Advanced School on Tropical-Extratropical Interactions
on Intraseasonal Time Scales

Some Basic Mechanisms for Tropical-Extratropical Interactions

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(1) Mid-Latitude Response to Tropical Forcing: Can we use ideas from stationary wave theory?

(2) Changes in mid-latitude instabilities due to Tropical Forcing

(3) Possible ways in which the tropics may respond to mid-latitudes

(4) Are tropical and midlatitude fluctuations sometimes coupled ?

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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

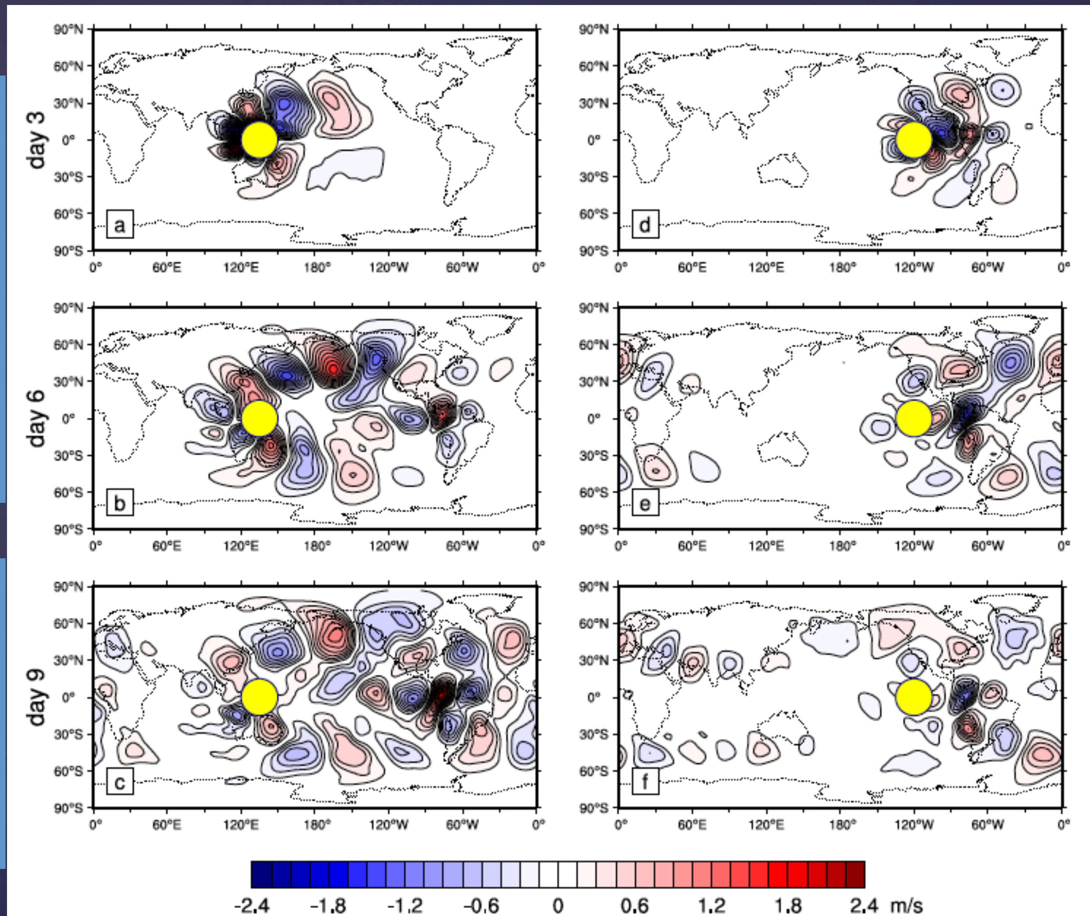


FIG. 3. Ensemble mean v300 response in CAM3 to a 2-day pulse of heat at 0°N, 135°E (a) 3, (b) 6, and (c) 9 days after the pulse begins. (d)–(f) As in (a)–(c), but for a pulse at 0°N, 120°W.

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

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.

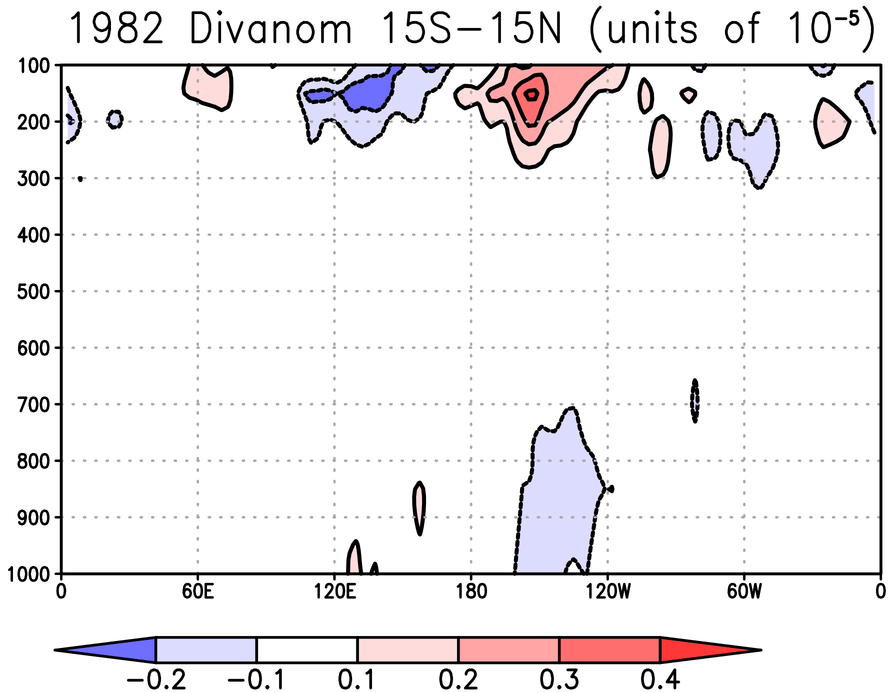
Grant Branstator, 2014: Long-Lived Response of the Midlatitude Circulation and Storm Tracks to Pulses of Tropical Heating. *J. Climate*, **27**, 8809-8826.

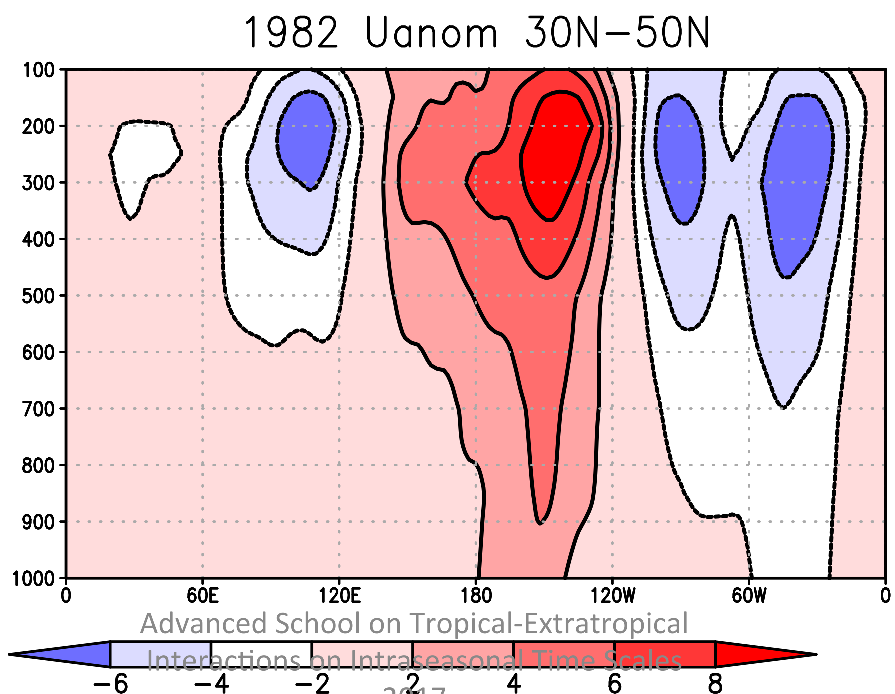
Tropical Div →

Response to ESNO warm event 1982/83

Anomaly of DJFM mean compared to 32 year DJFM climatology (1980/82 – 2011/12) ERA-Interim Reanalysis

Midlatitude U →





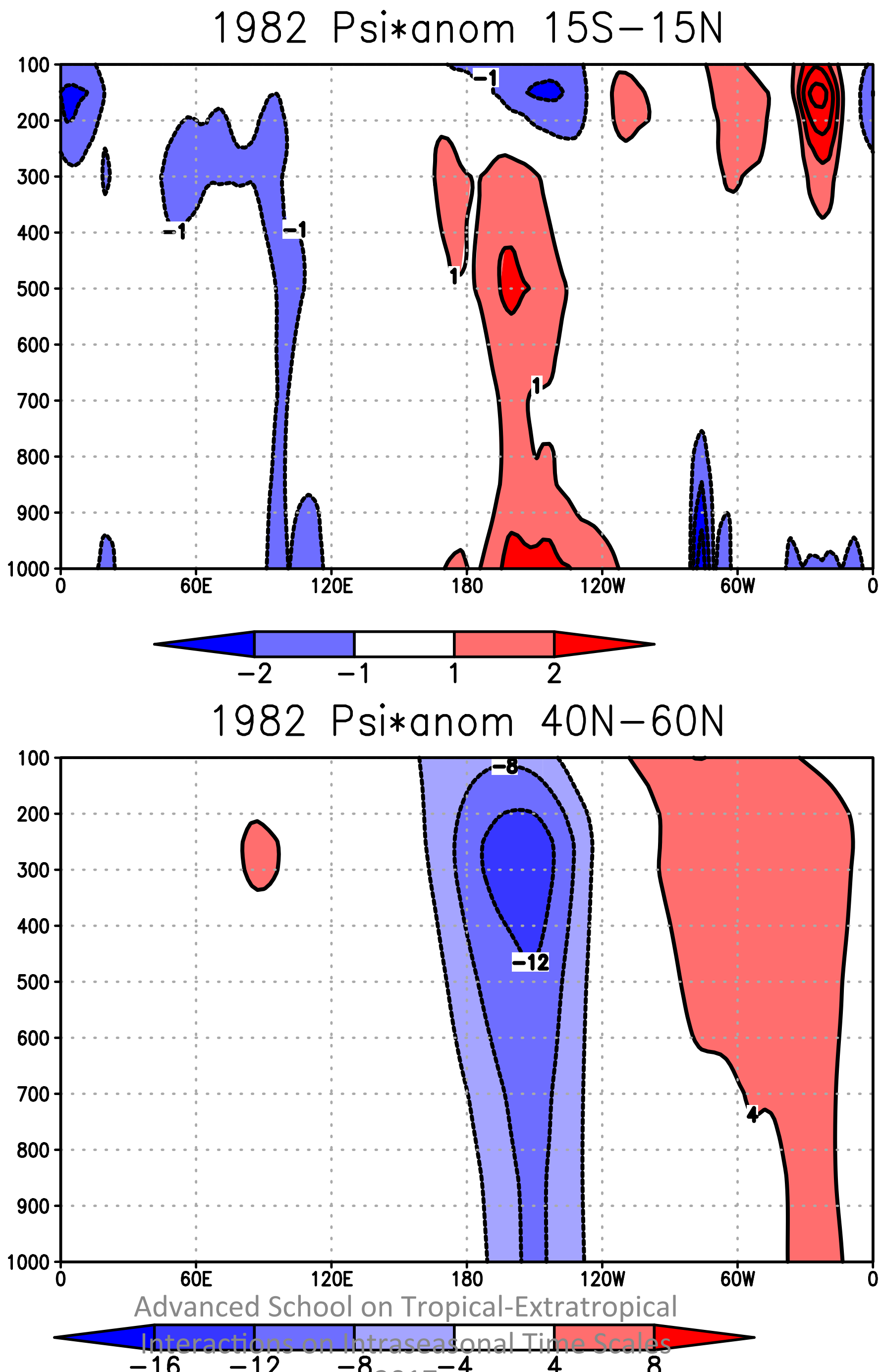
Vertical structure of extratropical response to tropical forcing - ENSO

Tropical ψ* →

Response to ESNO warm event 1982/83

Anomaly of DJFM mean compared to 32 year DJFM climatology (1980/82 – 2011/12) ERA-Interim Reanalysis

Midlatitude ψ* →



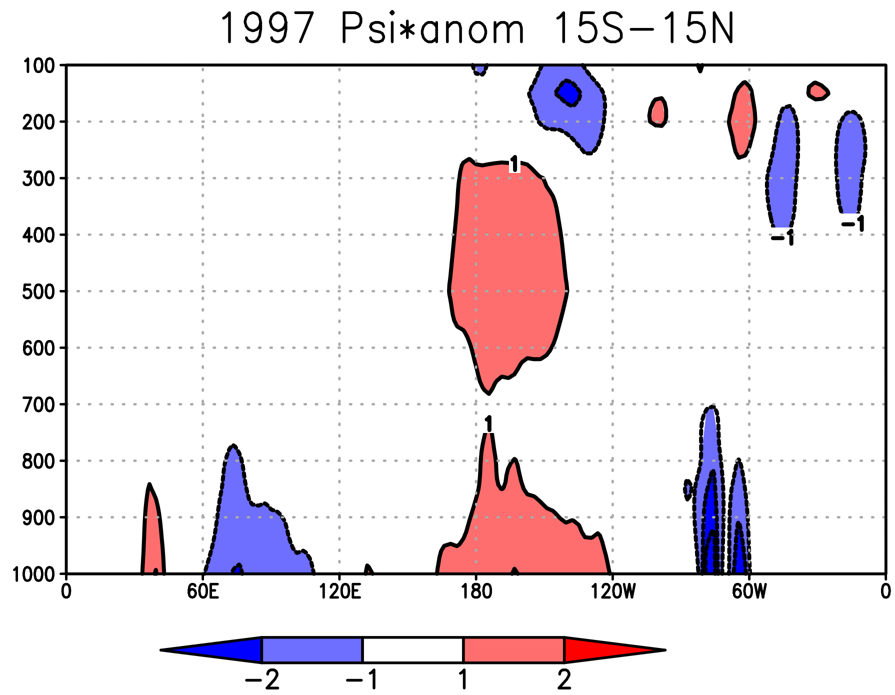
Vertical structure of extratropical response to tropical forcing - ENSO

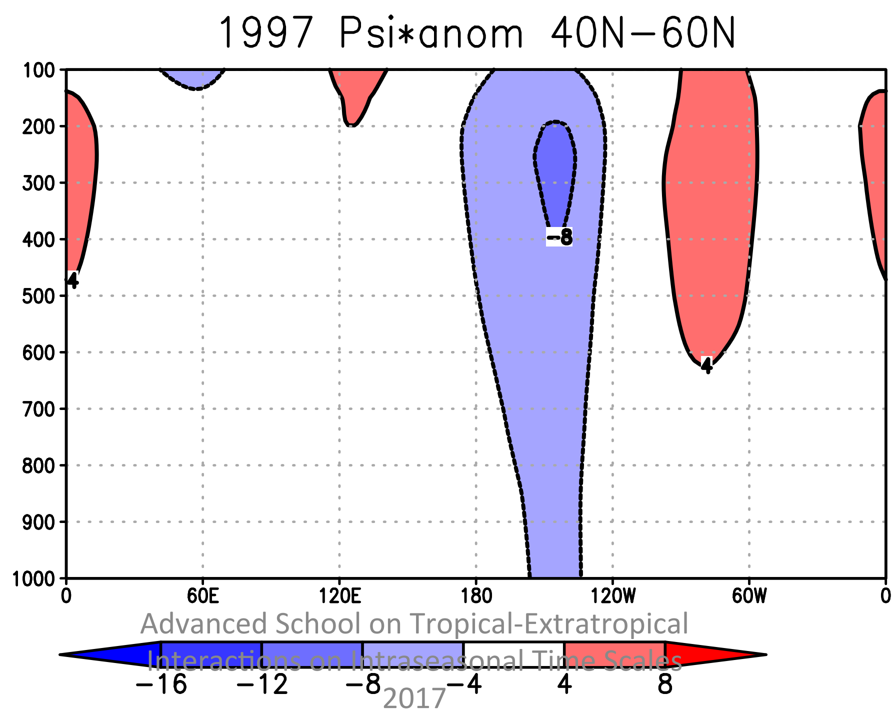
Tropical ψ* →

Response to ESNO warm event 1997/98

Anomaly of DJFM mean compared to 32 year DJMF climatology (1980/82 – 2011/12) ERA-Interim Reanalysis

Midlatitude ψ* →





Vertical structure of extratropical response to tropical forcing - ENSO

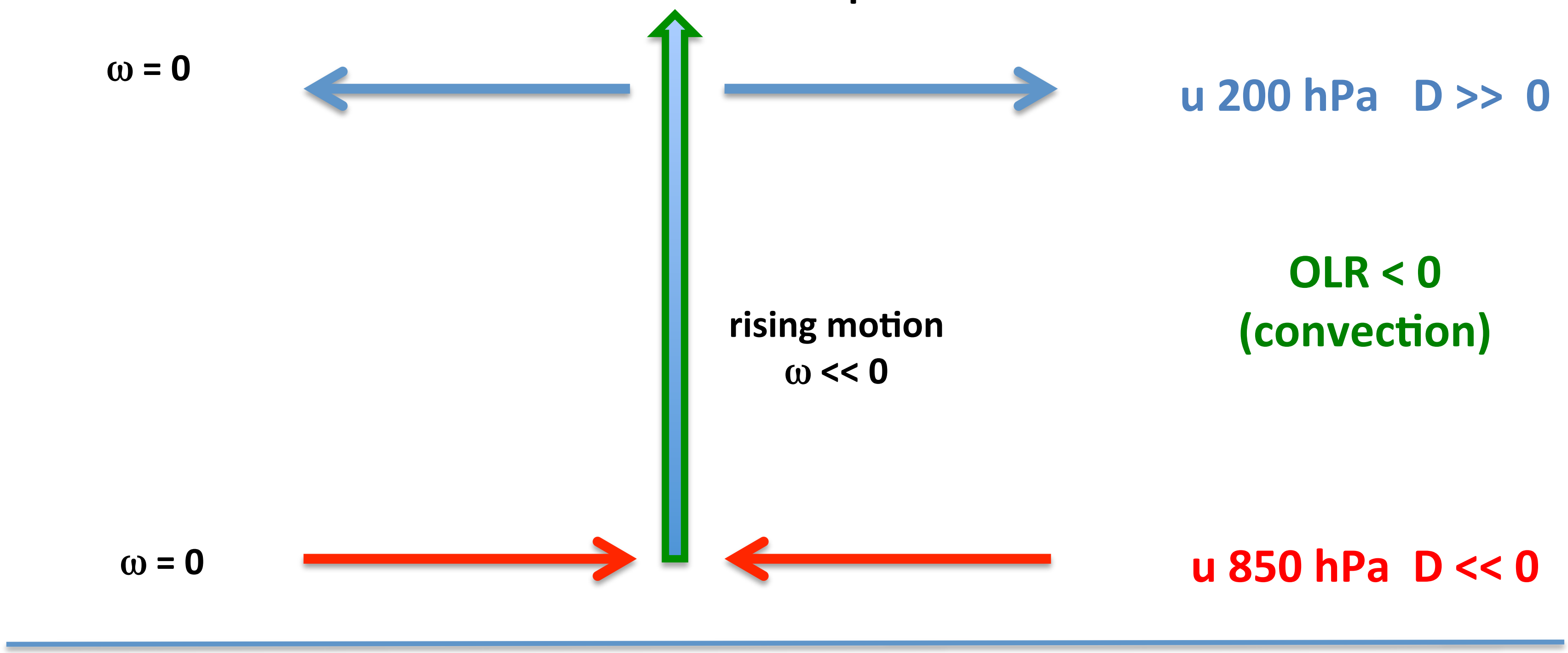
Tropical Forcing

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.*

Two Dimensional Tropical Convection



"First Baroclinic Mode"

The Rossby Wave Source*:
One level vorticity equation model for upper levels

The non-linear vorticity equation can be approximated as:

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla}\right)\zeta_a = -\zeta_a\, D + F = S + F$$

where ***v*** is the full horizontal velocity, ζ = **total** vorticity: $\zeta_a = \nabla^2\psi + f$
D = divergence, F is friction and **S is the Rossy Wave Source.**
(Vertical advection and twisting terms are ignored since vertical velocity is expected to be small)

BUT: **For equatorial forcing, the absolute vorticity is small, and often occurs in regions of background Easterlies* (e.g. in the western Pacific where Q is large).**

So how can S act as a source for mid-latitude Rossby waves?

*Sardeshmukh, P. D., and B. J. Hoskins, 1988: The Generation of Global Rotational Flow by Steady Idealized Tropical Divergence. *J. Atmos. Sci*., **45,** 1228-1251.

*Detour: Why do Background Easterlies Prevent Rossby wave propagation?

Barotropic Linear Wave Theory in Mercator Coordinates

Assume wave propagates eastward with zonal wavenumber *k*. What are the allowed meridional wavenumbers *l* ?

$$\psi \approx e^{i(kx+ly-\omega t)}$$

$$\omega = U_M - \beta_M \left(\frac{l}{k^2 + l^2} \right)$$

$$U_M = U / \cos(\phi) \quad \beta_M = \frac{\partial}{\partial y}(\zeta + f)$$

Stationary Waves ($\omega=0$)

$$\frac{U_M}{\beta_M} = \left(\frac{k}{k^2 + l^2} \right)$$

$$U_M < 0 \Rightarrow l^2 < 0$$

Easterlies → *l* is imaginary → waves are damped in the y-direction (NO PROPAGATION)

Hoskins B. J., and D. Karoly, 1981: The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing. J. Atmos. Sci., 38,1179-1196.

The Rossby Wave Source (continued)

The answer is that to describe mid-latitude Rossby waves, we can solve only for the rotational component of the flow*, and must specify the divergent component as part of the tropical forcing. This leads to a new Rossby Wave Source:

$$\left(\frac{\partial}{\partial t}+\vec{v}_{\psi}\cdot\vec{\nabla}\right)\zeta_a=-\vec{v}_{\chi}\cdot\vec{\nabla}\zeta_a-\zeta_a\,D+F\equiv\hat{S}+F$$

$$\hat{S}=-\vec{v}_{\chi}\cdot\vec{\nabla}\zeta_a-\zeta_a\,D$$

*Rotational component: $\vec{v}_{\psi}=\left(-\frac{\partial\psi}{\partial y},\frac{\partial\psi}{\partial x}\right)$ $\quad\zeta_{\psi}=\nabla^2\psi$ $\quad D=\vec{\nabla}\cdot\vec{v}_{\psi}=0$

Divergent component: $\vec{v}_{\chi}=\left(\frac{\partial\chi}{\partial x},\frac{\partial\chi}{\partial y}\right)$ $\quad\zeta_{\chi}=0$ $\quad D=\vec{\nabla}\cdot\vec{v}_{\chi}=\nabla^2\chi$

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

Traditional Source: Divergence x Vorticity

Additional Source: Vorticity Advection by the Divergent flow

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The Generation of Global Rotational Flow by Steady Idealized Tropical Divergence

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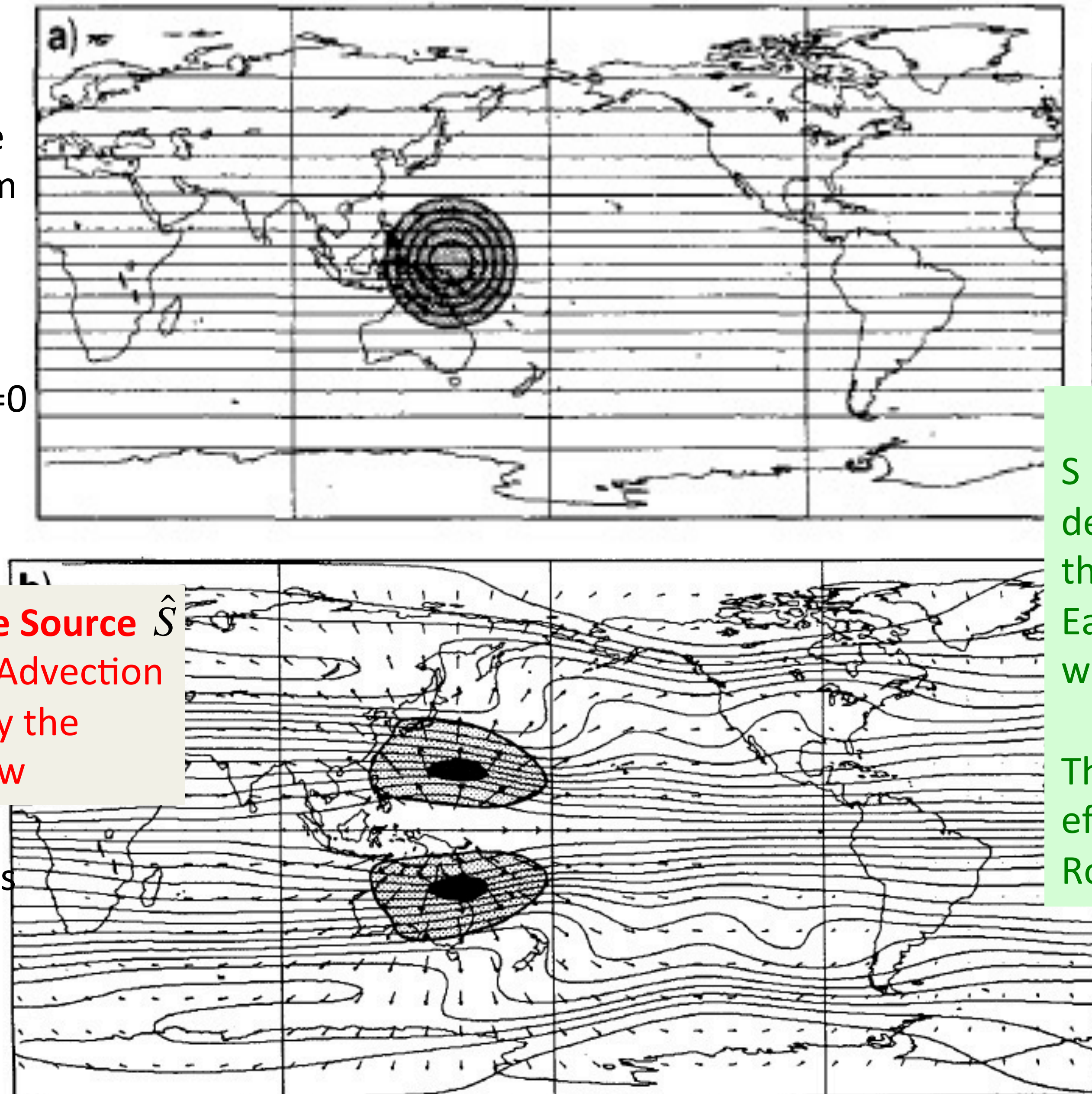
BRIAN J. HOSKINS

Rossby Wave Source S from Idealized D

Initial time t=0

Contour lines show absolute vorticity



Rossby Wave Source $\hat{S}$
Note role of Advection of vorticity by the divergent flow

Time t=8 days

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

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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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 <u>barotropic</u> instability would be of much less importance than <u>baroclinic</u> instability.

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

- 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.

Streamfunction of the most unstable mode at selected days within one half cycle of most rapidly growing mode: **Period of 45 days with e-folding time of < 7 days.**

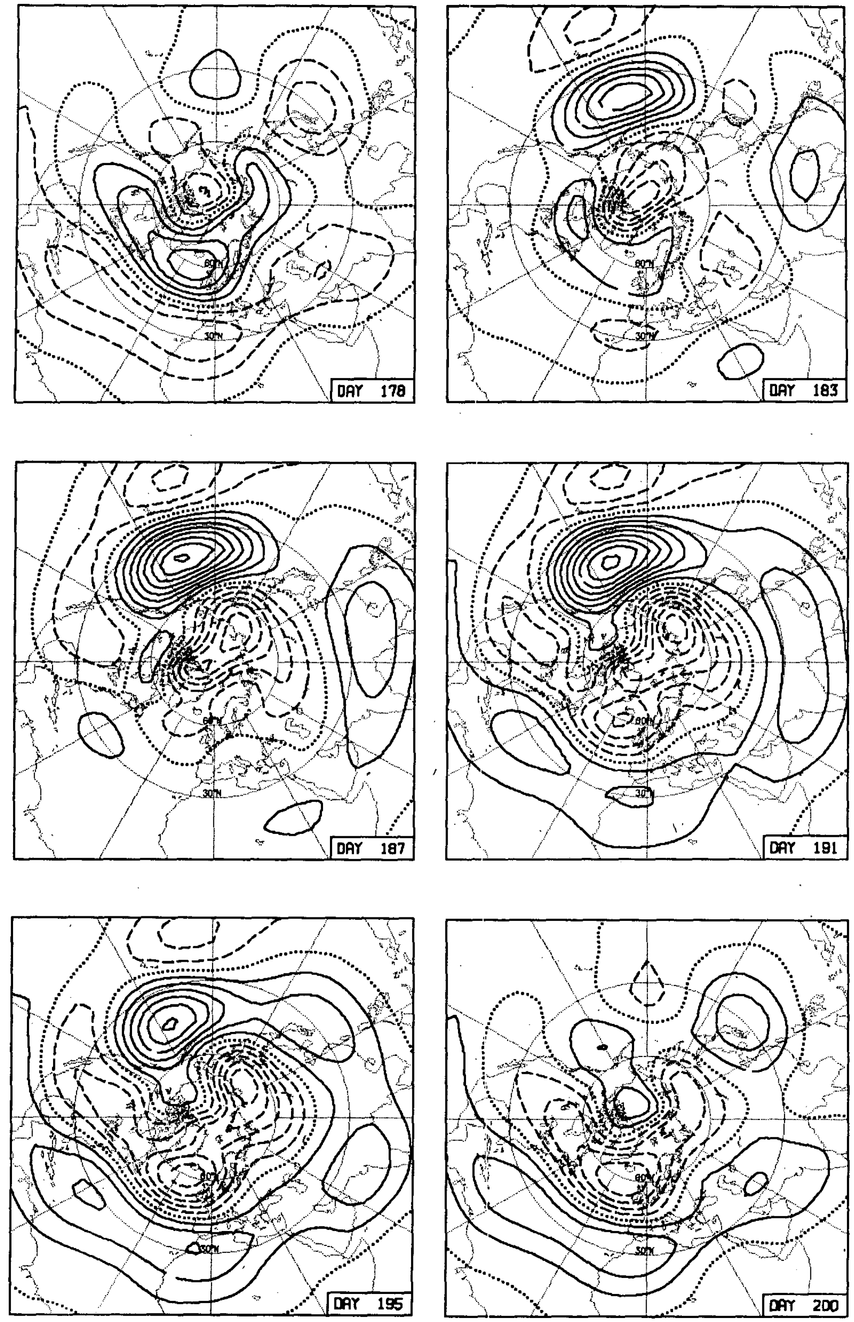
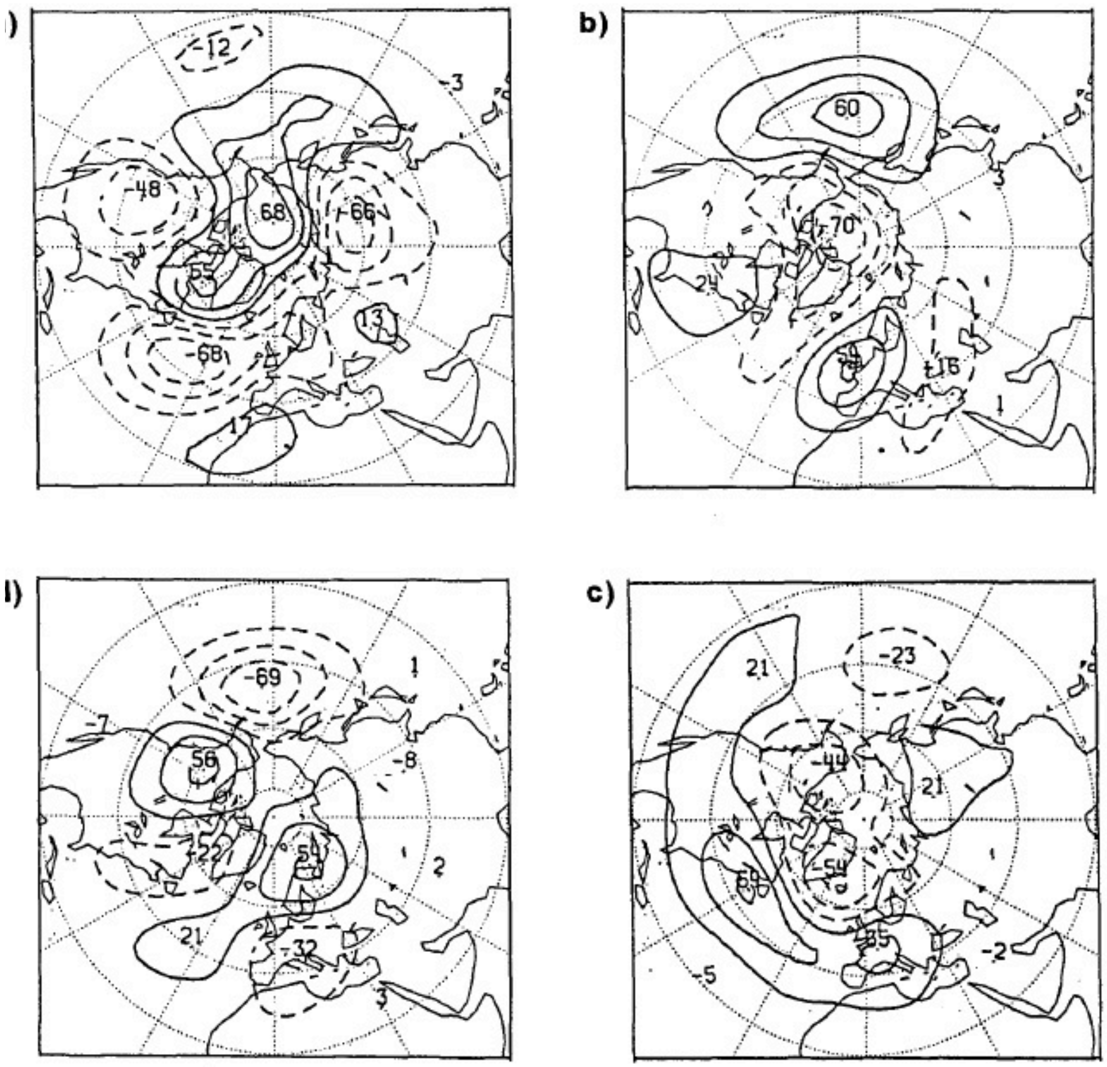


FIG. 11. The streamfunction of the most unstable normal mode at selected days within one-half cycle of its oscillation. The contour interval is arbitrary.



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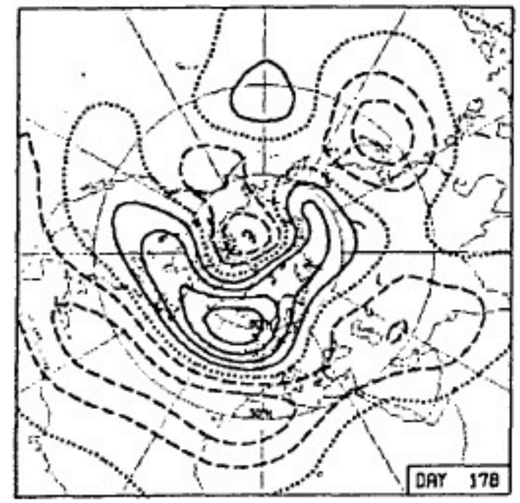

FIG. 9. Structure of the most unstable mo
shown as two phase-quadrature components (from Simmo

Barotropi
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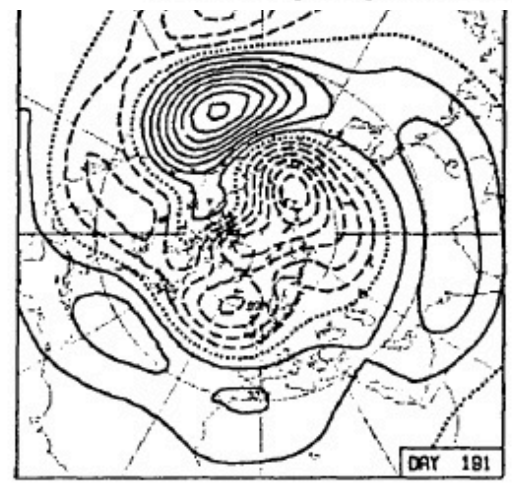
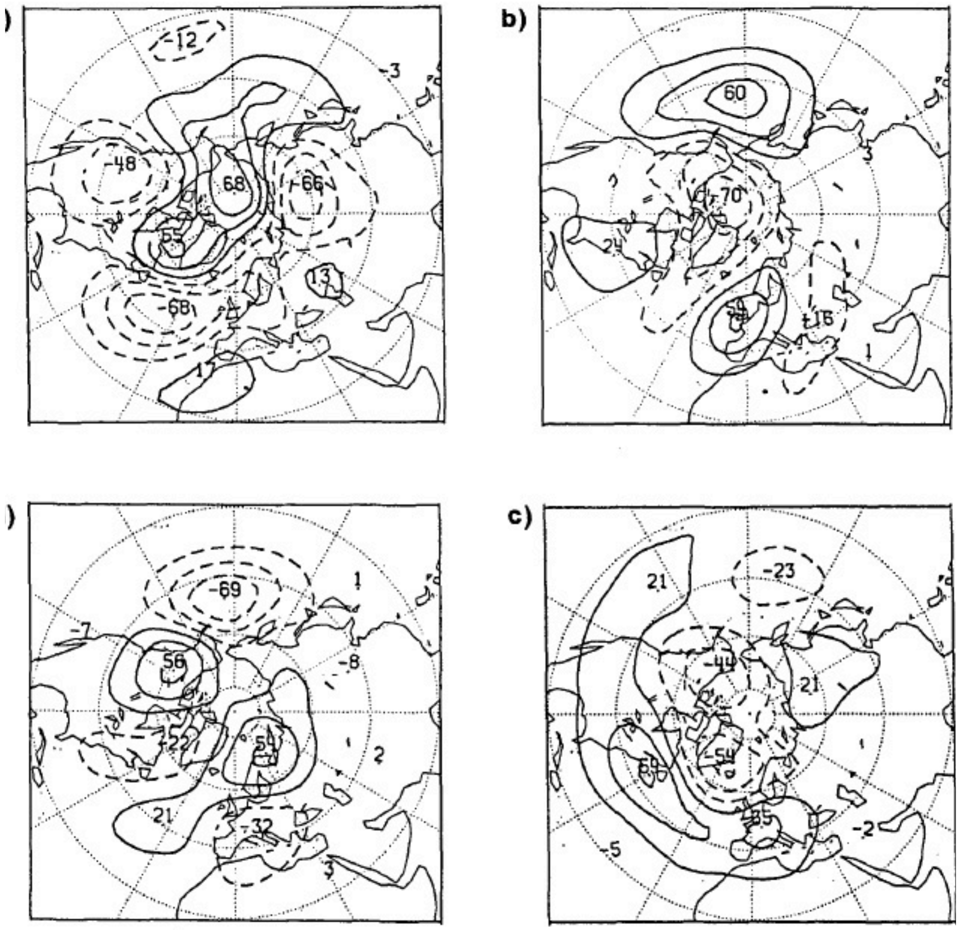
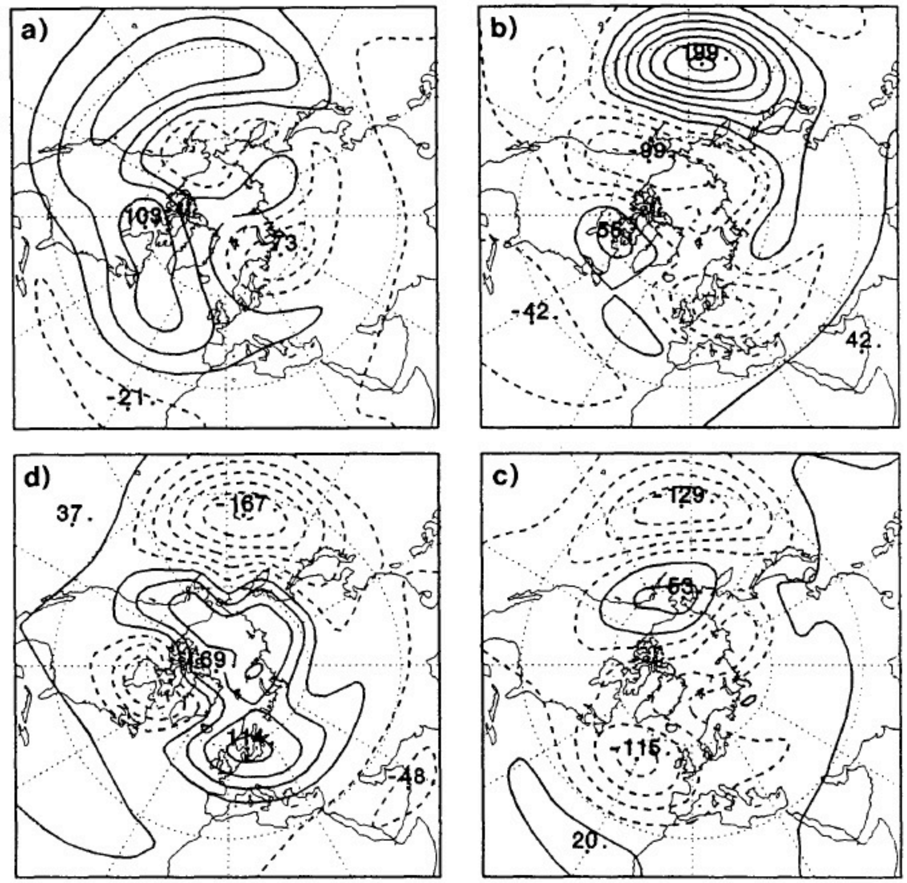


e of a January 300 mb basic state flow,

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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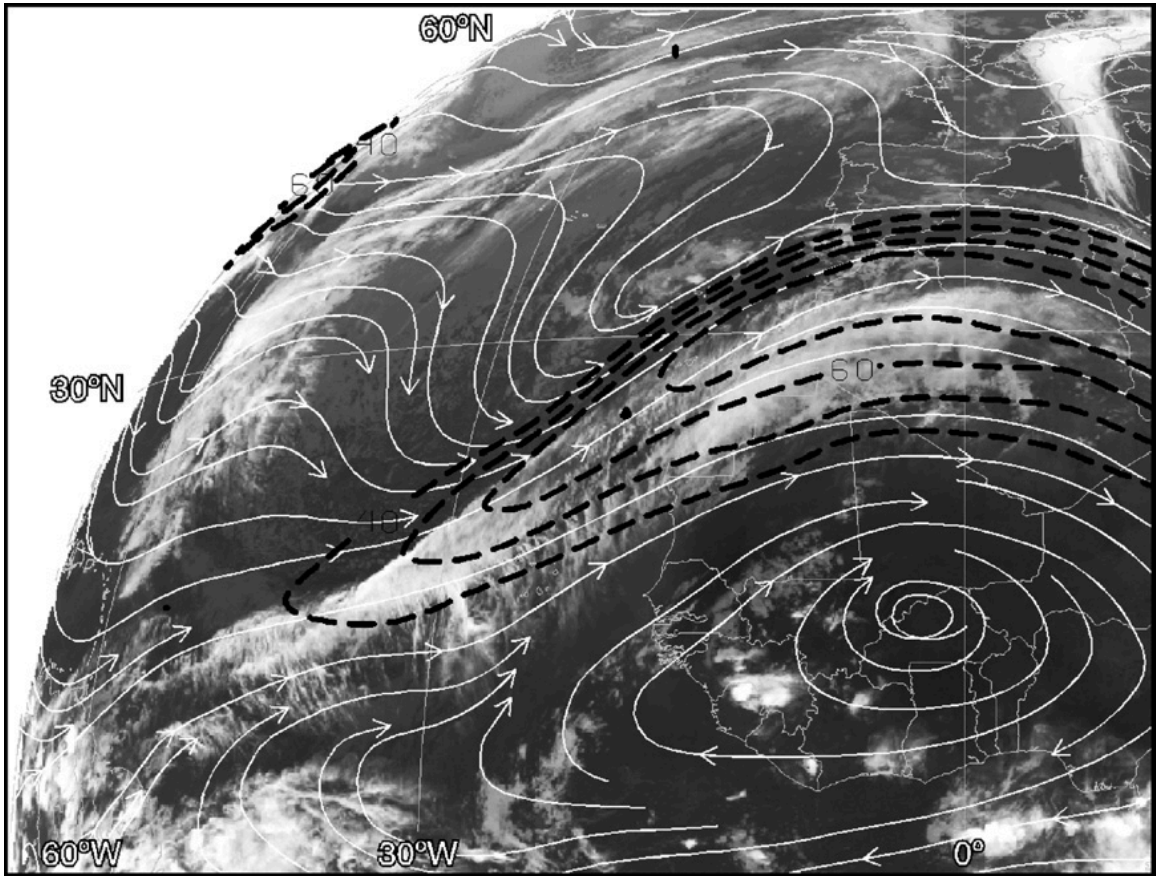
Tropical-extratropical interactions related to upper-level troughs at low latitudes



Meteosat infrared image of a tropical plume over northwest Africa at 00 UTC 31 March 2002.
Superimposed streamlines and isotachs on the 345-K isentropic level (dashed contours at 40, 50, 60, and 70 ms^{-1}) from the ECMWF TOGA analysis. The 345-K level is close to 200 hPa in the Tropics. Streamlines indicate extratropical wave incursion into the Tropics.

Knippertz, P., 2007: Tropical-extratropical interactions related to upper-level troughs at low latitudes. *Dyn. Atmos. Ocean.* **43**, 36-62.

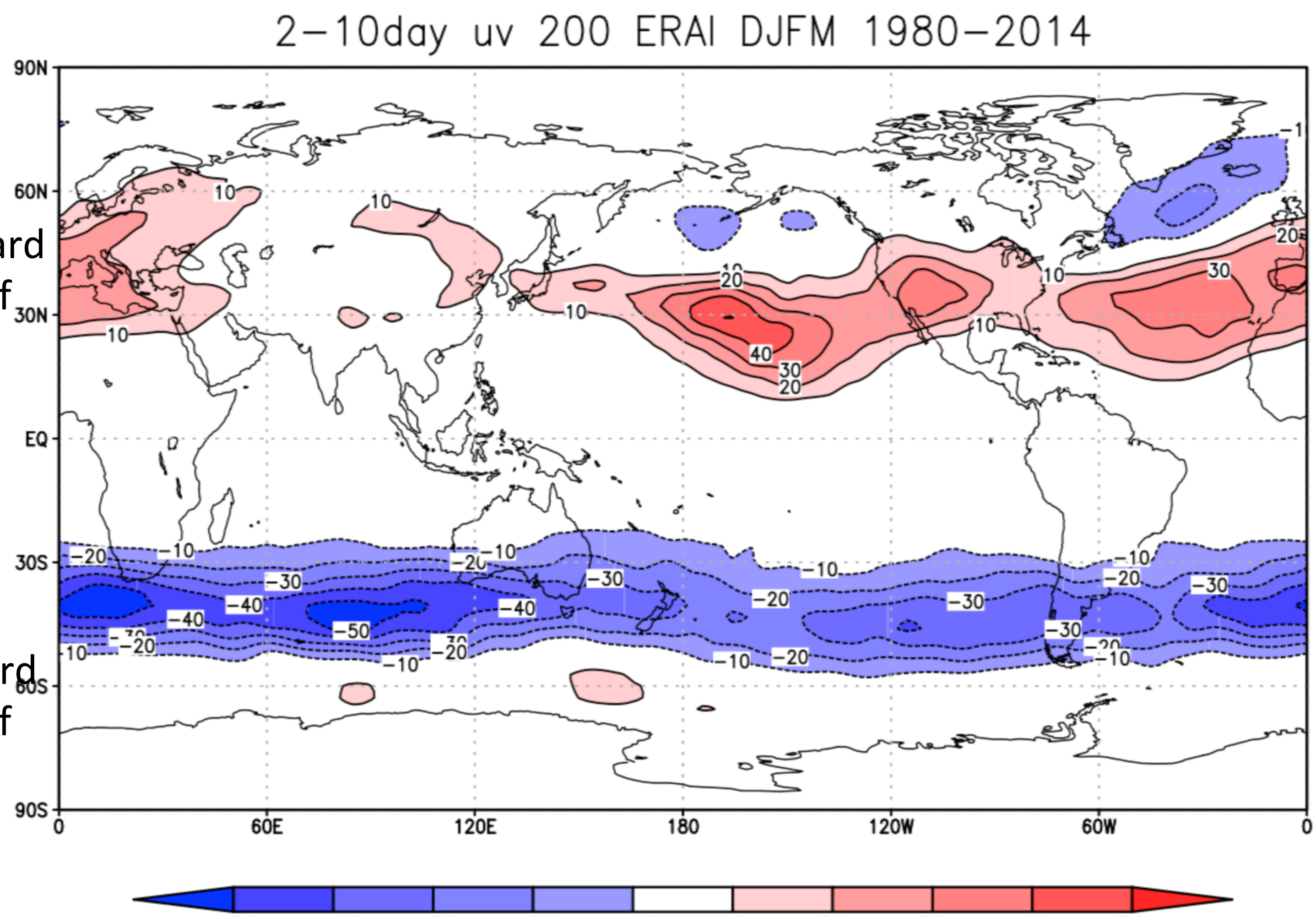
Momentum flux due to fluctuations with time scale less than 10 days

$\overline{u'v'} > 0 \Rightarrow$

NH Equatorward Propagation of waves

$\overline{u'v'} < 0 \Rightarrow$

SH Equatorward Propagation of waves

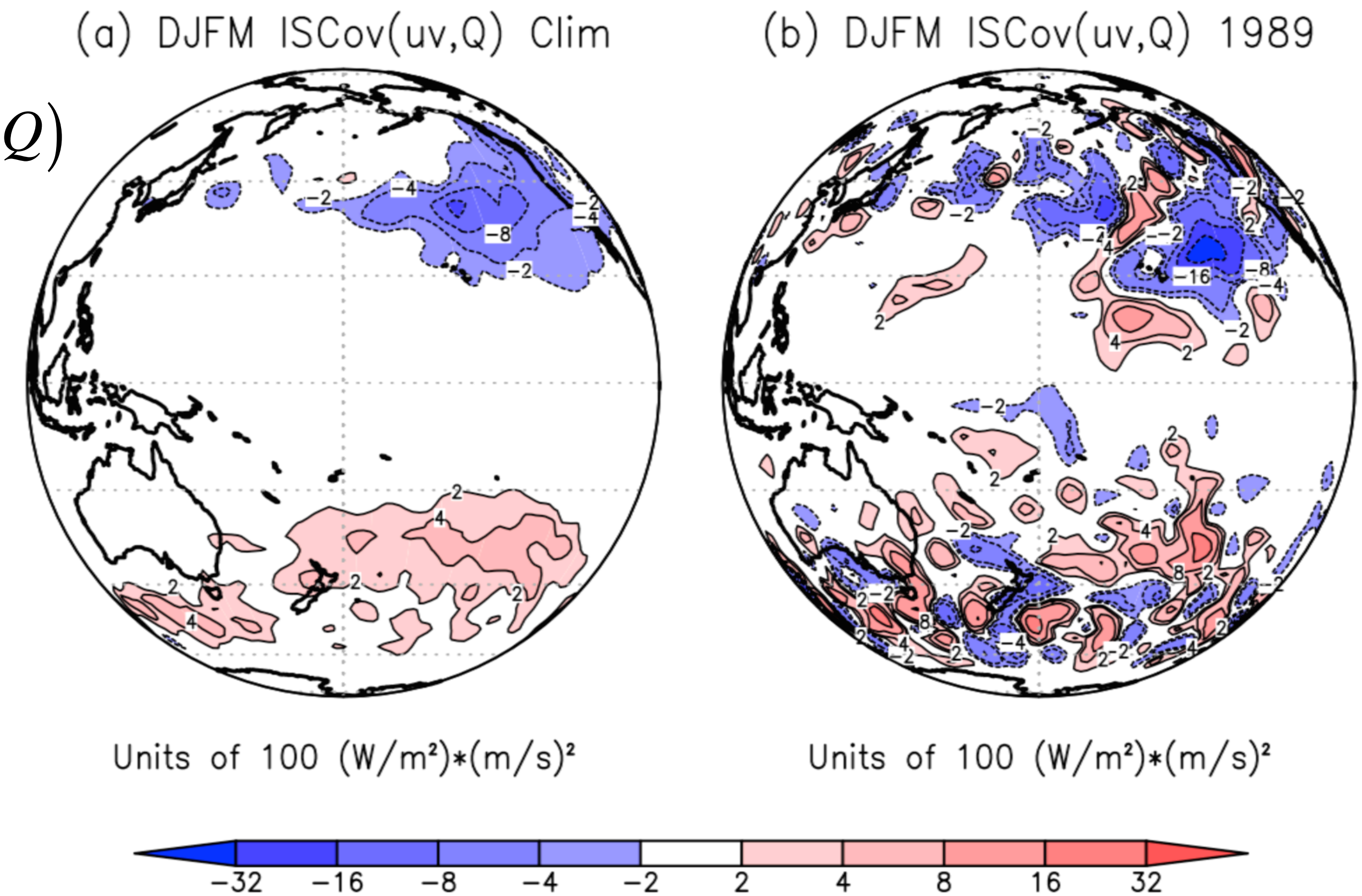


Climatology of boreal winter at 200 hPa, where **u** is the zonal wind, **v** the meridional wind, the primes denote a high-pass filter (retaining periods less than 10 days), and the overbar denotes an average from 01Dec – 16Mar. Computed from ERA-Interim reanalysis, averaged over the 35 winters 1980/81 through 2014/15.

Intra-seasonal covariance between momentum flux and diabatic heating Q

$$Cov(u'v',Q)$$

Climatology: no tropical action

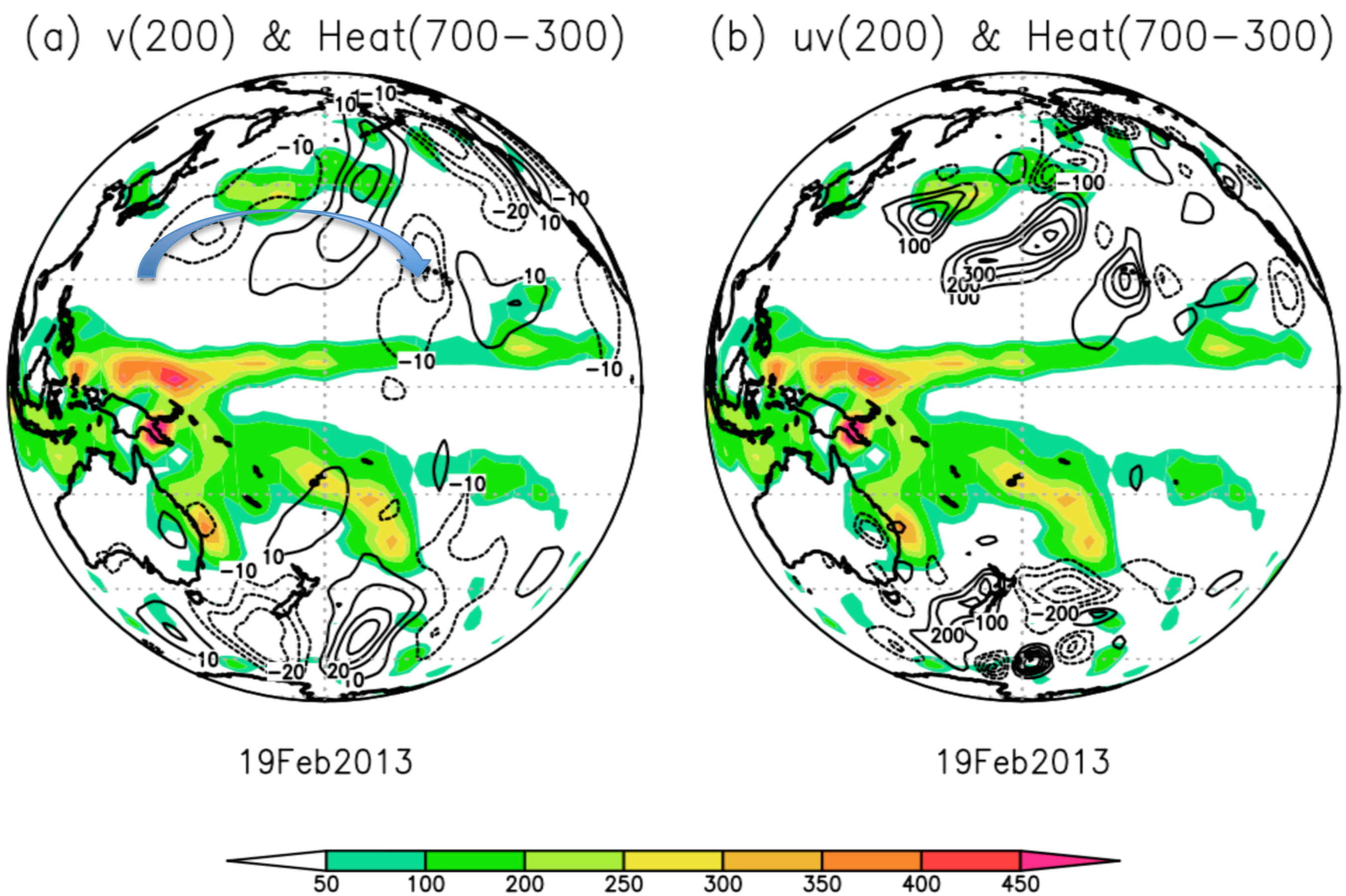


Equatorward Propagation & tropical Q > 0

Daily boreal winter (01Dec – 16Mar) intra-seasonal covariance between 200 hPa high-pass momentum flux and **low-pass layer integrated (700 – 300 hPa) diabatic heating Q,** averaged over all winters 1980/81 – 2014/15 (left panel), and for 1989/90 winter (right panel). Interval is 100 $(Wm^{-2})(m^2s^{-2})$. Map projections are orthographic with equatorial aspect. The central longitude is 180°E.

Interaction between equatorward propagting waves and heating on a single day

v’ contours
Q shading



u’v’
contours
Q shading

Left panel: High-pass meridional wind on 19Feb2013 (contours) and low-pass layer integrated (700 – 300 hPa) diabatic heating Q (shading). Right panel: Product of high-pass meridional and zonal wind (contours) and low-pass layer integrated (700 – 300 hPa) diabatic heating Q (shading). High-pass filter retains period less than 10 days, and the low-pass filter retains periods greater than 20 days. Interval is 10 m s^{-1} in the left panel, 100 (m^2s^{-2}) in the right panel. Heating in (Wm^{-2}). Map projections are orthographic with equatorial aspect. The central longitude is 180°E.

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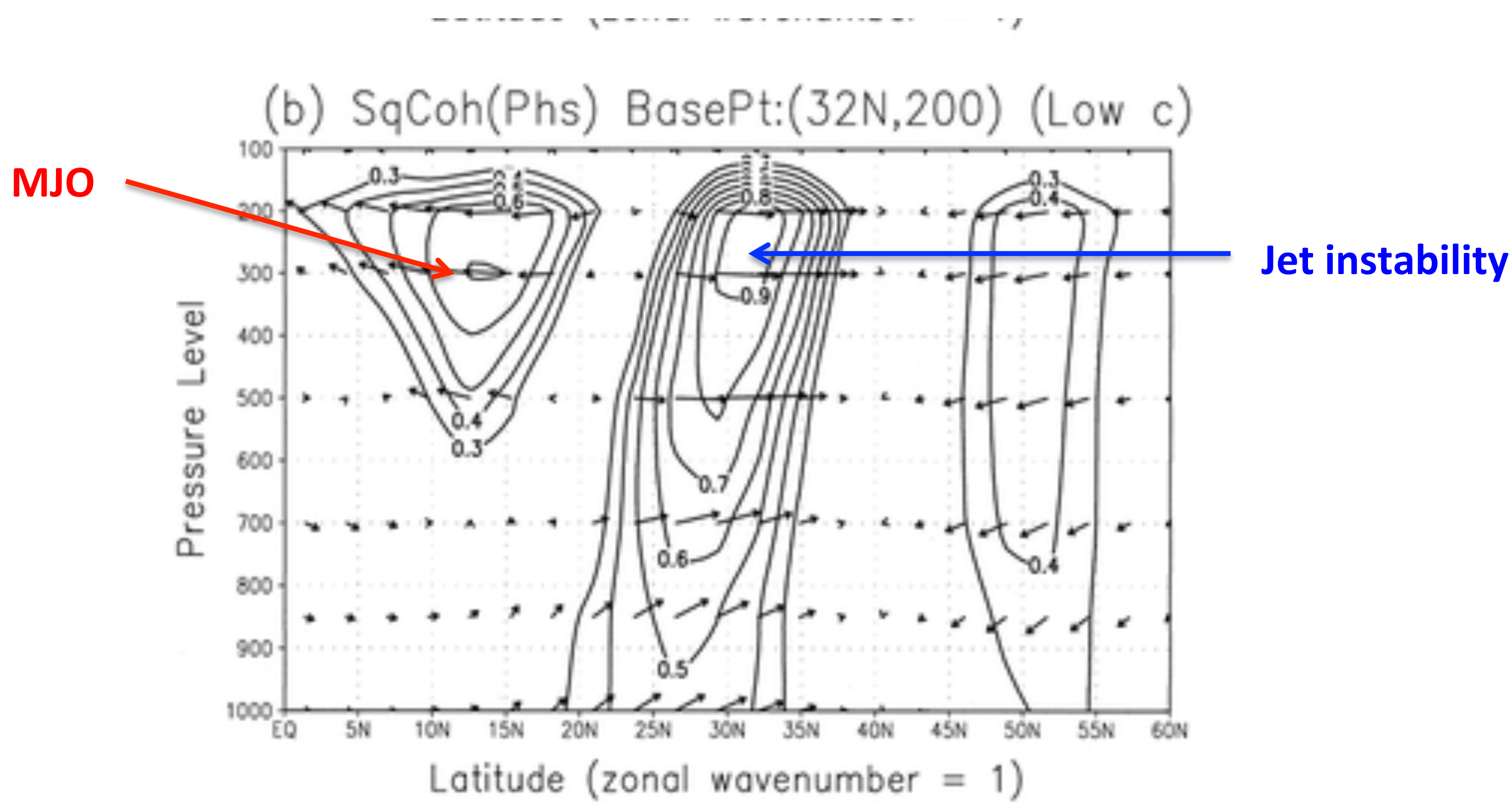
Tropical and Midlatitude intra-seasonal fluctuations are intrinsically linked?
(Straus and Lindzen, 2000)

- Studies of baroclinic instability on the sphere with realistic basic states indicate that the shorter waves (zonal wavenumber 8–15) are most unstable,and that these waves saturate relatively quickly.
- The more slowly growing longer waves are able to achieve higher amplitudes, particularly in the upper troposphere (Gall 1976a,b; Simmons and Hoskins 1978, Straus 1981).
- Theoretically expect phase speed ***c*** to be in the range of 1 − 10 m/sec, so that steering levels are close to the ground. $c = \omega / k$ (ω is frequency, ***k*** is dimensional wavenumber).
- **Phase speeds of 1 − 10 m/sec for k corresponding to zonal wave 1* have frequencies which strong overlap with MJO frequencies !!**
  *****(***zonal wave m=1 corresponds to k = a / cos(lat)***)
- **Thus long wave (m = 1) instabilities with phase speeds ~ 1 − 10 m/sec have same space and time scales as MJO circulation fluctuations.**

Tropical and Midlatitude intra-seasonal fluctuations are intrinsically linked? (continued)

- Study the ***coherence*** between eastward propagating planetary waves in the zonal wind field **u** between different latitudes and levels

- **Coherence measures the degree to which two time series have a similar phase relationship over a wide range of frequencies** (here those frequencies corresponding to phase speeds of 1-10 m/sec for zonal wave 1)



Squared coherence (contours) and phase (arrows) of eastward propagating fluctuations for **zonal wavenumber *m* = 1** with respect to a **base point of 32°N and 300 hPa**, as a function of latitude and pressure level.
Arrows pointing to the right indicate no phase shift, arrows pointing in the first quadrant mean that the indicated point leads the base point (wave ridge to the east of the base point), etc. The length of the arrows is proportional to the squared coherence.

Straus, D. M., and R. S.Lindzen, 2000: Planetary-Scale Baroclinic Instability and the MJO. *J. Atmos. Sci.*, **57**, 3609-3626.

Some Basic Mechanisms for Tropical-Extratropical Interactions

(1) Mid-Latitude Response to Tropical Forcing: Can we use ideas from stationary wave theory? **Tropics Force the Extratropics**

(2) Changes in mid-latitude instabilities due to Tropical Forcing: **Tropical forcing can excite mid-latitude barotropic instabilities.**

(3) Possible ways in which the tropics may respond to mid-latitudes: **Extratropical disturbances can lead to tropical heating.**

(4) Are tropical and midlatitude fluctuations sometimes coupled ? **There are mechanisms for directly coupling the tropics and extratropics.**

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