ICTP Workshop on

Teleconnections in the Present and Future Climate

The Influence of the Madden-Julian Oscillation on the Boreal Winter Extra-Tropics (especially the Euro-Atlantic Weather Regimes)

David M. Straus
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2. The MJO: Quasi-periodic, highly intermittent low frequency tropical heating. Is the steady response paradigm relevant?

3. Circulation Regimes in the Euro-Atlantic Region: A summary of intra-seasonal variability.

4. Observed statistics: How does the MJO affect the likelihood of residing in a particular regime? Is this seen in re-forecasts?

5. Experiment designed to provide some insight into mechanisms.

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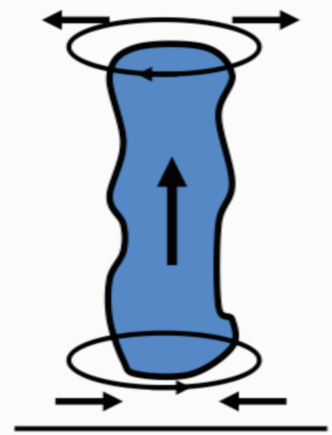
Tropical Response to Deep Heating Source
Rising Motion and Divergence at Upper Levels

$$H \xrightarrow{\;1\;} w\,(\mathbf{v}_\chi) \xrightarrow{\;2\;} \xi \xrightarrow{\;3\;} \theta$$

1. Thermodynamic equation $N^2 w = H$

2. Vorticity equation

3. Thermal wind balance $g\,\theta'/\theta_0 = f\,\partial\xi/\partial z$



$N^2H^2/f^2L^2 > 1$

Analysis of Large-Scale Dynamics for Specified Heating (H)

Courtesy of Bin Wang

The Rossby Wave Source

Tropical heating gives rise to rising motion, since the adiabatic cooling term balances the diabatic heating.

$$\omega \frac{\partial \theta}{\partial p} \cong \frac{1}{c_p} \left(\frac{p_0}{p} \right)^{\kappa} Q$$

For mid-level rising heating, you expect divergence (D>0) aloft (200 hPa) and convergence (D<0) below (850 hPa). This response has the form of the *first baroclinic mode.*

Since the mid-latitude response is often nearly barotropic, we use the barotropic vorticity equation, and put all terms related to the divergence D and the divergent component of the flow $\mathbf{v}_\chi$ on the right-hand side, and consider it as a forcing term.

$$\vec{v}_\chi = \vec{\nabla} \chi$$

$$D = \vec{\nabla} \cdot \vec{v}_\chi = \vec{\nabla} \cdot \vec{v}$$

$$\frac{\partial \zeta}{\partial t} + J(\psi, \zeta + f) = S = -\vec{\nabla} \cdot \left(\vec{v}_{\chi} \zeta \right) = -D\zeta - \vec{v}_{\chi} \cdot \vec{\nabla} \zeta$$

Traditional Source: Divergence x Vorticity
Vorticity ~ ***f*** (Coriolis parameter)
D used to specify tropical "heating"

Additional Source: Vorticity Advection by the Divergent flow

1228 JOURNAL OF THE ATMOSPHERIC SCIENCES VOL. 45, NO. 7

The Generation of Global Rotational Flow by Steady Idealized Tropical Divergence

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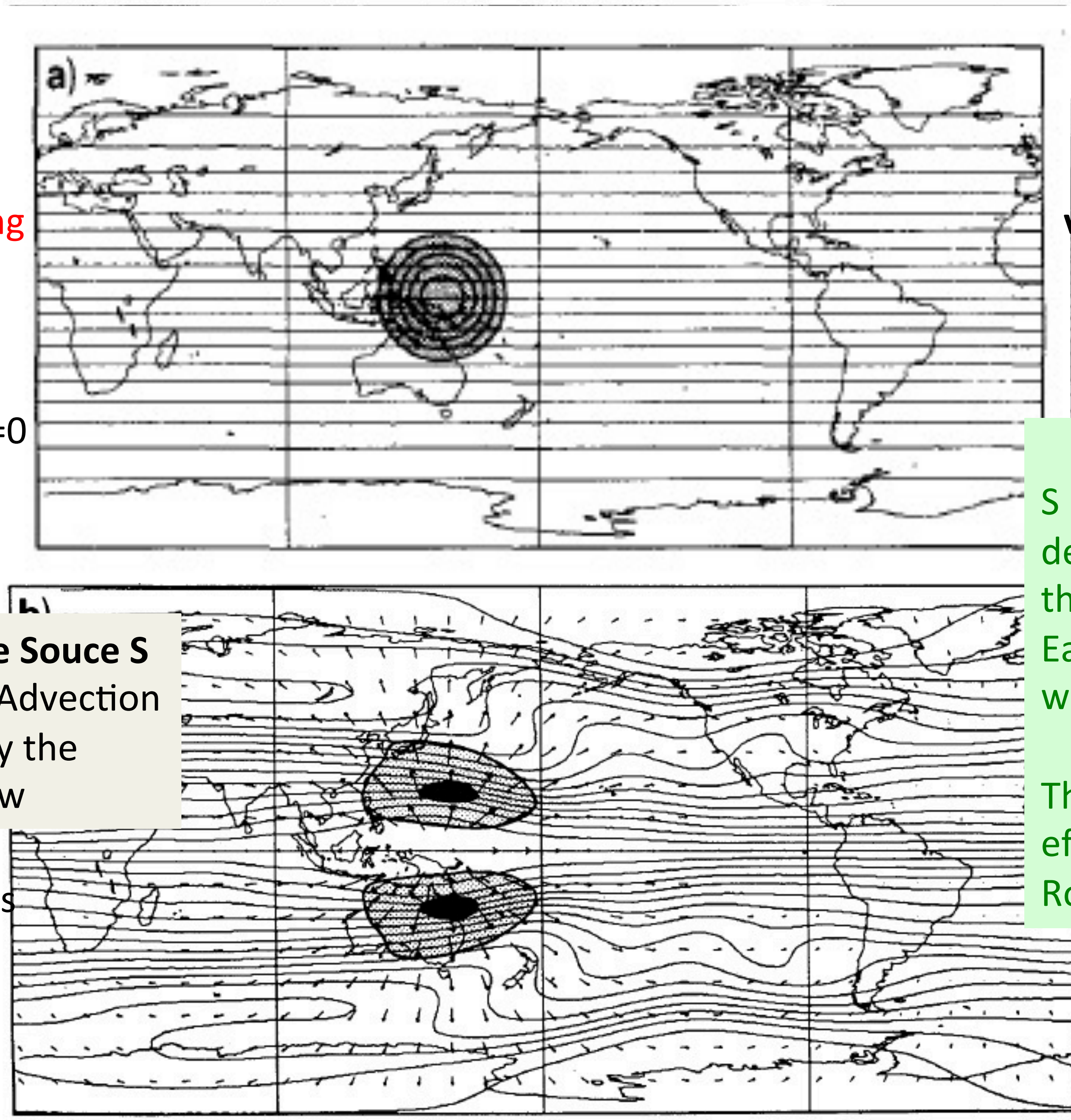
Idealized D corresponding to tropical heating

Initial time t=0

Absolute vorticity given by light lines



Critical Result:
S is pulled out of deep tropics, out of the region of Easterly background winds at 200 hPa.

Thus S is more effective in forcing Rossby waves

Rossby Wave Souce S
Note role of Advection of vorticity by the divergent flow

Time t=8 days

FIG. 2. (a) Rossby wave source S (shaded; units 10^{-11} s^{-2}) on day 0. The steady divergent wind vectors and the initial absolute vorticity (10^{-5} s^{-1}) that determine this source are also shown. (b) as in (a) but on day 48 of the fully nonlinear integration. The largest divergent winds in the subtropics are about 5 m s^{-1}.

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Diagnosis of intra-seasonal tropical heating modes:

Use OLR as a proxy for convection and therefore heating.
Use U850, U250 to resolve first baroclinic mode.

To focus on longitude and time variability of large-scale *near equatorial* convective intra-seasonal variability, average U850, U250 and OLR across 15S-15N

Remove annual cycle, filter to retain periods of about 20 – 100 days
(Thus focusing on slowly evolving intra-seasonal variations)

Principal Component Analysis (EOFs, PCs)

Put all fields on an equal basis by normalizing each field by a *single* number that represents their typical standard deviation:

Then we represent the normalized U850, U250, OLR together as a single vector

Carry out *Principal Component Analysis* to get a hierarchy of modes, each characterized by:

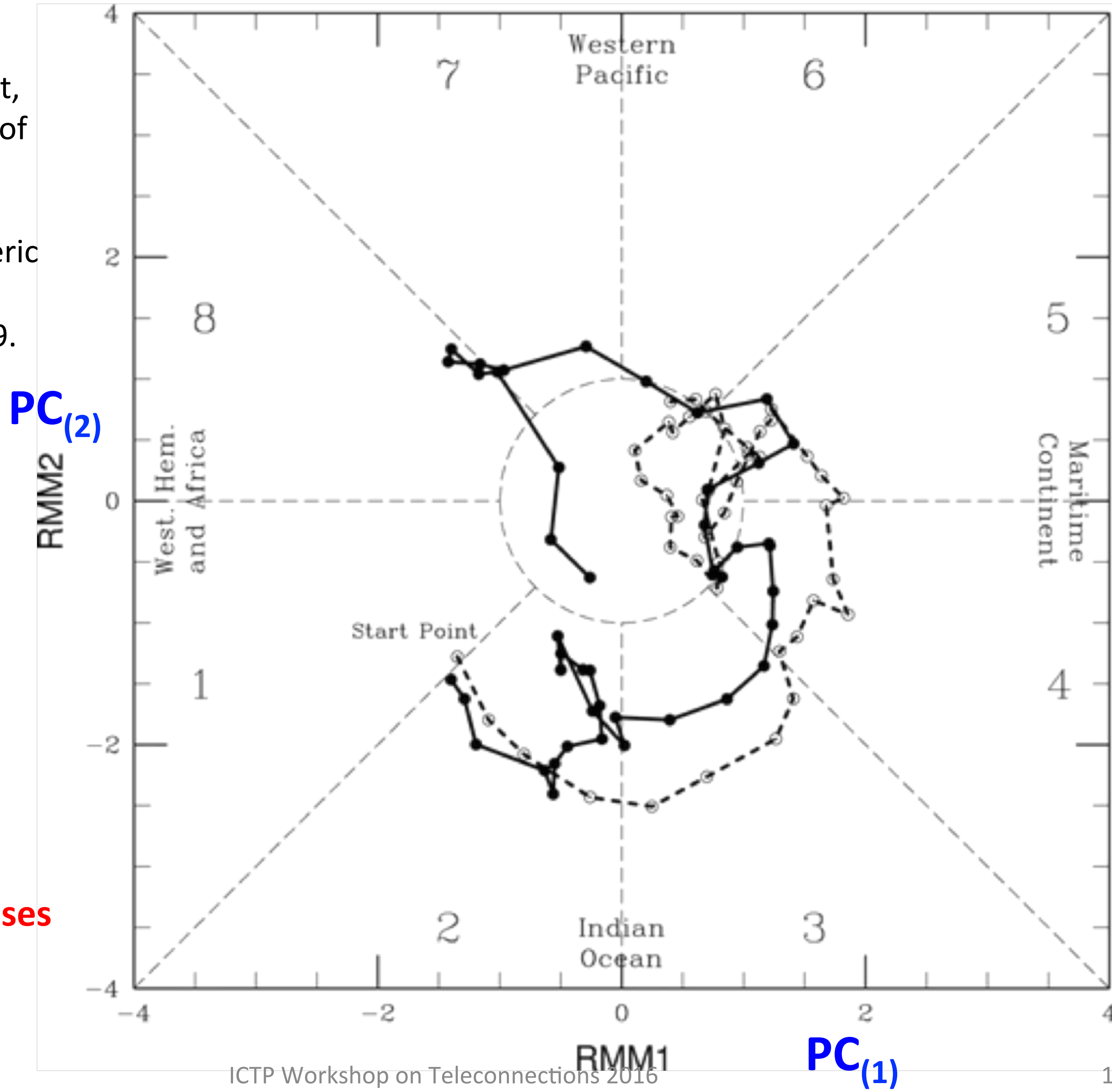
(a) vector (Empirical Orthogonal Functions, EOFS) – each represents a normalized pattern. EOFs of different modes are orthogonal
(b) Time series (Principal Components) of each mode

(c) It turns out that the field represented by the *first two modes only*:

$$F(\lambda,t) = EOF_{(1)}(\lambda)*PC_{(1)}(t) + EOF_{(2)}(\lambda)*PC_{(2)}(t)$$

has about 44% of the total temporal variance (integrated across all longitudes) of the original set of data vectors AND the **variance of PC(1) = variance of PC(2)**

Lin, H. and G. Brunet, 2008, Forecast Skill of the Madden-Julian Oscillation in Two Canadian Atmospheric Models. *Mon. Wea. Rev*. **136**, 4130-4149.



Polar Plot of $PC_{(1)}$ & $PC_{(2)}$ yields a cyclic behavior

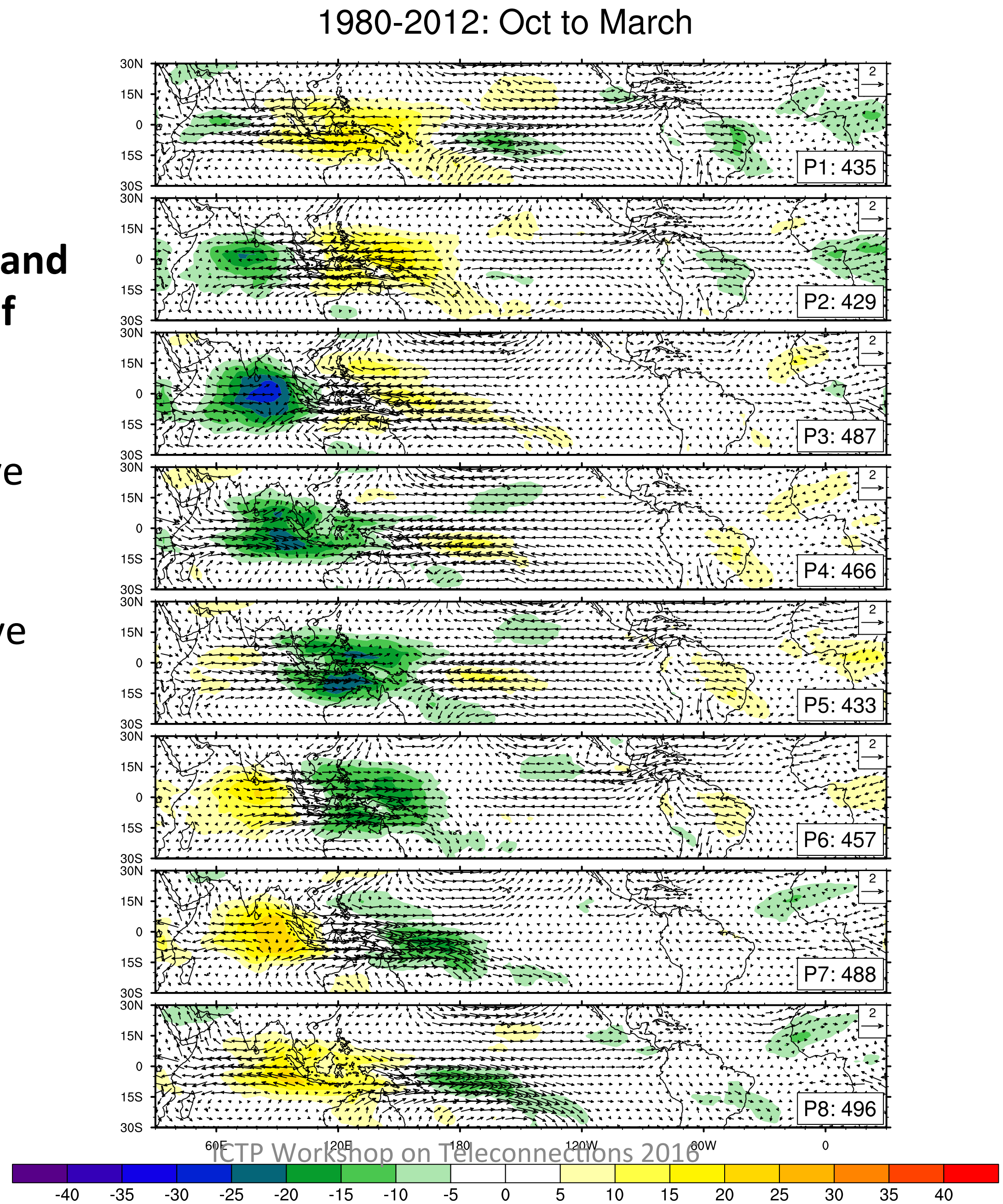
Phase plot of the MJO. Defines 8 conventional phases

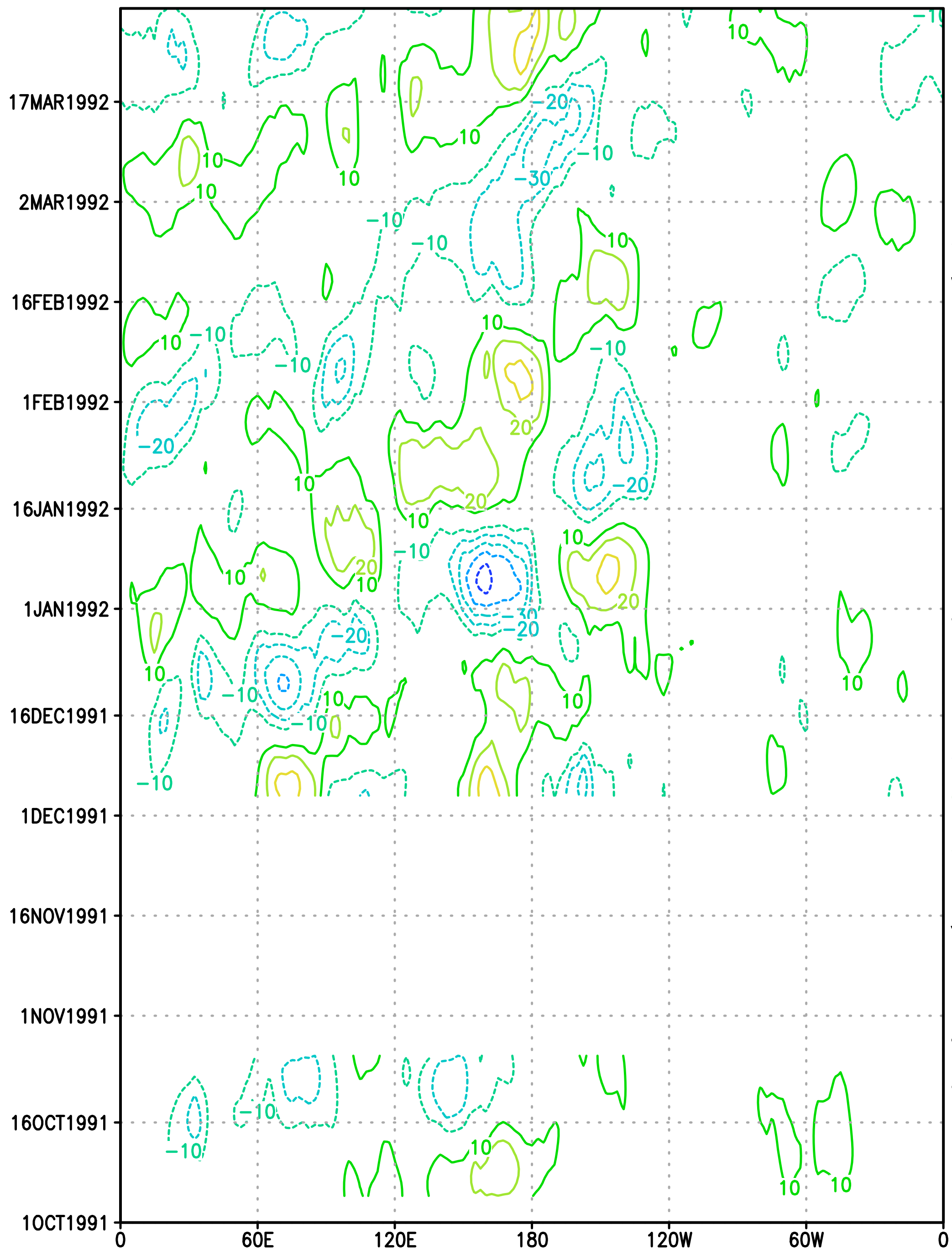
Yadav, P. and D. M. Straus, 2016: Circulation Response to Fast and Slow MJO Episodes, *Mon. Wea. Rev.*, submitted

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

Blue colors – positive heating anomalies

Red colors – negative heating anomalies





Observed OLR averaged 15S - 15N as a function of time for the extended winter Oct. 1991 - Mar. 1992. Contour interval is 10W m^{-2}.

Filtered to retain periods of 20 -100 days.

Periods when amplitude < 1 not shown

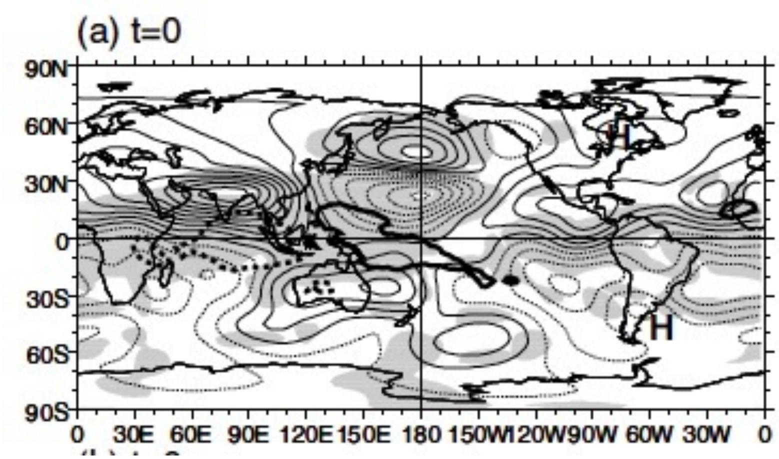
Blue (OLR < 0) positive heating anomalies
Green (OLR > 0) negative heating anomalies

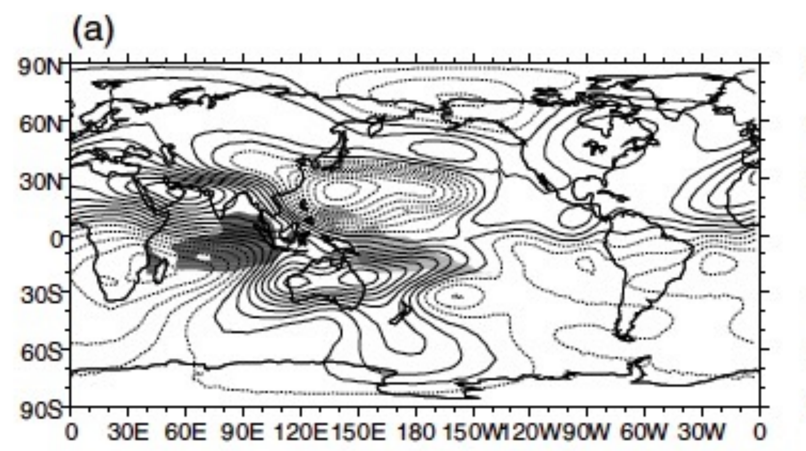
Yadav, P. and Straus, D. M. 2016: Circulation Response to Fast and Slow MJO Episodes, *Mon. Wea. Rev.*, submitted.

Simplest Theory for Mid-Latitude Response to MJO Heating:

The Response to each phase of MJO heating is essentially *the stationary response to that heating* (that is the response that would occur if that heating were constant)*, but with a delay of about 10 days.* (Matthews et al. 2004*)

Method: Use simplified baroclinic model with specified heating, initialized from zonal mean state − only the direct response to heating measured (no synoptic feedback)





Regression of OLR and 200 ψ on phase MJO with OLR min over Indian Ocean

Day 15 200 ψ of model run forced by heating from Left Panel

*Matthews, A. J., B. J. Hoskins and M. Masutani, 2004: The global response to tropical heating in the Madden-Julian oscillation during the northern winter. *Q. J. R. Meteorol. Soc.*, **130,** 1991-2011

2-day pulse at 0ºN,135ºE 2-day pulse at 0ºN, 120ºW

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

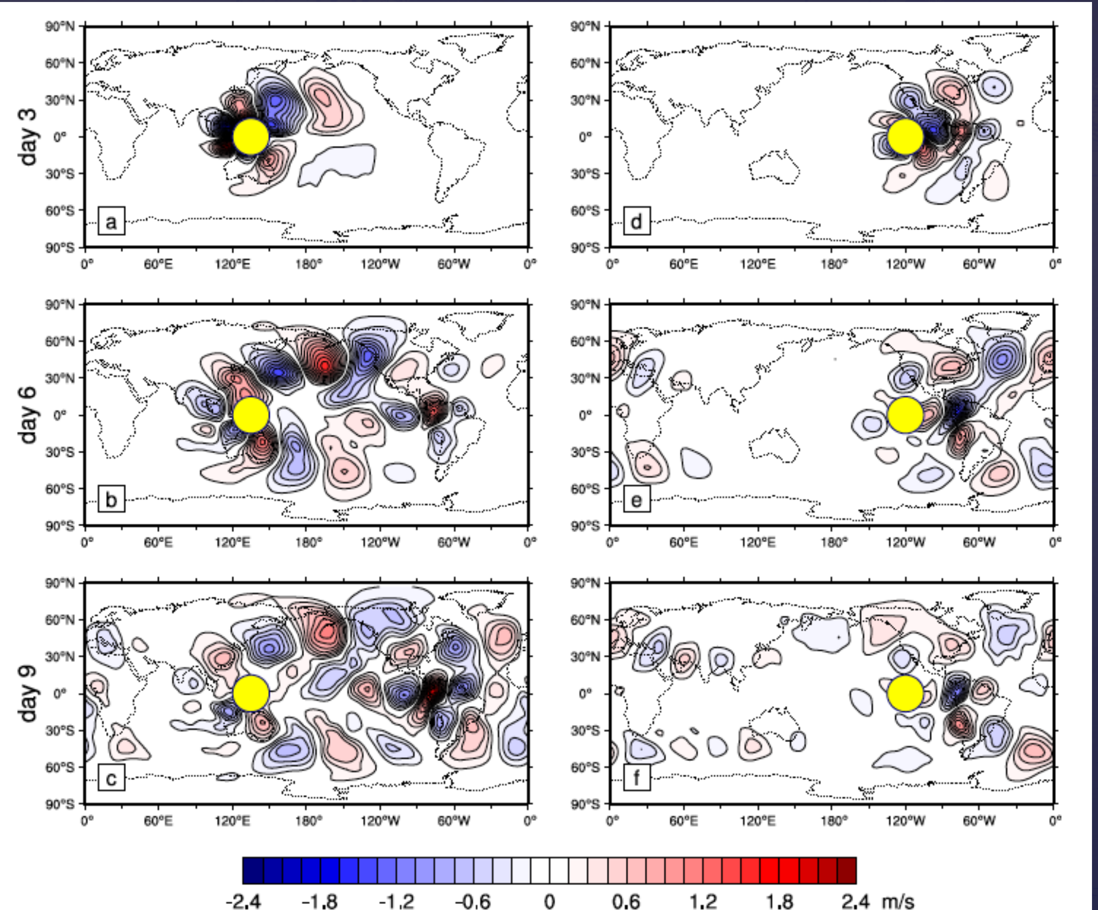


FIG. 3. Ensemble mean v300 response in CAM3 to a 2-day pulse of heat at 0°N, 135°E (a) 3, (b) 6, and (c) 9 days after the pulse begins. (d)–(f) As in (a)–(c), but for a pulse at 0°N, 120°W.

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

Pulses turned off after days but response keeps growing

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

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

Implications of Branstator's Experiments

The MJO heating is *no*t a single localized source but a cycle in both space and time, consisting of negative and positive anomalies.

From a linear point of view, both the heating and cooling at one particular time may be thought of as sources for wave trains.

The remote response at any point some time later will involve the sum of these wave trains, each having traveled a different distance to reach the given point and thus in a different phase of its life cycle.

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Representation of circulation patterns in the Euro-Atlantic Region

Principle Component Analysis Yields EOFs (patterns) and PCs (time series) that **capture the space-time variance of the original field vectors in an optimal way.**

An important use of this analysis is to **drastically reduce the dimension of the data set:**

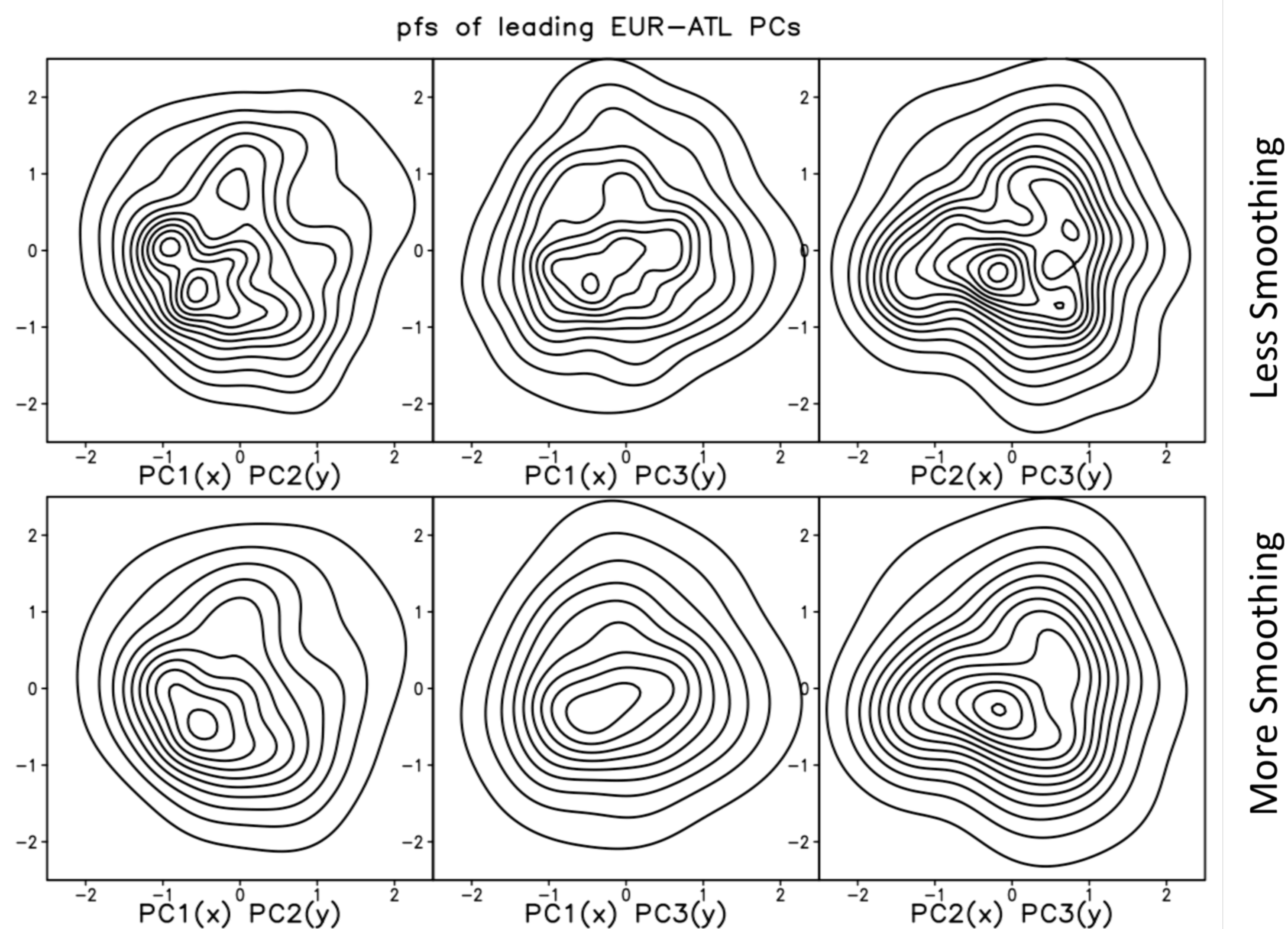
$\mathbf{N_{grid} \times N_{levels} \times N_{fields}} \rightarrow$ **M** = number of modes retained, that is the truncation.

Given the M EOF patterns calculated from the original data vectors, the PCs give the **new coordinates: Each state is represented by a point in an M-dimensional space**.

Each dataset then is reduced to a set of discrete points in this space, which is an estimate of a **multi-variate probability distribution function (pdf).**

Three dimensional pdf of low frequency (t > 20 day) fluctuations of 500 hPa height Over the Euro-Atlantic region for boreal winter (with two different smoothings)

Contours represent likelihood of finding a state nearby



Straus, D. M., F. Molteni, and S. Corti, 2016: Atmospheric Regimes: The Link between Weather and the Large Scale Circulation, (in *Nonlinear and Stochastic Climate Dynamics,* Edited by C. Franzke, Cambridge University Press), in press.

The estimates suggest that some states are "preferred" , that is more likely than we would expect based on a multi-dimensional Gaussian pdf (a reasonable null hypothesis).

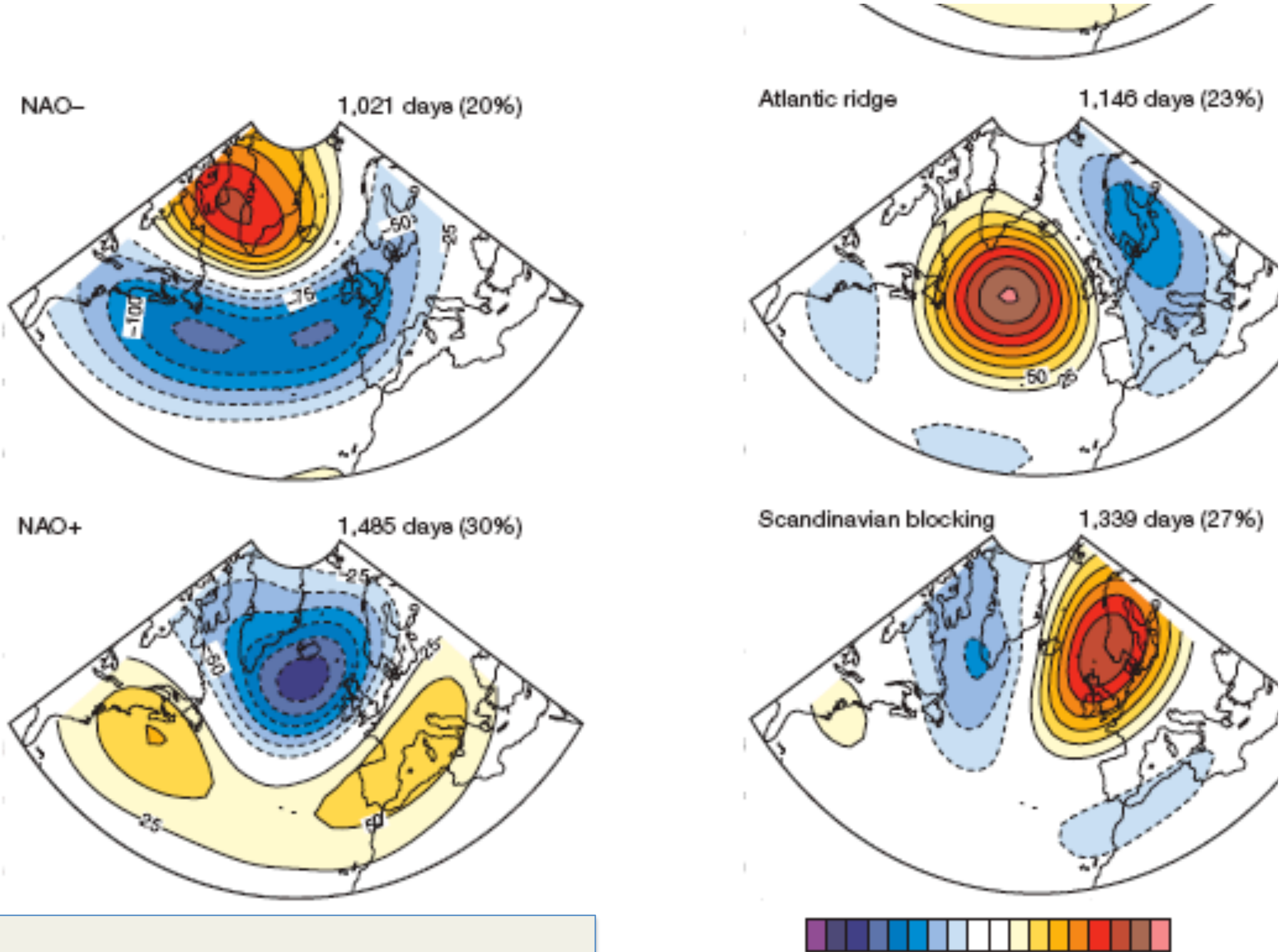
One way of testing if this is true, and to identify discrete states (points in the multi-dimensional pdf) that are preferred, is called <u>cluster analysis.</u>

Results from cluster analysis are particularly robust over the Euro-Atlantic region for boreal winter.

We show results for four preferred states from two studies, *but others agree!*

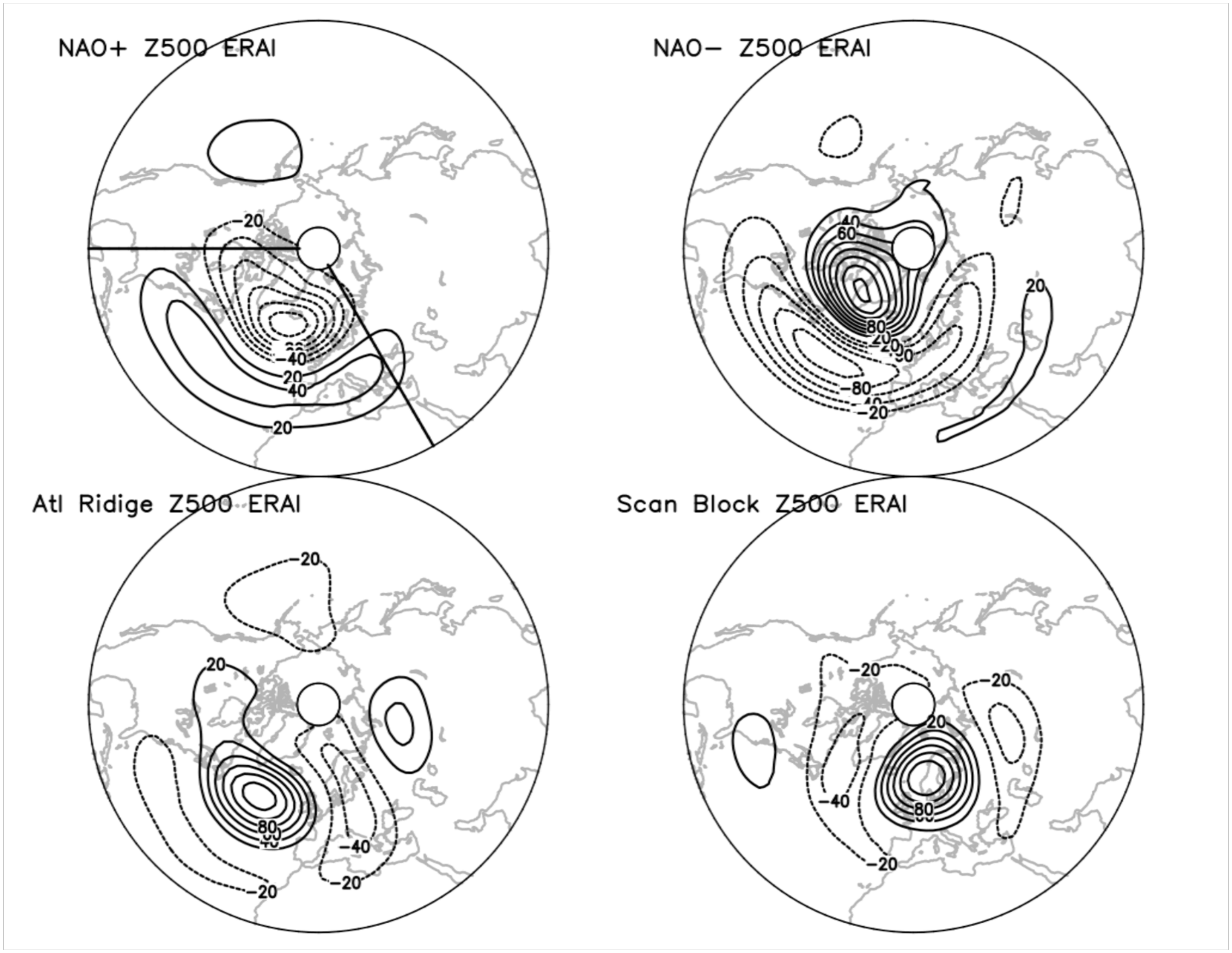
(1) Cassou, C., 2008: Intrseasonal Interation between the Madden-Julian Oscillation and the North Atlantic Oscillation. *Nature, 455,* 523-527.

(2) Straus, D. M., F. Molteni, and S. Corti, 2016: Atmospheric Regimes: The Link between Weather and the Large Scale Circulation, (in *Nonlinear and Stochastic Climate Dynamics,* Edited by C. Franzke, Cambridge University Press), in press.



Cassou 2008

Figure 1 | Wintertime North Atlantic weather regimes. Co four weather regimes obtained from daily anomalous geopo



NAO+ Z500 ERAI
NAO− Z500 ERAI
Atl Ridige Z500 ERAI
Scan Block Z500 ERAI

Straus, 2016

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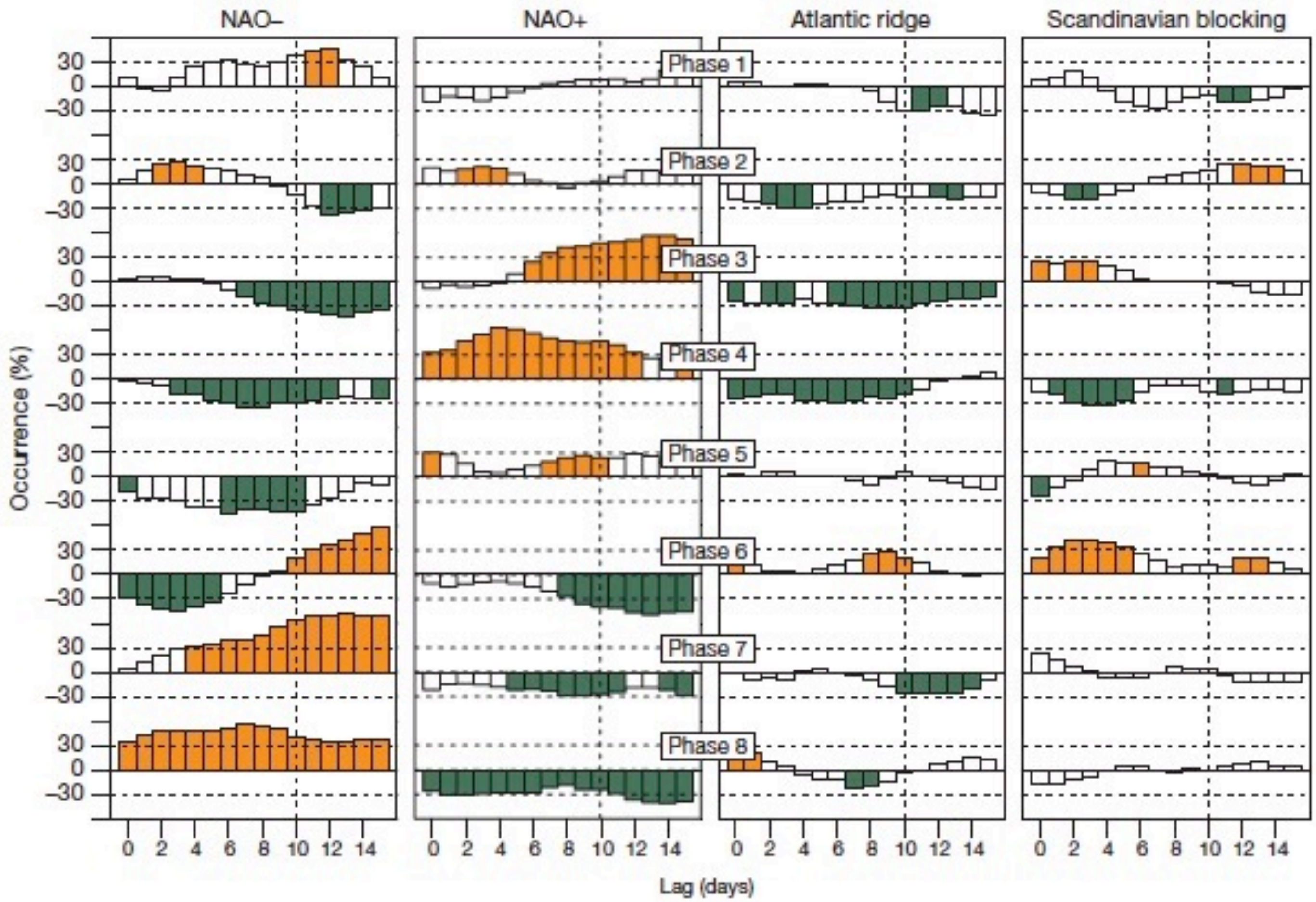
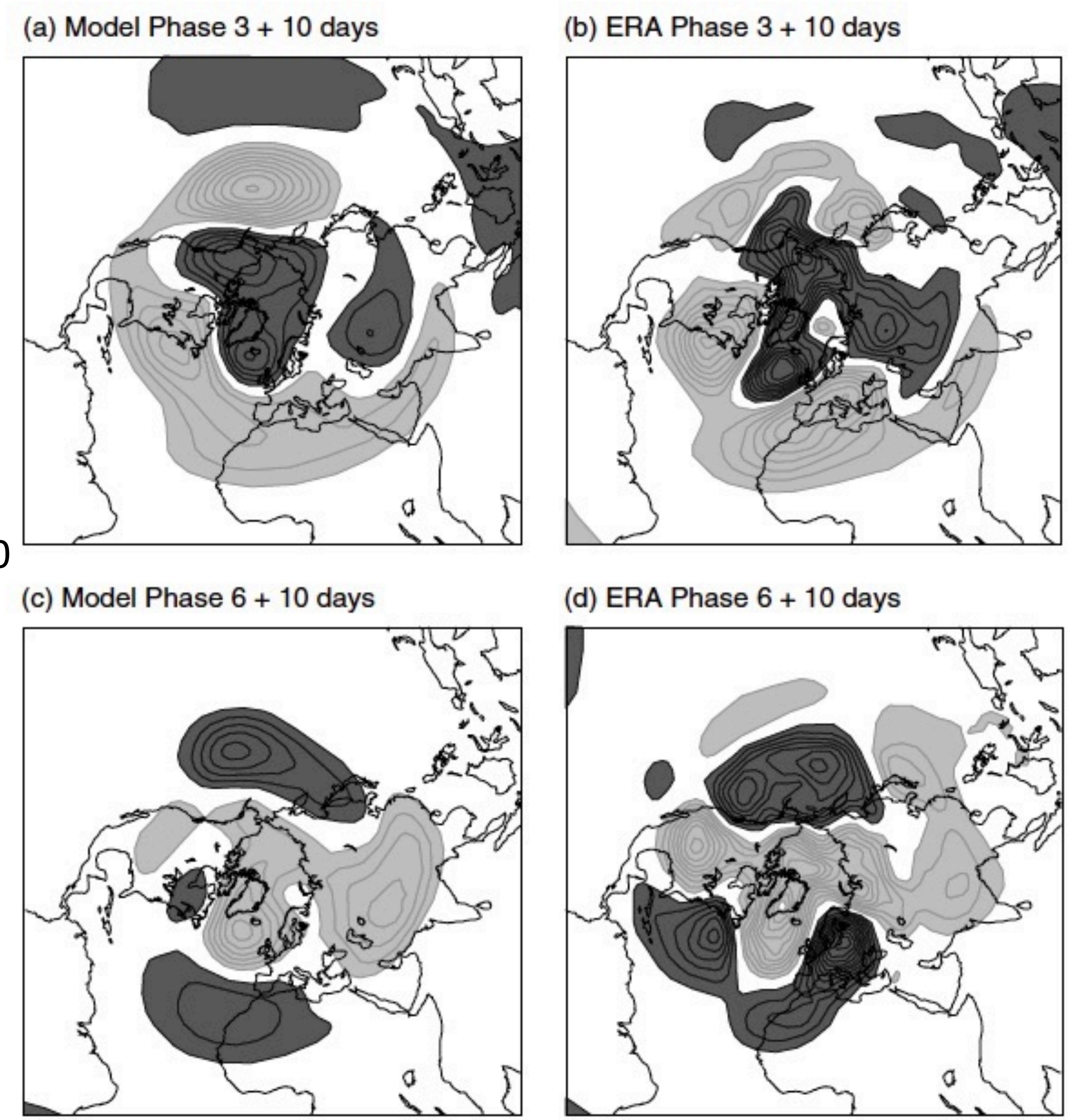


Figure 3 | Lagged relationships between the eight phases of the MJO and the four North Atlantic weather regimes. Table of contingency between the MJO phases (rows) and the North Atlantic weather regimes (columns). For each MJO phase, I plot the anomalous percentage occurrence of a given regime as a function of lag in days (with regimes lagging MJO phases). The 0% value means that the MJO phase is not discriminative for the regime whose occurrence is climatological. A 100% value would mean that this regime occurs twice as frequently as its climatological mean; −100% means no occurrence of this regime. The presence of a slope as a function of lag is suggestive of the MJO forcing. For white bars, either the change in the distribution between the four regimes is not significant on the basis of χ^2 statistics at the 99% significance level, or the individual anomalous frequency of occurrence is lower than the minimum significant threshold tested at 95% using a Gaussian distribution (approximation for binomial distribution because of the sufficiently large sampling). For orange and green bars, the regimes occur significantly more or, respectively, less frequently than their climatological occurrences.

Cassou 2008

ECMWF reforecasts

Vitart, F. and F. Molteni, 2010 *QJRMS* **246**, 842-855.



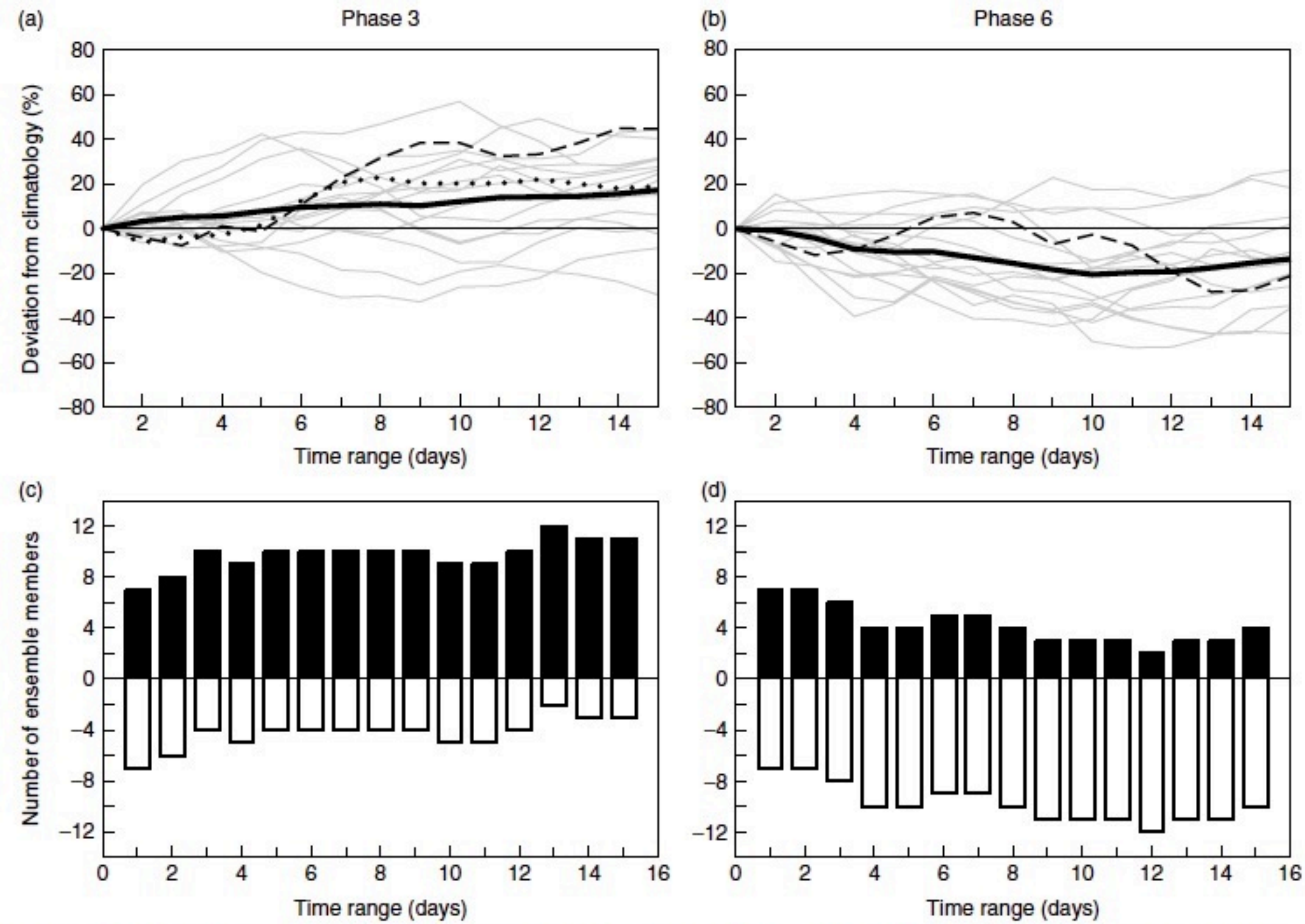
Light Shading Z500 positive

Dark Shading Z500 negative

Figure 8. MJO 10-day lagged composites of 500 hPa geopotential height anomaly for phase 3 for (a) the day 16–45 hindcasts and (b) ERA-Interim. (c, d) are as (a, b), but for phase 6. Light shading indicates positive anomalies, and dark shading negative anomalies. The lowest contour is at 10 m and the contour interval is 5 m.

dashed line: ERA-Interim change in NAO+ regime occurrence (percent)
solid line: ensemble mean
light lines: forecast ensemble members

Vitart & Molteni, 2010



The occurrence of some of these preferred circulation patterns are increased or decreased depending on the phase of the MJO that occurs 10 days previously. How to understand this?

The MJO heating is *no*t a single localized source but a cycle in both space and time, consisting of negative and positive anomalies.

From a linear point of view, both the heating and cooling at one particular time may be thought of as sources for wave trains.

The remote response at any point some time later will involve the sum of these wave trains, each having traveled a different distance to reach the given point and thus in a different phase of its life cycle.

The dependence of the linear response to time-dependent forcing on the entire past history of the forcing is well known in classical electrodynamics

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Defining a mechanistic MJO response in the context of a full coupled GCM

An ensemble of CESM Oct-Mar seasonal runs (N=48)

For each control run*, a parallel heating run* was made from the same IC, with a specified MJO heating added at each time step to the temperature tendency in the model. The evolution of the ***specified additional heating is identical*** in each of the 48 heating simulations. Specified heating captures realistic MJO heating evolution from TRMM. Three full MJO cycles are incorporated, including seasonal cycle effects.

The full set of model parameterizations still operates, so that, for example, the added heating is able to induce added vertical motion which may induce further condensation, latent heat release, and changes in the associated cloudiness and radiation. *SST interactions and feedbacks are included.*

Reference: 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**, 660-681.

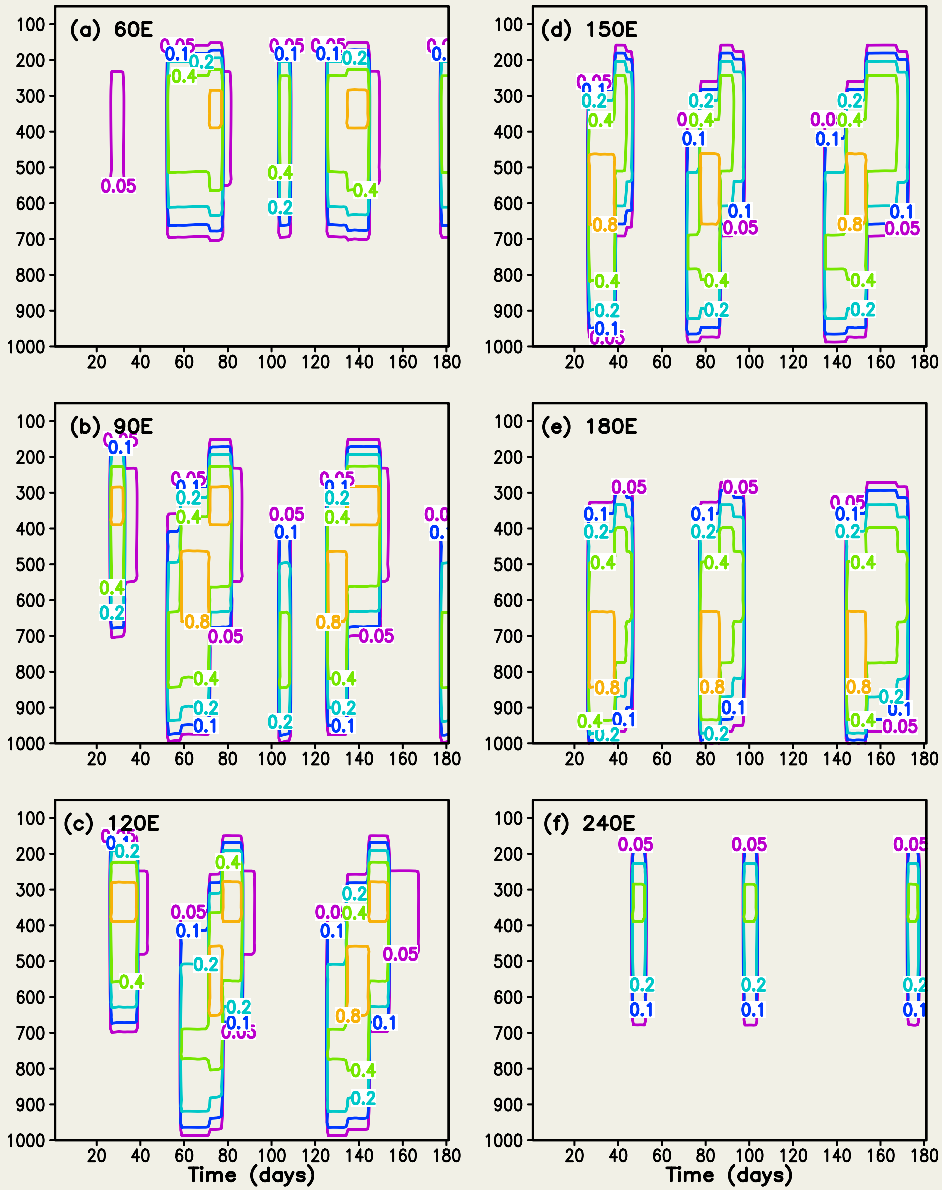


FIG. 1. Temperature tendency due to additional heating at various longitudes, averaged from 25°S to 25°N as a function of time (abscissa) and pressure (ordinate). Contours (various colors) of 0.05, 0.10, 0.20, 0.40, 0.80 K day^{-1}. Time is in days (1–181 days), with day 1 corresponding to 2 Oct. Pressure is in hectopascals.

Heating added as a temperature tendency, added to each of the simulations identically (25 S – 25 N average)

x-axis: time in days
y-axis: pressure level

Shown at various longitudes

Hovmoeller plots of heating avg 10S-10N

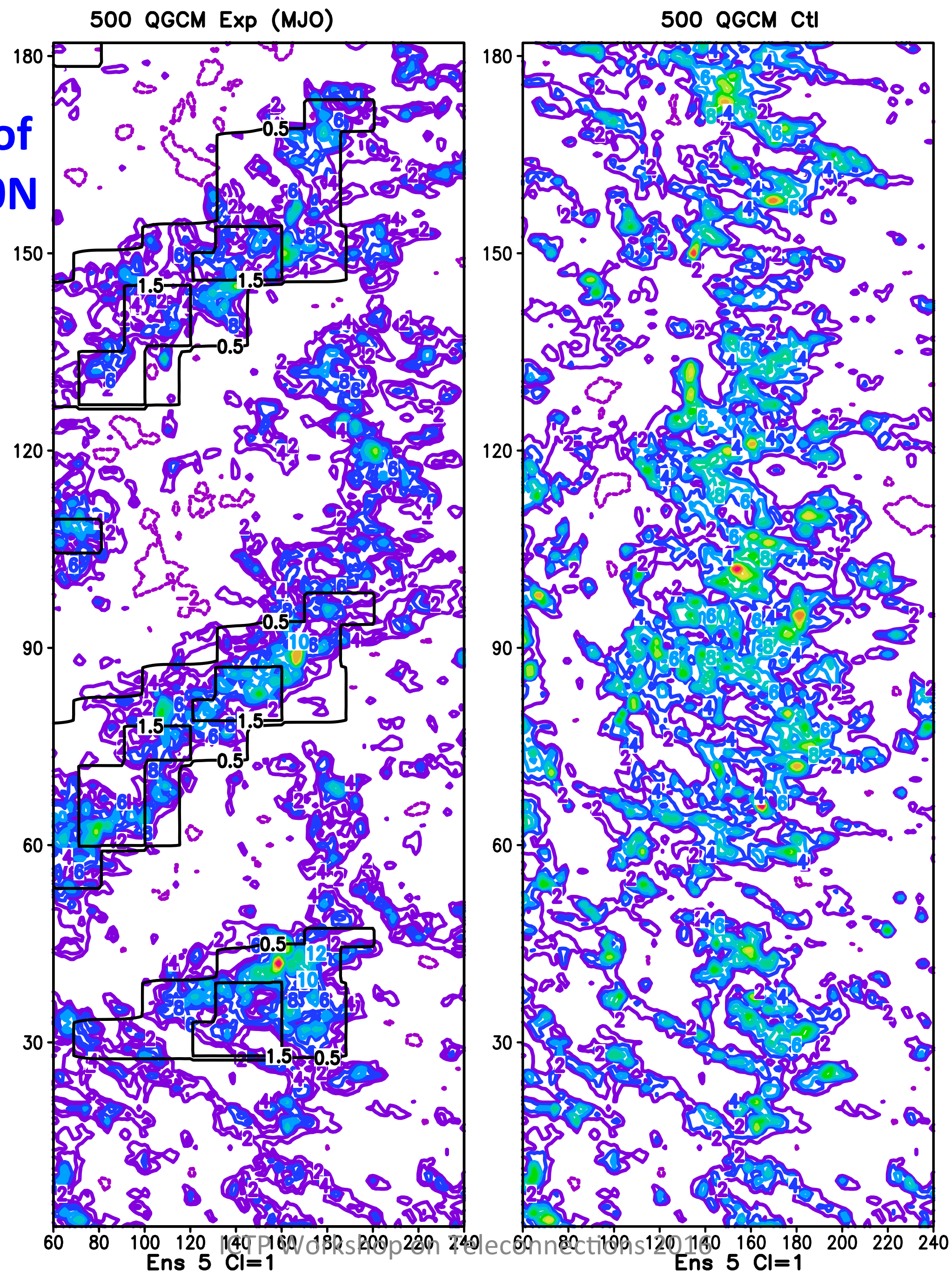
CESM total heating (colors)
(CI = 2 deg /day)

MJO added heating (black contours at 0.5 and 1.5 deg /day)

Time: 1 – 180 days
Longitude: 60 – 240 E

500 hPa
Ensemble Member 5

Left: MJO CESM
Right: Control CESM



Hypothesis: Each simulation has an evolving component in common.

Raw Signal = temporal standard deviation of daily ensemble means
Noise = square root of mean daily intra-ensemble variance

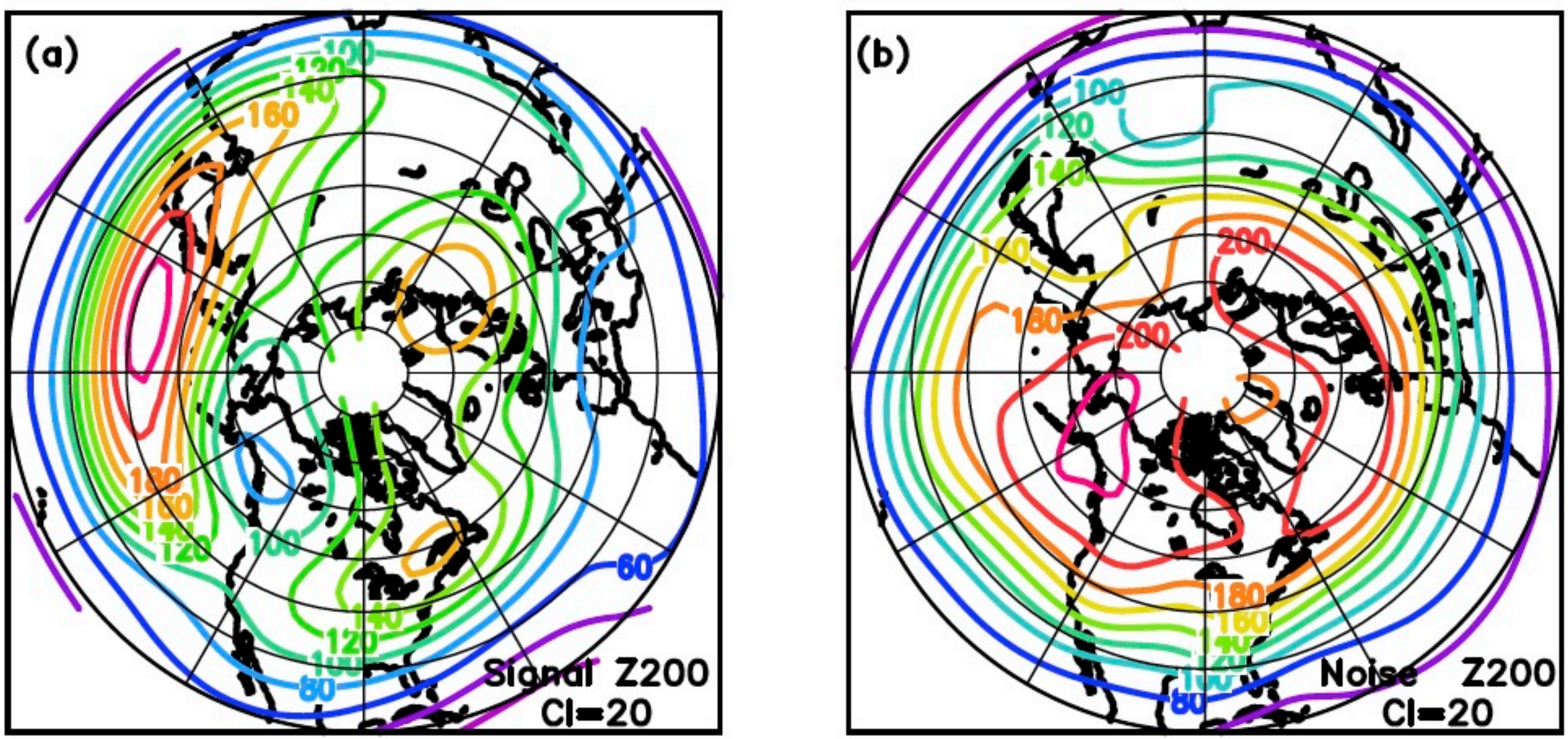


FIG. 7. (a) Signal of 200-hPa height, given as the square root of the variance of daily ensemble means. (b) Square root of the mean daily intra-ensemble variance. Contour interval is 20 m. Grid lines drawn every 10° in latitude from 20° to 80°N. See text for further details.

Raw total signal to noise ratio is rather small in most locations.

We need a technique to extract the time-evolving modes that are *most in common* among the ensemble of simulations.

Use "Predictable Component Analysis" (also called Signal-to-Noise Maximizing EOFs)

Isolate modes which have largest signal-to-noise ratios. Need daily data from all ensemble members

Apply this analysis separately to:

- **200 hPa height (Z200)**
- **Rossby Wave Source**
- **Tendency of Height at 300 hPa due to barotropic action of eddies with time scales less than 10 days:**

$$\frac{\partial \psi}{\partial t} = -\nabla^{-2}\left(\vec{\nabla}\cdot\left(v'\zeta'\right)\right)$$

$$\frac{\partial Z}{\partial t} = \frac{f}{g}\frac{\partial \psi}{\partial t}$$

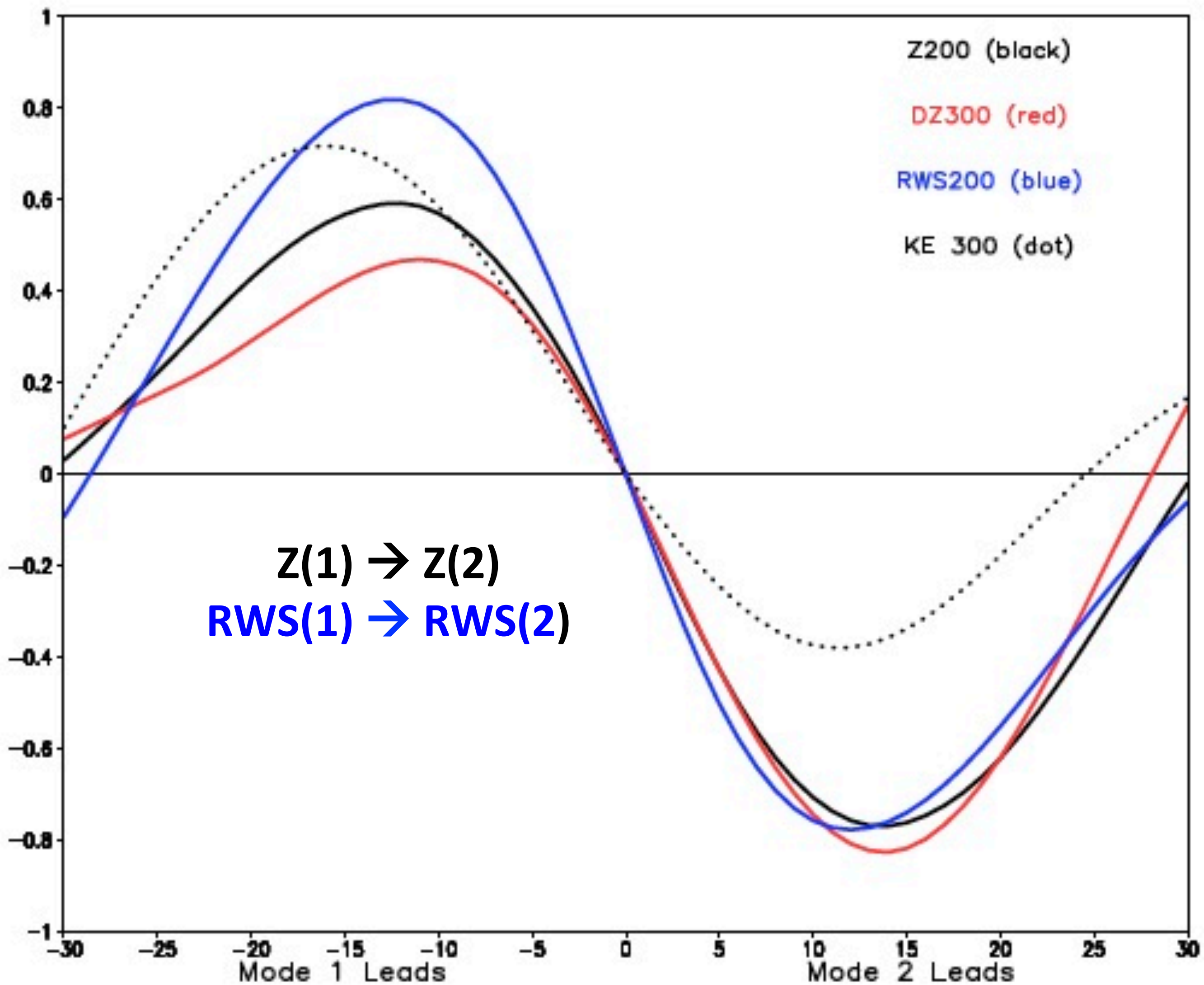
“Predictable Component Analysis” (also called Signal-to-Noise Maximizing EOFs)

Isolate modes which have largest signal-to-noise ratios. Need daily data from all ensemble members

References:

Venzke, S., M. R. Allen, R. T. Sutton, and D. P. Rowell, 1999: The atmospheric response over the North Atlantic to decadal changes in sea surface temperature. *J. Climate*, **12**, 2562–2584.

DelSole, T., and P. Chang, 2003: Predictable component analysis, canonical correlation analysis, and autoregressive models. *J. Atmos. Sci.*, **60**, 409–416



Lag Correlation Between two leading modes of a number of fields;
Two leading modes indicate a single oscillatory mode in each case

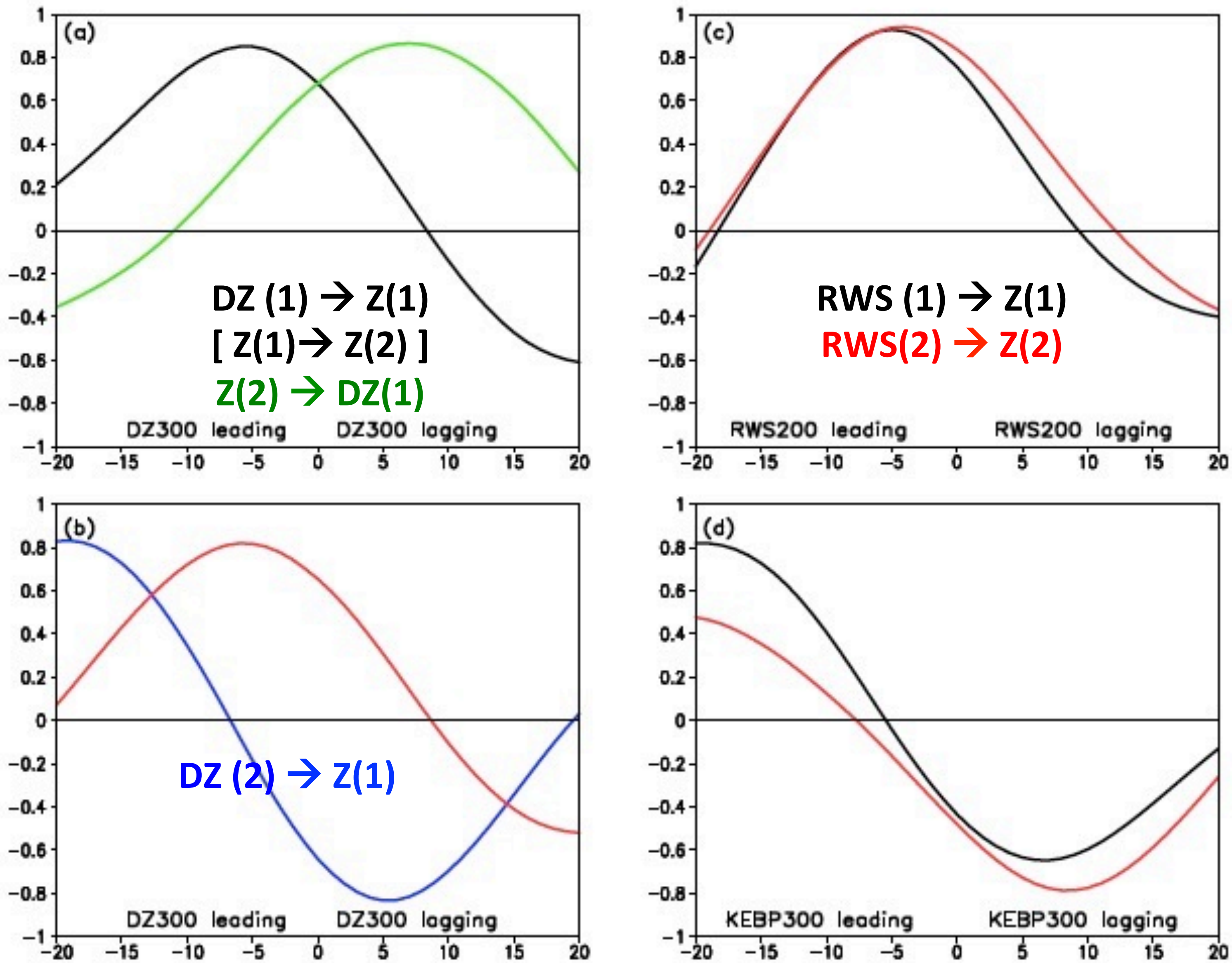
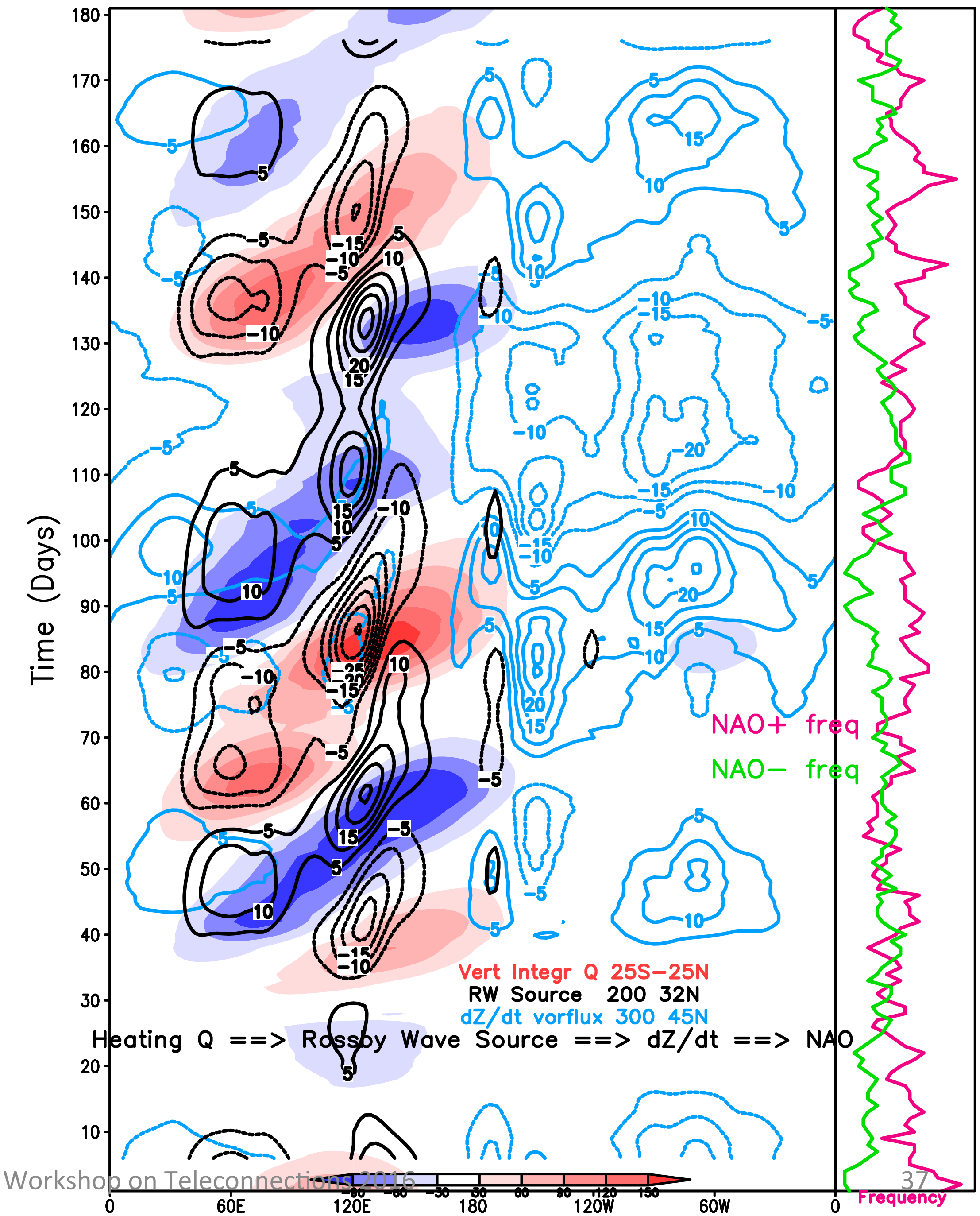
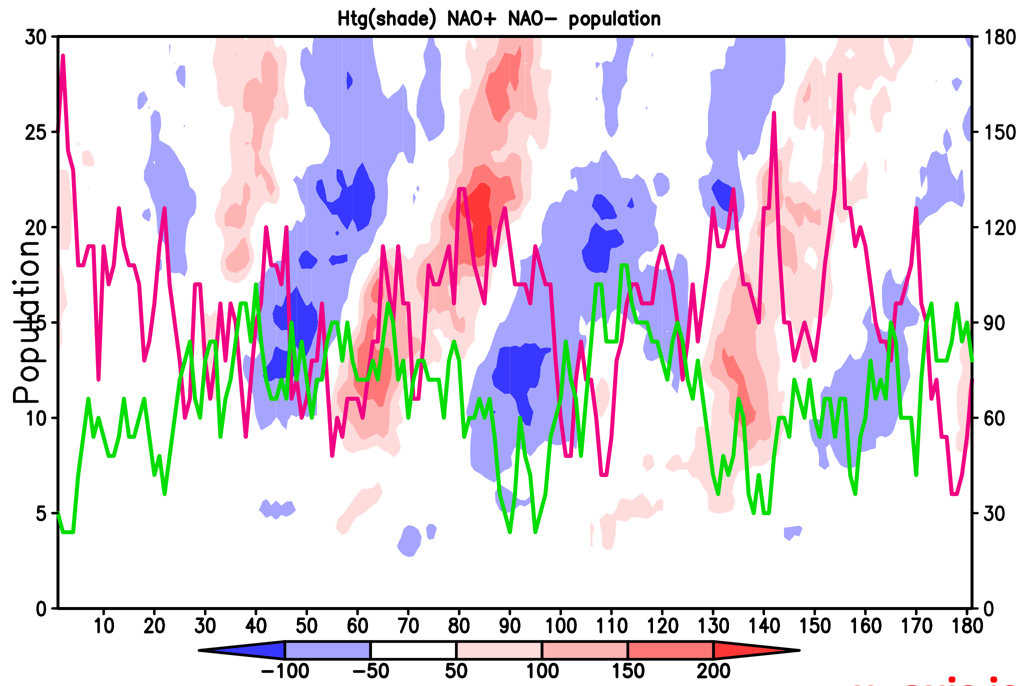


FIG. 10. Cross lag correlation between the ensemble-averaged time series of (a) modes 1 and 2 of Z200 with mode 1 of DZ200, shown in black and green curves, respectively; (b) modes 1 and 2 of Z200 with mode 2 of DZ200, shown in blue and red curves, respectively; (c) modes 1 and 2 of Z200 with corresponding modes of RWS200, shown in black and red curves, respectively; and (d) modes 1 and 2 of Z200 with corresponding modes of KEBP300, shown in black and red curves, respectively.

Synthesis of leading two most predictable components at all times for **RWS200 at 32°N** (black contours, interval 5.0 × 10^{-11} s^{-1}), **300-hPa height tendency from synoptic-scale vorticity flux** at 45°N (blue contours, interval 5 m day^{-1}), **vertically integrated diabatic heating,** averaged from 25°S to 25°N, with scale shown at the bottom of the figure (W m^{-2}). Red (green) curves on the right show the frequency of occurrence of NAO+ (NAO−) clusters (see text for details). Abscissa is longitude and ordinate is in time in days.

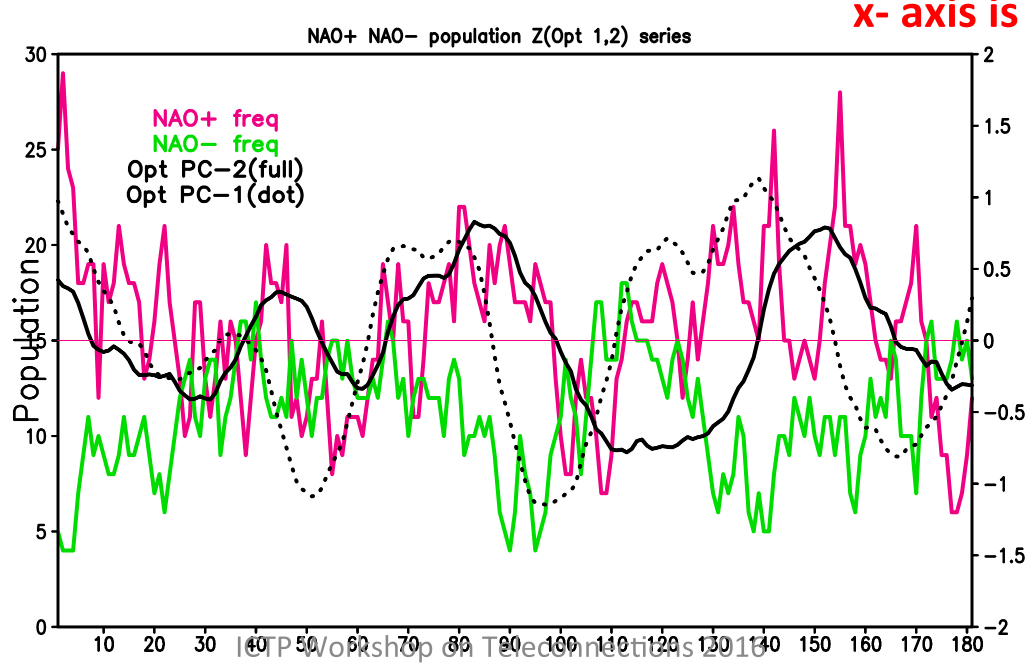


Ensemble Mean heating evolution vs. Frequency of occurrence of NAO+, NAO-



Longitude of ensemble mean heating

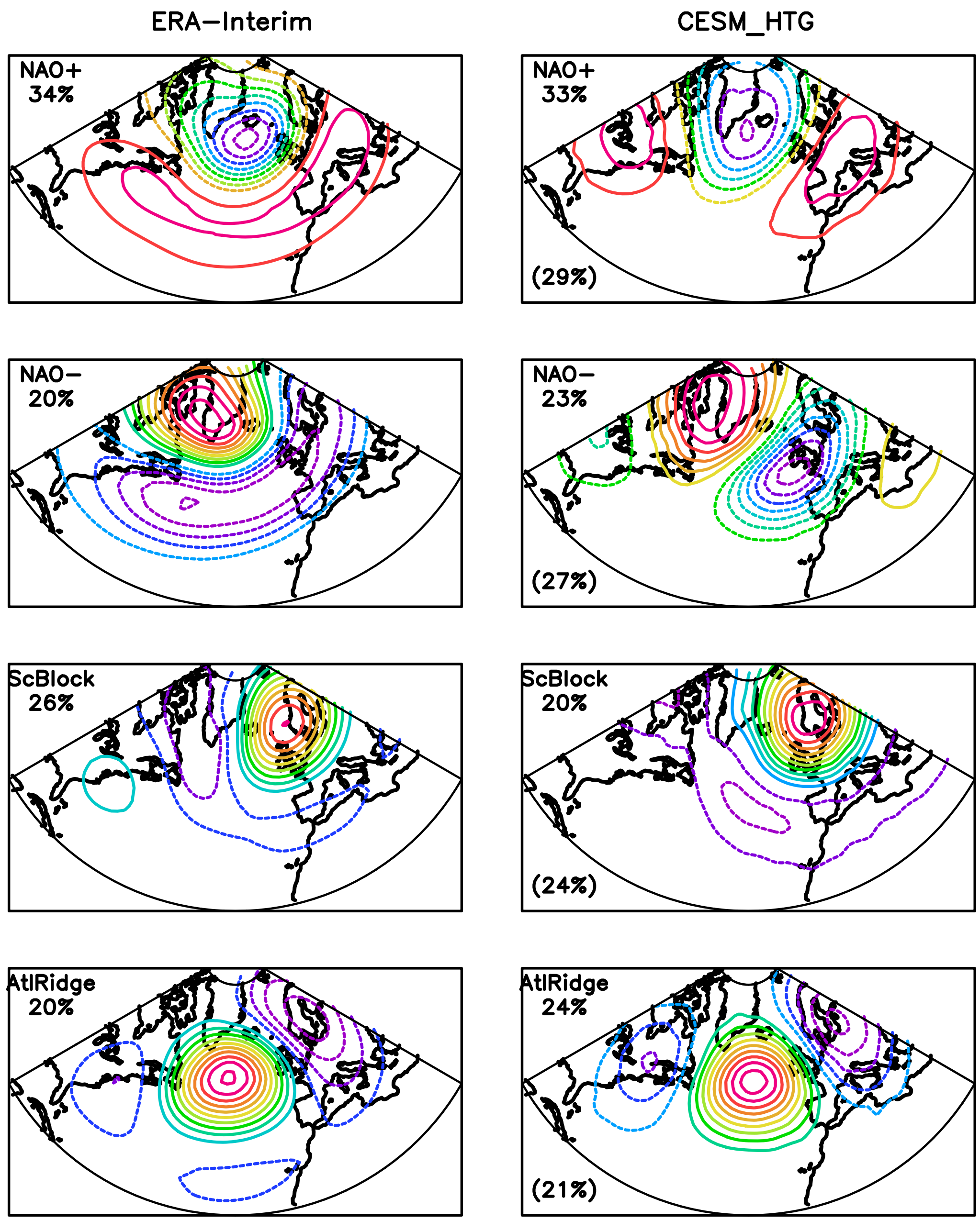
x- axis is time in days



One view of the Atlantic Circulation

Preferred states (clusters) of Z 200

Adding the MJO does not improve the patterns, but it improves the relative frequency of occurrence of the NAO phases



Top percent (HTG)

Bottom percent (Control)

The NAO+ has occurred much more frequently than the NAO- (34% vs. 20%) from 1980-2011.

Control model misses this (29% vs. 27%)

Heating runs reproduce this: (33% vs. 23%)

Some thoughts…

The model-generated MJO heating does not propagate with a single phase speed but shows modulations The extratropical circulation modes share this character.

Thus, some inter-event variability is captured within the seasonal MJO cycle. In particular the time lag between MJO-related convection crossing a particular longitude and its downstream effects varies within the seasonal evolution.

The realism of the evolution synthesized from the leading optimal modes suggests that in nature, the midlatitude response to theMJO also depends on the history of heating and cooling, and is not simply a response to heating at some longitude with a fixed time lag.

It turns out that the observed Euro-Atlantic Response is quite different for MJO episodes that propagate slowly from Indian Ocean to the western Pacific comared to those that propagate rapidly. (Yadav and Straus, 2016). Modeling studies are underway to understand this better.