Understanding Tropical – Extratropical Interactions and the MJO

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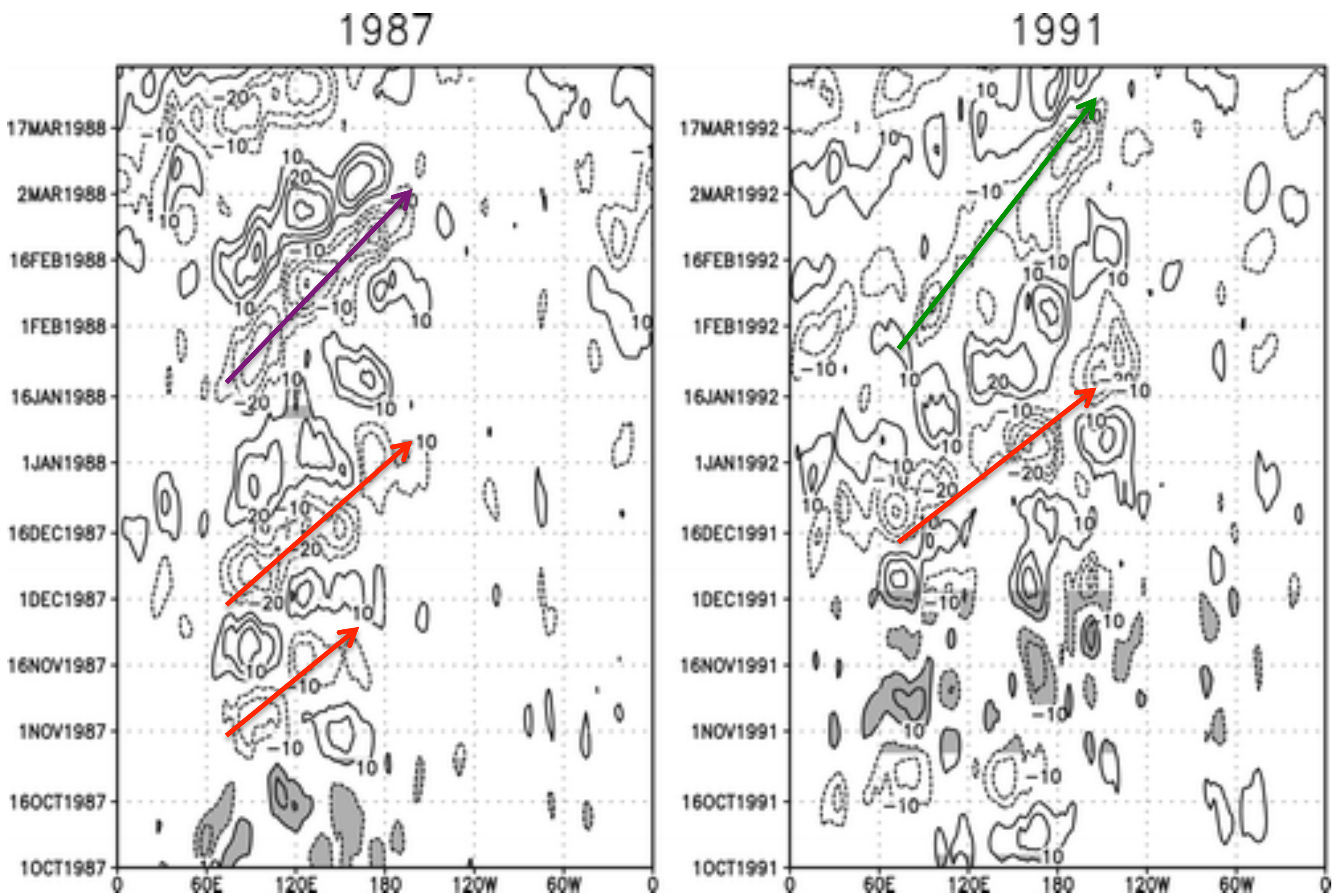
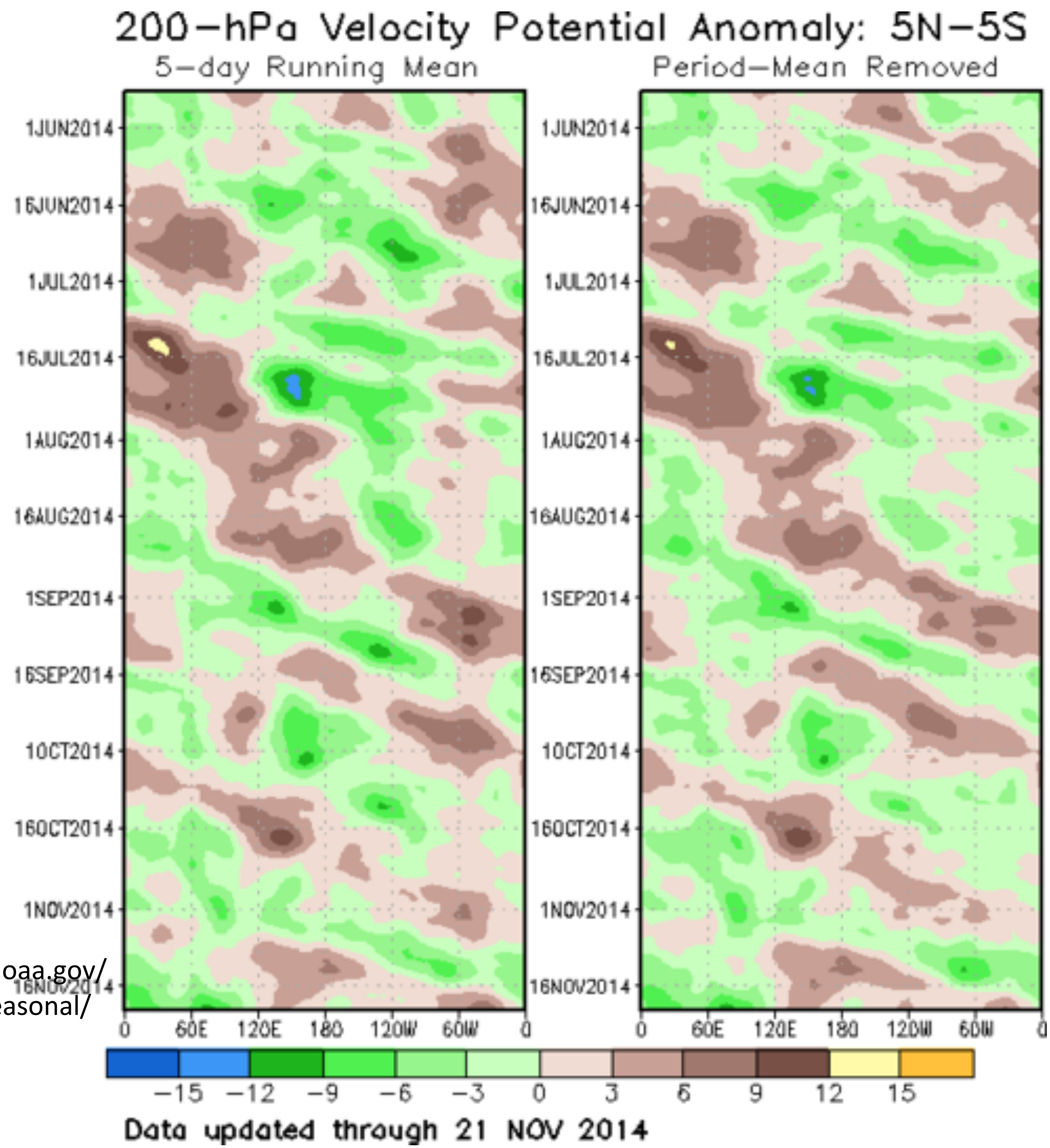
The **Madden–Julian oscillation (MJO)** is the largest element of the intraseasonal (30–90 day) variability in the tropical atmosphere, and was discovered by Roland Madden and Paul Julian in 1971.

Large-scale coupling between atmospheric circulation and tropical deep convection.

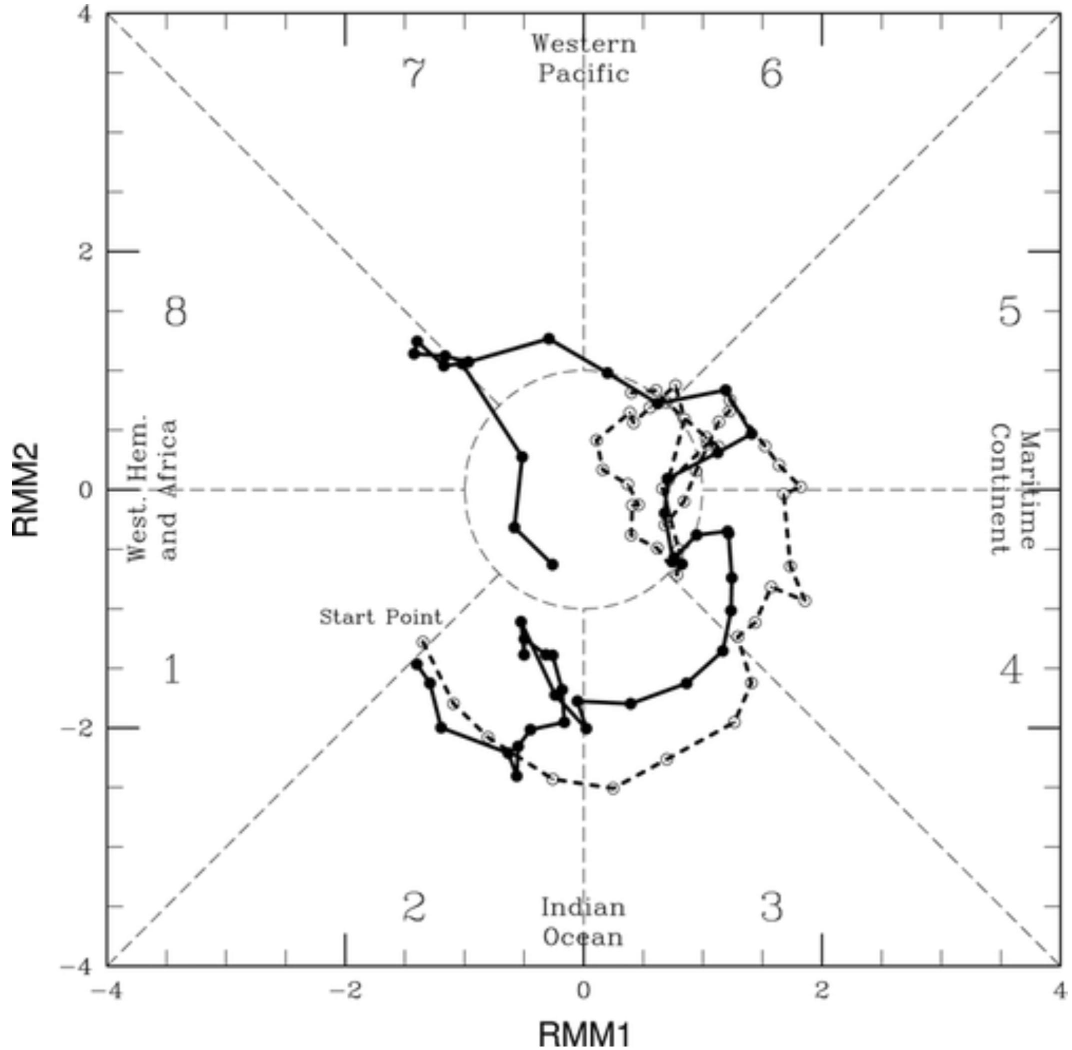
The MJO is a traveling envelope of enhanced and suppressed convection that propagates eastward at approximately 4 to 8 m/s.



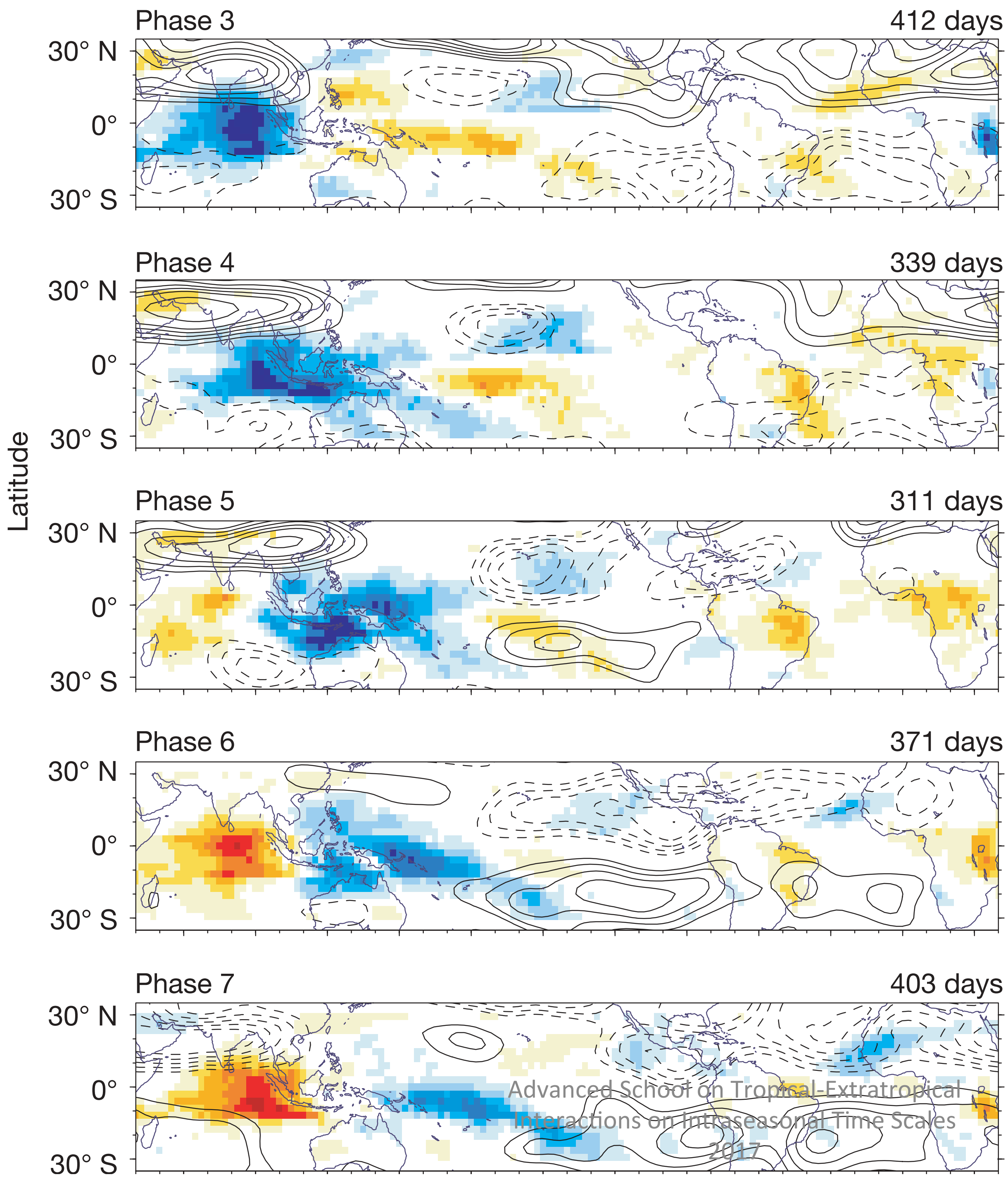
Yadav, P., and D. M. Straus, 2017: Circulation Response to Fast and Slow MJO Episodes., Mon. Wea. Rev., 145, 1577-1596.



http://www.cpc.ncep.noaa.gov/products/intraseasonal/vpot_tlon.shtml



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

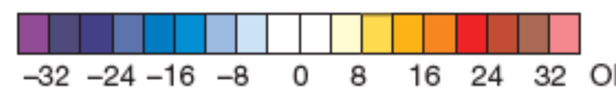


Phase 3: Convection in Indian Ocean, equatorial westerlies at dateline

Madden-Julian Oscillation (MJO)

MJO Standard Phases

Pictures show stream function at 300 hPa and OLR (W/m^2)



Phase 6: Convection in W. Pacific, equatorial easterlies at dateline

Cassou, C., 2008: Intraseasonal interaction between the Madden–Julian Oscillation and the North Atlantic Oscillation. *Nature*, **455**, 523–527

Understanding the extra-tropical response to the MJO

- Measures of the observed Response:
  - Simple regression, or composites of upper level fields (Z200) based on different phases of the MJO. Should Z200 lag the MJO heating, and by how much?
  - Changes in probability of teleconnection patterns (NAO, AO) and/or circulation regimes.

- Stationary Wave Theory:
  - Use of stationary wave models (and other simplified models) to determine the steady state response to the diabatic heating associated with each phase of the MJO. (Ignore transient nature of heating)

- Response to Tropical Pulses of heating

- Role of mid-latitude instabilities in the extratropical MJO response:
  - Barotropic instability and the Simmons-Wallace-Branstator modes
  - Baroclinic instability and the role of storm track shifts

- Response to the full cycle of MJO transient heating
  - Intervention Experiments
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- Current Work and Future Directions

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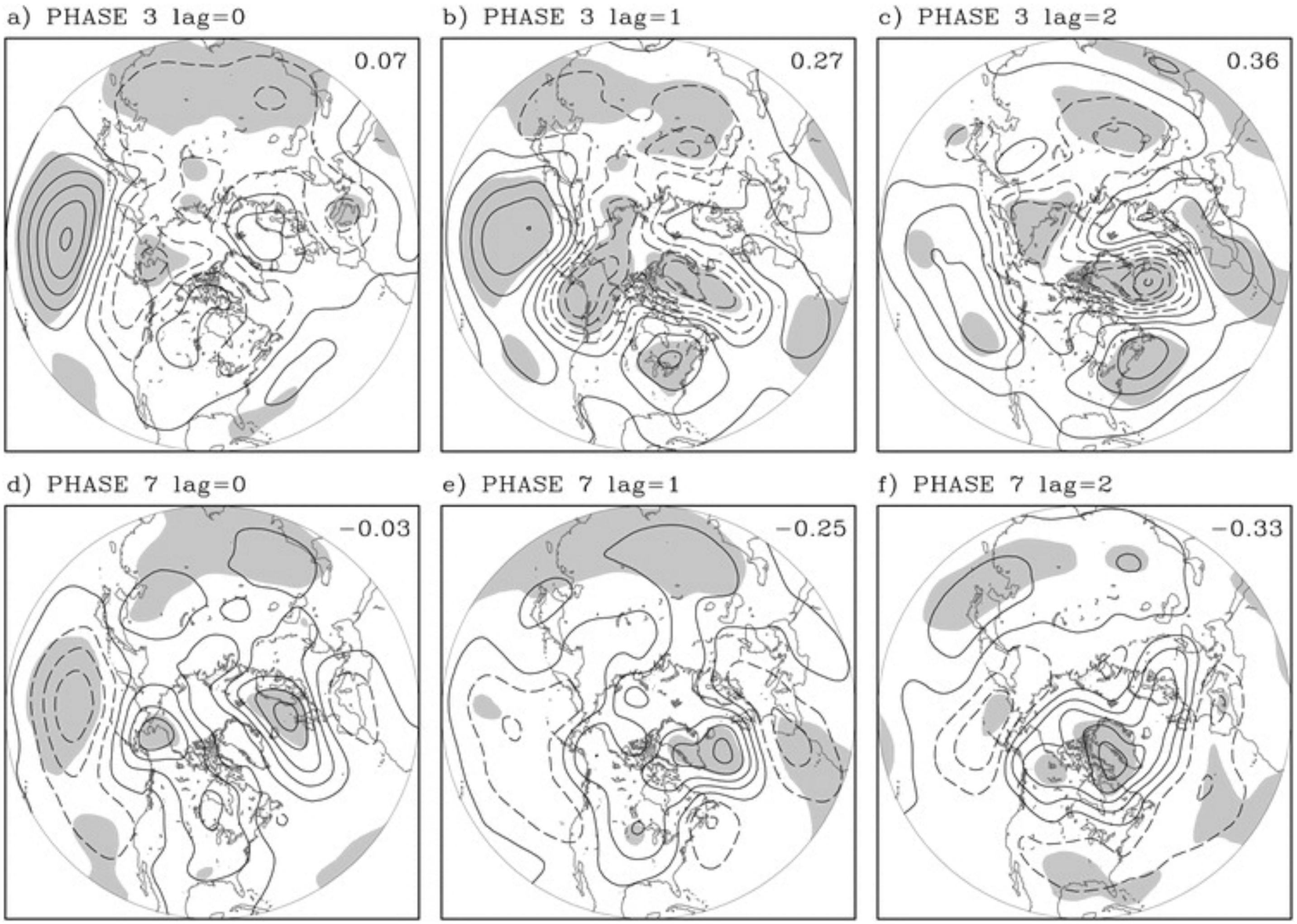
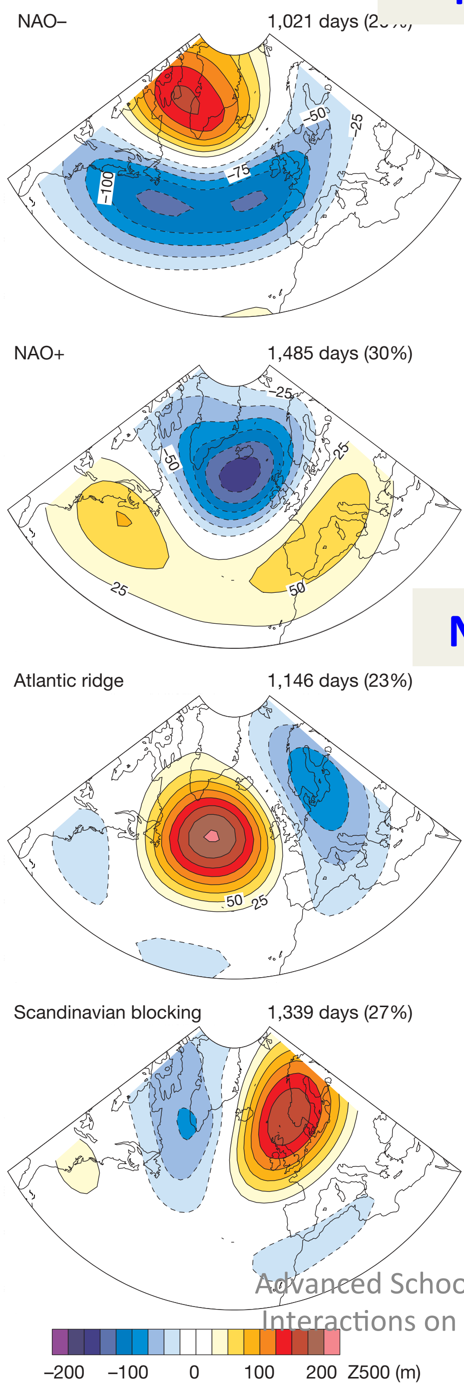


Lagged composites of Z 500-hPa anomaly for MJO (a)–(c) phase 3 and (d)–(f) phase 7. Contour interval is 10 m. numbers in upper right corners are the projection of the composite anomalies onto the NAO

Lin, H., G. Brunet and J. Derome, 2009: An Observed Connection between the North Atlantic Oscillation and the Madden-Julian Oscillation. *J. Climate*, **22**, 364–380.

Z 500 regimes

NAO -



NAO +

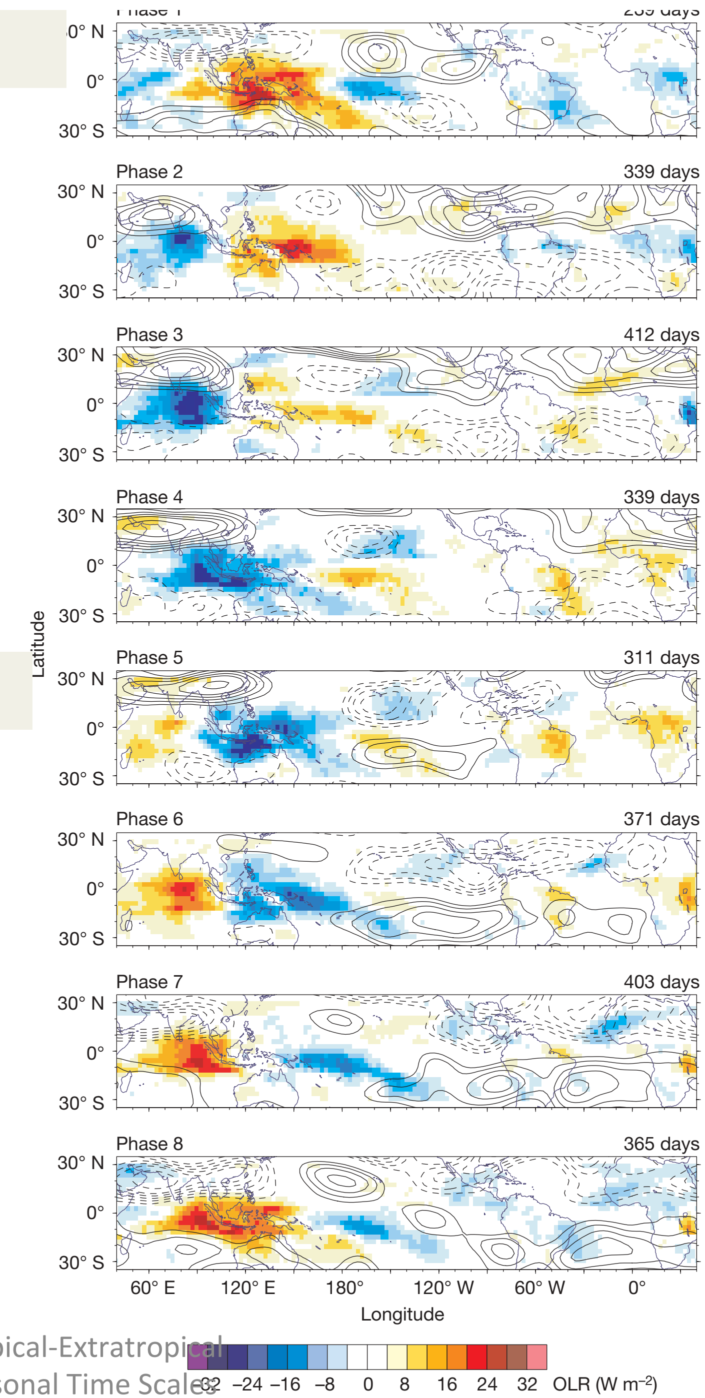
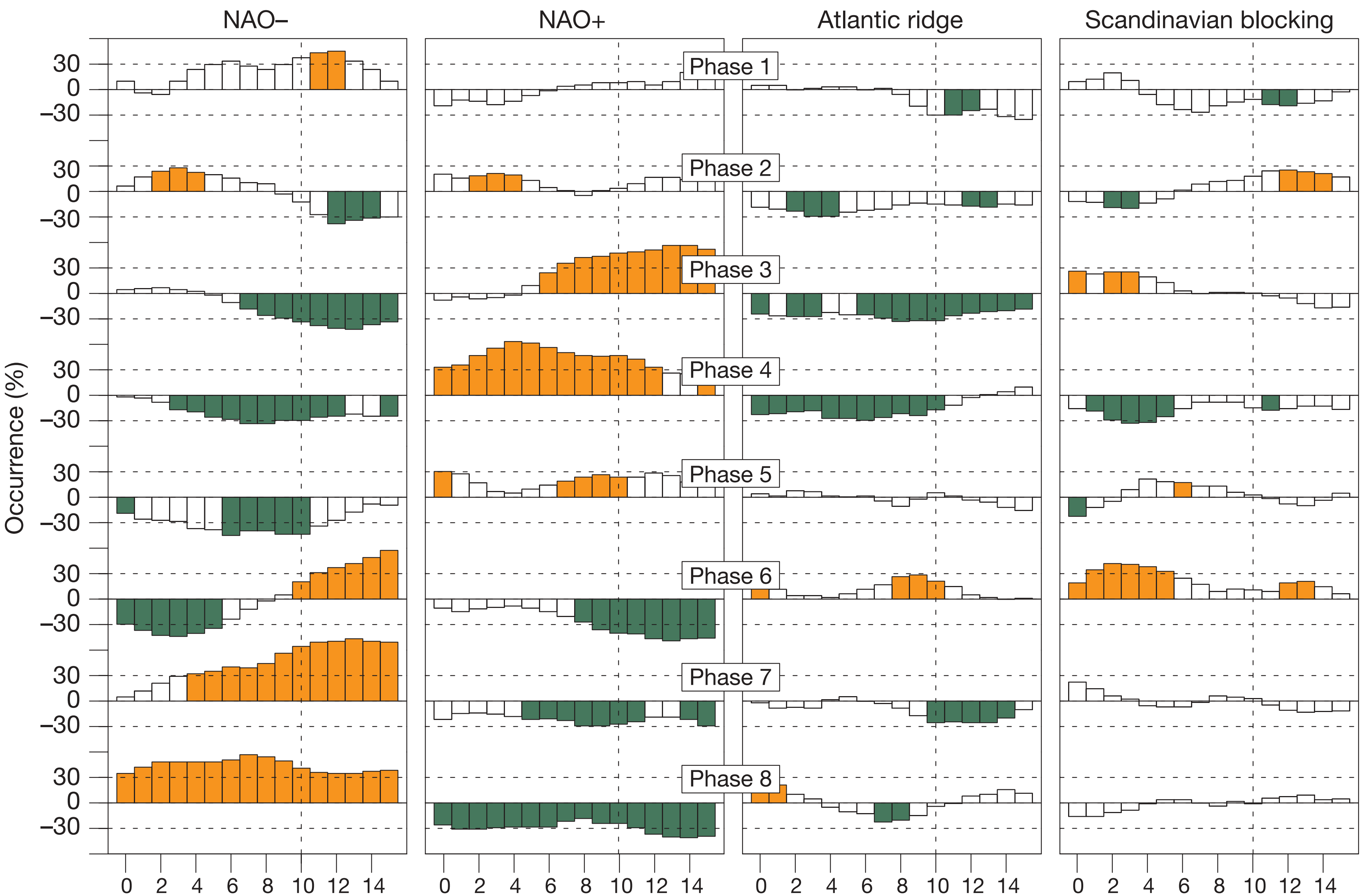


Figure 2 | Dynamical and thermodynamical signatures of the eight phases

Cassou 2008

Change of Occurrence of NAO+ / NAO- Associated with MJO Phases (Cassou, 2008)



The phase of the MJO influences the development of NAO life cycle two weeks later

Quasi-Stationary Wave Interpretation of Observed Response

- Rossby wave source is created in the Indian and western Pacific Oceans as MJO convection propagates eastward through the Indian Ocean and into the western and central Pacific

- Stationary wave trains lead to the retraction of the Pacific jet when the MJO-related convection is over the Indian Ocean and, hence, to changes in the associated fluxes of momentum − implications for Rossby wave breaking?

- Quasigeostrophic index of refraction relevant to the response − sensitivity to changes (or biases) in the "basic state"

- The propagation of the MJO influence into the North Atlantic region is less well understood, although the changes in storm tracks may play a role.

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

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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(Quasi-)Stationary Wave Modeling
(Matthews et al 2004)

The Basic Method:

- Dry non-linear T42 model (12 levels) – initialized about a 3D DJF climatological-mean basic state with constant forcing term.
- Response to imposed heating:
- After ~25 days of integration, baroclinic waves begin to dominate. but *during the first 25 days the direct response to the imposed fixed MJO heating anomalies can be diagnosed.*

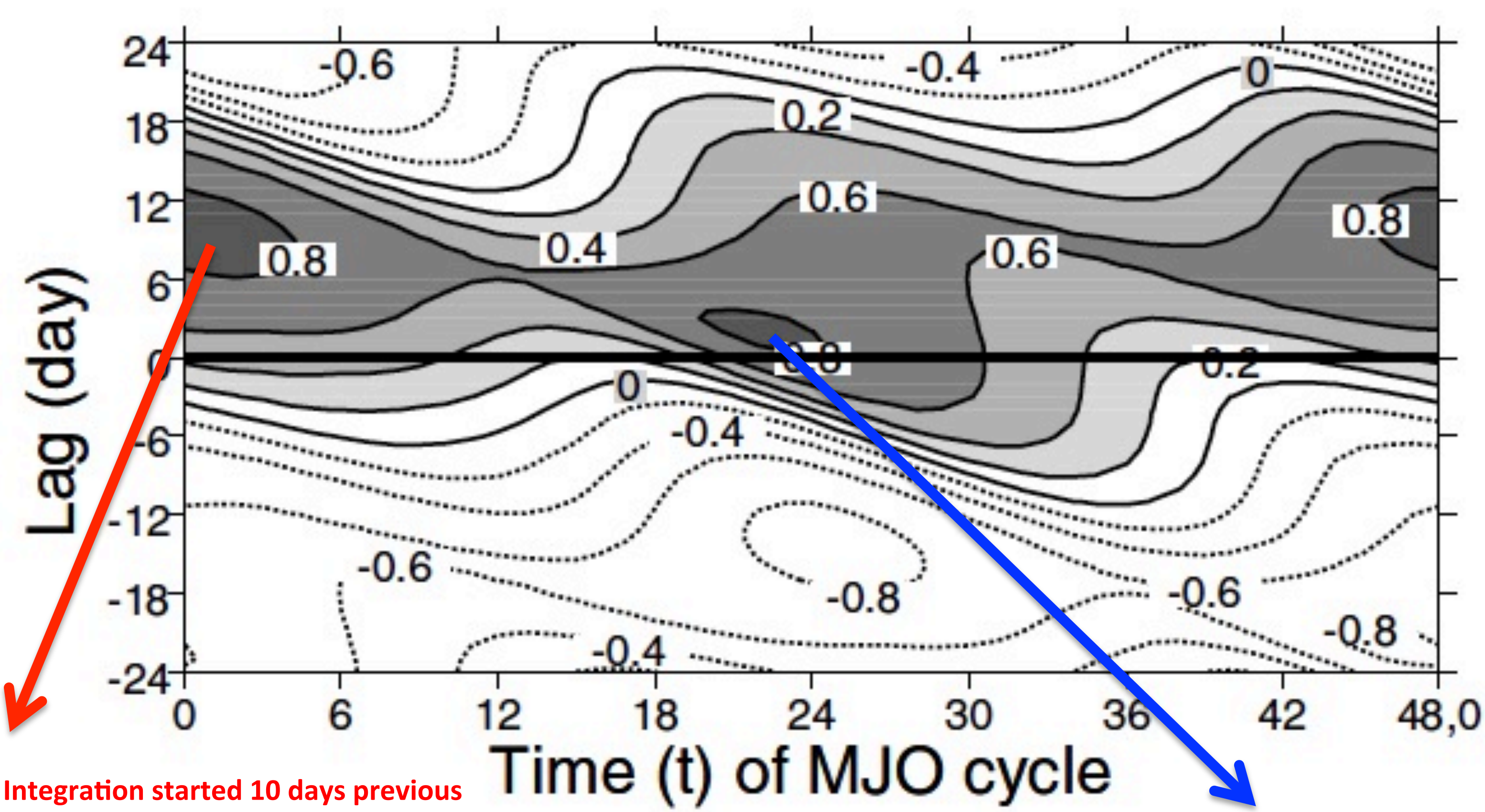
The Experiments:

Time-varying heating experiments:

- Tropical heating anomalies (corresponding to 48 day regular MJO cycle) are prescribed with fixed vertical structure
- Model integrations started at days 1, 2, …, 48 of imposed heating cycle.
- Pick a fixed forecast time (19 days) in each run so that response to heating is well-developed but not overwhelmed by baroclinic transients

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, Quart. J. Royal Meteor. Soc., 130, 1991-2011.

U200 Pattern correlation (20-90N) between Model U at day 19 and observed U at time t in the MJO cycle.



Model Integration started 10 days previous to time=0 in the MJO cycle. Day 19 field matches OBS U at day 0 in MJO cycle

Model Integration started 2 days previous to time=24 in the MJO cycle. Day 19 field matches OBS U at day 24 in MJO cycle

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, *Quart. J. Royal Meteor. Soc.*, **130**, 1991-2011

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Response to Tropical Pulses of Heating

(Branstator, 2014)

Mid-latitude response to localized equatorial heating events that last 2 days AGCM. Responses to such pulses serve as building blocks with which to study the impacts of more general heating fluctuations.

Short-lived heating produces responses in mid-latitudes at locations far removed from the source and these responses persist much longer than the pulses themselves.

Response to steady heating can be reconstructed from responses to a sequence of 2-day pulses, each evaluated with the appropriate time delay.

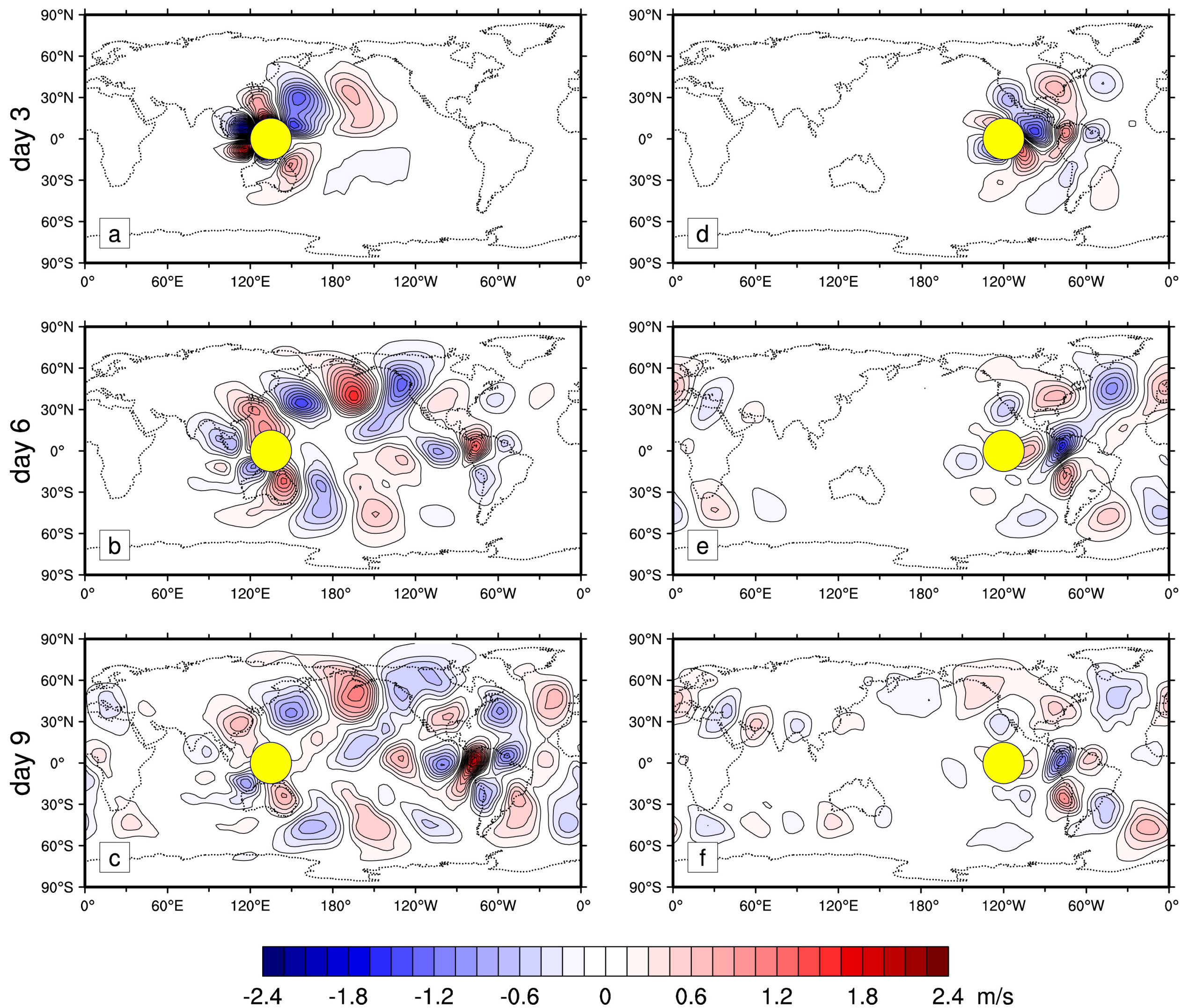
Limitations:

- low-resolution GCM: T42 (CAM3)
- Only equatorial heating (idealized hor. & vert. structure), 24 locations

BUT:

- Large Ensemble Size: 100 integrations of length 62 days for each heating

*Branstator, G., 2014: Long-lived response of the midlatitude circulation and storm tracks to pulses of tropical heating. J. Climate., 27, 8809-8826.



Ensemble mean *v*300 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

The MJO heating is *not* 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 distribution Q(**x**,t) at one particular time may be thought of as sources for wave trains.

The remote response $R(\vec{x},t)$ at any point **x** some time t 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.

$$R(\vec{x},t) = \int G(\vec{x},\vec{x}';t,t')\, Q(\vec{x}',t')\, d^3x'dt'$$

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The role of mid-latitude barotropic instability

(Simmons et al., 1983)

- Low frequency fluctuations which derive their kinetic energy from barotropic instability of the mean flow.

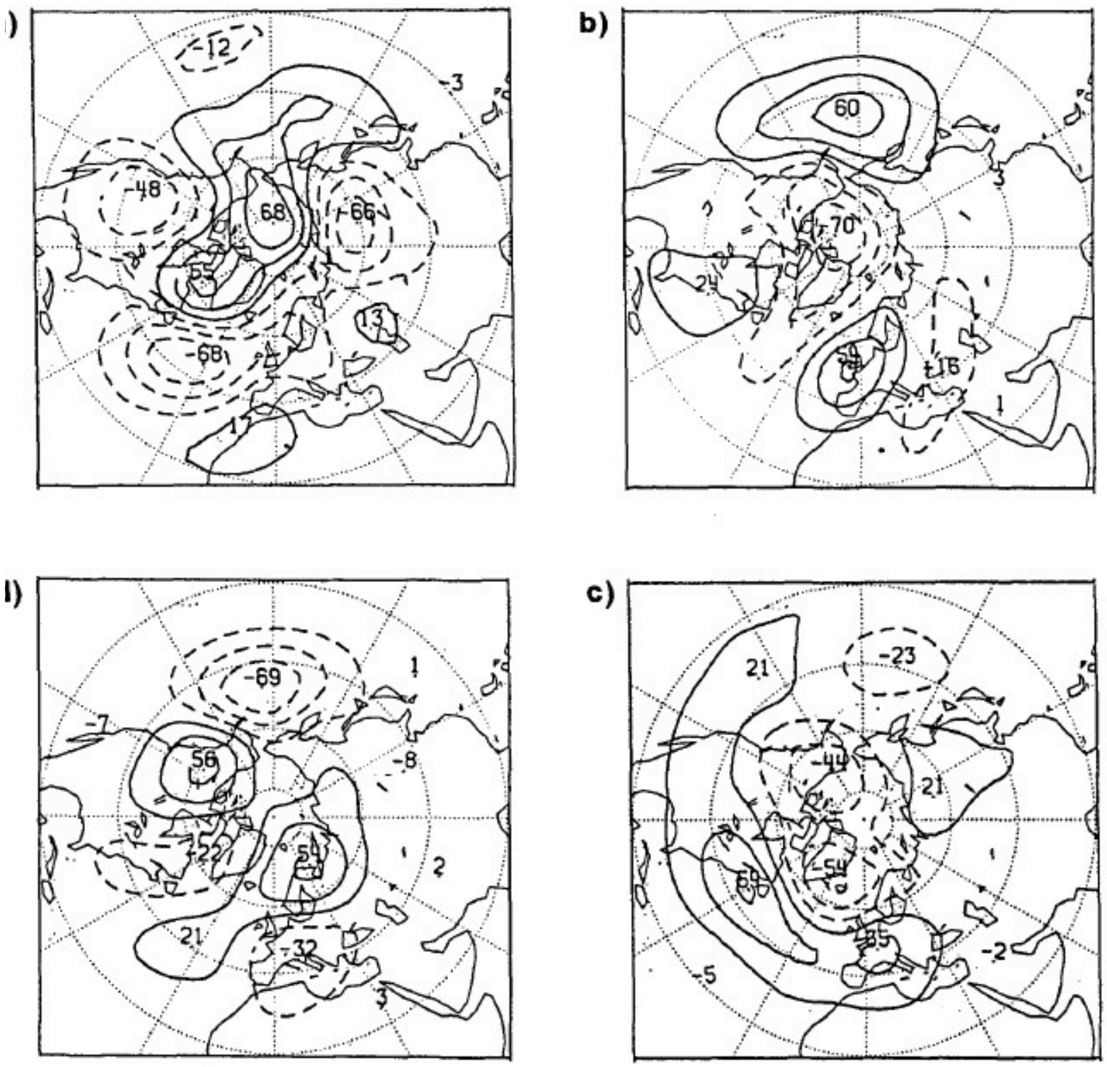
- Climatological 300 hPa flow has fastest growing barotropic mode of period about 45 days, and e-folding time of ~6.8 days.

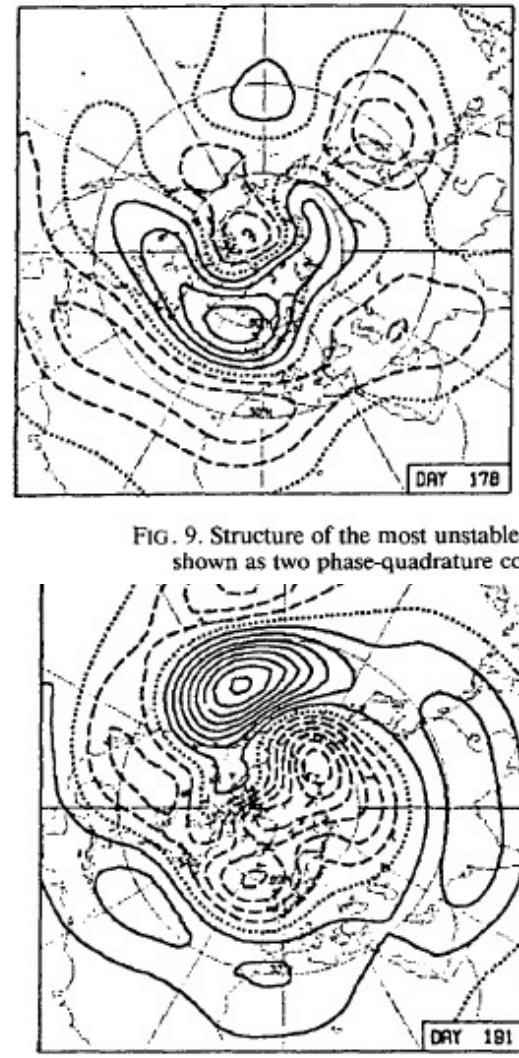
- With an e-folding time of the order of a week or more for the most unstable normal mode, it might be thought that this barotropic instability would be of much less importance than baroclinic instability.

- However, this e-folding time defines the growth of a global, low-frequency mode. Locally in space and time, their may be episodes of rapid growth.

- This mode may play a large role in the response to MJO heating, which has time scales similar to the mode itself.

Simmons, A. J., J. M. Wallace, and G. W. Branstator, 1983: Barotropic Wave Propagation and Instability, and Atmospheric Teleconnection Patterns. *J. Atmos. Sci.*, **40,** 1363-1392.





Barotropic unstable & propagating modes: two phases in quadrature

FIG. 9. Structure of the most unstable mo... shown as two phase-quadrature components (from Simmo

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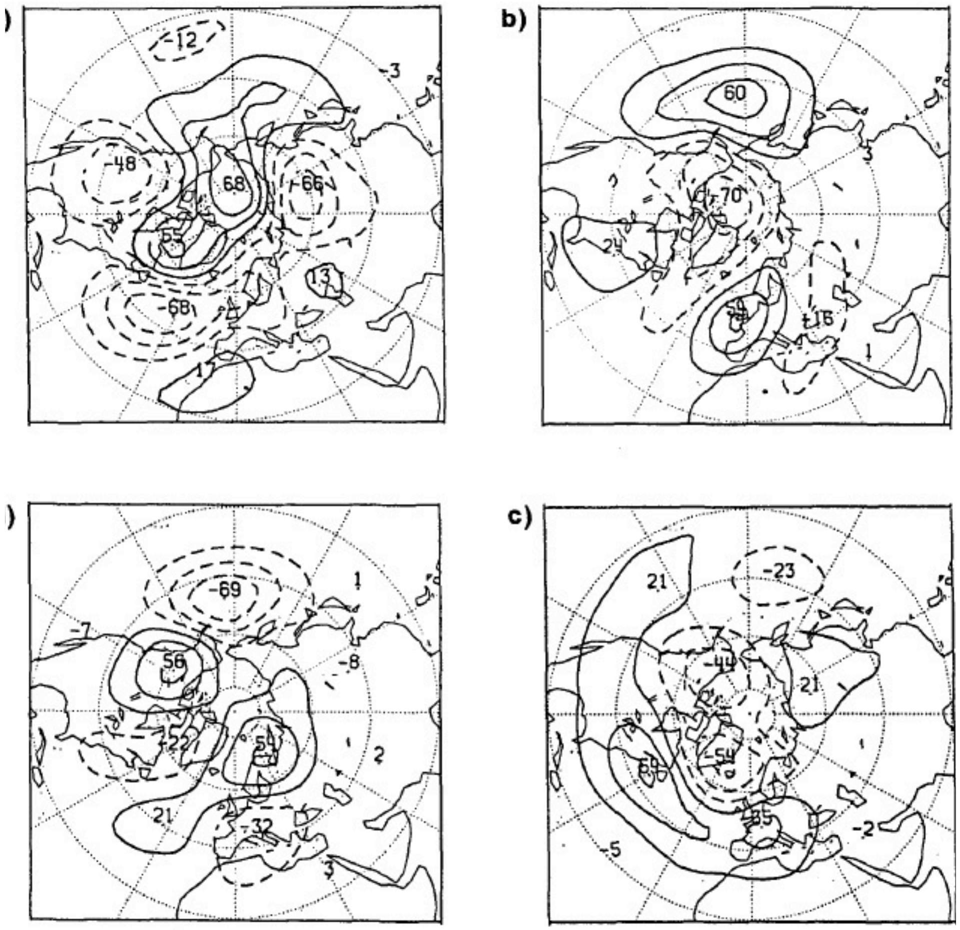
the

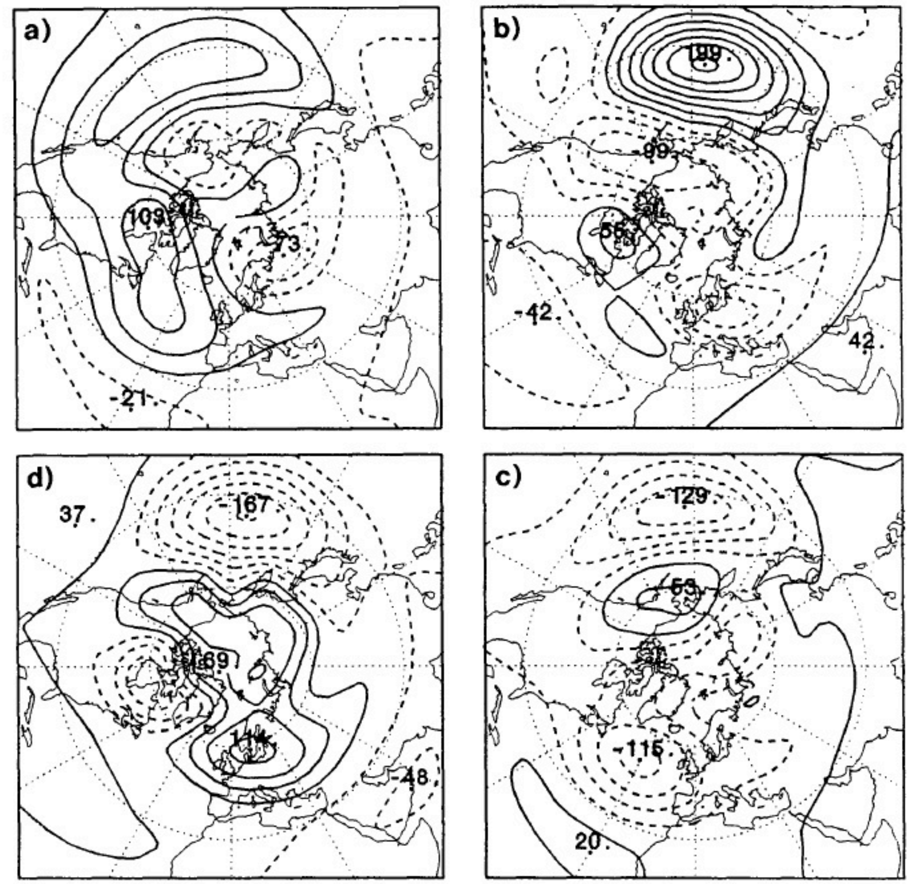
e of a January 300 mb basic state flow,

Composite Z500 based on four phases of the MJO (determined from EOFs 1,2 or OLR. Contour interval of 20 m. (Ferranti et al, 1990)

Barotropic Unstable Mode of Simmons, Wallace and Branstator (1983): Period of 45 days with e-folding time of < 7 days.



Composite Z500 based on four phases of the MJO (determined from EOFs 1,2 of OLR. Contour interval of 20 m



12-day mean Z response from barotropic model forced by 48-day MJO cycle, with Rossby Wave Source included. Contour interval of 30 m

Ferranti, L., T. N. Palmer, F. Molteni and E. Klinker, 1990: Tropical-extratropical interaction associated with the 30-60 Day Oscillation and Its Impact on Medium and Extended Range Prediction. *J. Atmos. Sci.*, **47**, 2177-2199.

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Response to the full cycle of MJO transient heating

Intervention Experiments

- Use full ocean-atmosphere coupled model as a tool
- Don't force the model with specified heating evolution, but "nudge it"
- ADD MJO-like heating evolution $Q_{add}(x,y,p,t)$ to the model's own internally generated diabatic heating.
- Add the identical evolution of heating $Q_{add}(x,y,p,t)$ to each member of a large ensemble (each member having different ICs). This allows you to pull out the *daily* time varying response with Predictable Component Analysis
- Leave all internal feedbacks in the model untouched

The Specified Additional MJO heating*

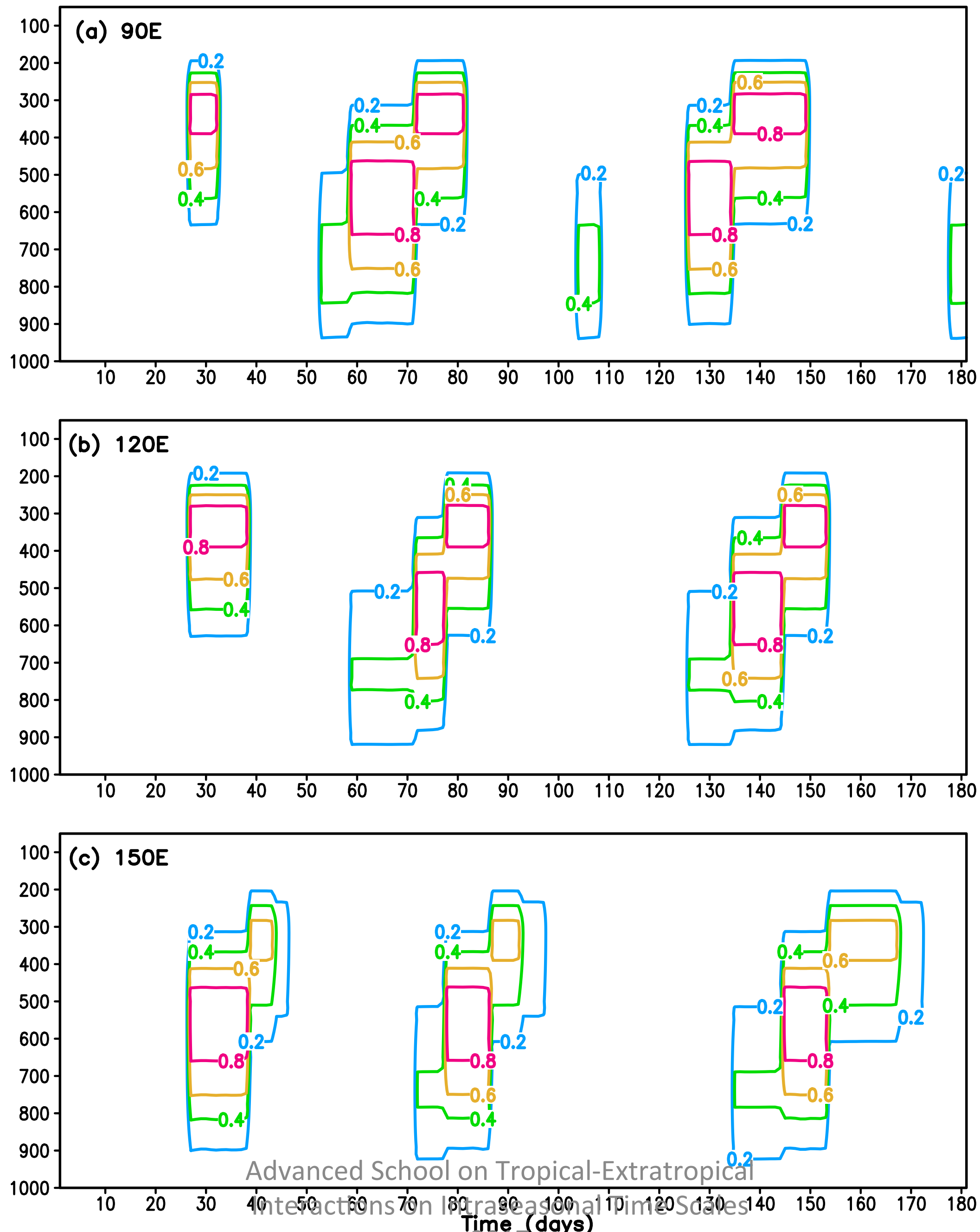
- The three-dimensional heating is based on TRMM radar observations
- The observed climatology of heating for each month/day for each MJO phase is taken into account
- The evolution of the additional heating runs through slightly more than 3 full cycles of the MJO, starting the first cycle with phase 5 (convection in the Indian Ocean) on 27 October and ending the last cycle with phase 6 (convection in the western Pacific on 15 April, for a total of 24 total phases

*Straus, D.M., E. K. Swenson and C.-L. Lappen, The MJO Cycle Forcing of the North Atlantic Circulation: Intervention Experiments with the Community Earth System Model. *J. Atmos. Sci.*, **72,** 660-681.

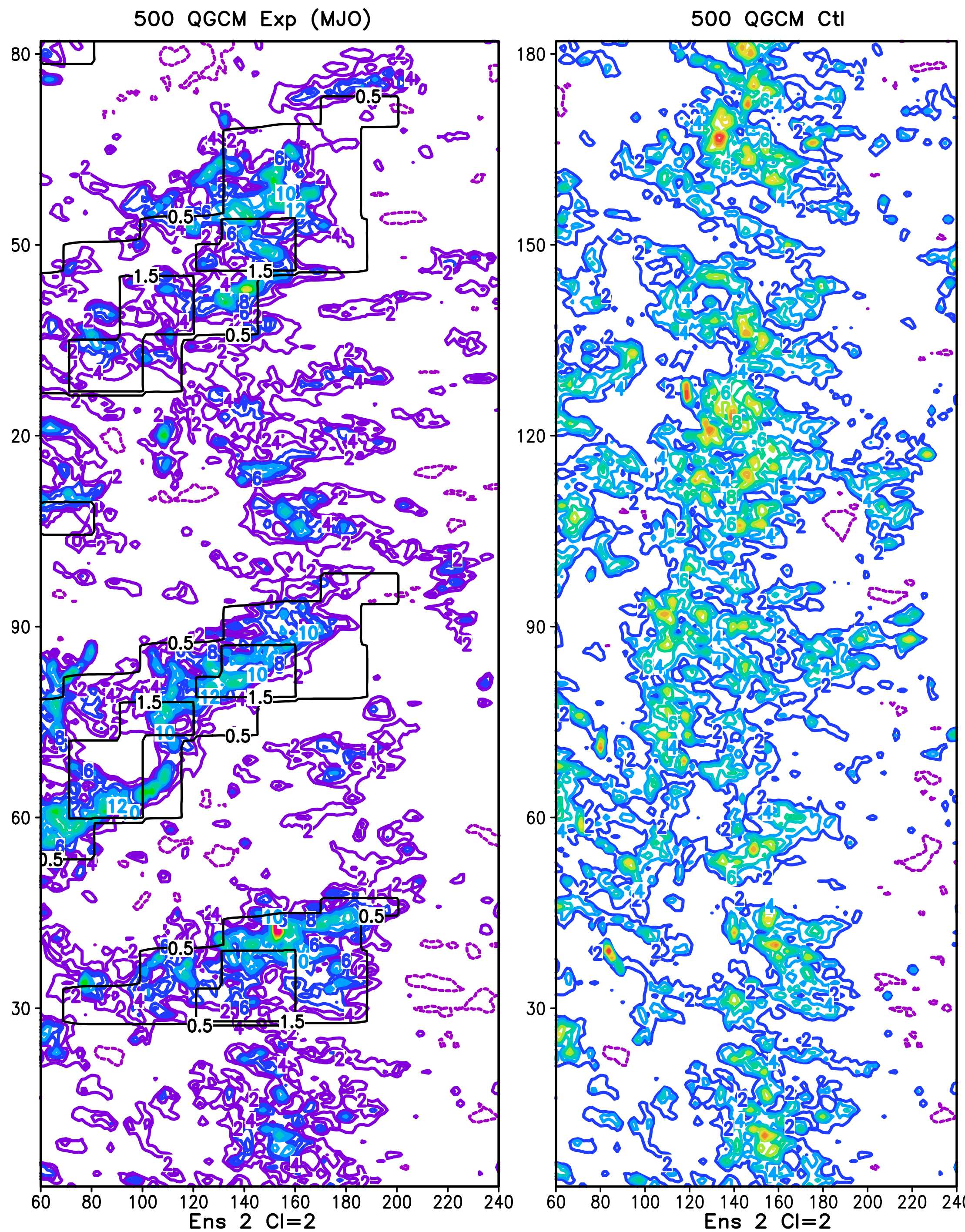
Temperature tendency due to additional heating at various longitudes (ave. 25S – 25N) as a function of time (abscissa) and pressure (ordinate).

Day 1 corresponds to 02 October.

Pressure in hPa.



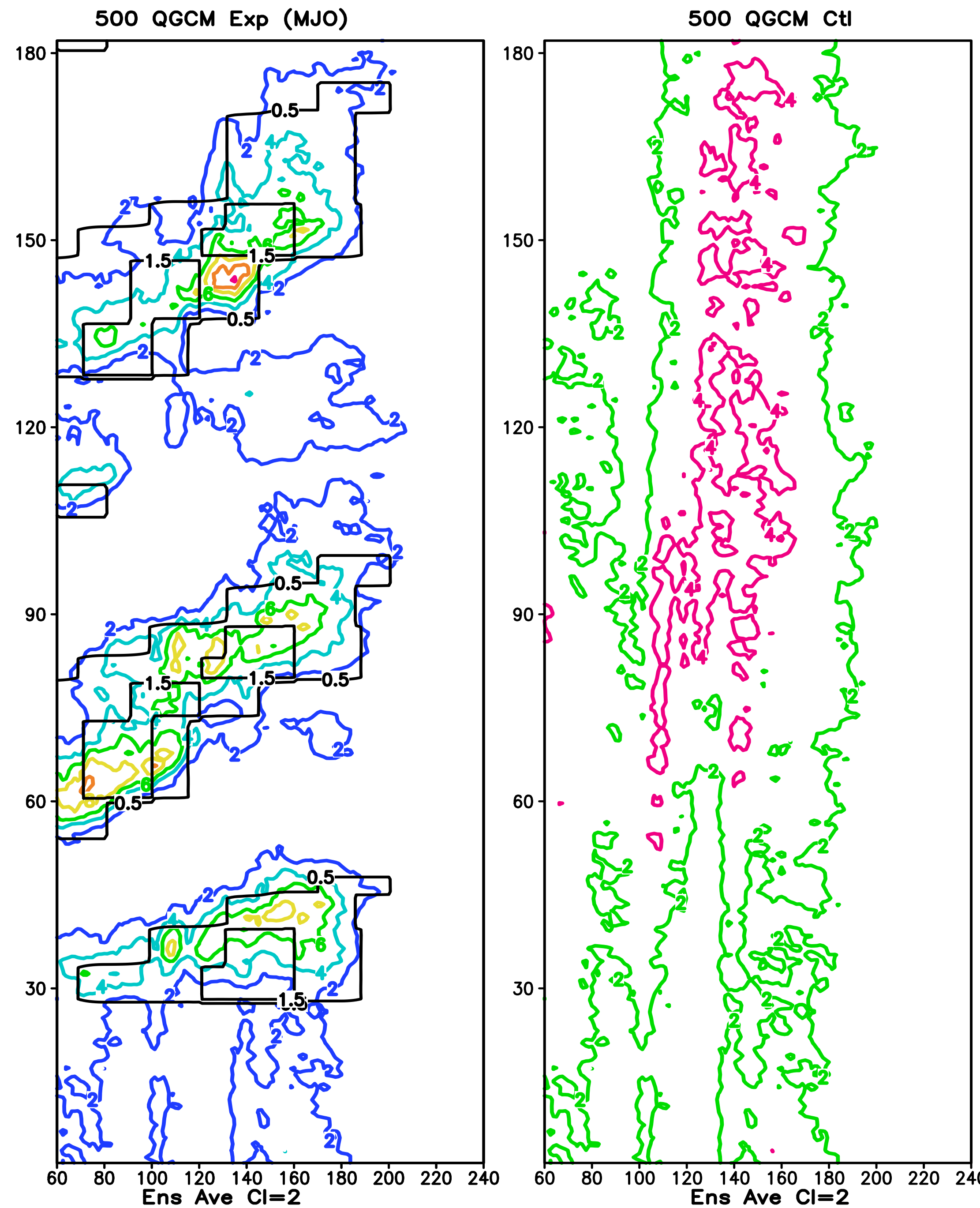
Temperature tendency due to all diabatic heating processes (including the additional heating) from a single ensemble member in colored contours from longitudes 60E- 240E. (averaged 10S-10N; interval 2 deg K / day). The Heating run is shown in the left panel, the corresponding Control run is shown on the right. The additional heating is shown in black contours (interval 0.5 deg K /day). The abscissa is longitude in degrees, the ordinate is forecast time (1 to 181 days), with day 1 corresponding to 02 October



Temperature tendency due to all diabatic heating processes (including the additional heating) from the ensemble average in colored contour from longitudes 60E-240E. (averaged 10S-10N; interval 2 deg K / day).

The Heating ensemble average is shown in the left panel, the corresponding Control average is shown on the right. The additional heating is shown in black contours (interval 0.5 deg K /day). The abscissa longitude in degrees, the ordinate is forecast time (1 to 181 days), with da 1 corresponding to 02 October.

A



Important point:
Full tropical heating (added + model generated) is different in each simulation

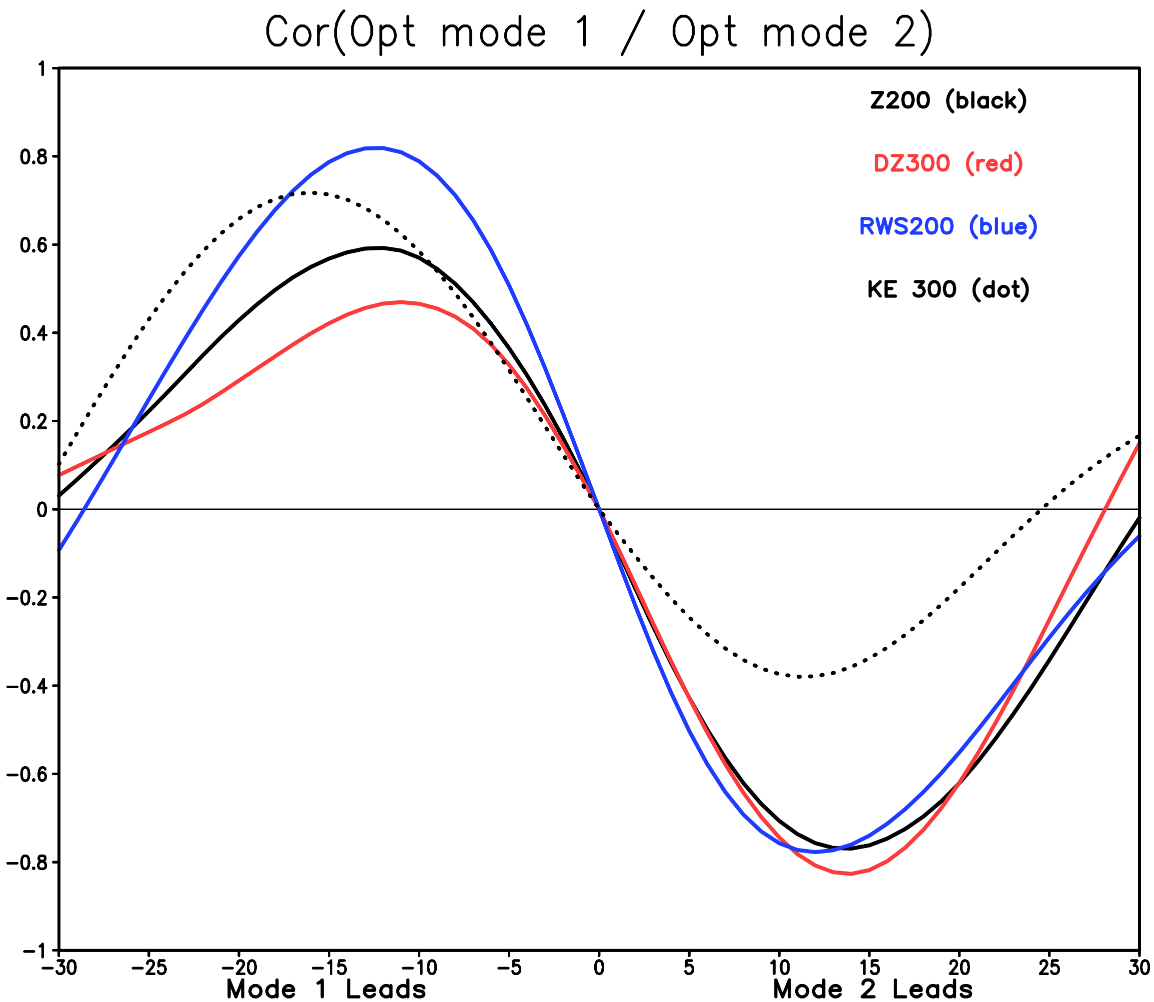
How to extract the "mechanistic mode" = mode in common among all simulations?

"Predictable Component Analysis"

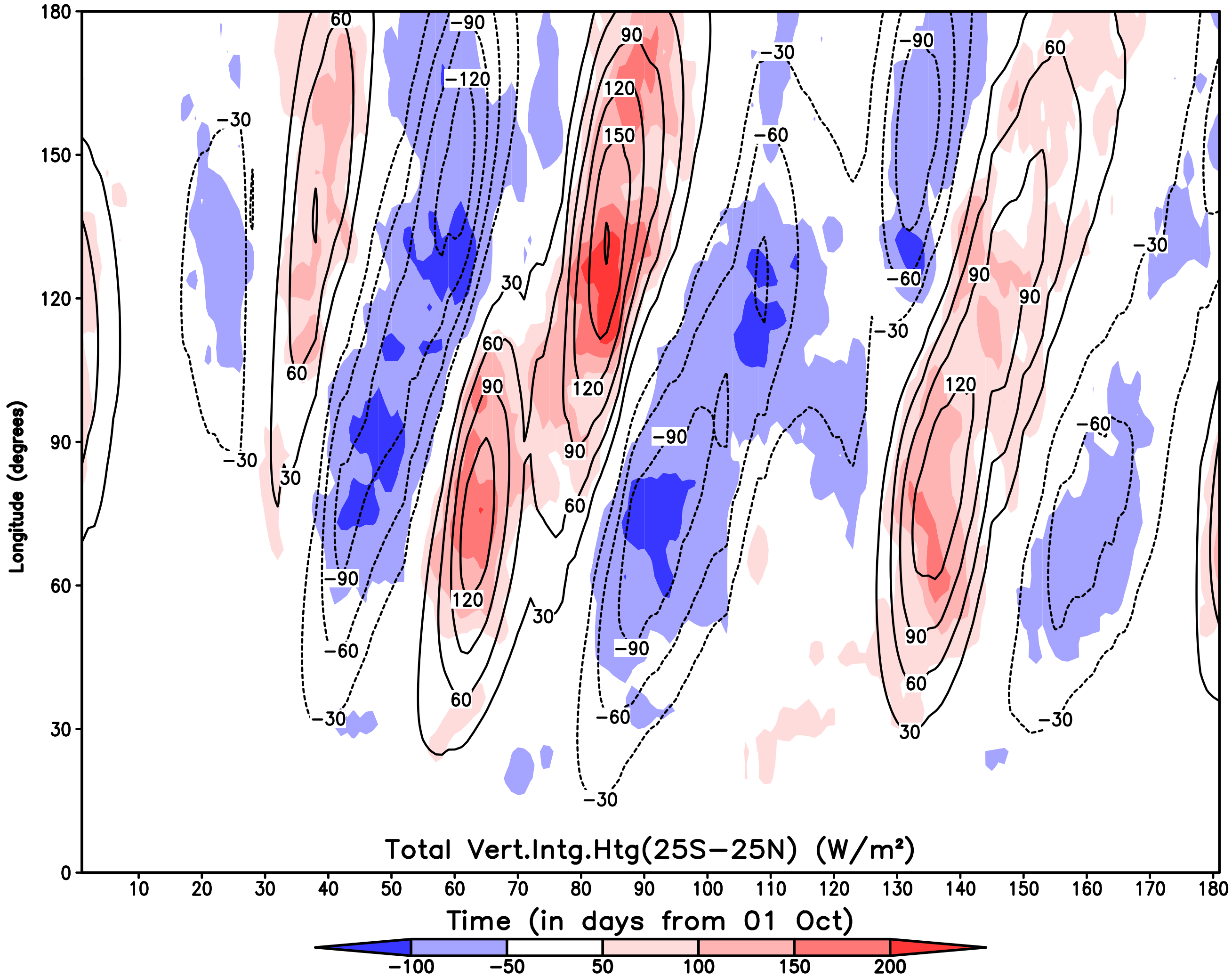
- also called "Signal-to-Noise Optimizing EOFS"
- Expand any field (at all seasonal times, all years and all ensemble members) as a linear combination of "modes" each with its own pattern
- The coefficient of expansion (*the variate*) depends on time, year and ensemble member
- **Maximize the "signal" / "noise" ratio of the *variates***
- "Signal" = variability of the ensemble means of the variates
- "Noise" = variance of deviations about the ensemble mean of the variates

- Modes ordered by signal to noise ratio (measured by the F-value)

Each mode represents an oscillation of about 30 days



Lag correlation between the two most predictable (optimal) modes for **200 hPa geopotential height** (black), **300 hPa synoptic wave geopotential height tendency** (red)**, 200 hPa Rossby wave source** (blue). and 300 hPa envelope of transient kinetic energy (dotted line).



Ensemble average vertically integrated diabatic heating anomalies due to all processes, including the additional heating, averaged 25S-25N, shown in shading in W/m^2. Contours show the planetary wave component **reconstructed from the leading two optimal modes**, averaged 25S-25N.

Role of transients diagnosed via high-frequency vorticity flux convergence

$$\frac{\partial z}{\partial t} = \frac{f}{g}\frac{\partial \psi}{\partial t} = \frac{f}{g}\nabla^{-2}\left(-\vec{\nabla}\bullet\left(\overline{v'\zeta'}\right)\right)$$

$$\zeta = \nabla^2 \psi$$

(primes denote 2- 10 day time scale filtered fields)

Encompasses both:

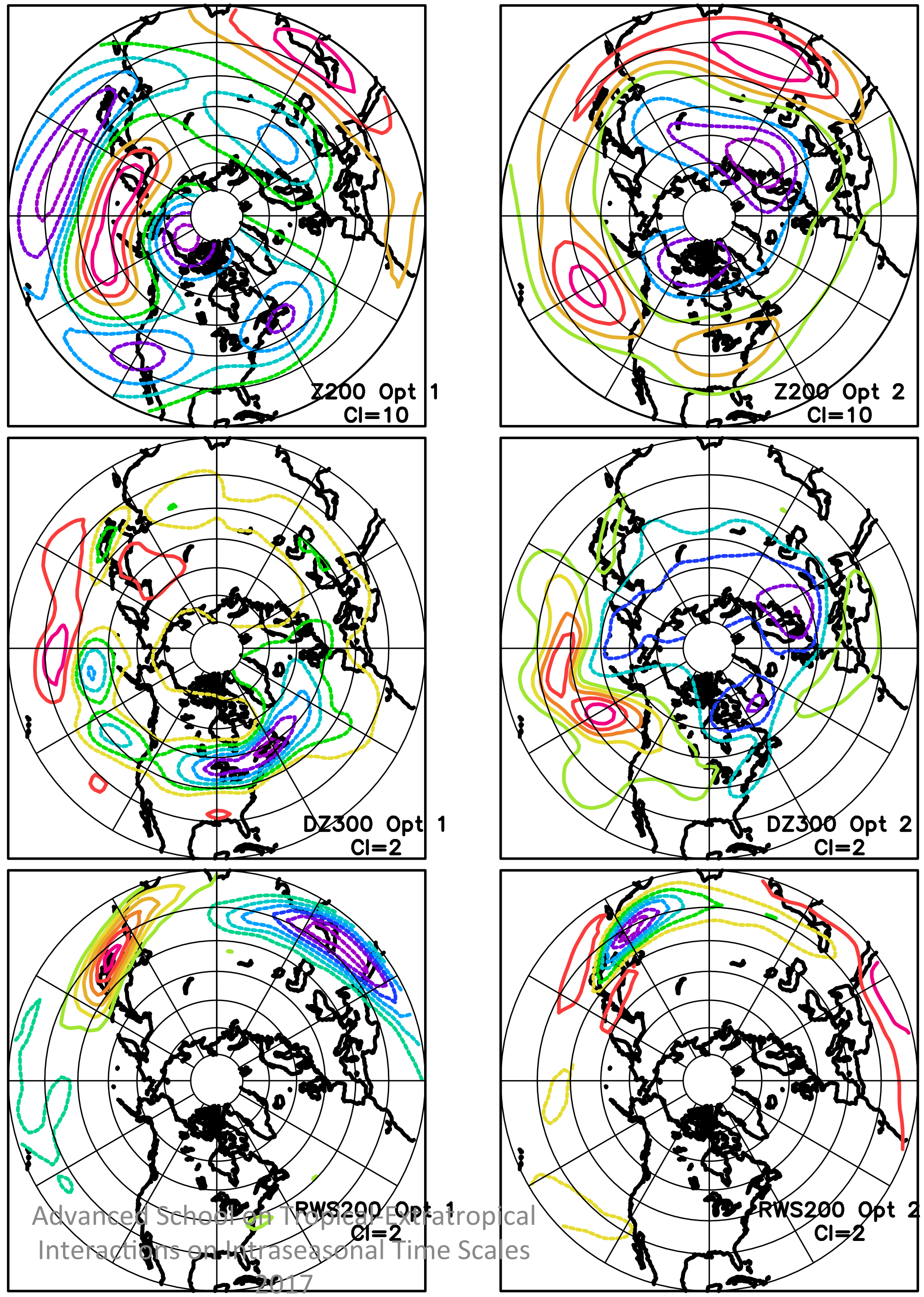
- **Extraction of kinetic energy from the mean flow (as in slow barotropic instability modes of SWB)**
- **Effects of the corresponding momentum fluxes in forcing the jets (Rossby wave breaking)**

Patterns of two most predictable (optimal) modes for:
200 hPa geopotential height (top row)

300 hPa synoptic wave geopotential height tendency (middle row),

200 hPa Rossby wave source (lower row).

Contour intervals are:
10 m (upper)
2 m/d (middle)
2×10^{-11} s^{-2} (bottom)



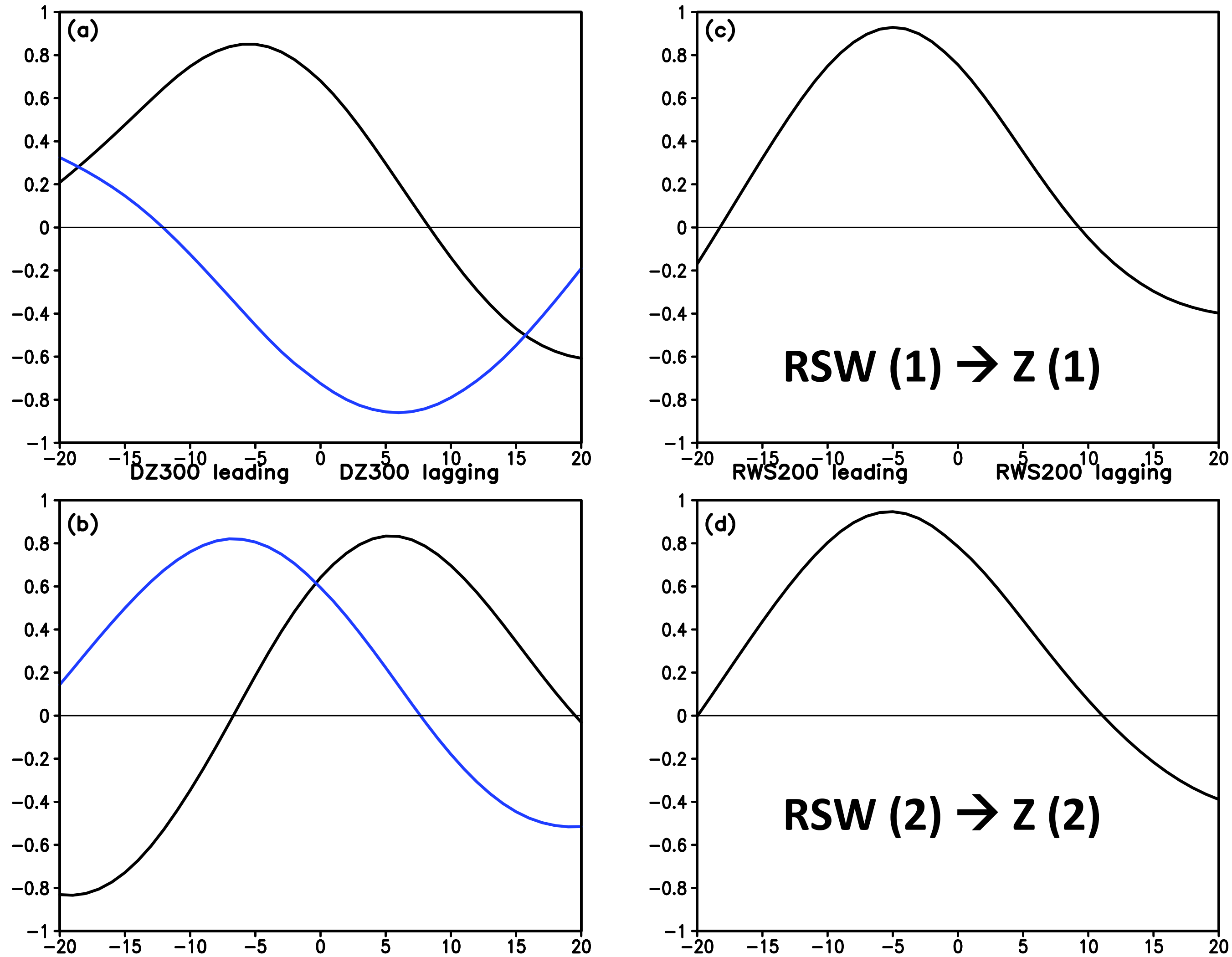
Mode 1 (2) Z200 with DZ300 mode 1

Mode 1 RWS200 with DZ300 mode 1

DZ (1) → Z (1)

DZ (2)→ Z (2)

Z (2) → DZ(1)



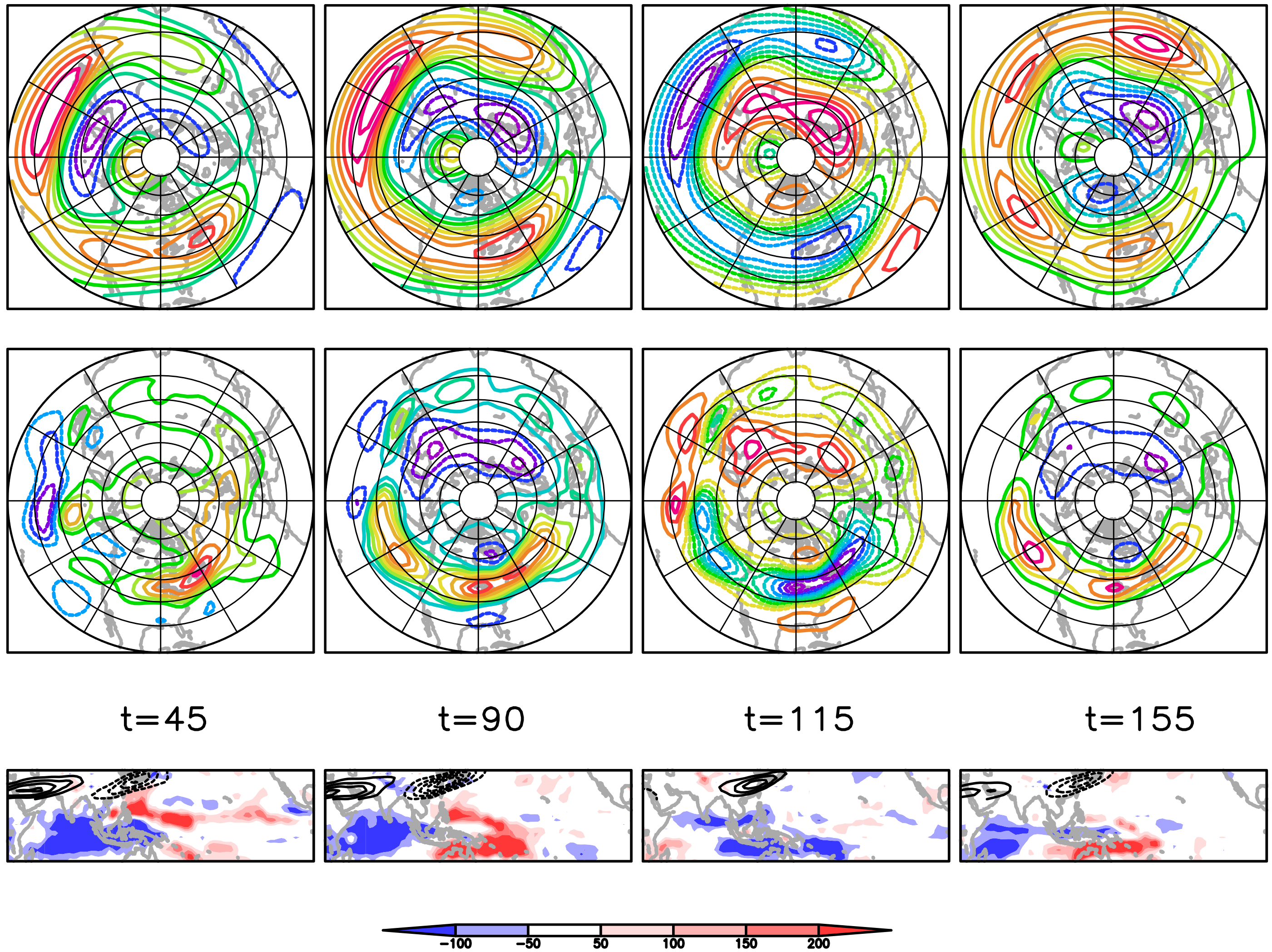
Mode 1 (2) Z200 with DZ300 mode 2

Mode 2 RWS200 with DZ300 mode 2

Z 500

DZ/Dt synoptic transients

Heating (color)
Rossby wave source



Synthesis of leading two most predictable components at selected times for Z200 (top row), 300 hPa height tendency from synoptic scale vorticity flux (middle row), and 200 hPa Rossby wave source (contours) and ensemble averaged diabatic heating (shaded), bottom row. Contour is 10 m for Z200, 2.5 m/d for height tendency, and $5 \times 10^{-11}\ s^{-1}$ for Rossby wave source.

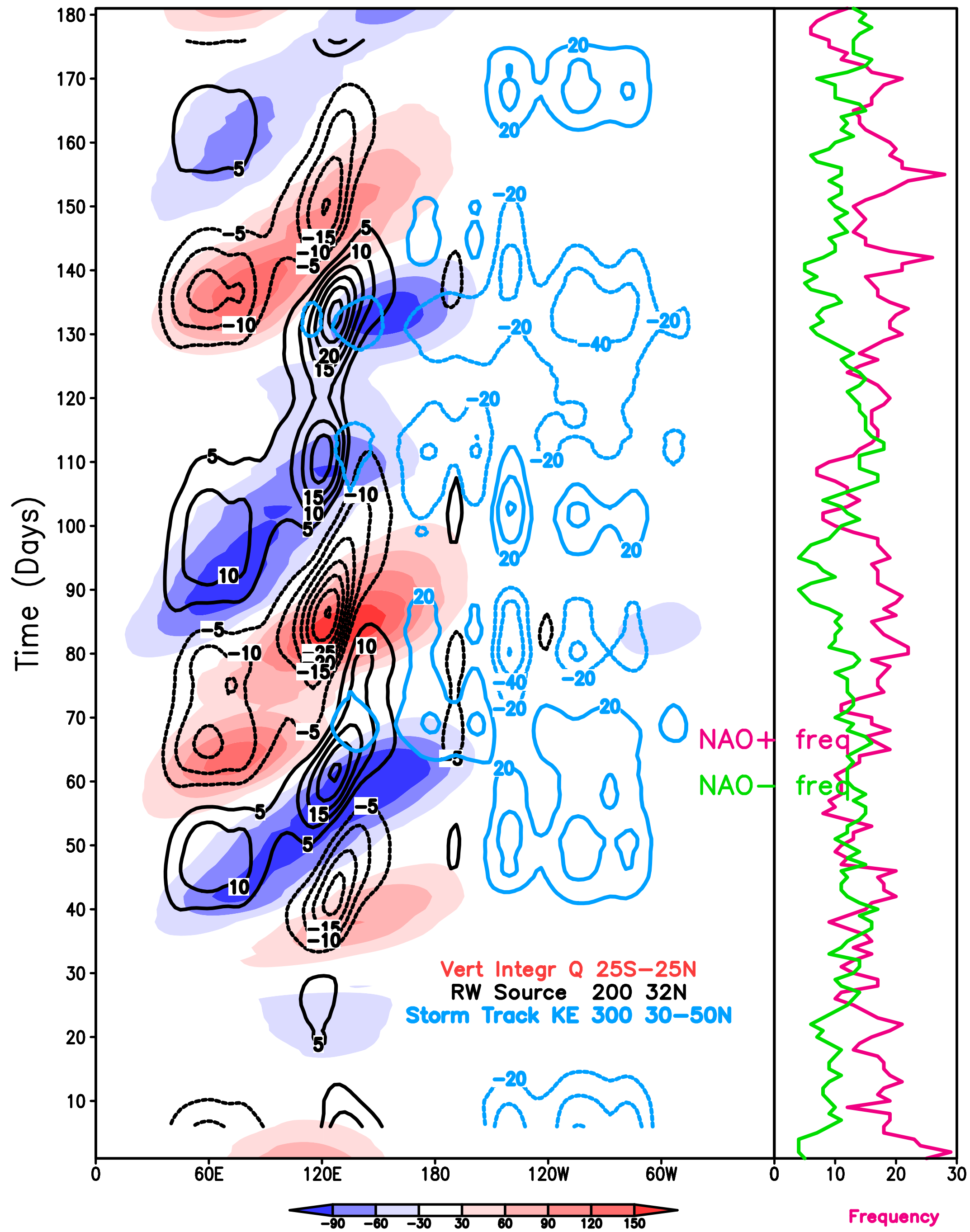
Synthesis of leading two most predictable components for:

RWS200 at 32N:
Interval of 5 x 10^{-11} s^{-1}

300 hPa high pass kinetic energy (30-50N):
Interval 20 m^2/s^2

Vertically integrated diabatic heating (averaged 25 S - 25 N) in W m^{-2}.

Red (**green**) curves on right show *frequency of occurrence* of **NAO+** (**NAO-**) clusters (set text for details). Abscissa is longitude, ordinate in time in days



What have we learned from this intervention experiment?

- Strongly propagating nature of Predictable Component: Cycle of MJO heating leads to propagating, not stationary response
- Elements of Stationary wave theory are in play: Rossby wave source, tight coupling of baroclinic (high frequency) vorticity flux convergence and geopotential height
- Further interrogation of the results needed to determine the roles of:
  - Rossby wave breaking
  - Barotropic instability
  - Interaction with storm tracks
- Still assuming relatively uniform phase speeds for the MJO

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  - Changes in probability of teleconnection patterns (NAO, AO) and/or circulation regimes.

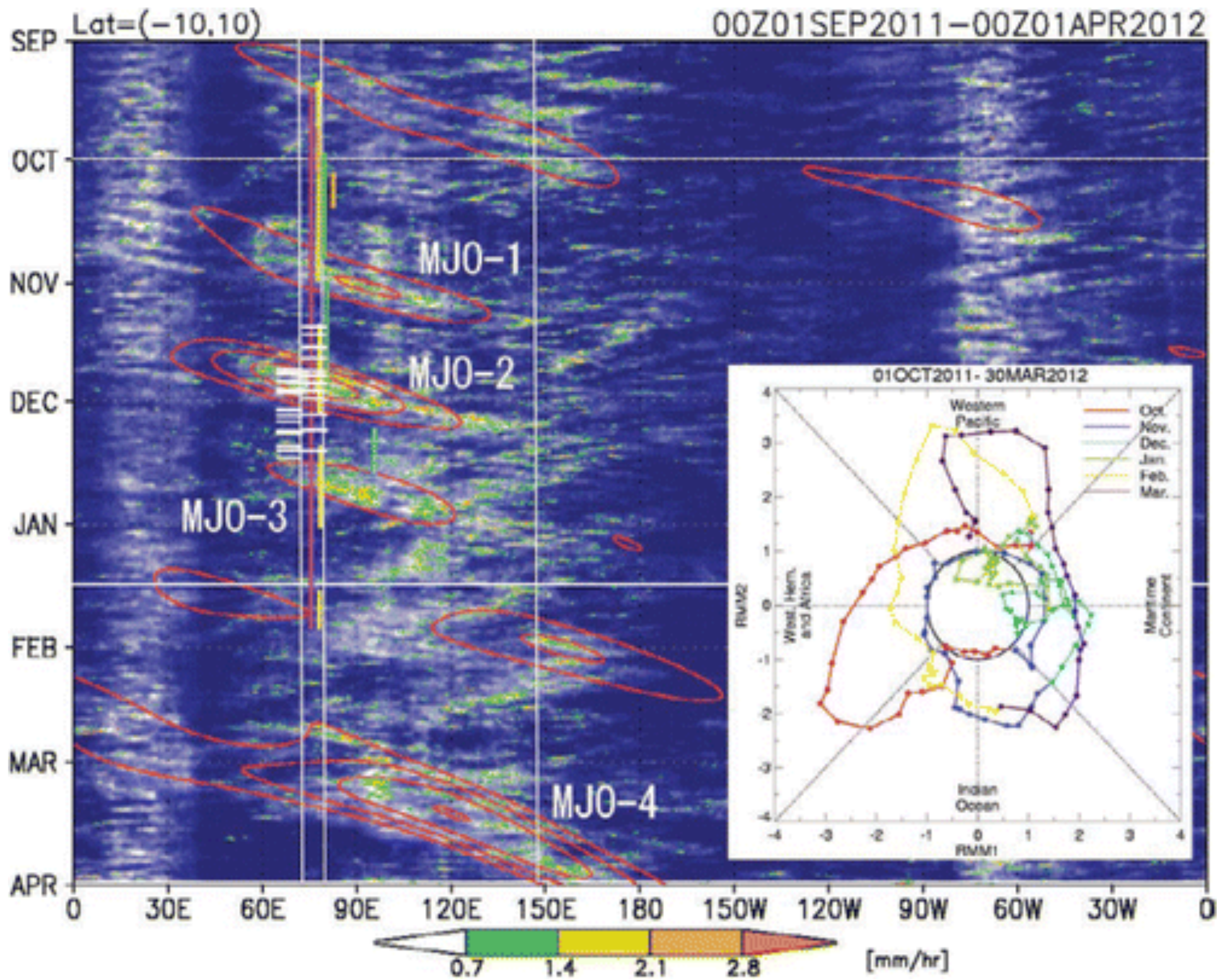
- Stationary Wave Theory:
  - Use of stationary wave models (and other simplified models) to determine the steady state response to the diabatic heating associated with each phase of the MJO. (Ignore transient nature of heating)

- Response to Tropical Pulses of heating

- Role of mid-latitude instabilities in the extratropical MJO response:
  - Barotropic instability and the Simmons-Wallace-Branstator modes
  - Baroclinic instability and the role of storm track shifts

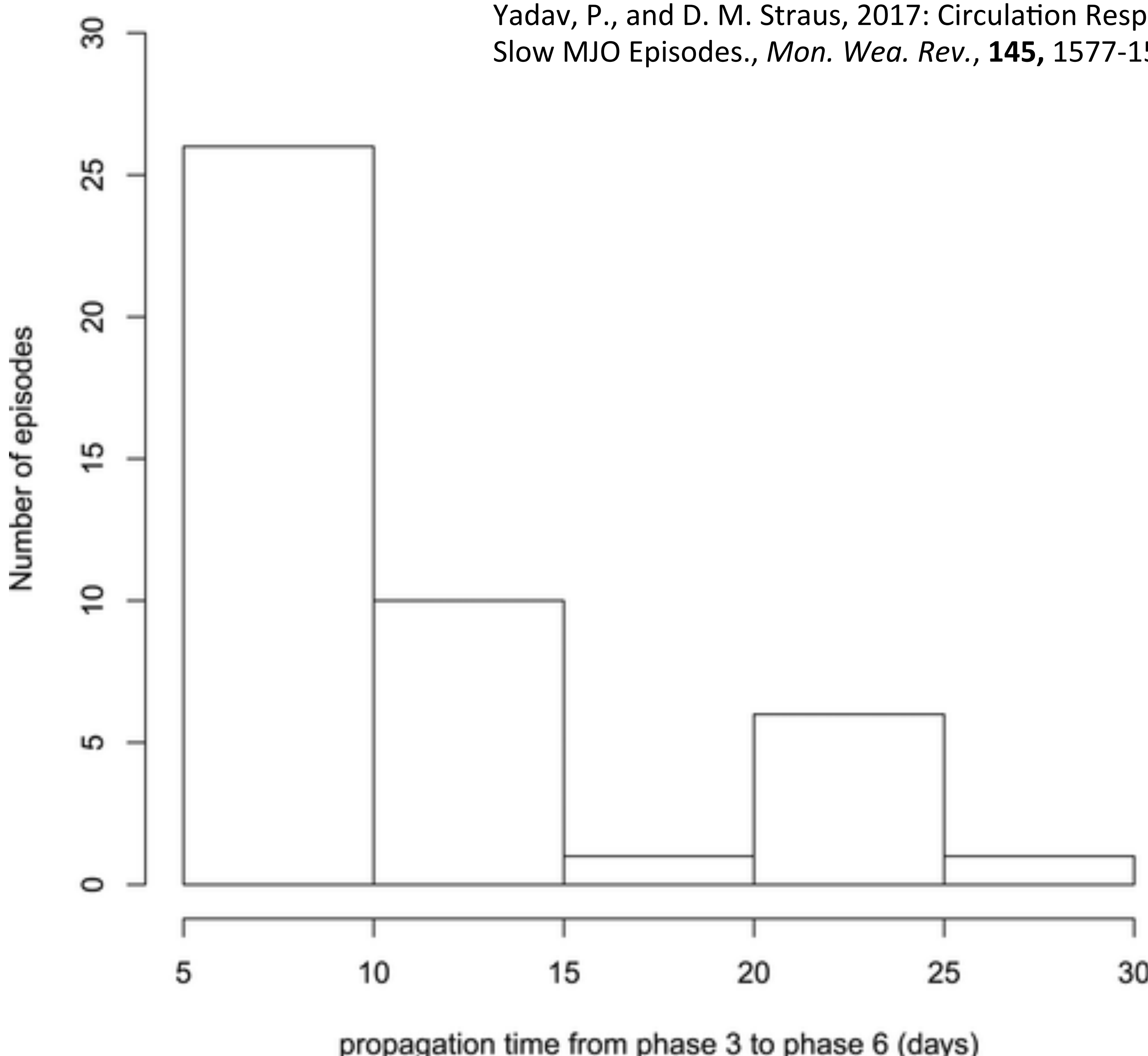
- **Response to the full cycle of MJO transient heating**
  - Intervention Experiments
  - **Response to Fast vs. Slow MJO Episodes**

- Current Work and Future Directions



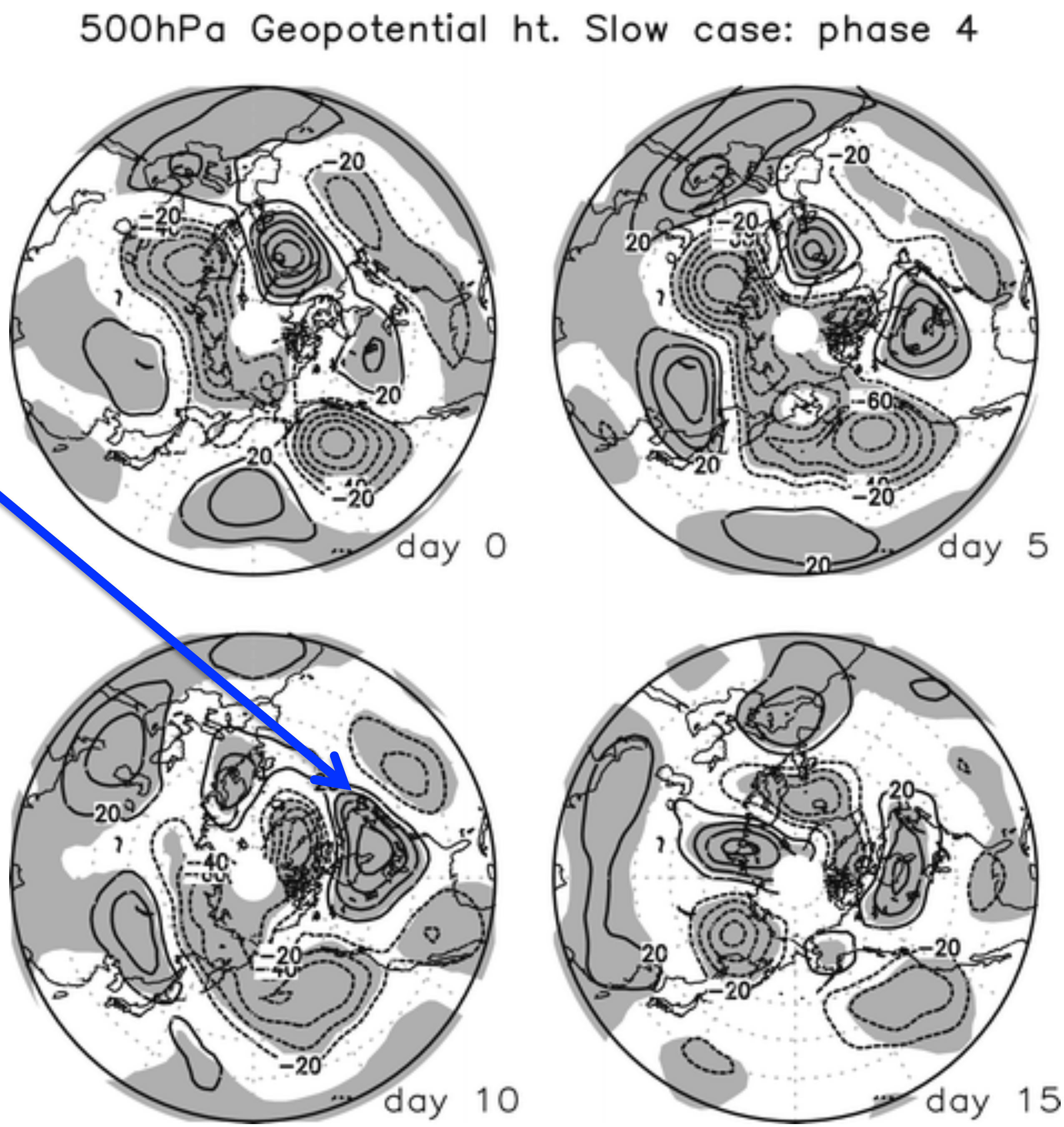
Kunio, Y., C. Zhang, and C. N. Long, 2013: Tracking pulses of the Madden–Julian Oscillation. Bull. Amer. Meteor. Soc., 94, 1871–1891

Yadav, P., and D. M. Straus, 2017: Circulation Response to Fast and Slow MJO Episodes., *Mon. Wea. Rev.*, **145,** 1577-1596.



Slow MJO Episodes: Strongest NAO+ response occurs 10 days after middle of phase 4.

Response is stronger and later than in composites using all MJO episodes

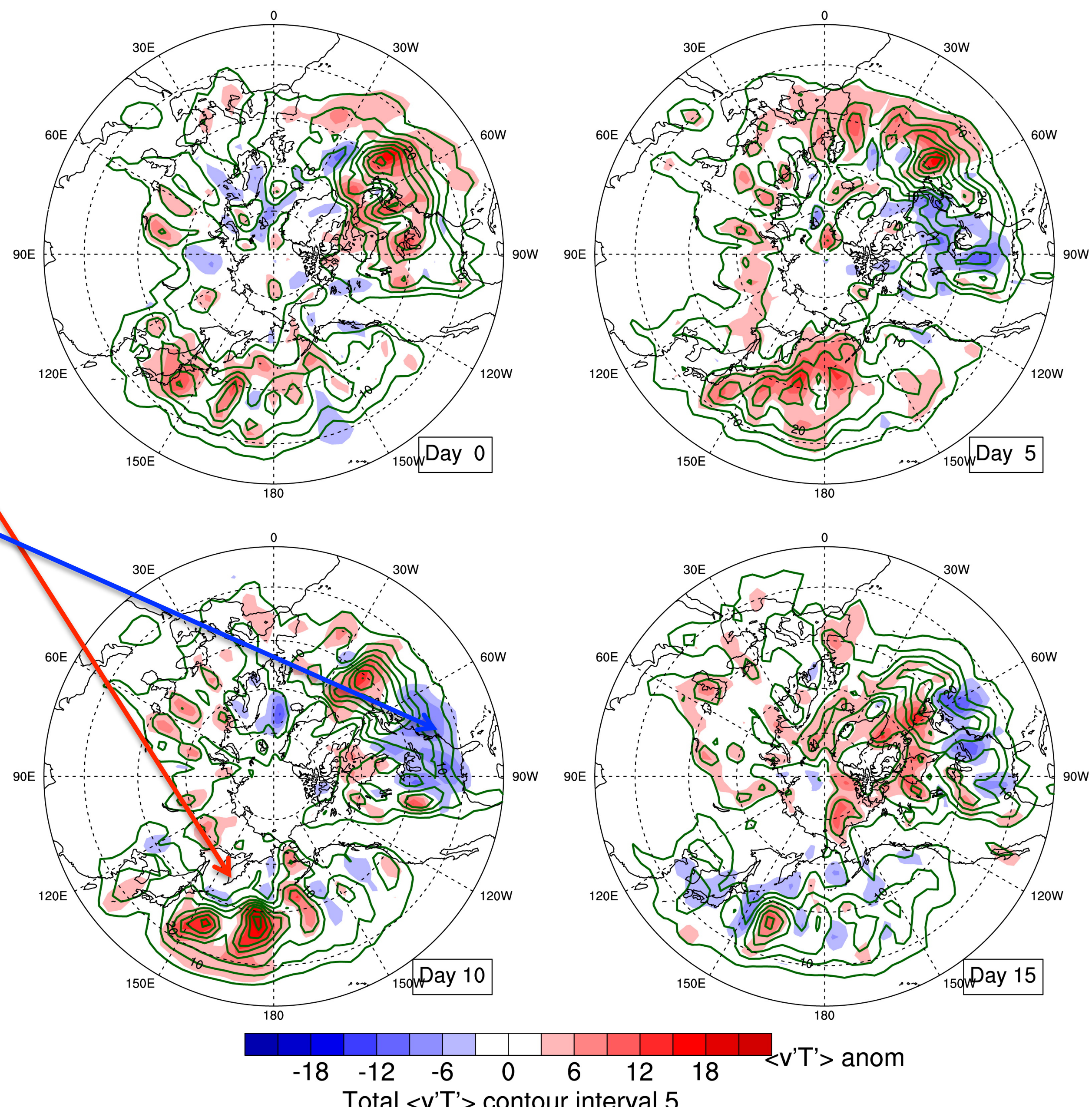


Slow Case (Phase 3): v'T' Total and v'T' anomaly at 850hPa

Strong enhancement of baroclinic storm tracks (high pass v'T') in Pacific after phase 3.

Strong shift in Atlantic storm tracks.

→ Do these changes set up the strong NAO+ response?



Current Work

- Further interrogation of existing experiments on the response to MJO cycles − both fast and slow episodes.

- Re-Forecast intervention experiments involving slow and fast MJO episodes separately

Future Directions

- What is the role of barotropic instability? Does it contribute to:
    - The predictable signal
    - The signal-modulated noise
    - Pure Noise

- To what extent would a "very good" prediction of MJO tropical convection 2 – 4 weeks in advance be associated with dramatically improved extra-tropical predictions?

- Can we identify MJO "windows of opportunity" when the atmosphere is in a state favorable for the propagation of the tropical signal.