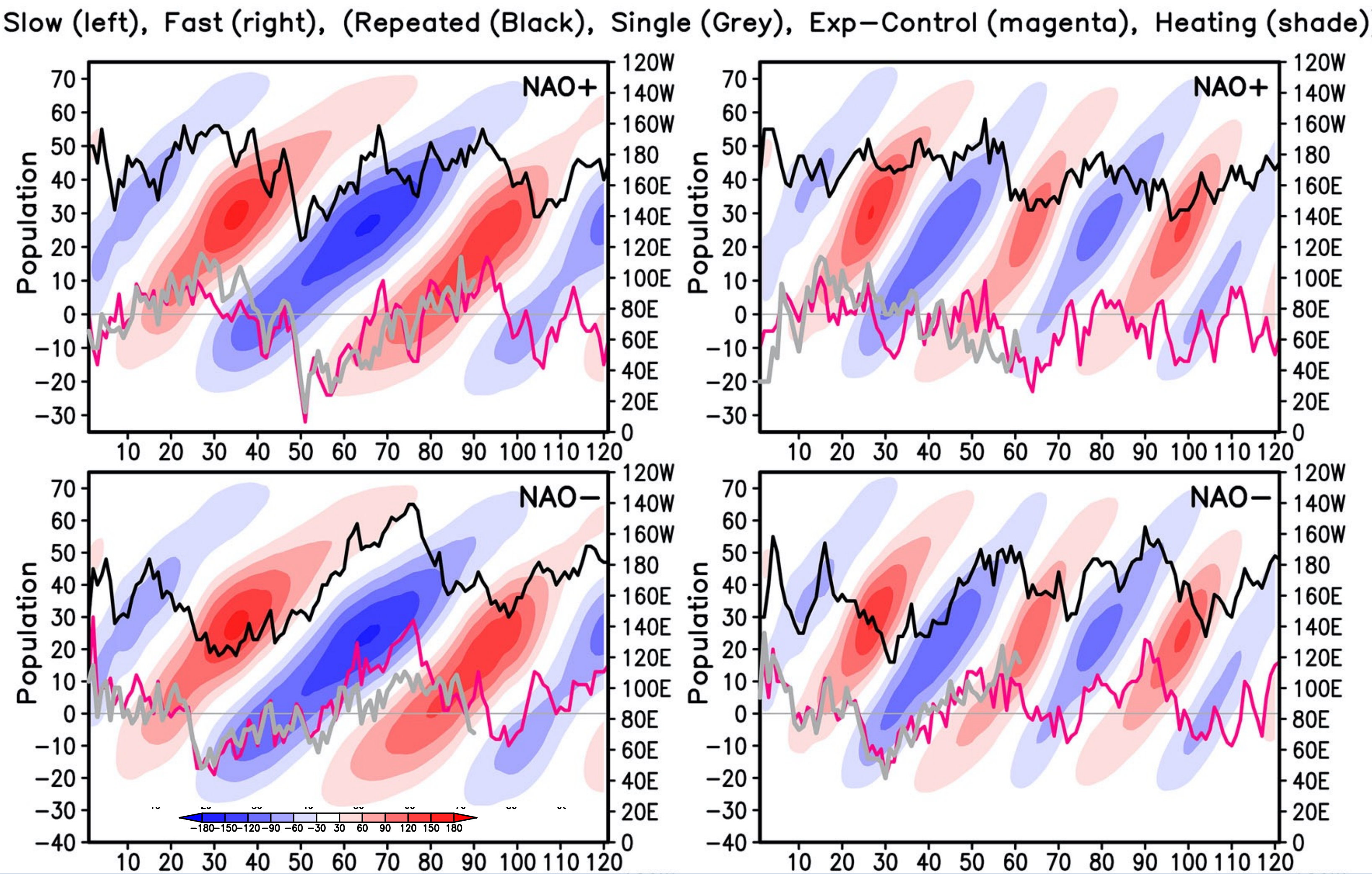
Correlation as a function of lag (in days)



Temporal Structure

Slow repeated cycles

Planetary Wave heating in Wm^{-2}



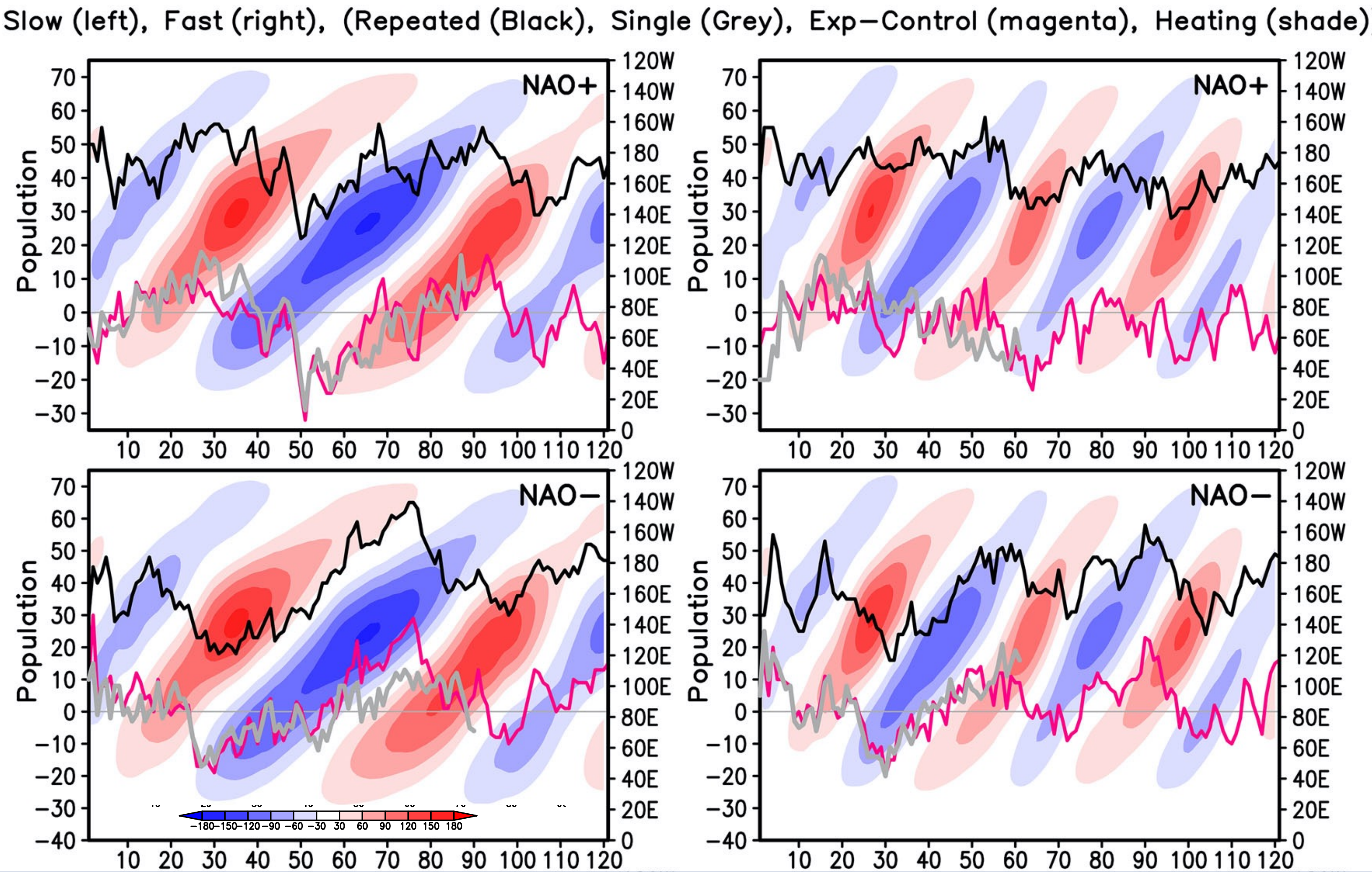
Fast repeated cycles

Planetary Wave heating in Wm^{-2}

Shading: 2 leading modes of heating put together as a function of time in days (x-axis) and longitude (right y-axis)

Slow repeated cycles

Slow minus CTL



Fast repeated cycles

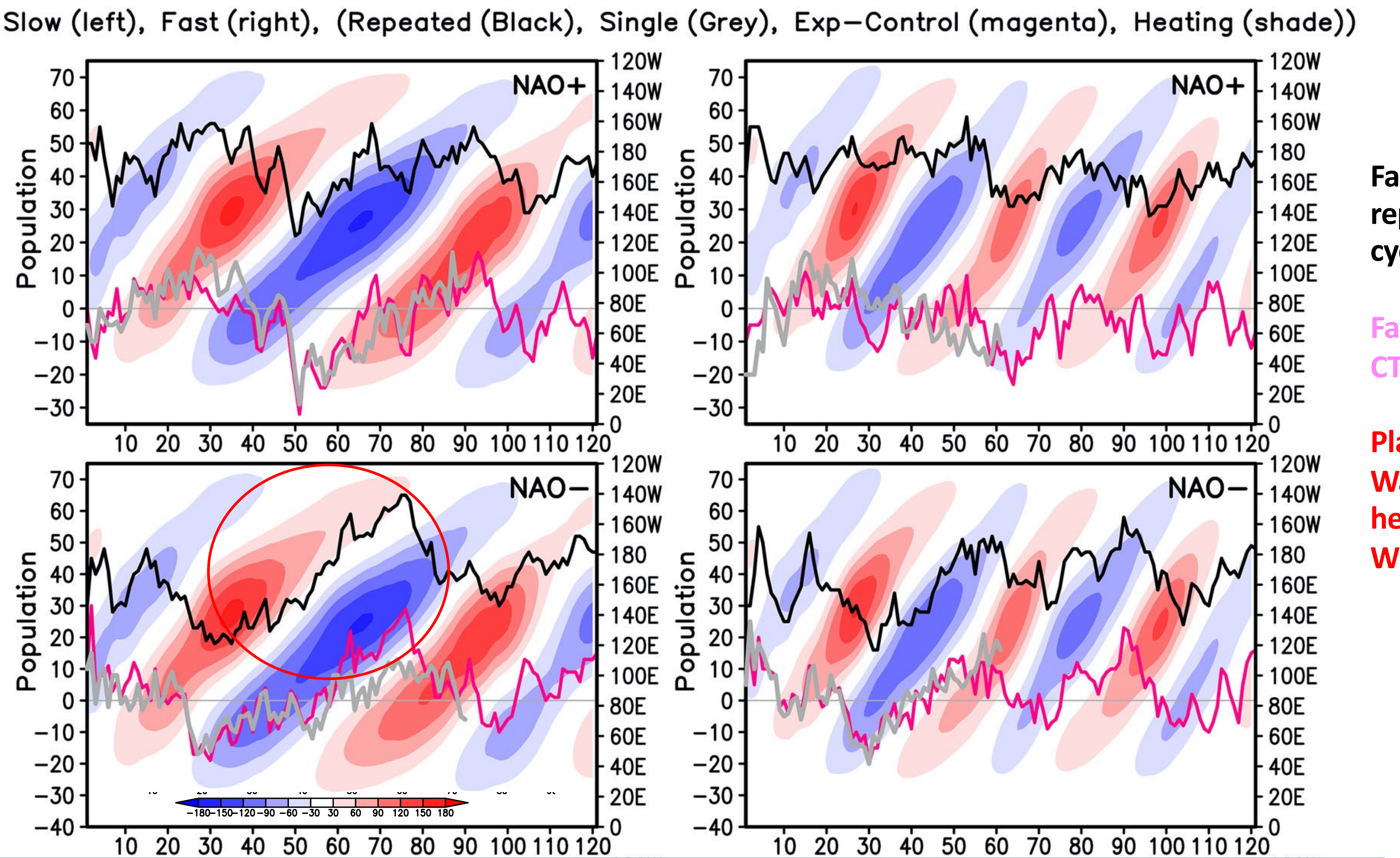
Fast minus CTL

Lines: Total number of occurrences of NAO+ and NAO- in 50 ensemble members (left – yaxis)

Slow repeated cycles

Slow minus CTL

Planetary Wave heating in Wm^{-2}



Fast repeated cycles

Fast minus CTL

Planetary Wave heating in Wm^{-2}

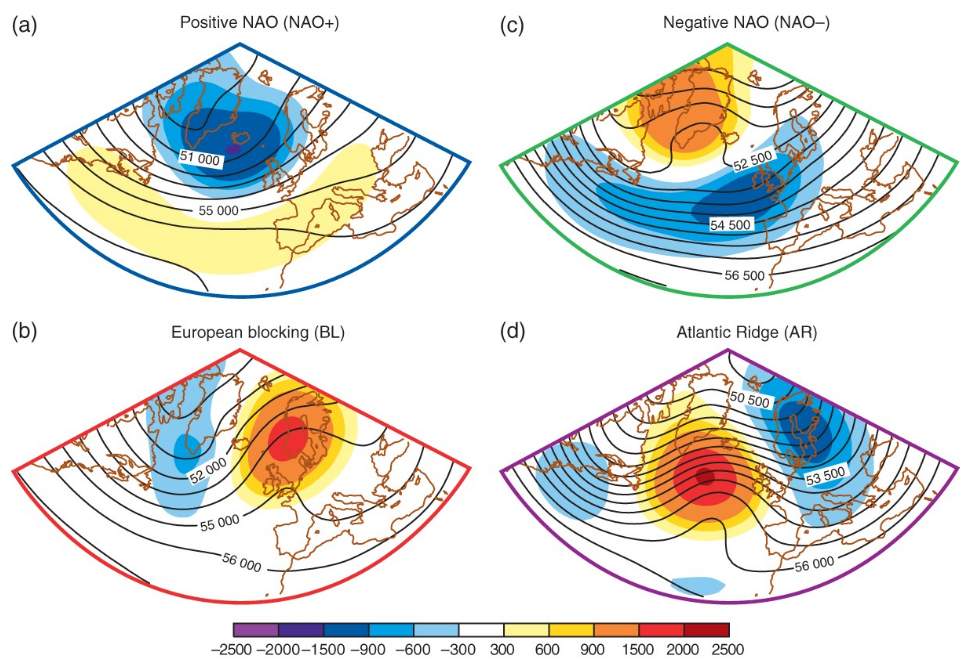
What stands out in the slow response is the NAO- increase after the heating is in MJO Phase 6

Quick Review of Application of Intervention Techniques

(1) **Experiment:** Specified heating to understand whether the intermittency in tropical heating during El-Nino impacts the remote response. Note that model feedbacks are killed!
Conclusion: It Does!
Implication: Models should get not only the mean El-Nino tropical heating right, but also the variability.

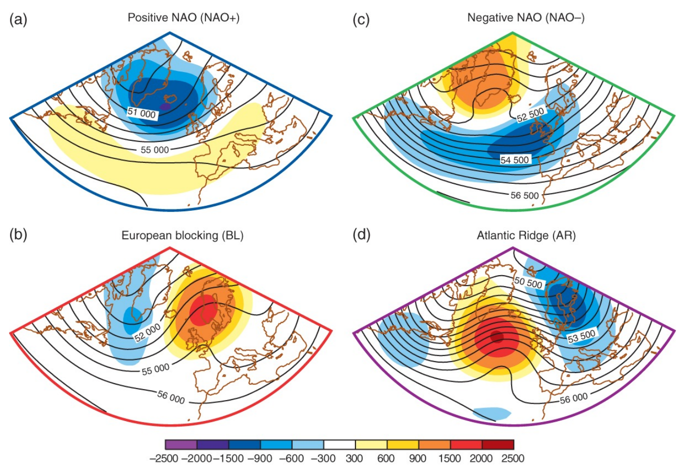
(2) **Experiment**: Added heating to better understand the response to slow MJO episodes (vis-à-vis fast ones).
Here the technique does not interfere with model feedbacks.
Conclusion: Slow episodes impact MJO- very strongly.
Implication: Does this have implications for predictability?

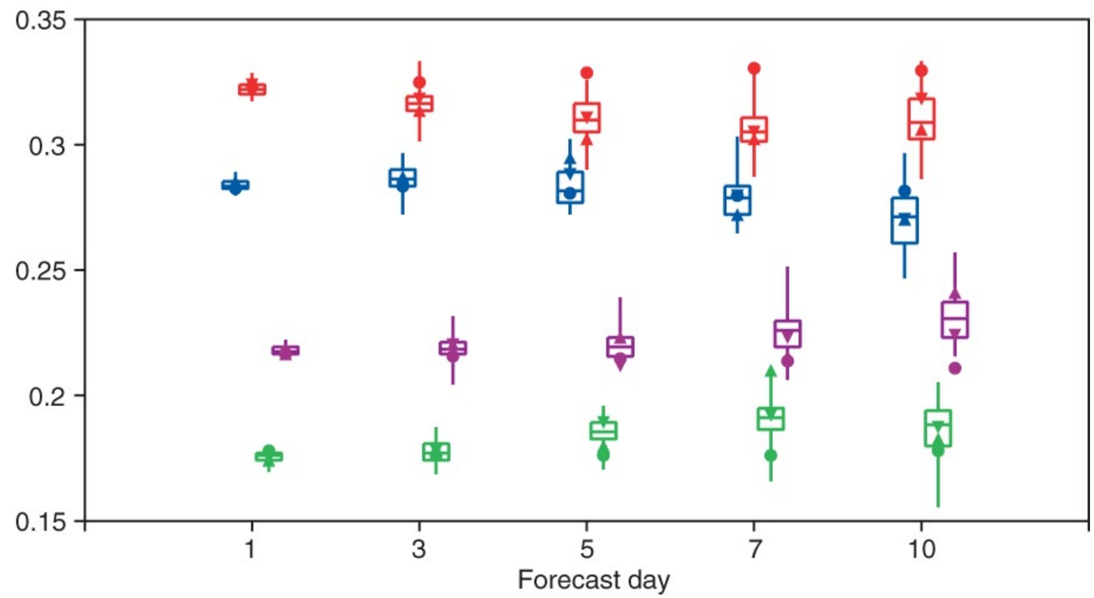
Flow-dependent verification of the ECMWF ensemble over the Euro-Atlantic sector



Quarterly Journal of the Royal Meteorological Society, Volume: 141, Issue: 688, Pages: 916-924, First published: 10 June 2014, DOI: (10.1002/qj.2411)

Flow-dependent verification of the ECMWF ensemble over the Euro-Atlantic sector

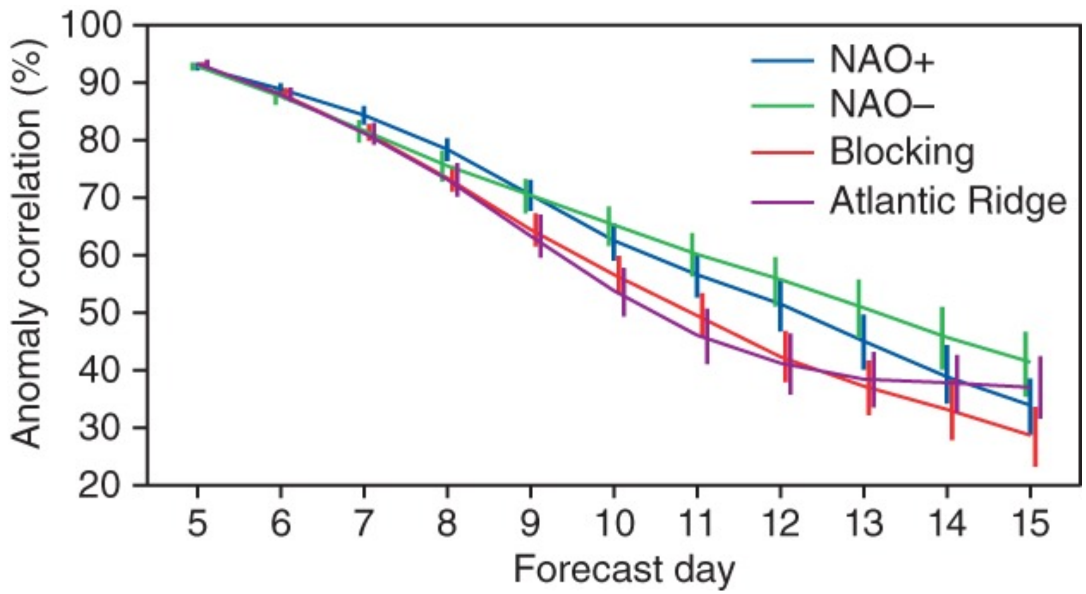




Climatological frequency distribution for the four Euro-Atlantic regimes as simulated by the ECMWF ensemble at different forecast ranges. Red indicates the frequency of the BL regime, blue (green) the frequency of the NAO+ (NAO−) and violet the frequency of the AR regime. A circle indicates the frequencies observed. The frequency distribution of the 50 perturbed forecasts is represented by the box plot. The limits of the whiskers indicate the extremes and those of the box the 25 and 75% values.

Quarterly Journal of the Royal Meteorological Society, Volume: 141, Issue: 688, Pages: 916-924, First published: 10 June 2014, DOI: (10.1002/qj.2411)

Flow-dependent verification of the ECMWF ensemble over the Euro-Atlantic sector



Anomaly correlation of the ensemble means over Europe (12.5°W–42.5°E, 35.0°N–75.0°N) for the four forecast categories as a function of forecast range. Red refers the BL regime, blue to the NAO+, green to the NAO− and violet to the AR regime. The bars, based on 1000 subsamples generated with the bootstrap method, indicate the 95% confidence intervals.

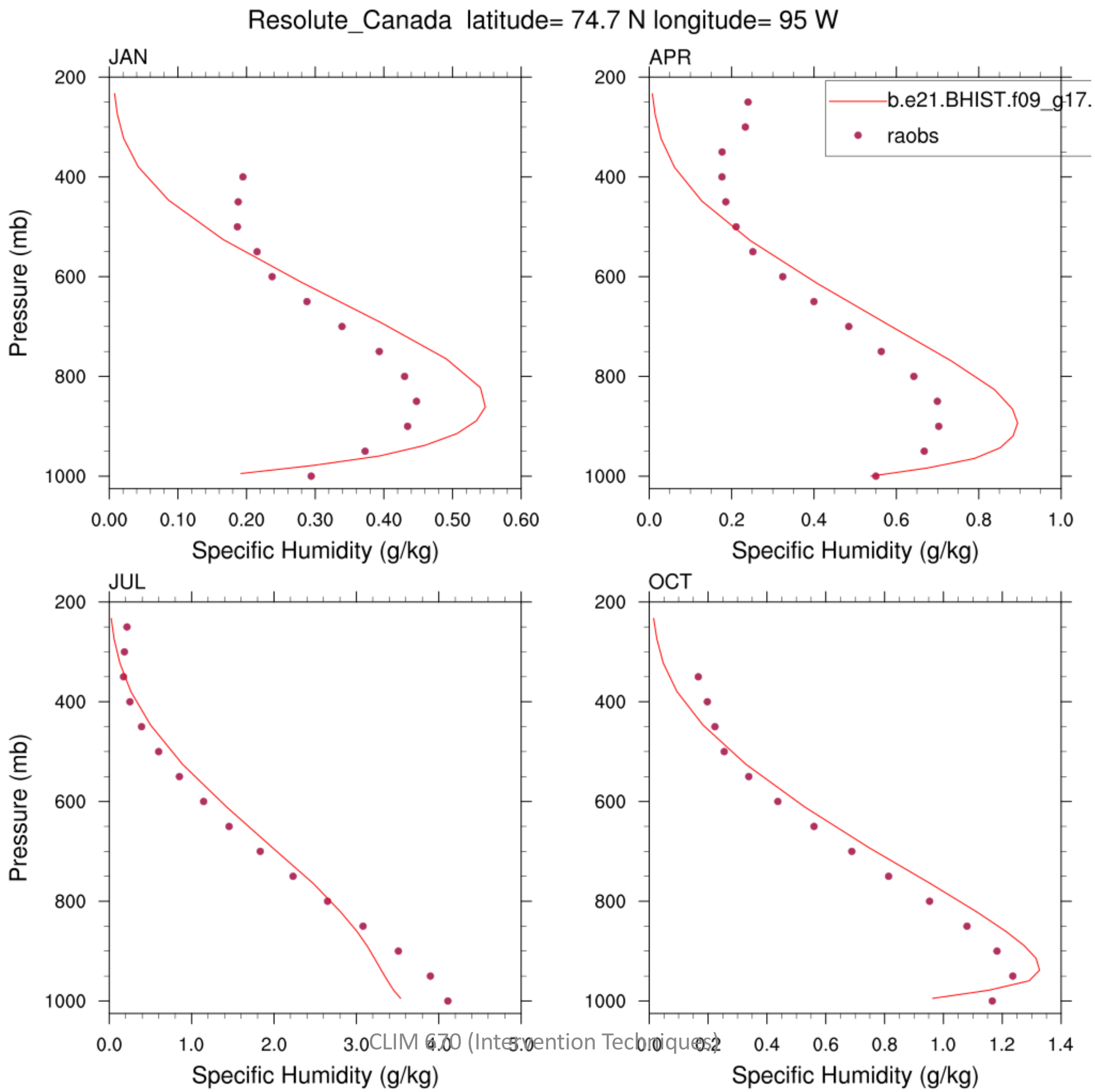
Quarterly Journal of the Royal Meteorological Society, Volume: 141, Issue: 688, Pages: 916-924, First published: 10 June 2014, DOI: (10.1002/qj.2411)

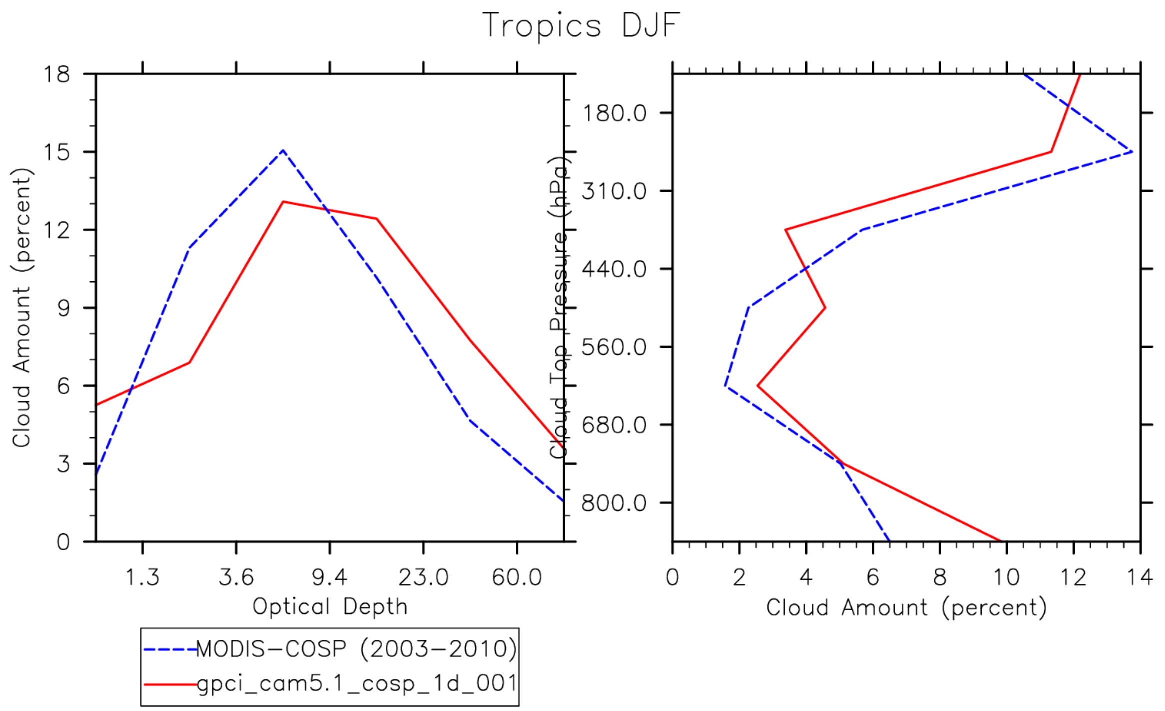
CMIP6 ISMIP6 CESM2 historical-withism experiment with CAM6, interactive land (CLM5), coupled ocean (POP2), interactive sea ice (CICE5.1), and coupled and evolving land ice (CISM2.1).

This is a concentration driven historical forcing with land use held constant at 1850 usage. Same as the concentration driven CMIP6 historical experiment except with land use and land cover change (LULCC) held constant at pre-industrial conditions.

Title CMIP6 20th century experiments (1850-2014) with CAM6, interactive land (CLM5), coupled ocean (POP2) with biogeochemistry (MARBL), interactive sea ice (CICE5.1), and non-evolving land ice (CISM2.1)** see plot next page

https://csegweb.cgd.ucar.edu/experiments/public/


Resolute_Canada latitude= 74.7 N longitude= 95 W
JAN
APR
JUL
OCT
Pressure (mb)
Specific Humidity (g/kg)
b.e21.BHIST.f09_g17.
raobs



https://webext.cgd.ucar.edu/FAMIP/gpci_cam5.1_cosp_1d_001/atm/gpci_cam5.1_cosp_1d_001-obs/