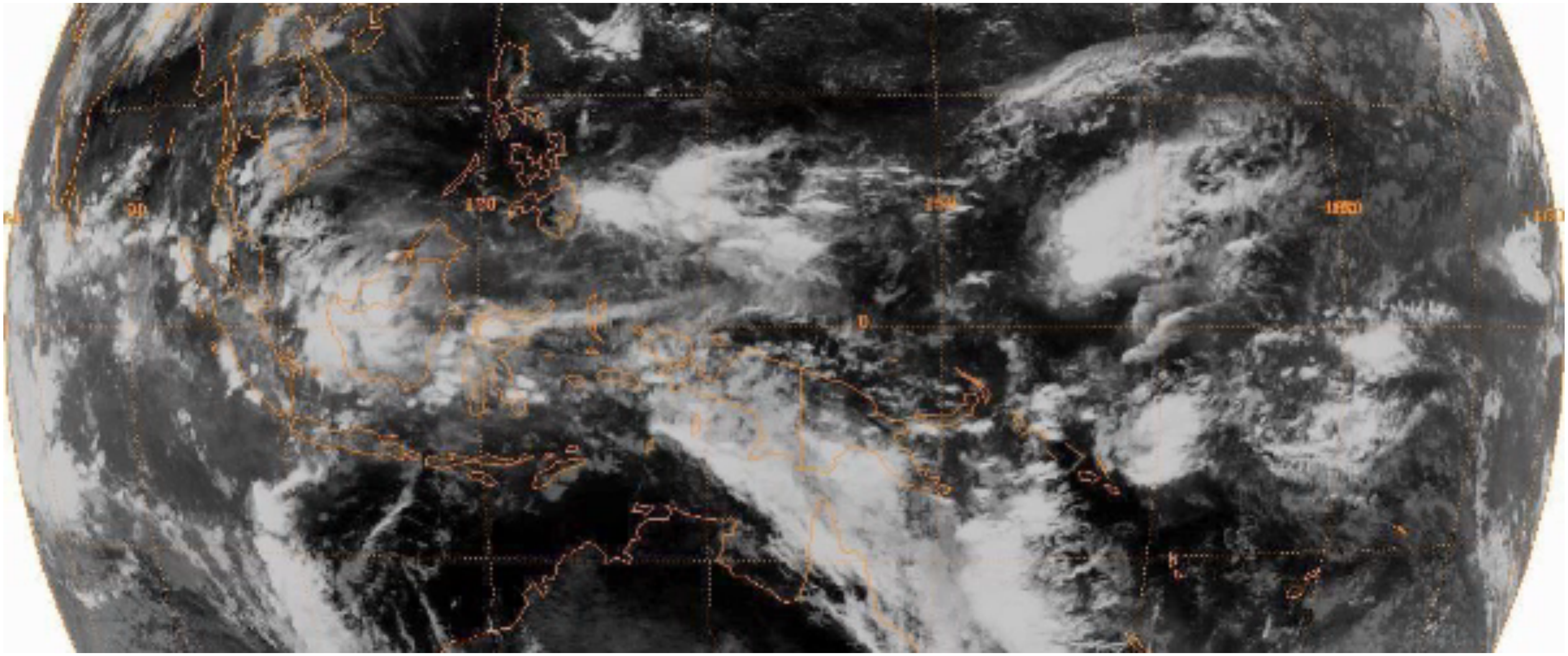
Some thoughts on convectively coupled (sub-seasonal) tropical transients

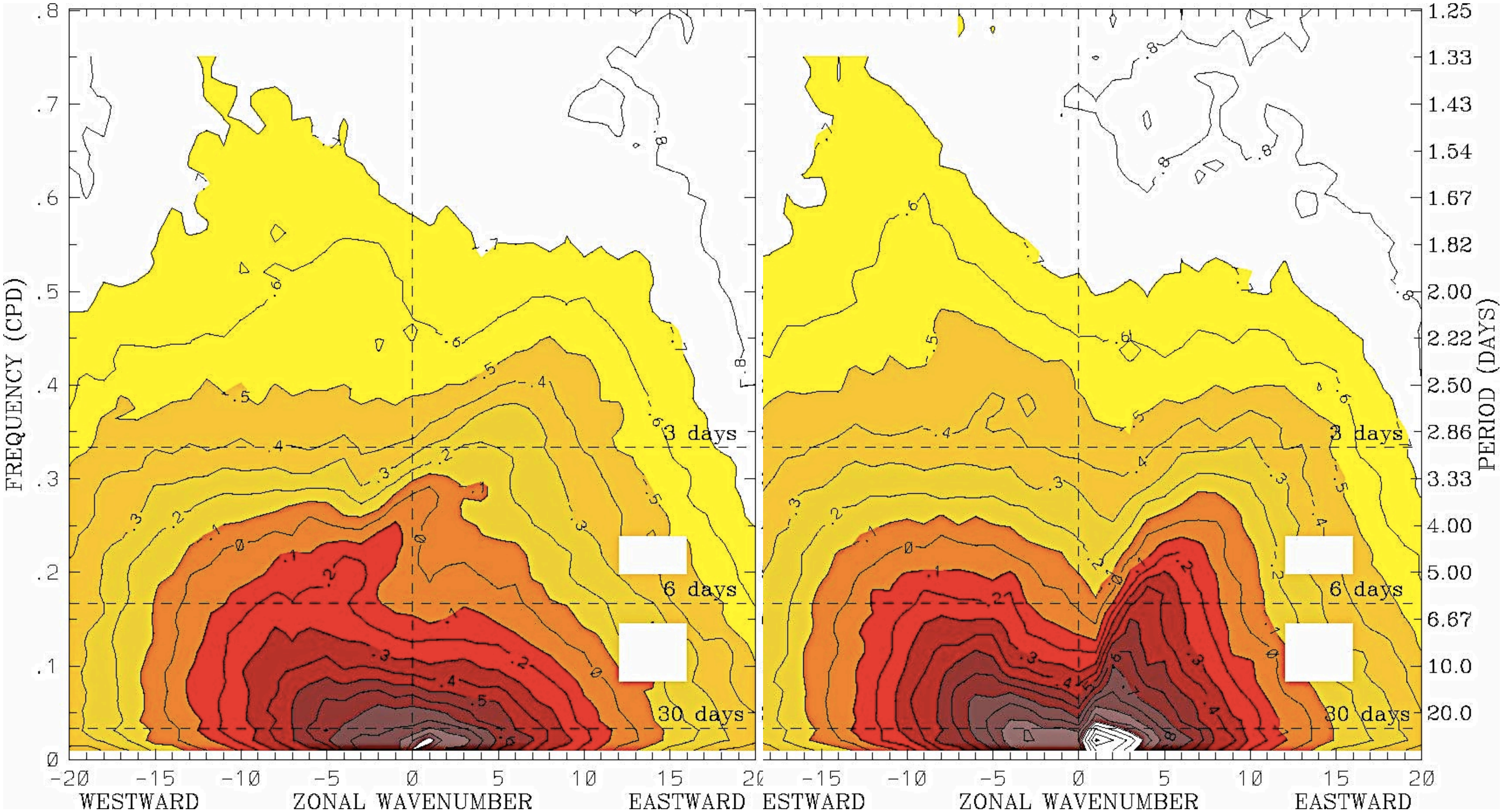
Zhiming Kuang



Movie courtesy of Brian Mapes

Space-time spectra of OLR ($\log_{10}$Power)

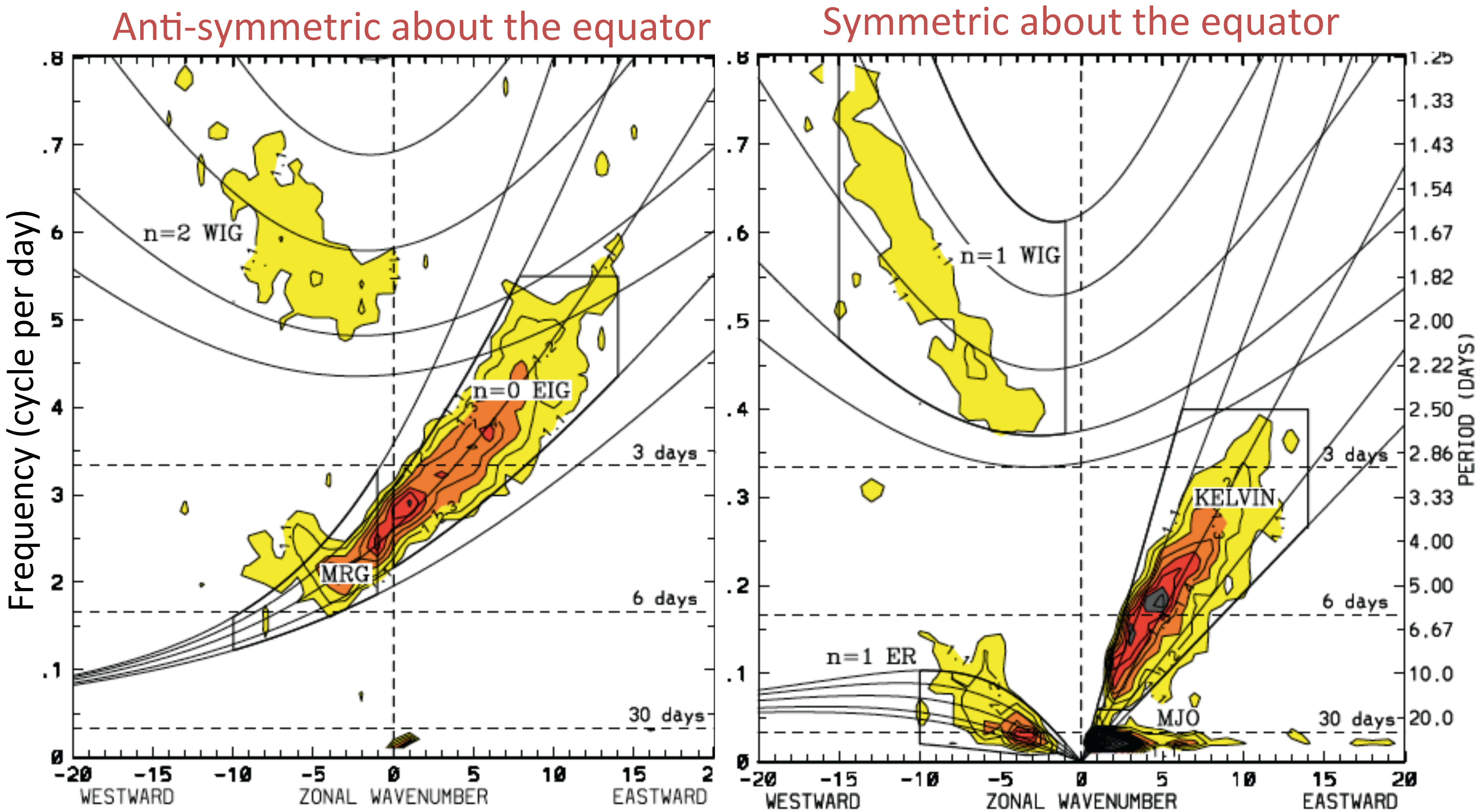
(averaged over 15N-15S, 20 years)



Wheeler and Kiladis, J. Atmos. Sci., 1999

Space-time spectra (averaged over 15N-15S, 20 years)

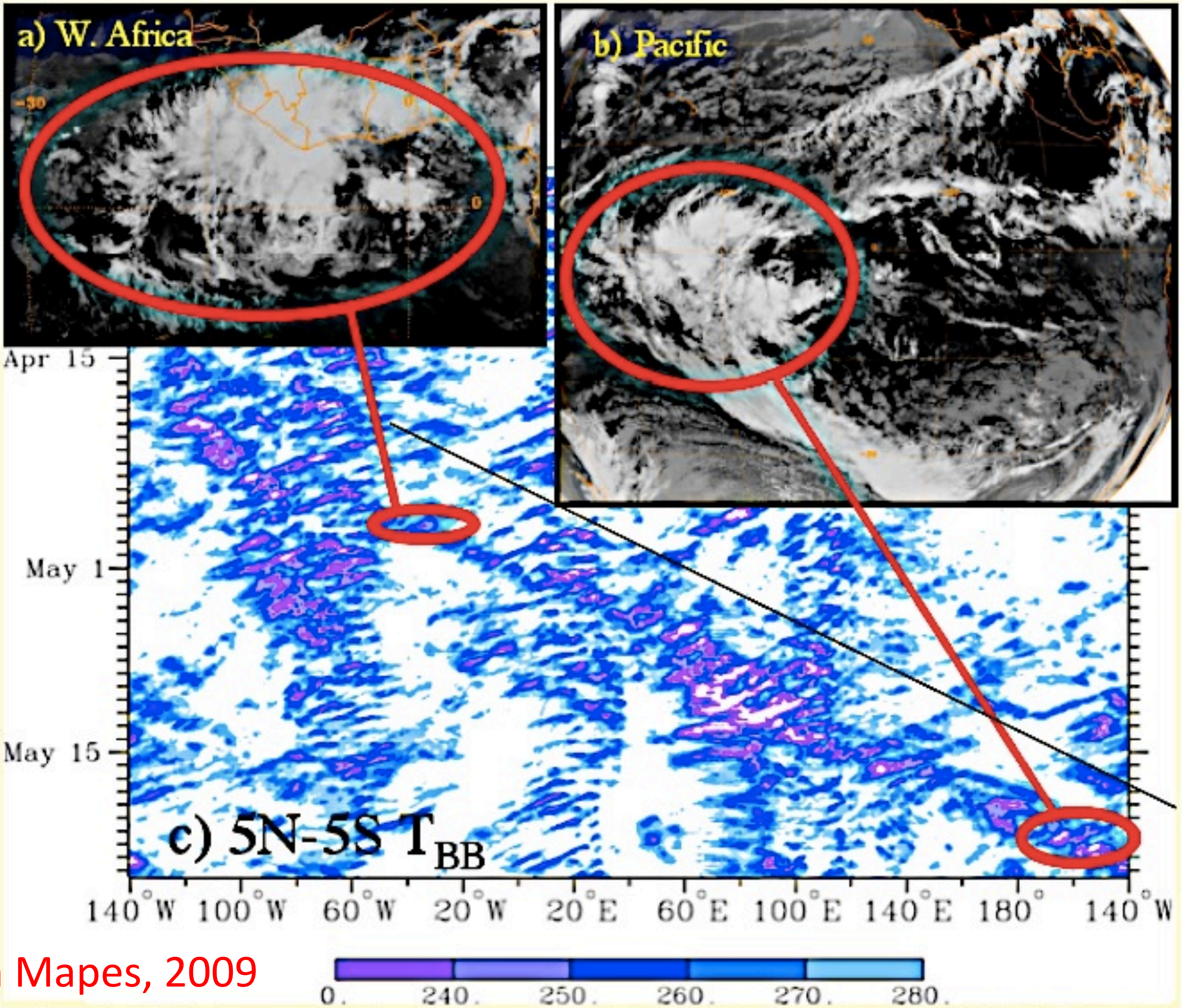
(with background red noise removed)



Overlaid are dispersion curves of linear equatorial shallow water modes of Matsuno 1966

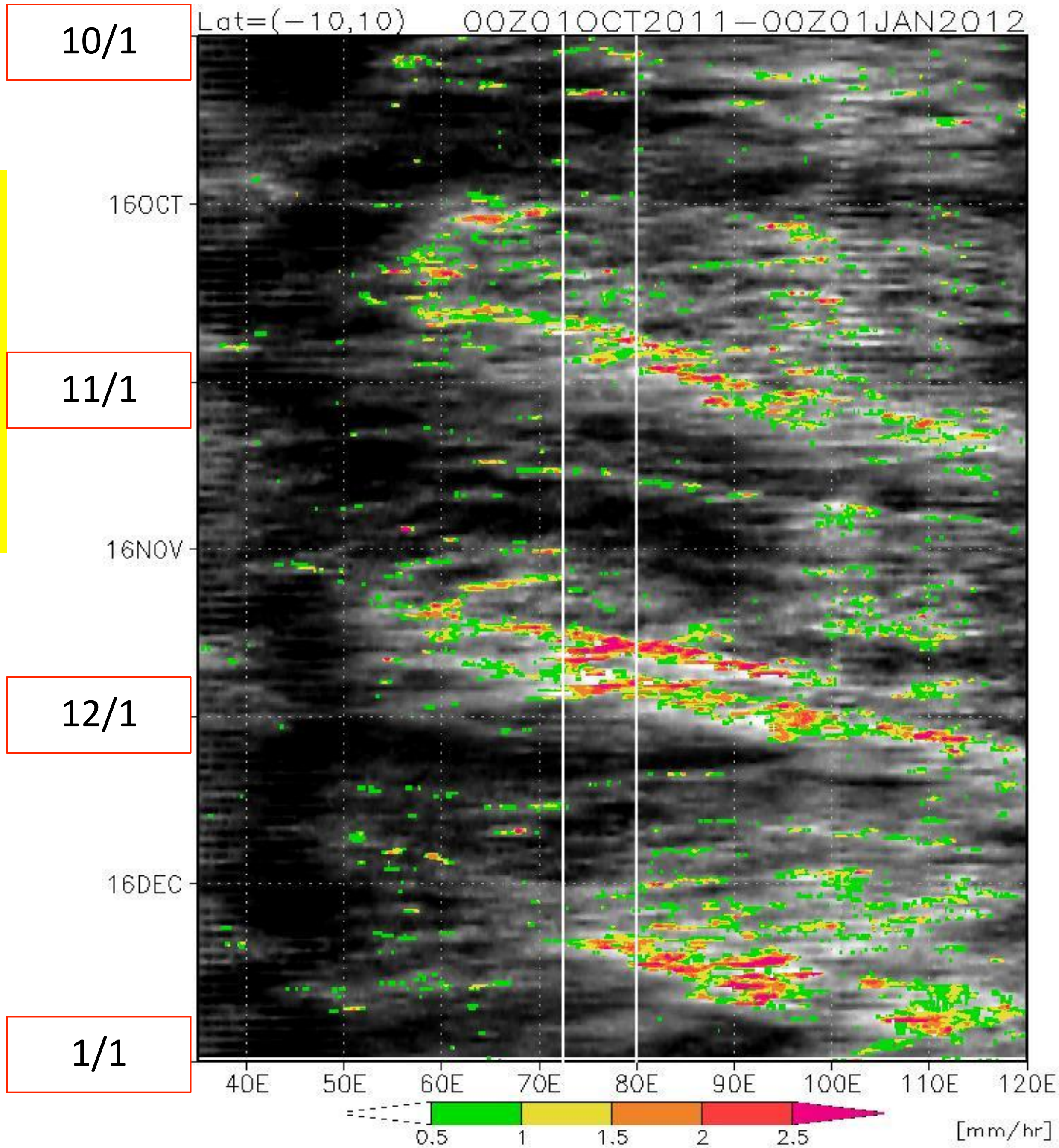
Wheeler and Kiladis, J. Atmos. Sci., 1999

1998



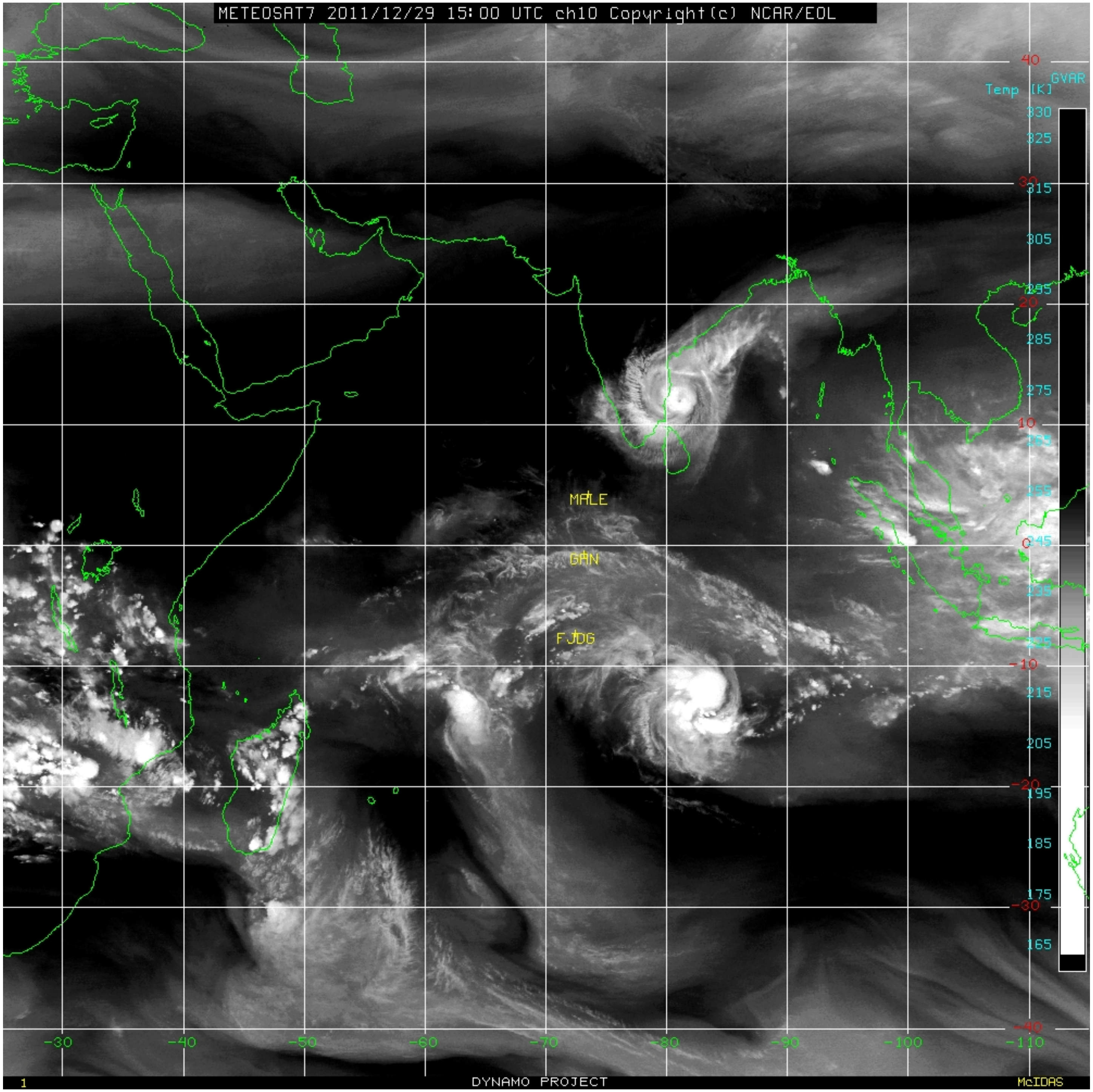
From Mapes, 2009

Examples from the recent DYNAMO/ CINDY/AMIE field campaign



Courtesy of Chidong Zhang and Kunio Yoneyama

Dec. 29, 2011
METEOSAT7
Ch10
Water vapor



Why tropical transients?

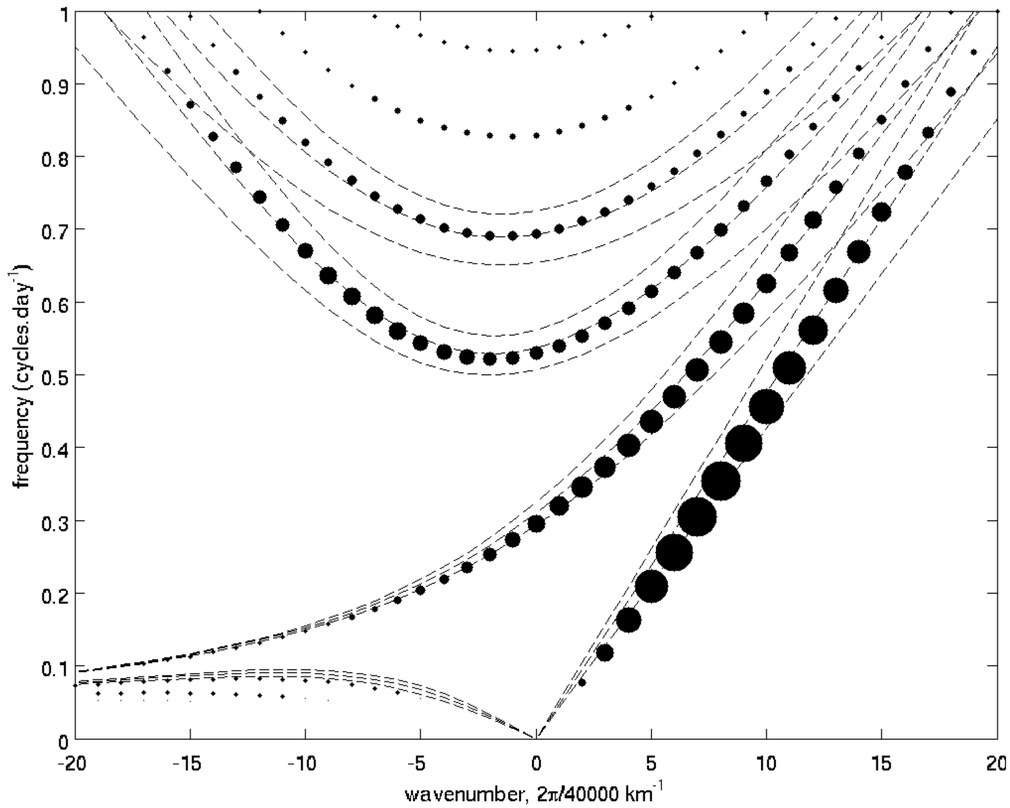
- Practical:
  - Tropical forecast, including monsoon, tropical cyclones etc. (e.g. Yasunari, 1979; Maloney and Hartmann, 2000)
  - ENSO (e.g. McPhaden, 1999)
  - Global medium range weather forecast (e.g. Ferranti et al., 1990)
  - Poster child of inadequacies of moist processes in climate models
- Theoretical:
  - Important examples of large-scale convective organization
  - Perturbations on a mean climate may be easier to understand than the mean climate itself

Three main features

- Convectively coupled equatorial waves
- The intra-seasonal spectral peak, i.e. the Madden-Julian Oscillation (MJO)
- A red noise background

Convectively coupled equatorial waves

- We have some understanding on the basic mechanisms for their existence and their scale and wave type selection (e.g. Mapes 2000, Khouider and Majda, 2006, Kuang 2008; Andersen and Kuang 2008)

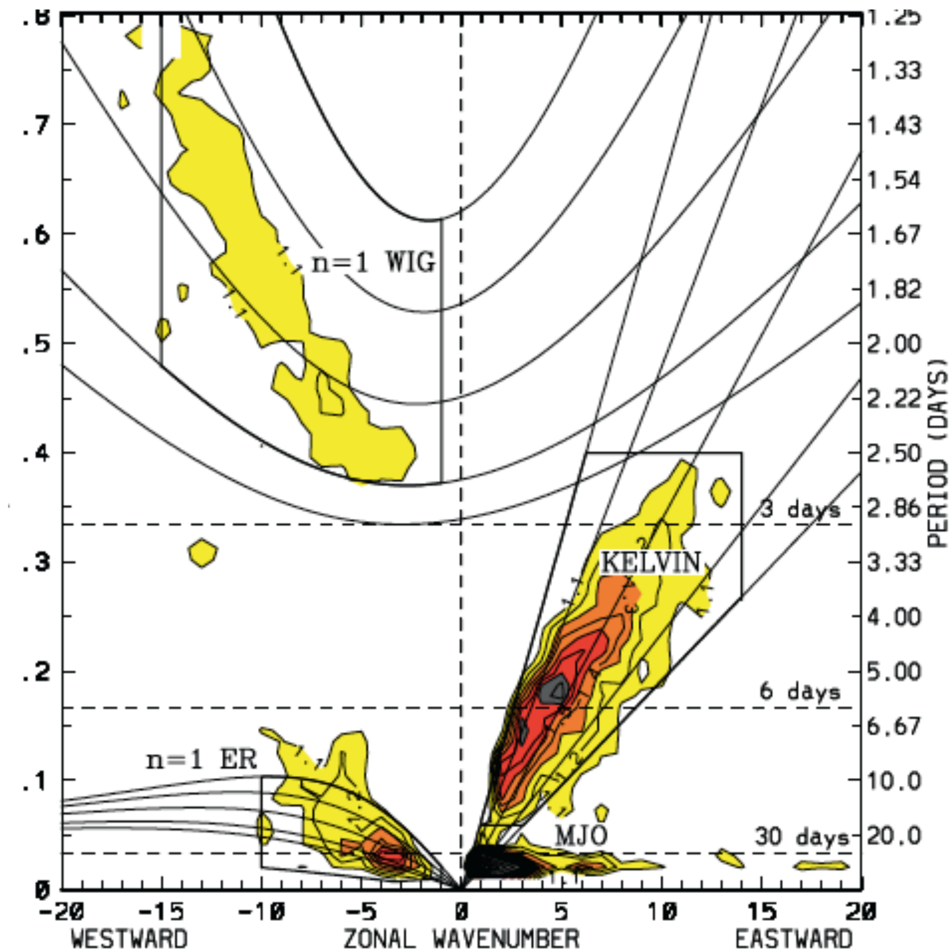


Dot size proportional to growth rate

Andersen and Kuang, 2008

The MJO

- is believed to have different dynamics from the convectively coupled waves.

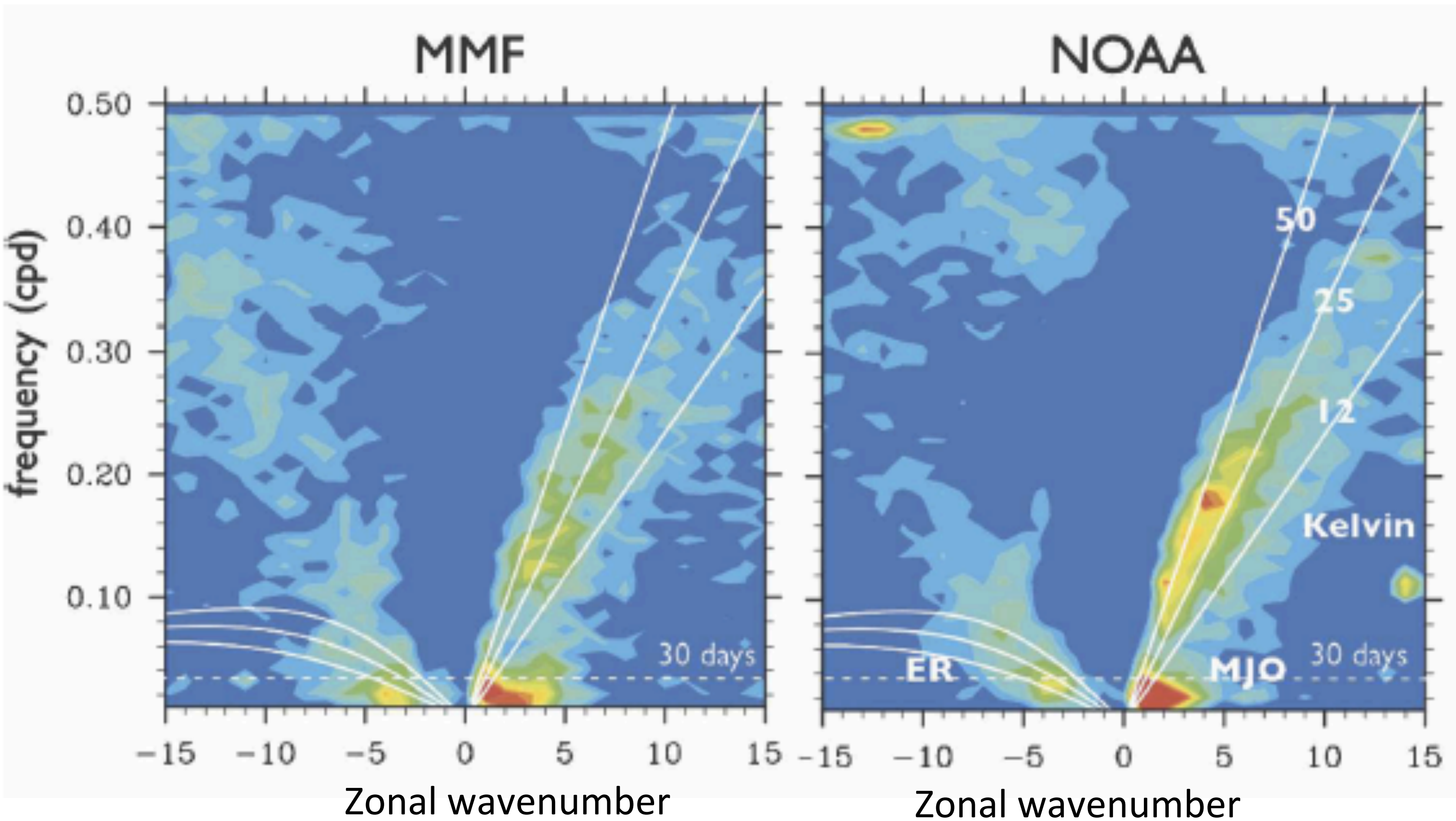


A framework based on column integrated moist static energy

(e.g .Neelin and Yu, 1994; Sobel et al., 2001; Fuchs and Raymond 2002; Maloney, 2009; Sugiyama, 2009ab, and many others)

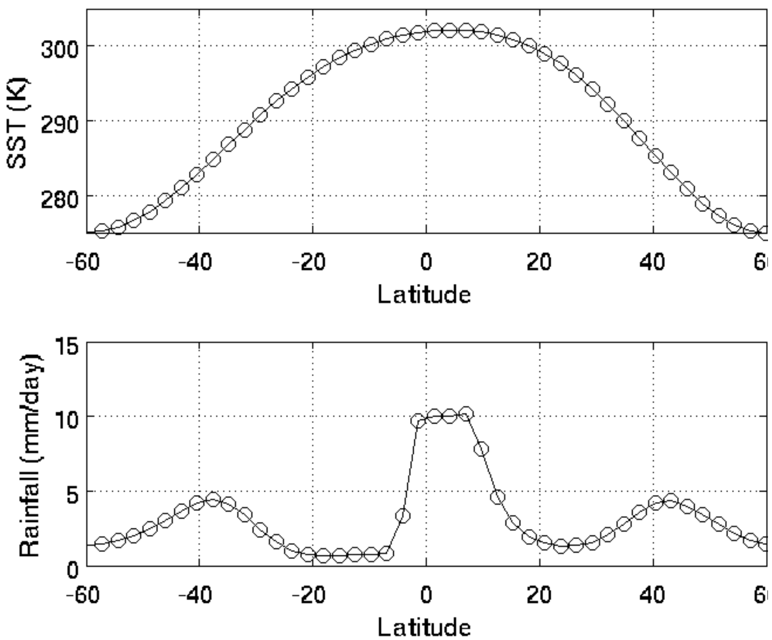
- Spectra of precipitable water show a strong MJO signal but weaker Kelvin waves (Roundy and Frank, 2004, Yasunaga and Mapes 2011). (Observational, but indirect)
- In idealized SPCAM simulations, damping column MSE anomalies eliminates the "MJO-like" signals but not Kelvin waves (Andersen and Kuang, 2012). (More direct, but in a model)

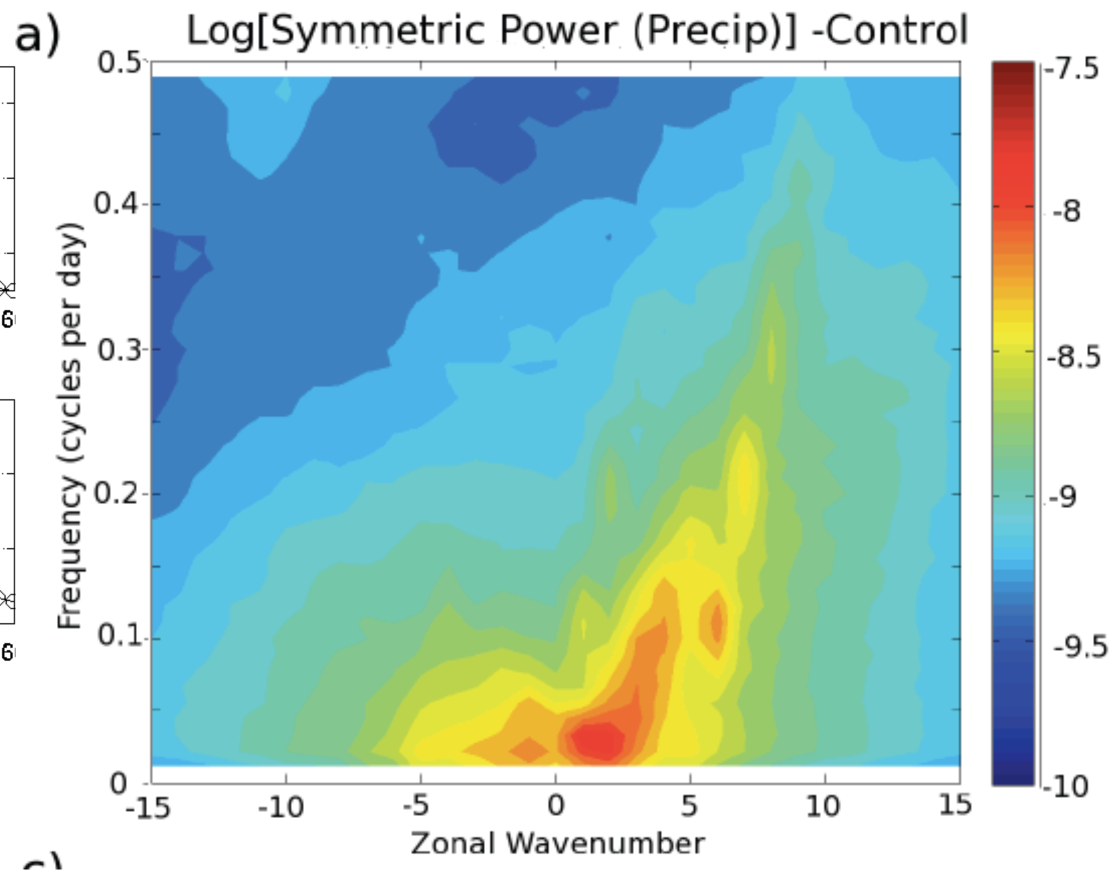
AMIP-style SPCAM simulations produce realistic tropical spectra



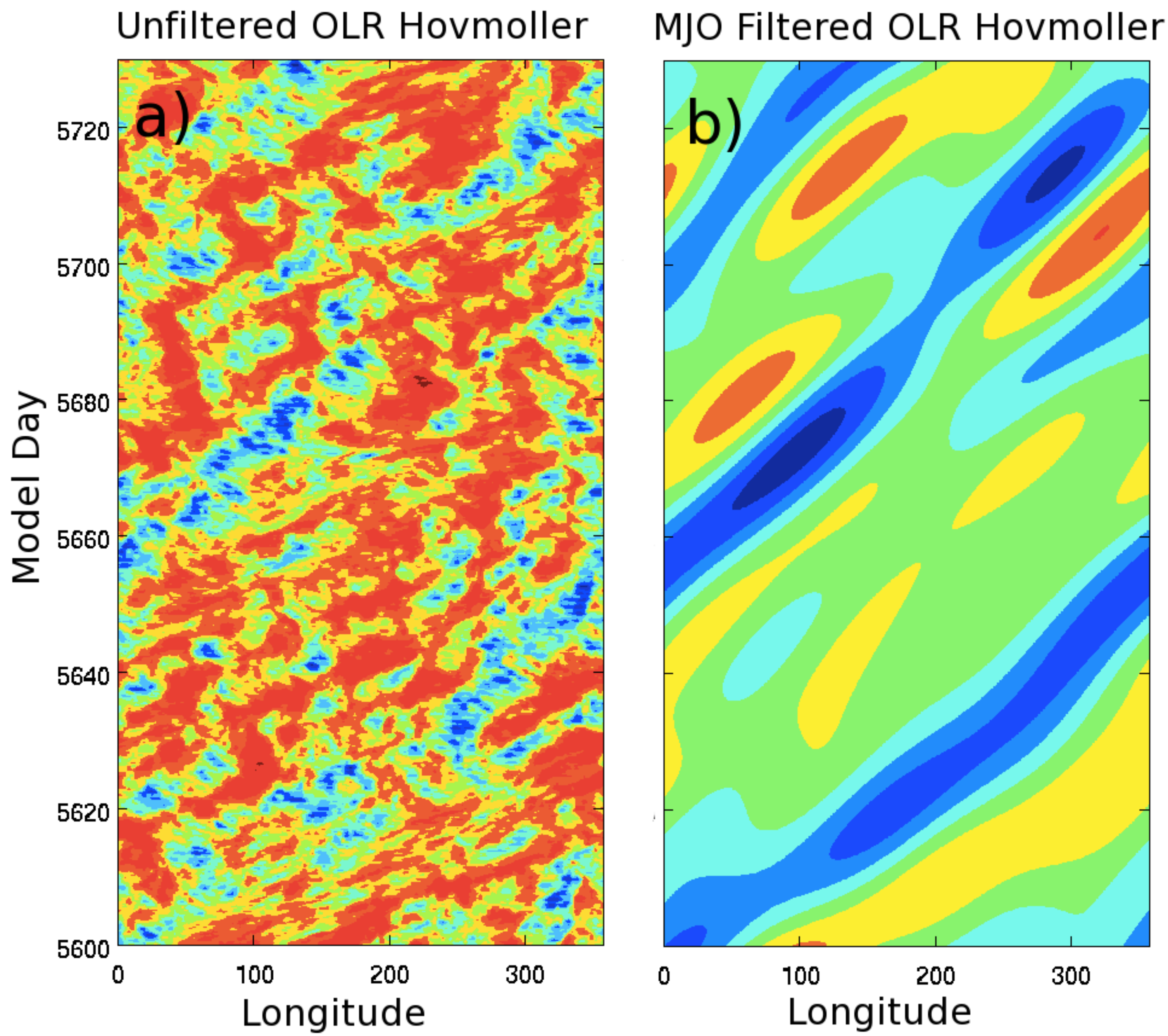
Khairoutdinov, M., C. A. DeMott, and D. A. Randall, 2008, J. Climate

Aquaplanet SPCAM results with an off-equatorial ITCZ
(Andersen and Kuang, J. Climate 2012)





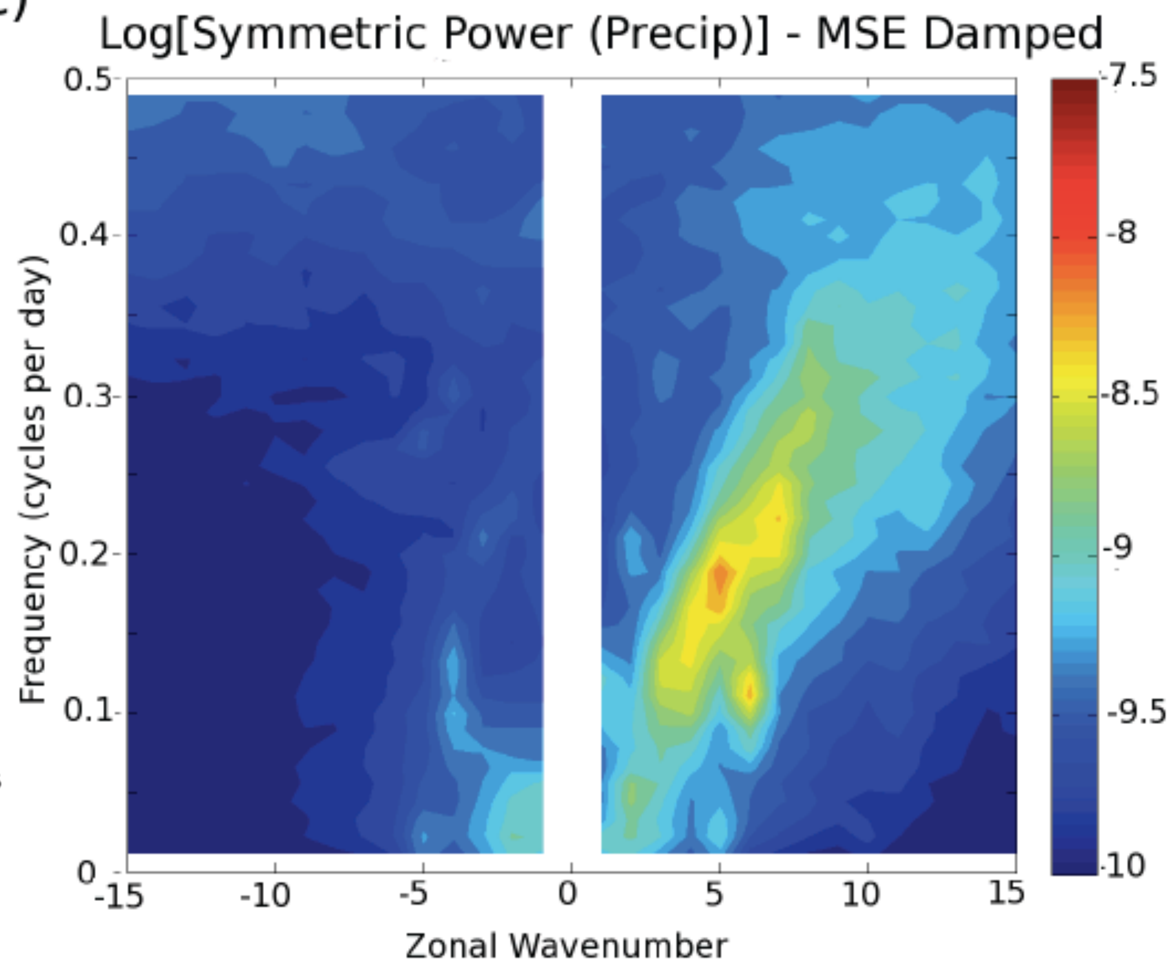
Marat Khairoutdinov and Dave Randall have shown similar simulations


Unfiltered OLR Hovmoller
MJO Filtered OLR Hovmoller
a)
b)
Model Day
5720
5700
5680
5660
5640
5620
5600
0
100
200
300
Longitude
0
100
200
300
Longitude

Damping column MSE anomaly

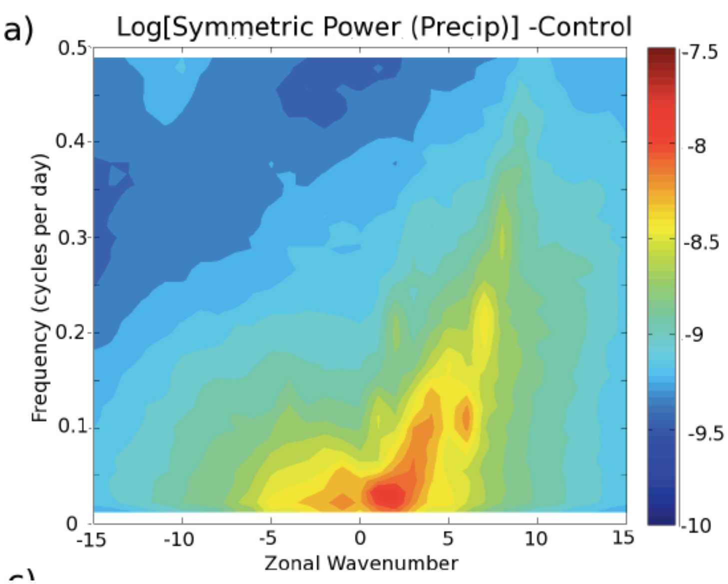
(with a 12-hr damping timescale)

c)



Full aquaplanet SPCAM

a)



The "MJO-like" signal and the red-noise background disappear but convectively coupled waves remain.

A column integrated moist static energy budget framework

$$\langle \partial_t h \rangle_{budget} = -\langle \omega \partial_p h \rangle - \langle v \cdot \nabla h \rangle + LH + SH + \langle LW \rangle + \langle SW \rangle,$$

Contribution to growth (fractional growth per time)

$$\frac{\|x \cdot \langle h \rangle\|}{\|\langle h \rangle^2\|}$$

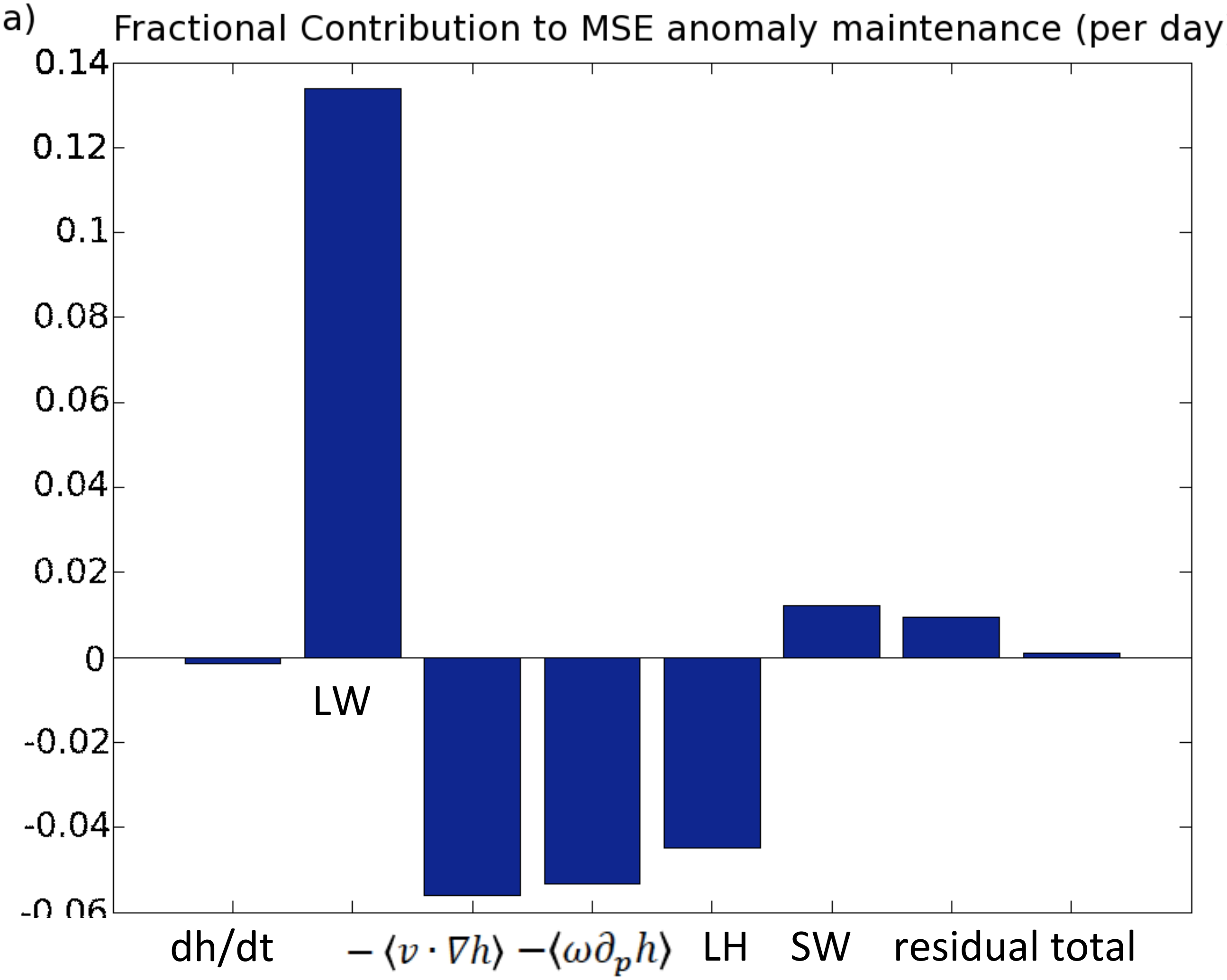
Contribution to propagation

$$\frac{\|x \cdot \langle dh/dt \rangle\|}{\|\langle dh/dt \rangle^2\|}$$

where $\|y\| = \iint_{ITCZ} y dA$ is the integral over the ITCZ

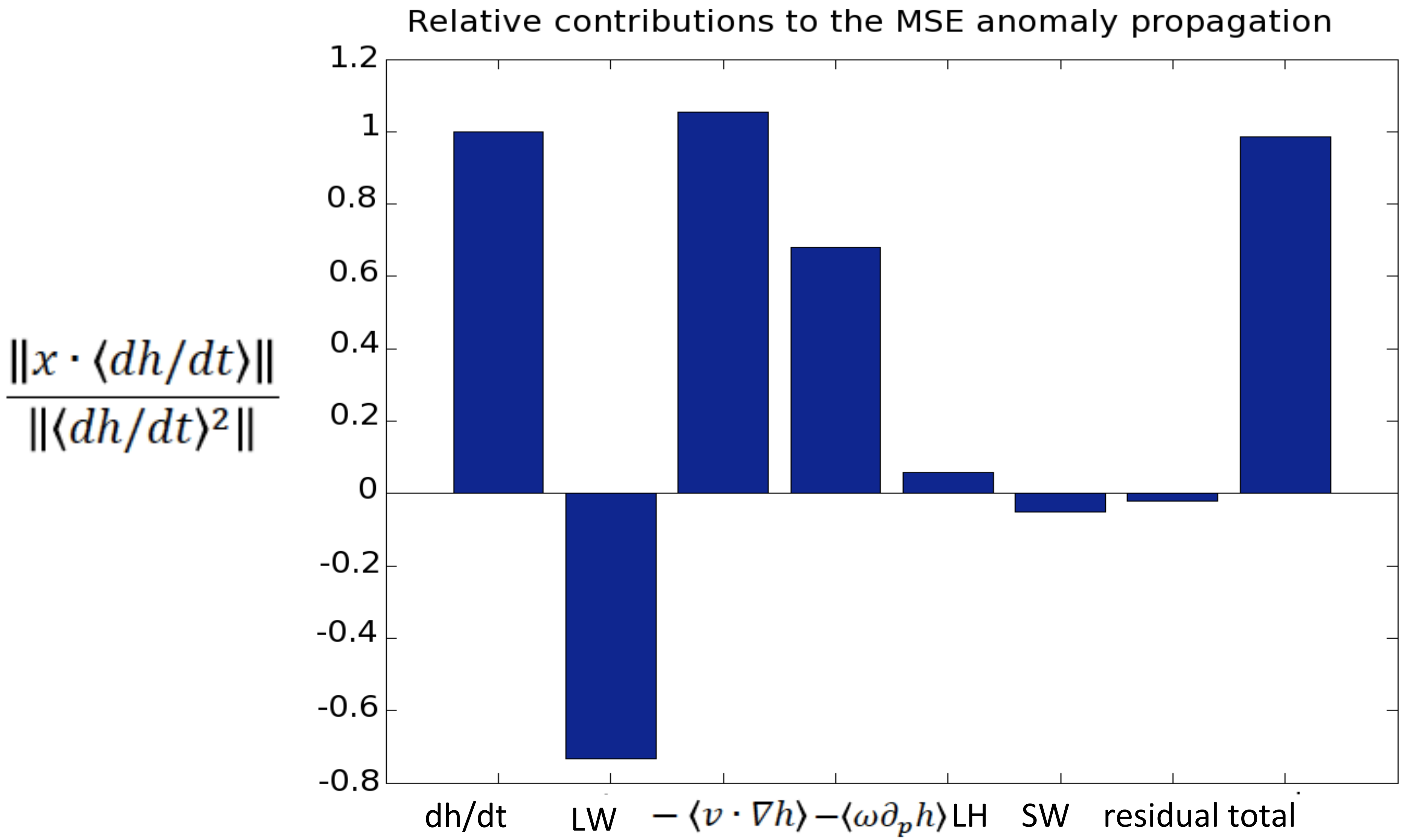
(Andersen and Kuang, J. Climate 2012)

a)



$$\frac{\|x \cdot \langle h \rangle\|}{\|\langle h \rangle^2\|}$$

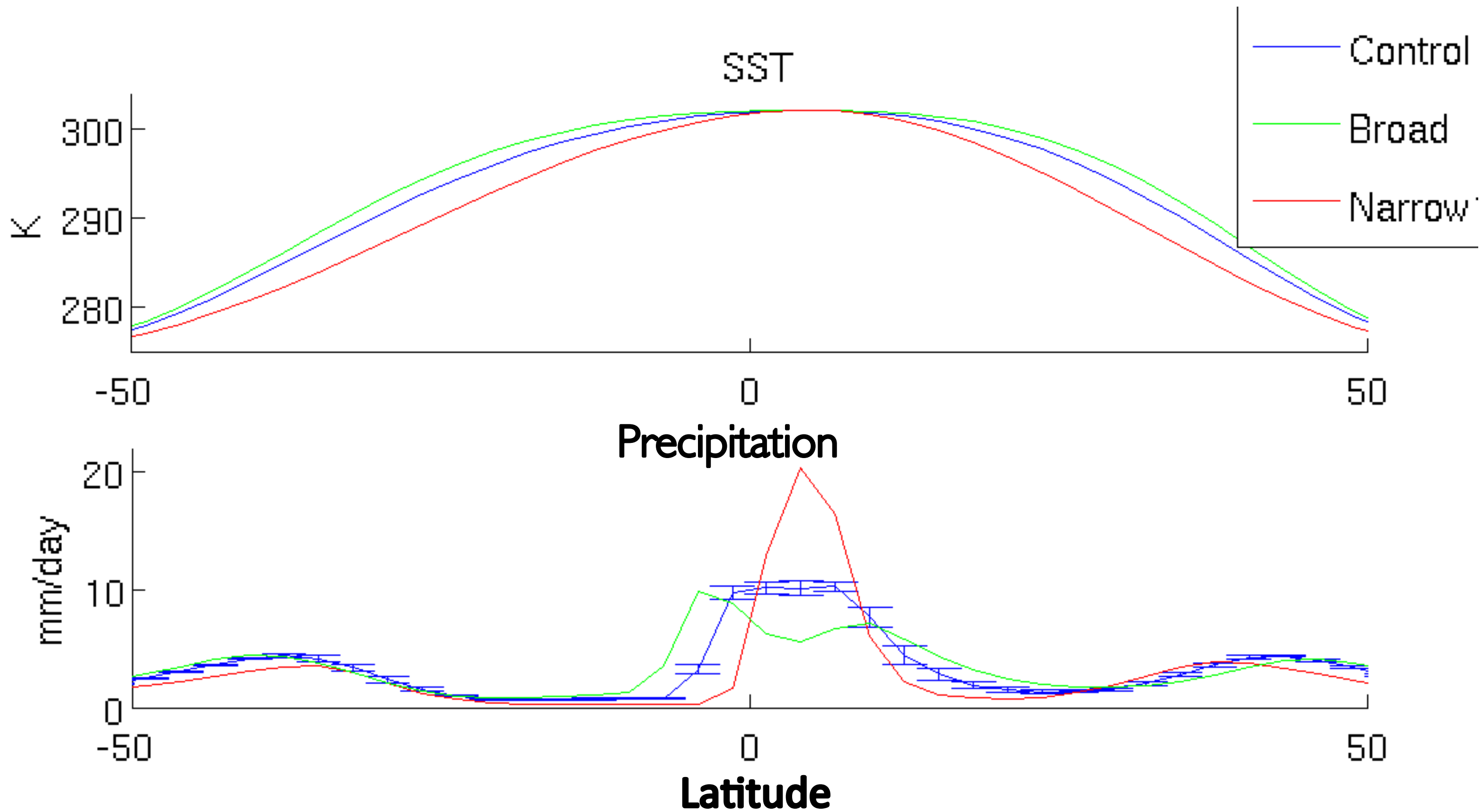
where $\|y\| = \iint_{ITCZ} y dA$ is the integral over the ITCZ


Relative contributions to the MSE anomaly propagation
$\frac{\|x \cdot \langle dh/dt \rangle\|}{\|\langle dh/dt \rangle^2\|}$
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
dh/dt
LW
$-\langle v \cdot \nabla h \rangle$
$-\langle \omega \partial_p h \rangle$
LH
SW
residual
total

Varying the mean state

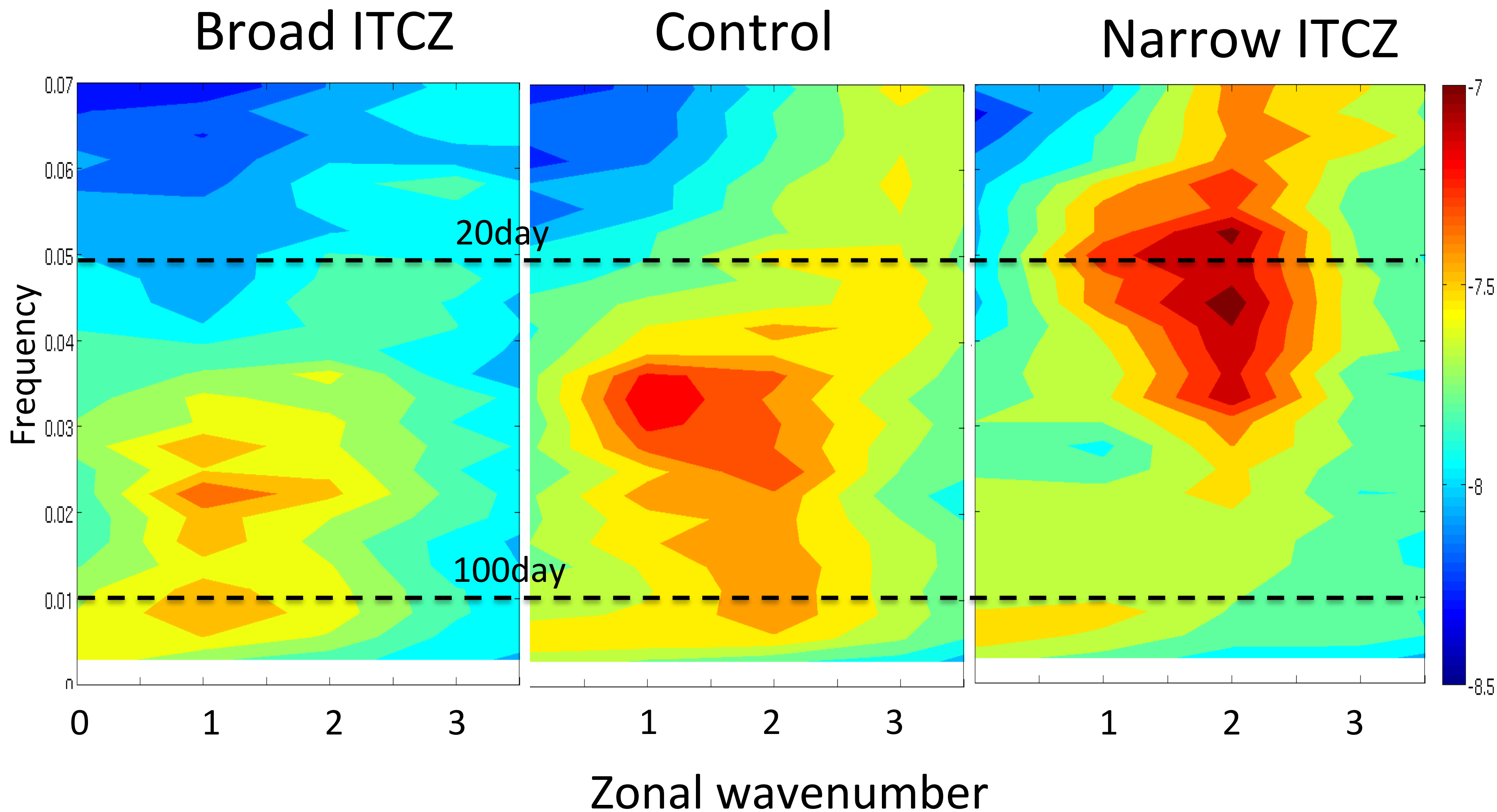
- By varying the climatological mean state and examining changes in the "MJO-like" disturbances, useful insights may be gained on the underlying processes.

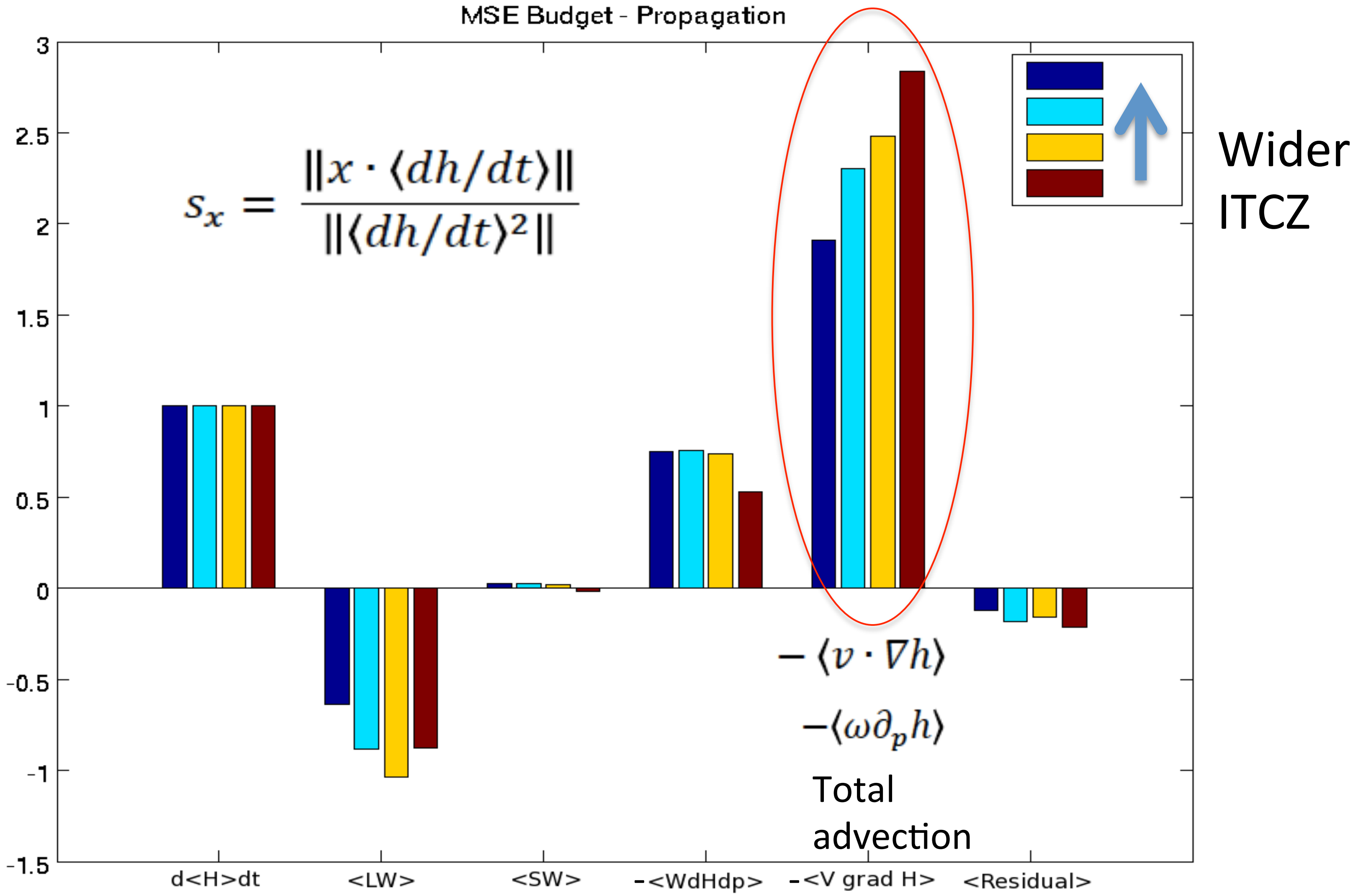
Varying ITCZ width



Unpublished work with Joe Andersen

Phase speed variations



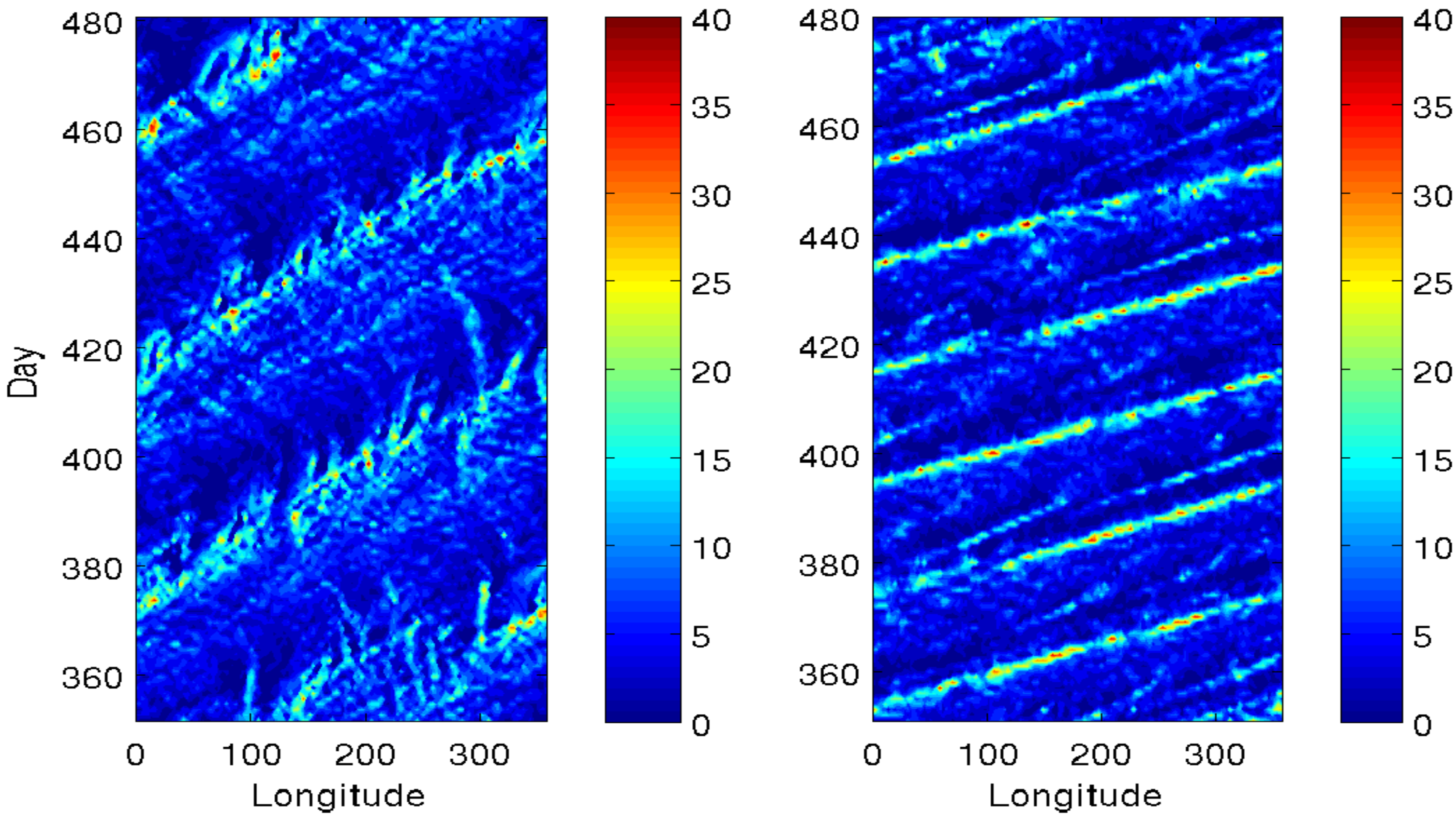


Further decomposition shows that changes in $-\langle v \cdot \nabla h \rangle$ are dominated by MJO-scale wind acting on progressively stronger background meridional MSE gradient: stronger background dh/dy implies faster propagation

Enhanced horizontal moisture advection increases the propagation speed

Normal horizontal moisture advection

Enhanced horizontal moisture advection $3 \times V' \nabla q$



In both cases, extratropical eddies are suppressed.

Global warming experiments

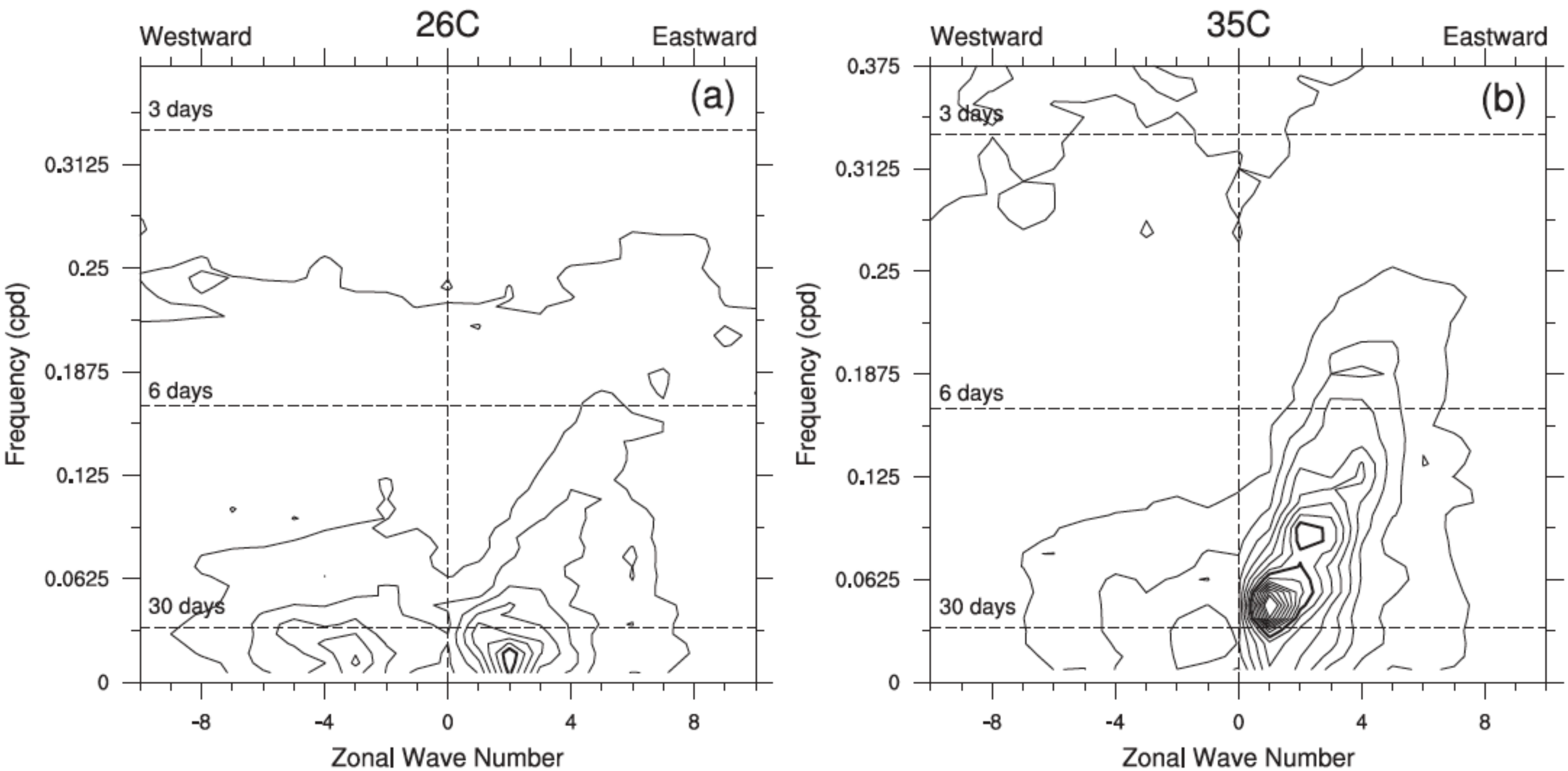
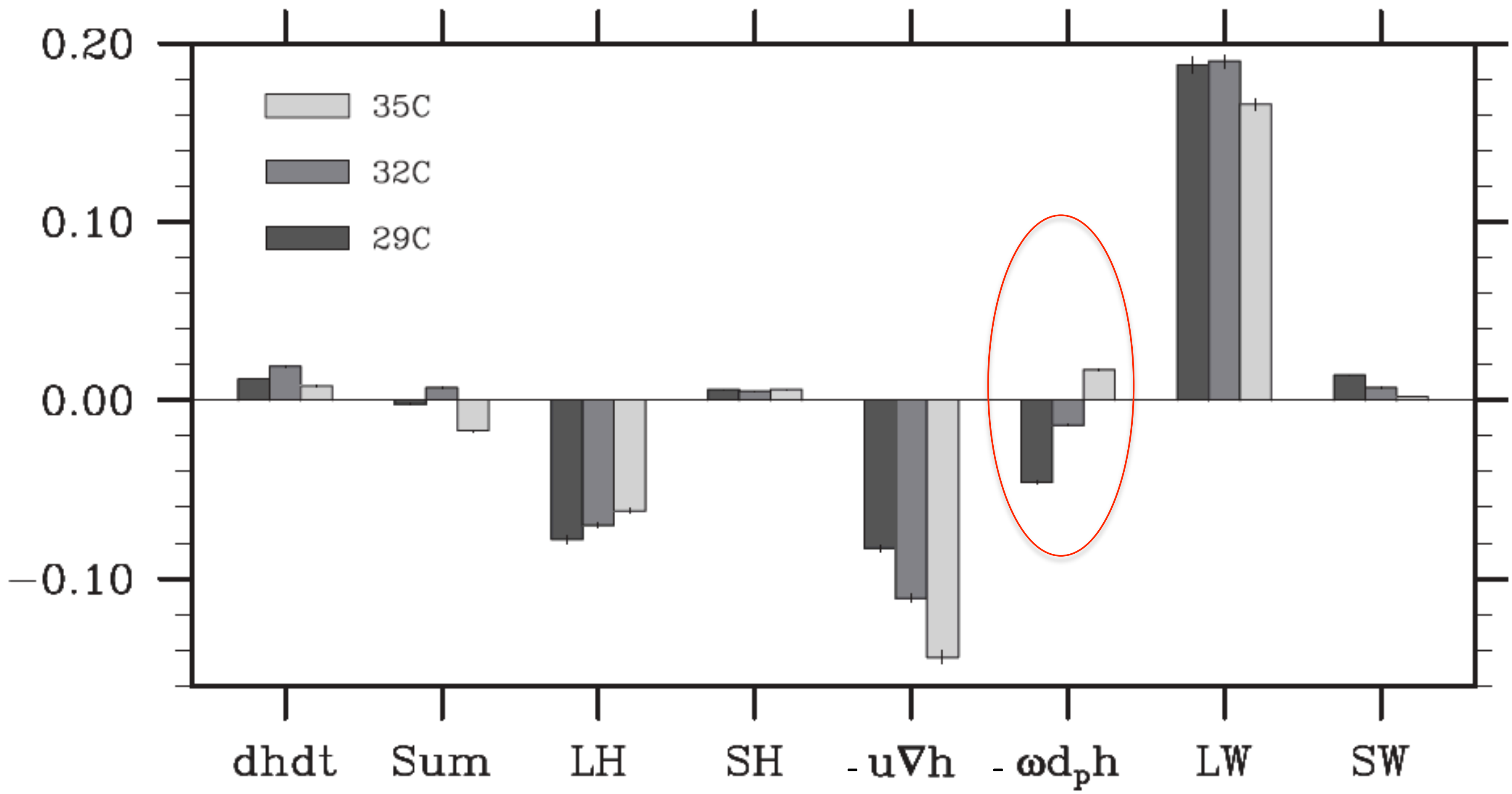
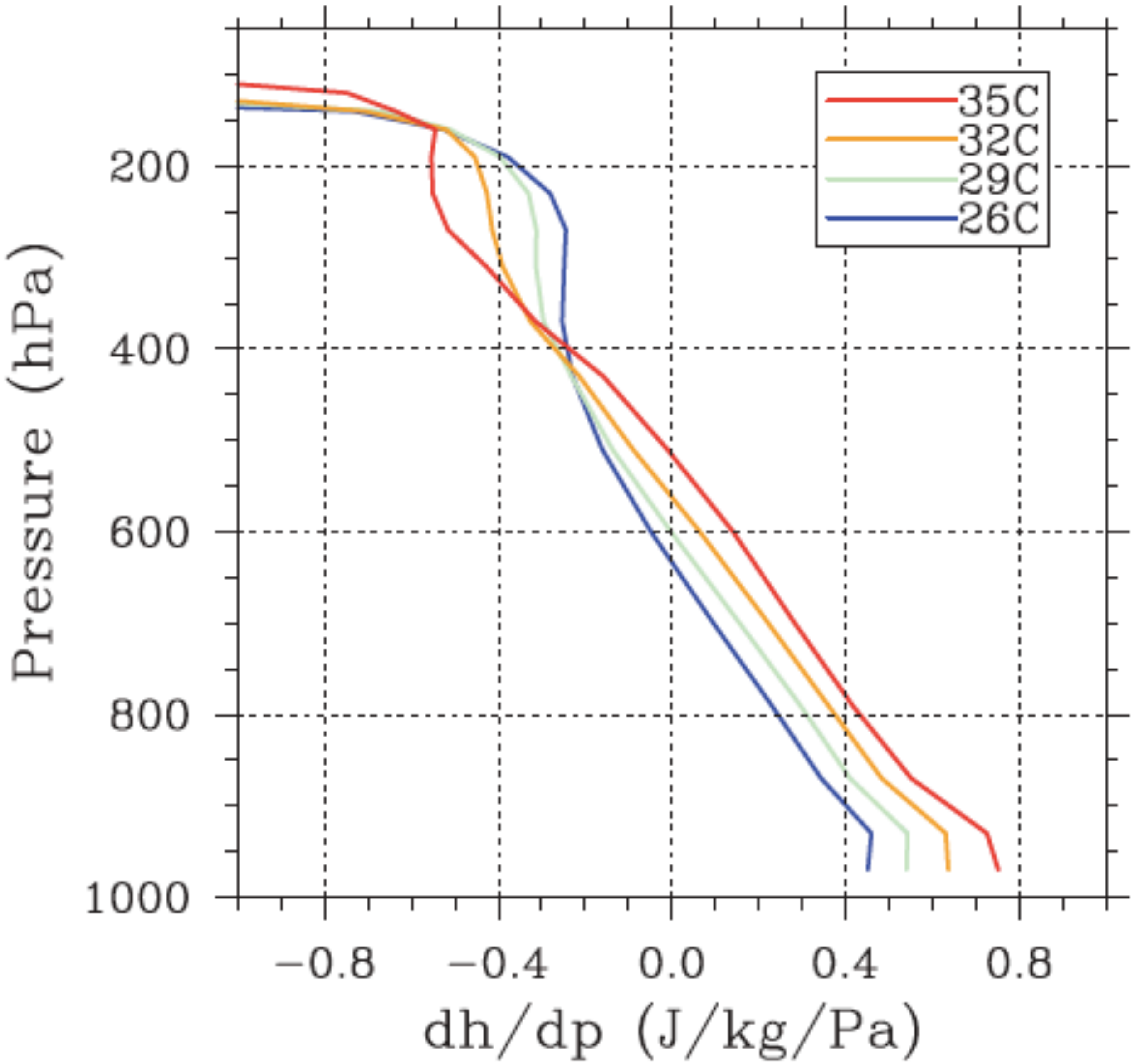


FIG. 3. Wavenumber–frequency power spectra of OLR for the (left) 26° and (right) 35°C simulations. Contour intervals are 1 $W^2\ m^{-4}$; the 9 $W^2\ m^{-4}$ contour is bold in both panels.

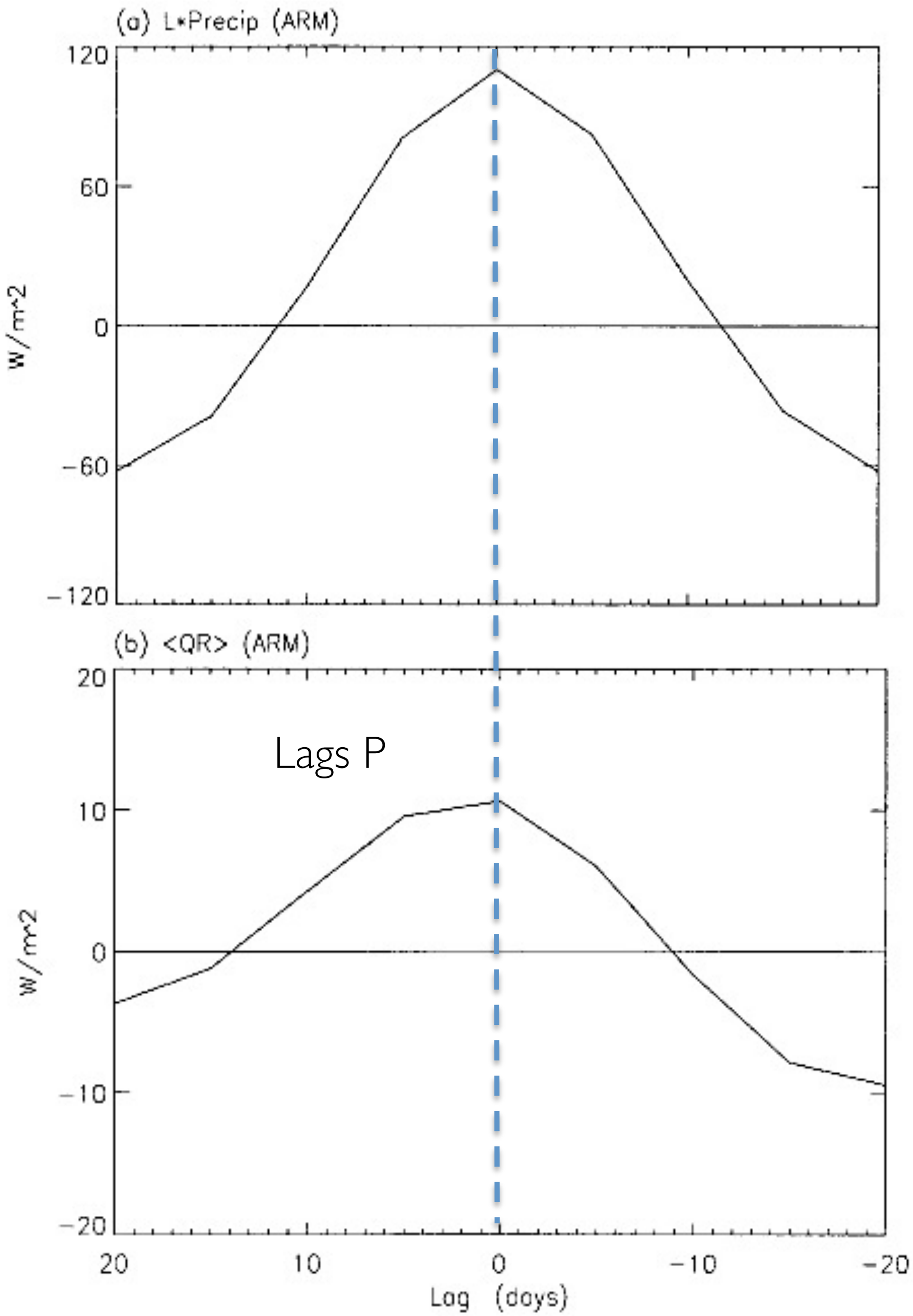
Arnold et al., 2013



Less export of MSE by vertical advection with warming



With Clausius-Clapeyron and constant RH, dh/dp in the mid-lower troposphere increases with warming.



Lin and Mapes (2004)

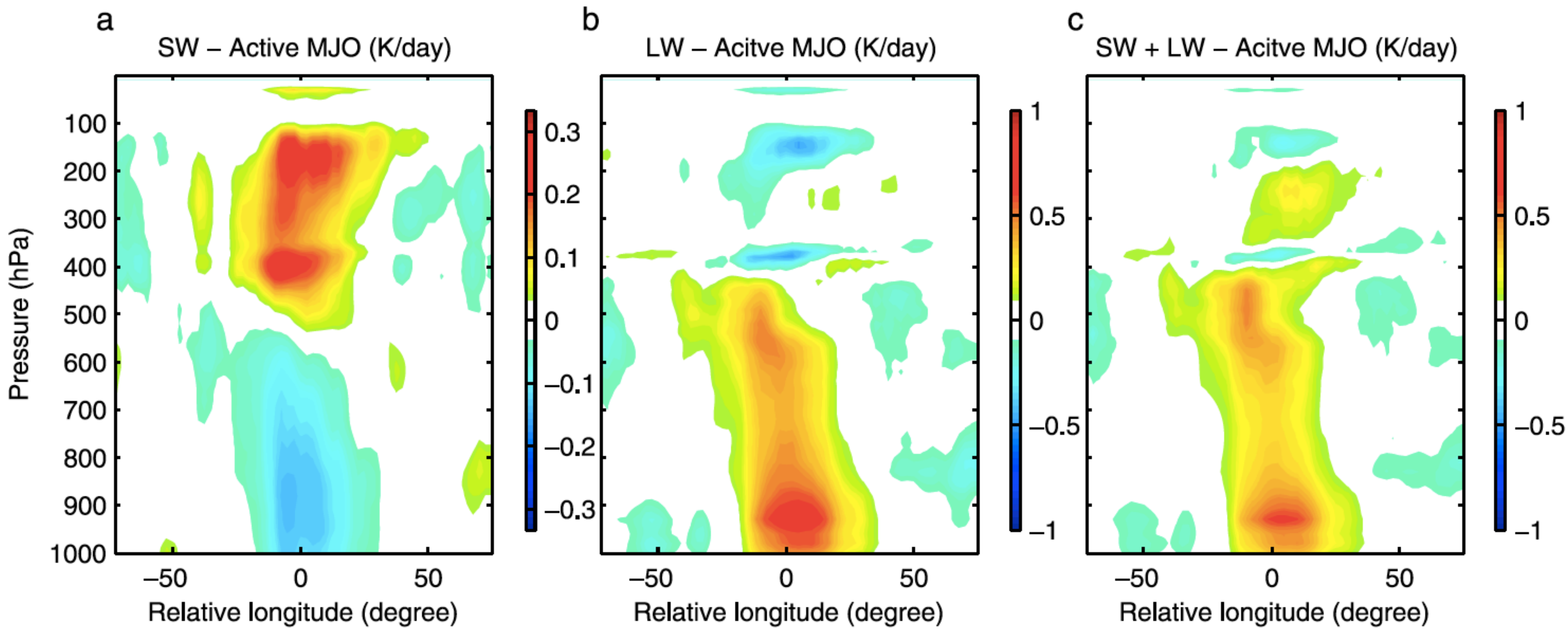
<QR>'~10-15%LP'

and dominated by OLR

In the SPCAM results, <QR>'~20%LP'

Vertical structure

Results using CloudSAT 2B-FLXHR (Ma and Kuang, GRL, 2011)



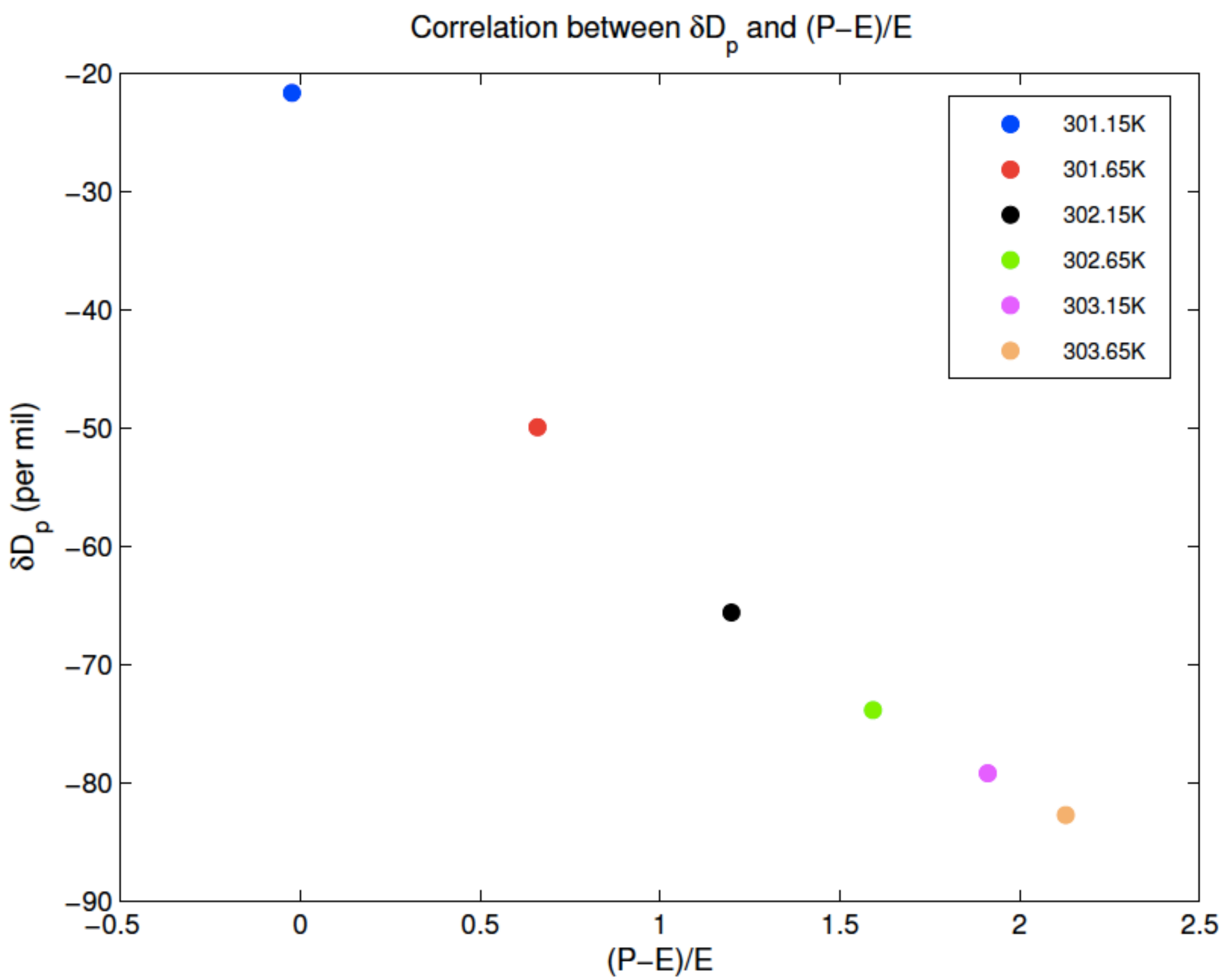
Caveat: radiative heating profile is a highly derived product

Everybody believes the experiment except the experimentalist; nobody believes the model except the modeler

How to better constrain the MSE budget observationally?

- Additional constraints, such as isotopic compositions?

Deuterium content in rain *versus* moisture convergence

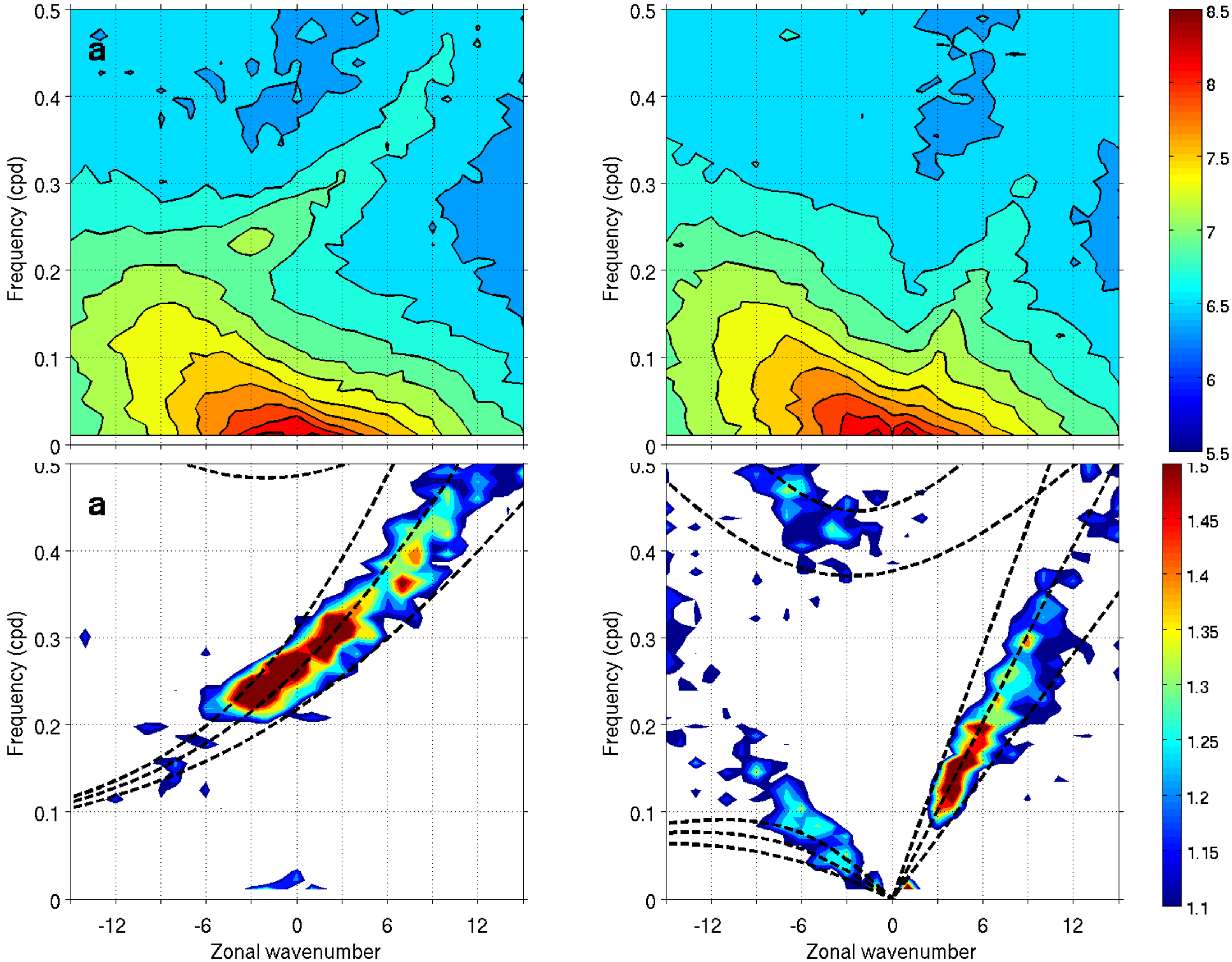


Moore, Kuang, and Blossey,
to be submitted

Red noise background

- what causes the red noise has not been studied much at all

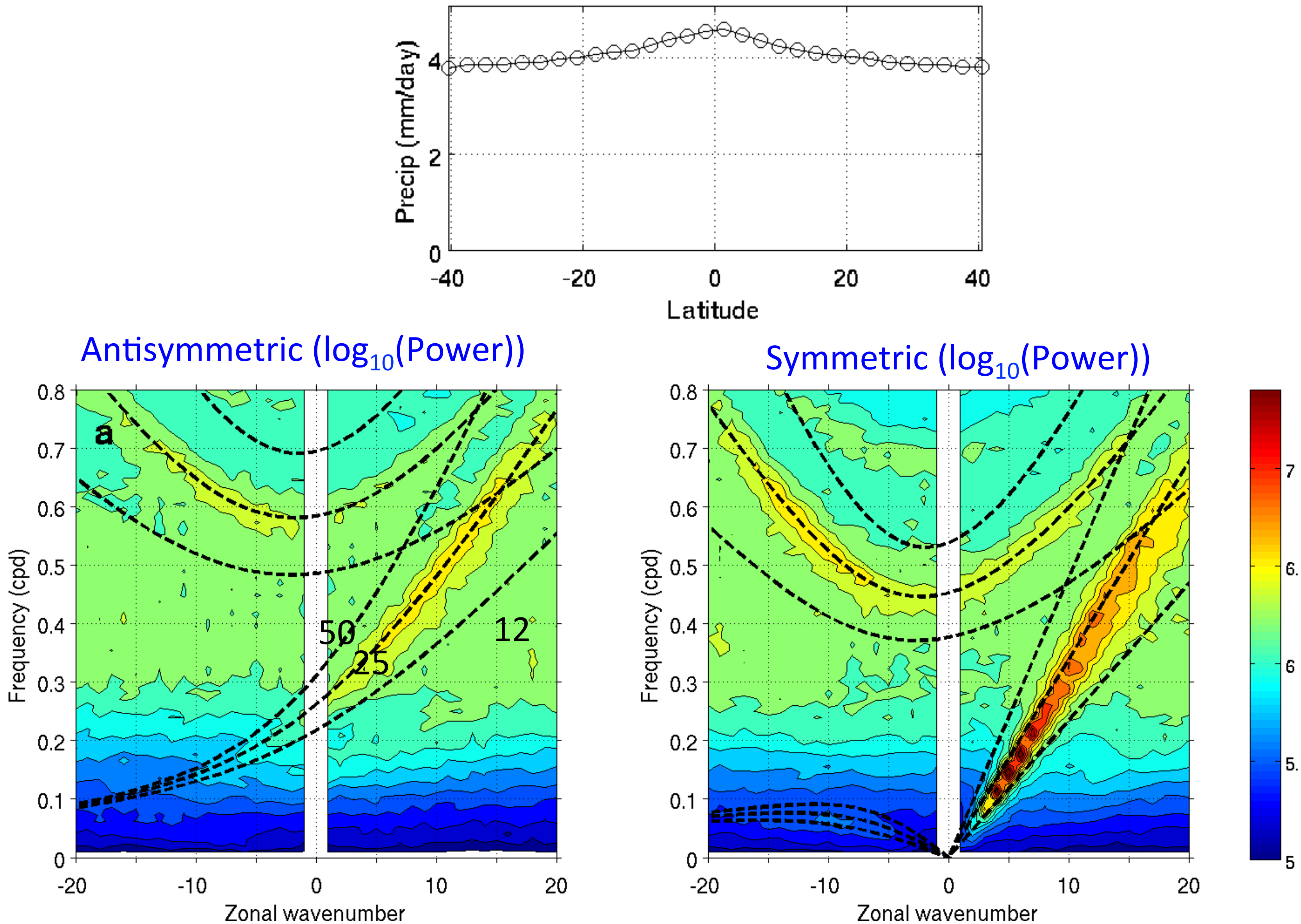
Global RCE simulations with SPCAM



Simplify it further

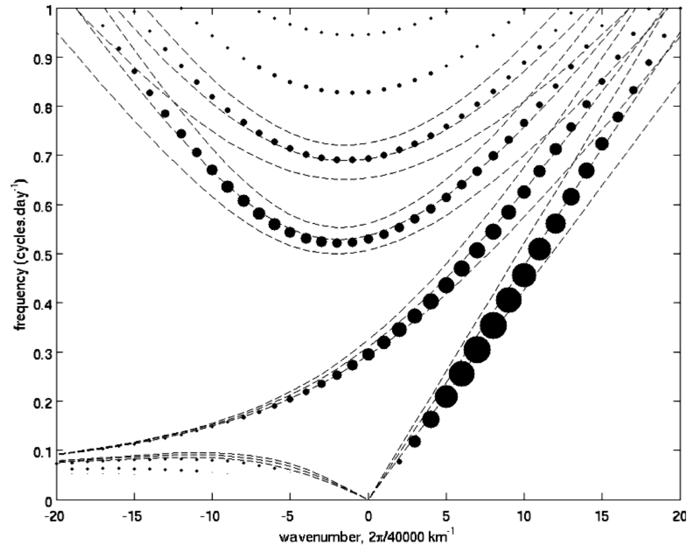
- Globally homogenize radiative heating, surface heat fluxes and surface drag
- A horizontally uniform, zero wind, mean state is maintained by nudging
- Retain only vertical advection of moisture and temperature, and neglect all other advection terms
- Newtonian damping used to control wave growth to stay in the linear regime

Rainfall climatology (5-day damping)



A simple linear model seems to capture the general behavior

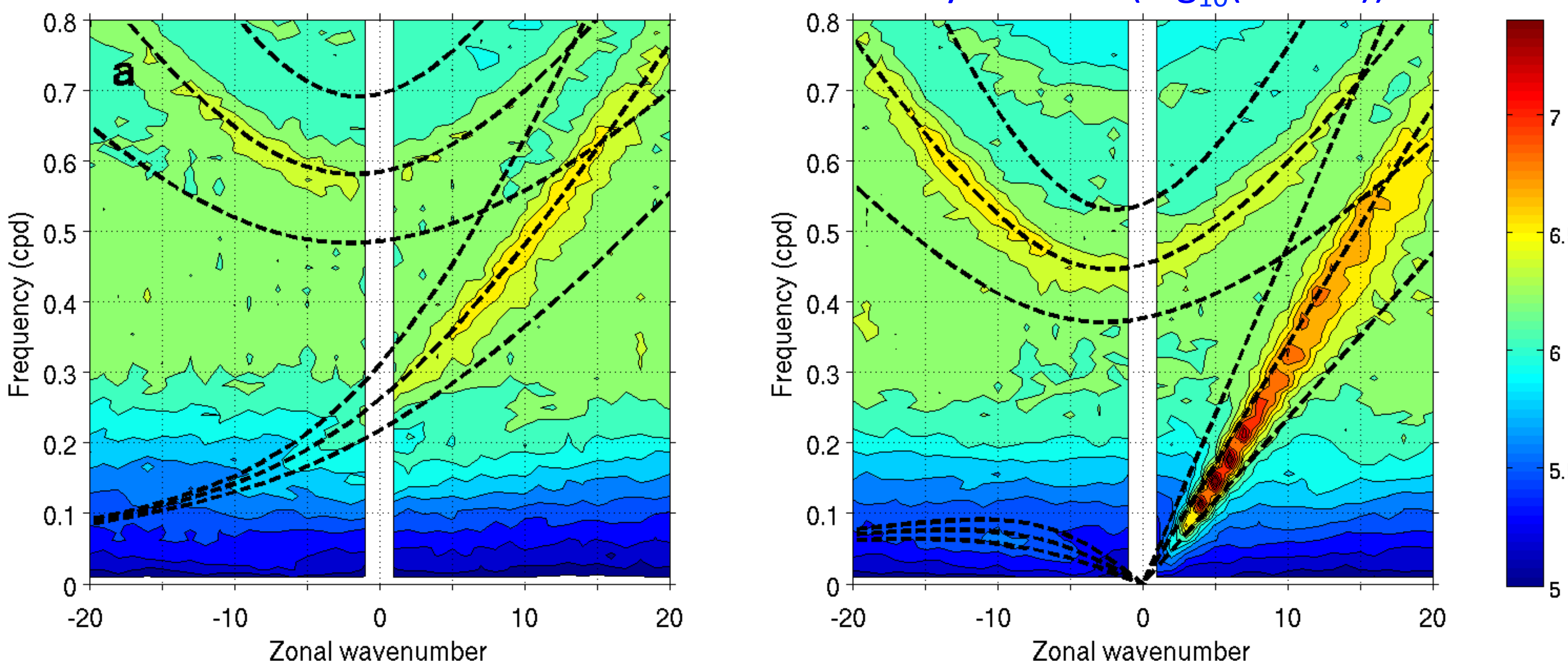
Andersen and Kuang, 2008



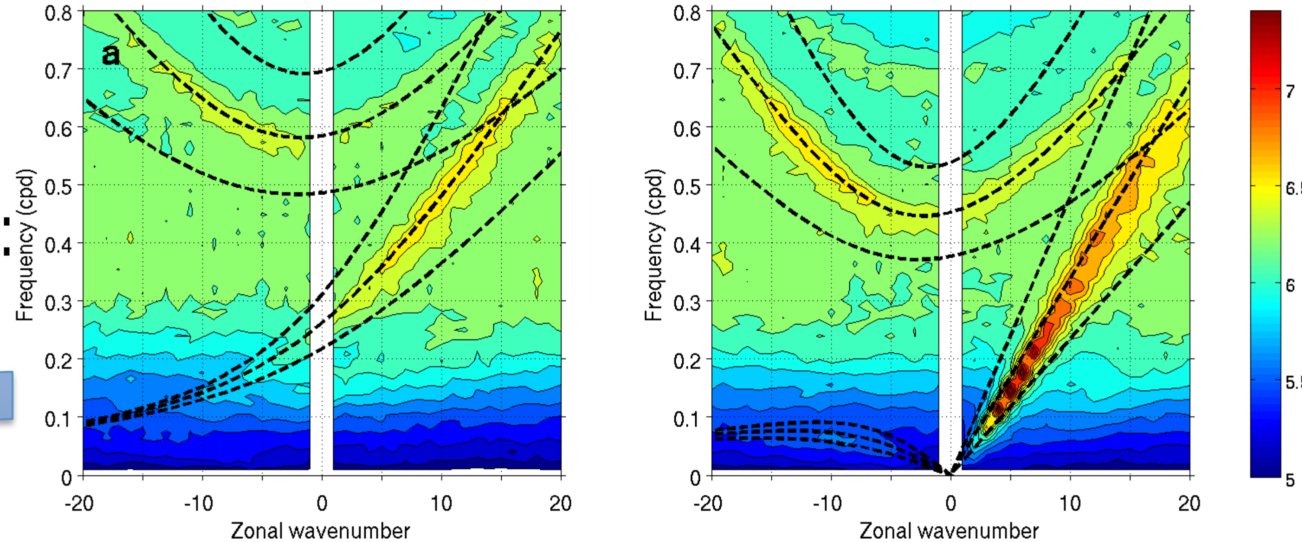
Dot size proportional to growth rate

Antisymmetric ($\log_{10}$(Power))

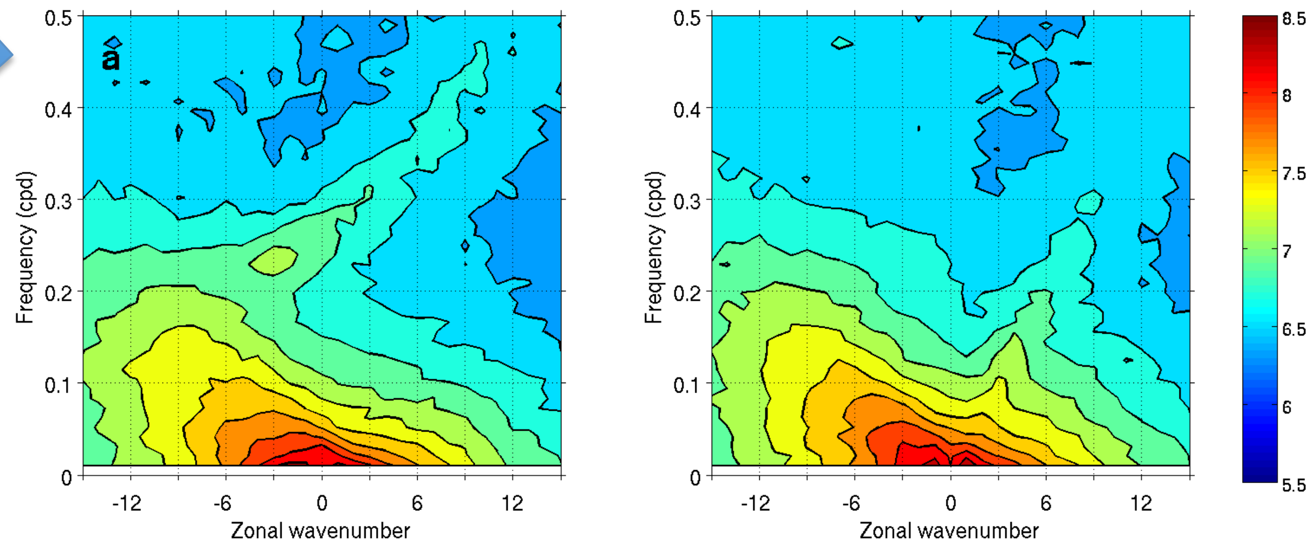
Symmetric ($\log_{10}$(Power))

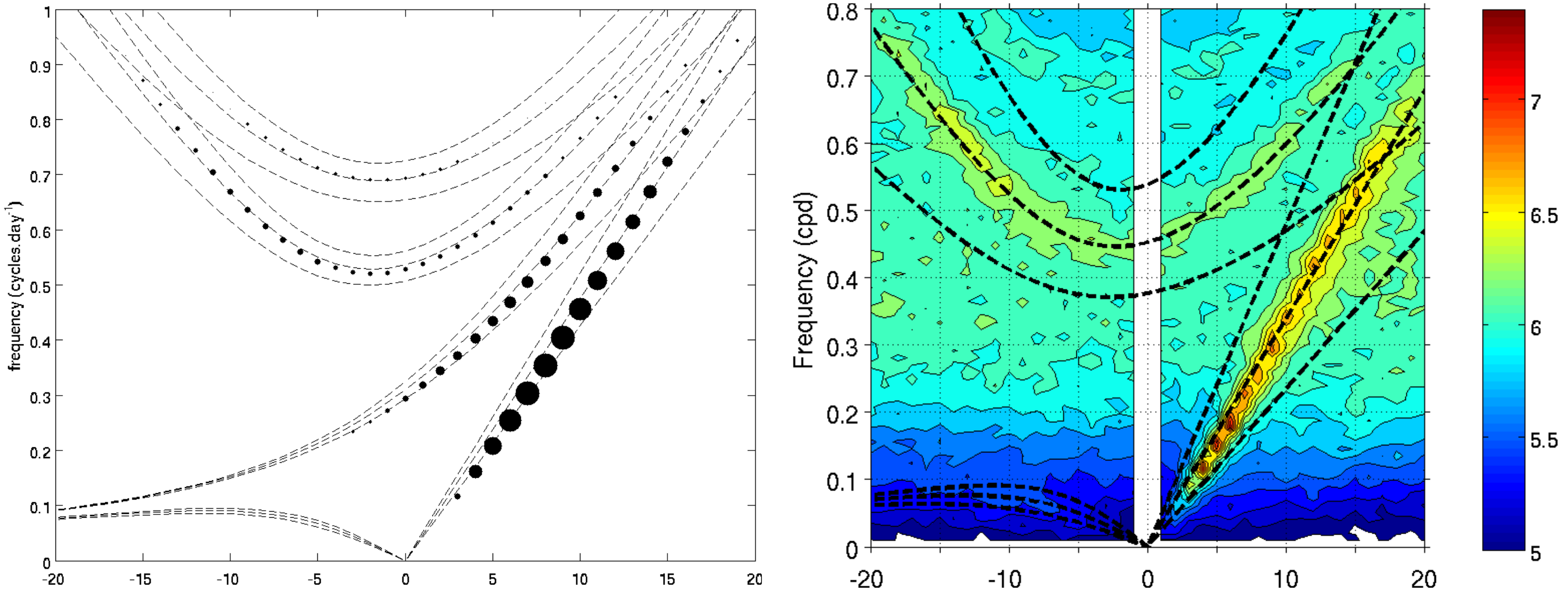


How to go from:

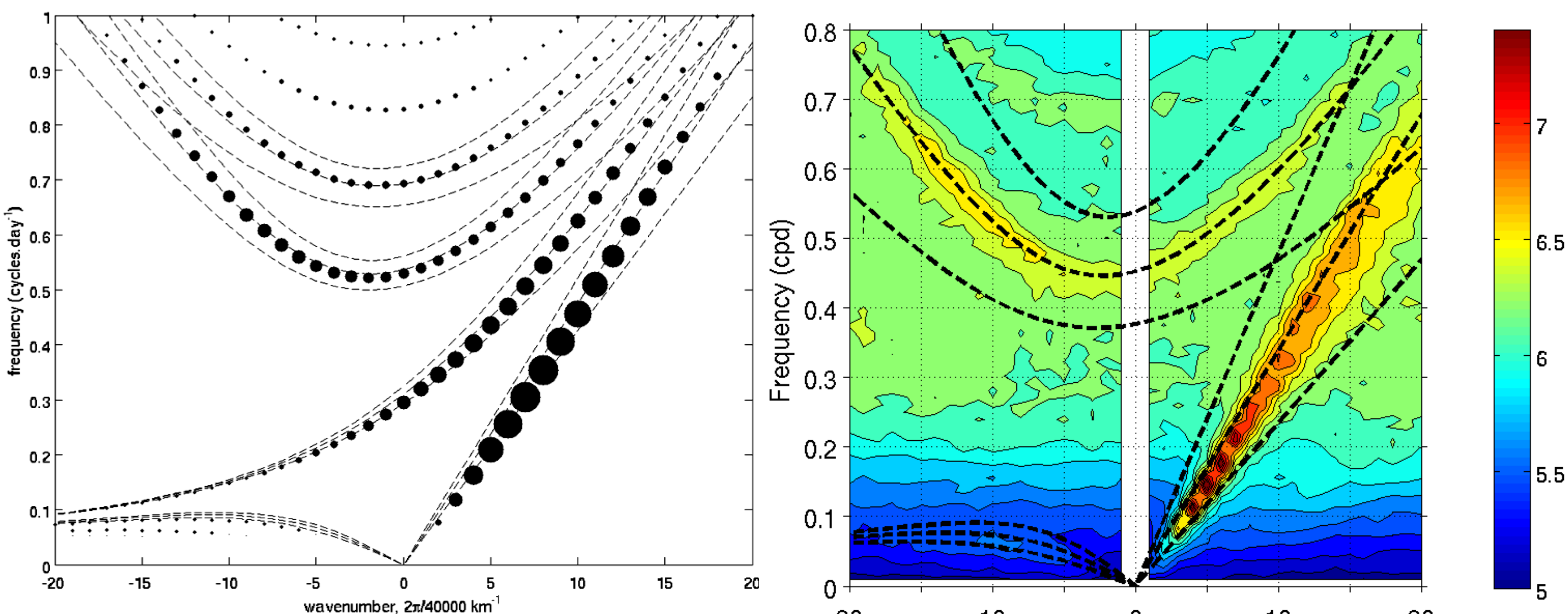


to:





With surface drag variation



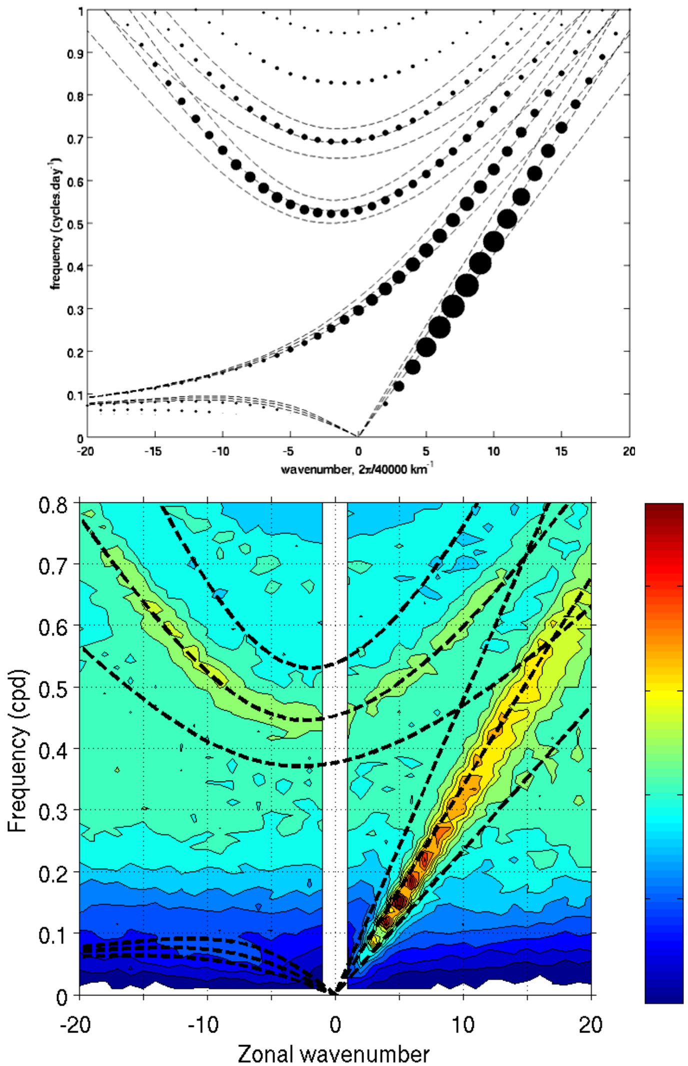
Without surface drag variation

Zonal wavenumber

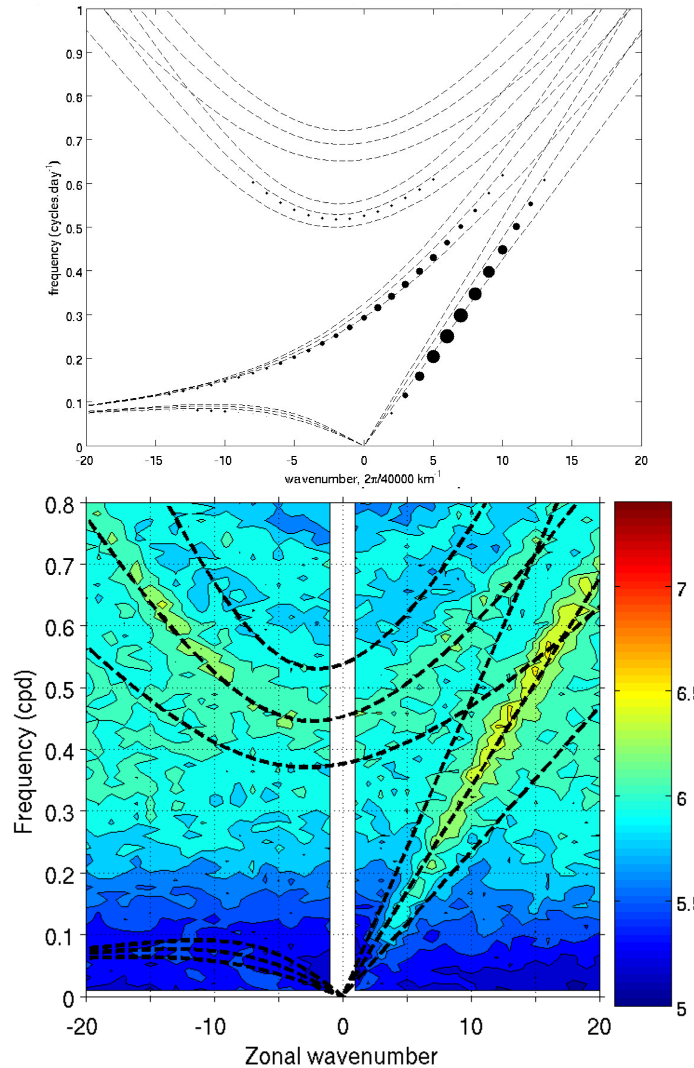
Zonal wavenumber

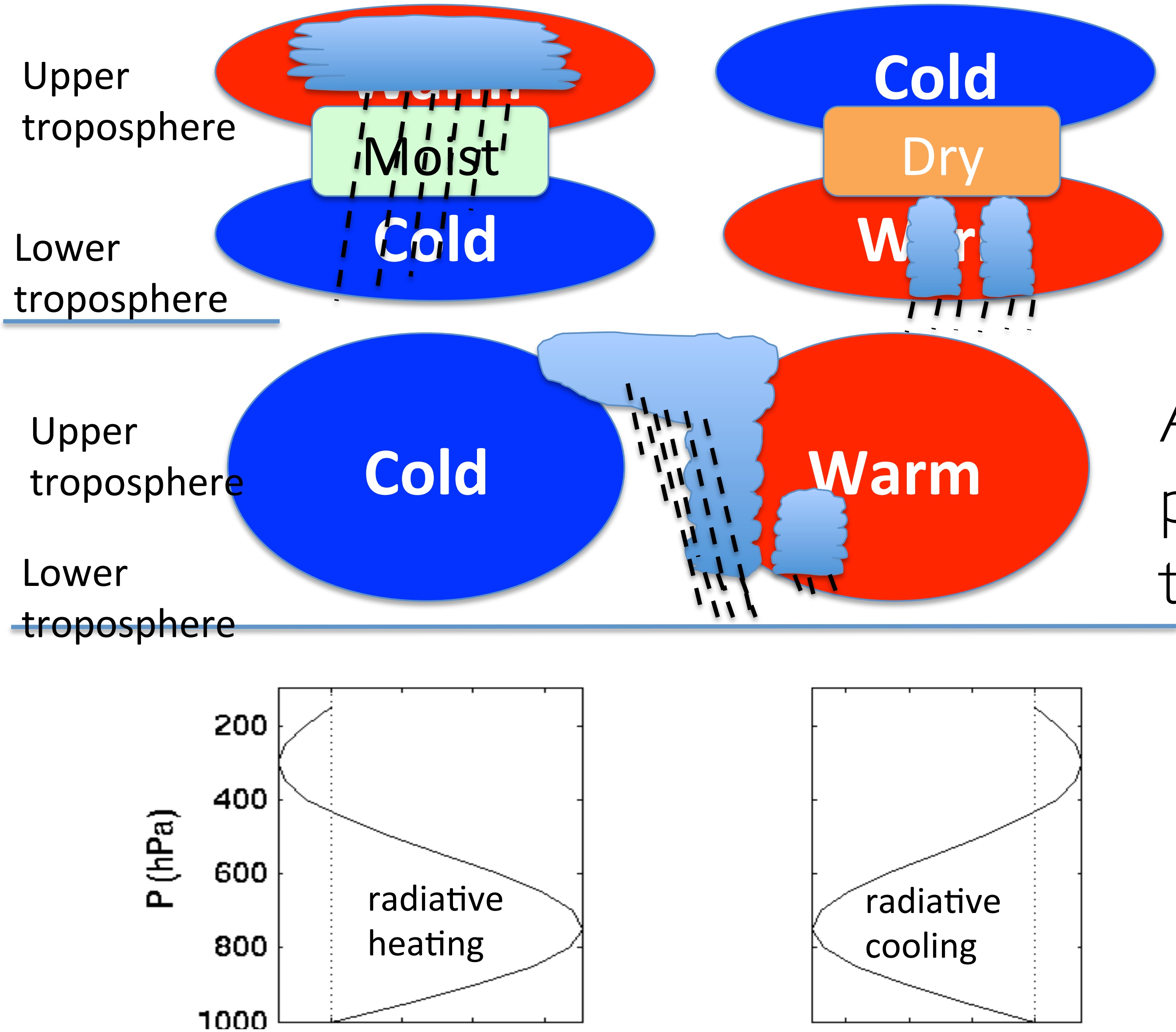
Radiative heating is bottom heavy and proportional to free troposphere moisture deficit

Without radiative feedback

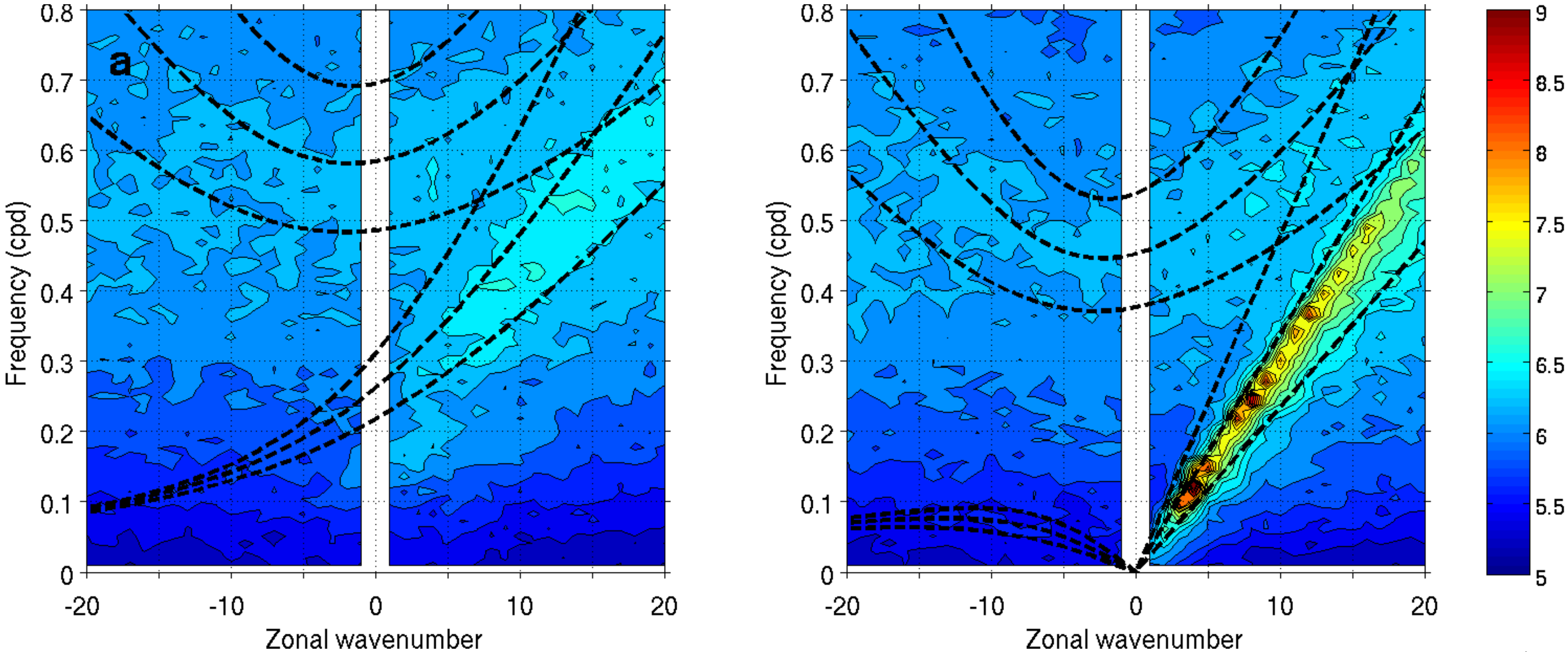


With radiative feedback

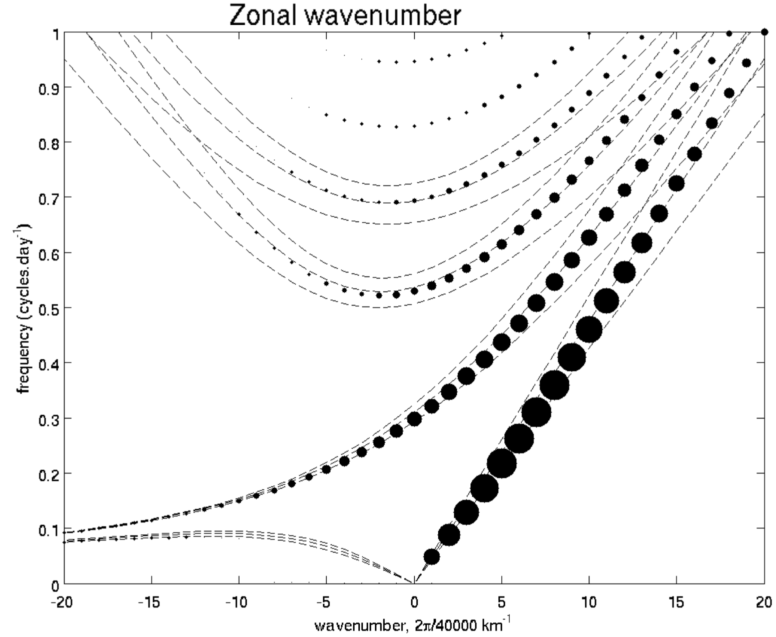




A wave propagating to the right

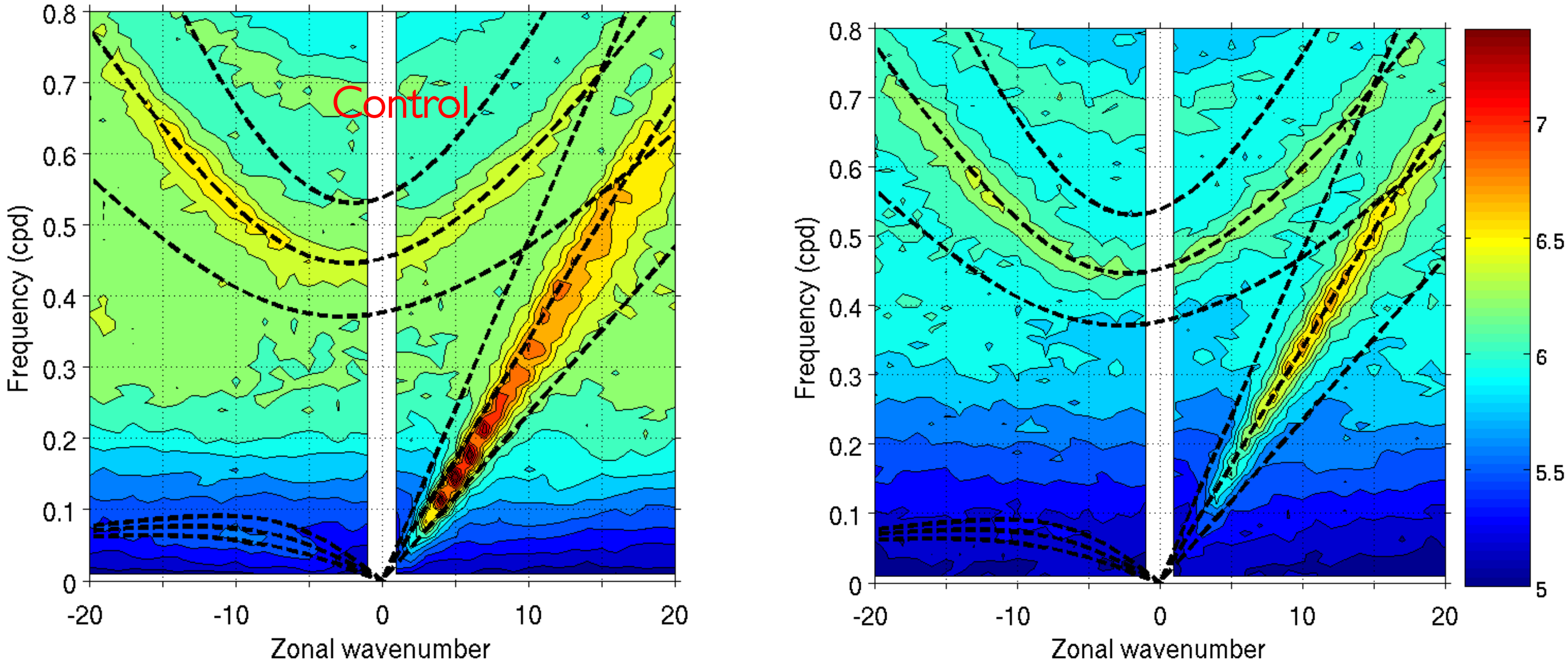


A WISHE term is included so that easterly wind anomalies give stronger surface fluxes: E' (in W/m^2)=-5U'(in m/s). Kelvin waves and eastward moving waves are strengthened



Plotted with a higher maximum growth rate

Damping column MSE anomalies with a 3hr timescale



•The convectively coupled waves are weaker in general but the most significant weakening is at low frequencies

•While convectively coupled waves modulate the column integrated MSE, column MSE budget is not key in setting their phase speeds and cannot be used to interpret variations in the phase speeds of CCWs (as sometimes done in the literature).

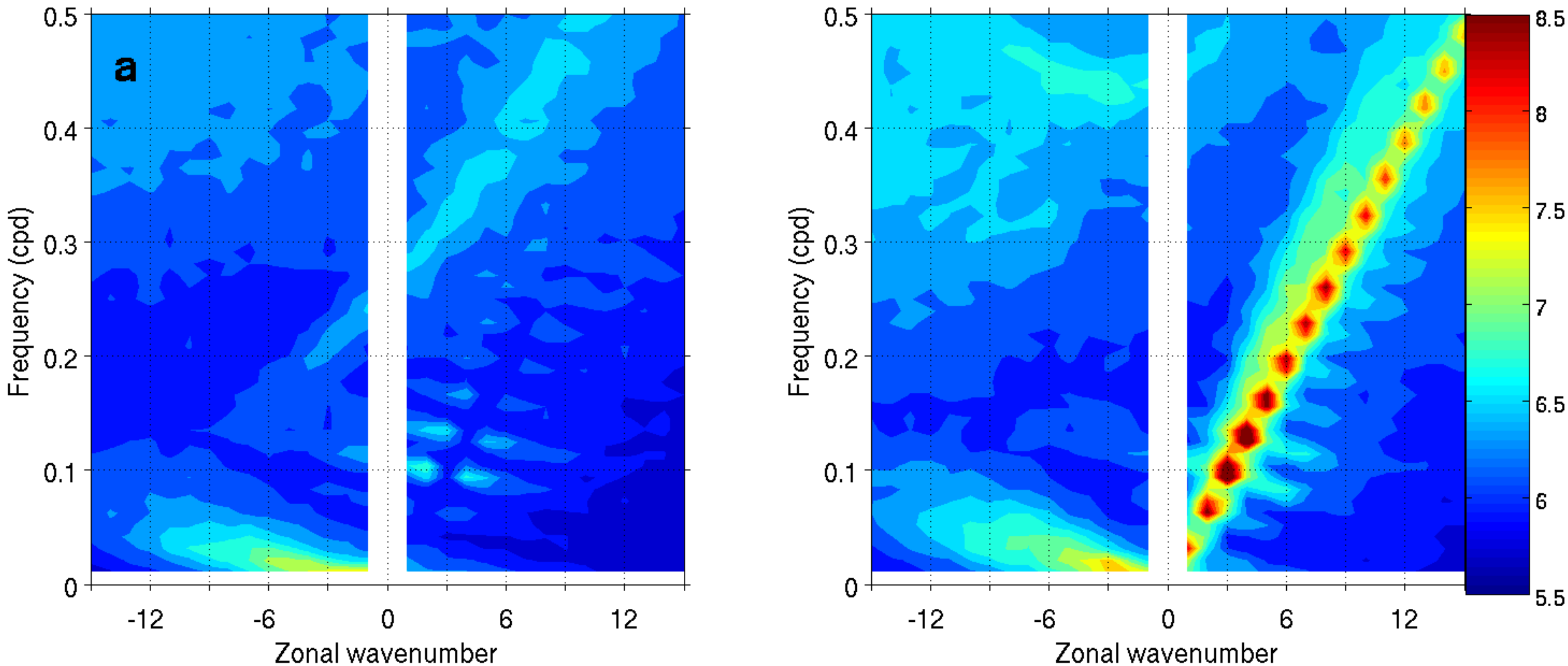
Going forward

- Extend this basic picture to include modifications by additional processes such as radiation, surface heat flux, surface drag, wind shear etc.
- The waves' dependence on the mean state (horizontal and vertical wind shear, width of the ITCZ etc.) is a particularly important direction to explore because observations of such dependences can provide additional tests for the theories.

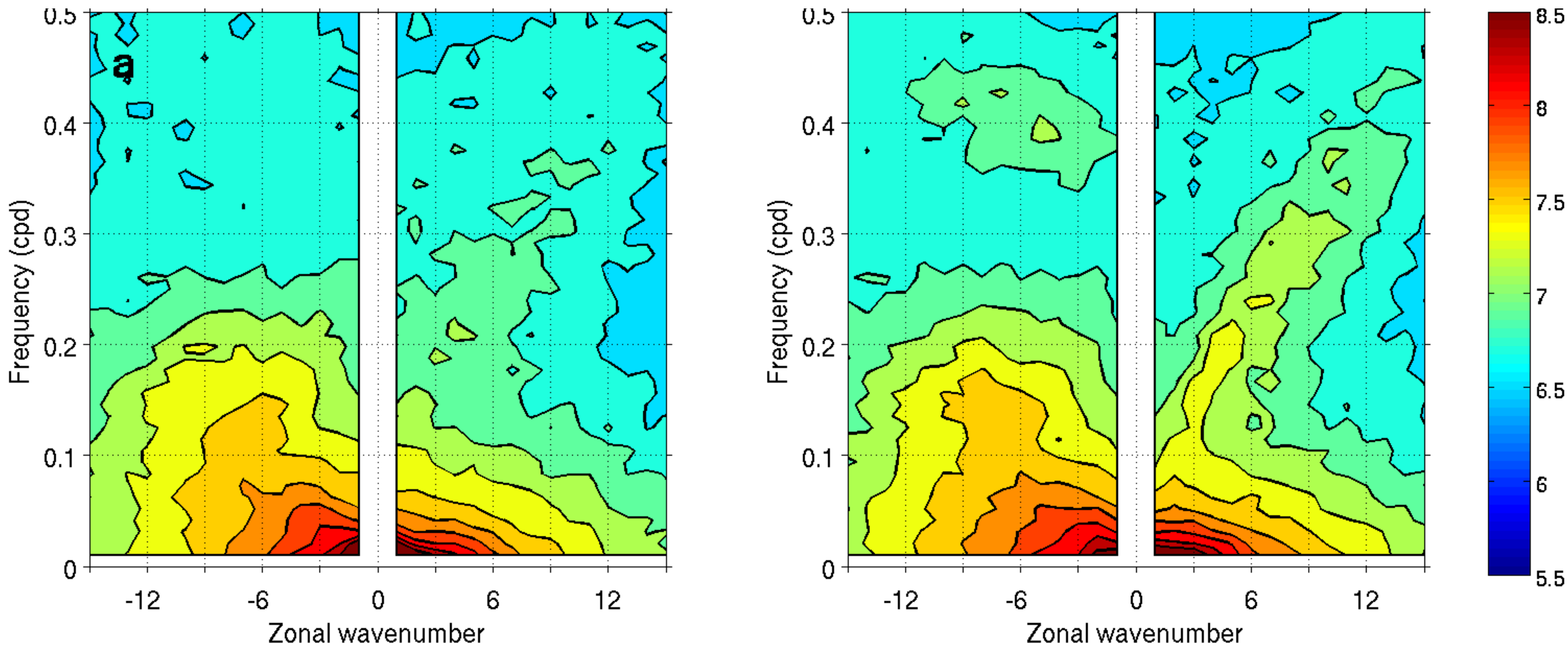
What causes the red noise background?

Allowing full radiative feedback and surface flux feedback without horizontal advection leads to model instability (negative gross moist stability)

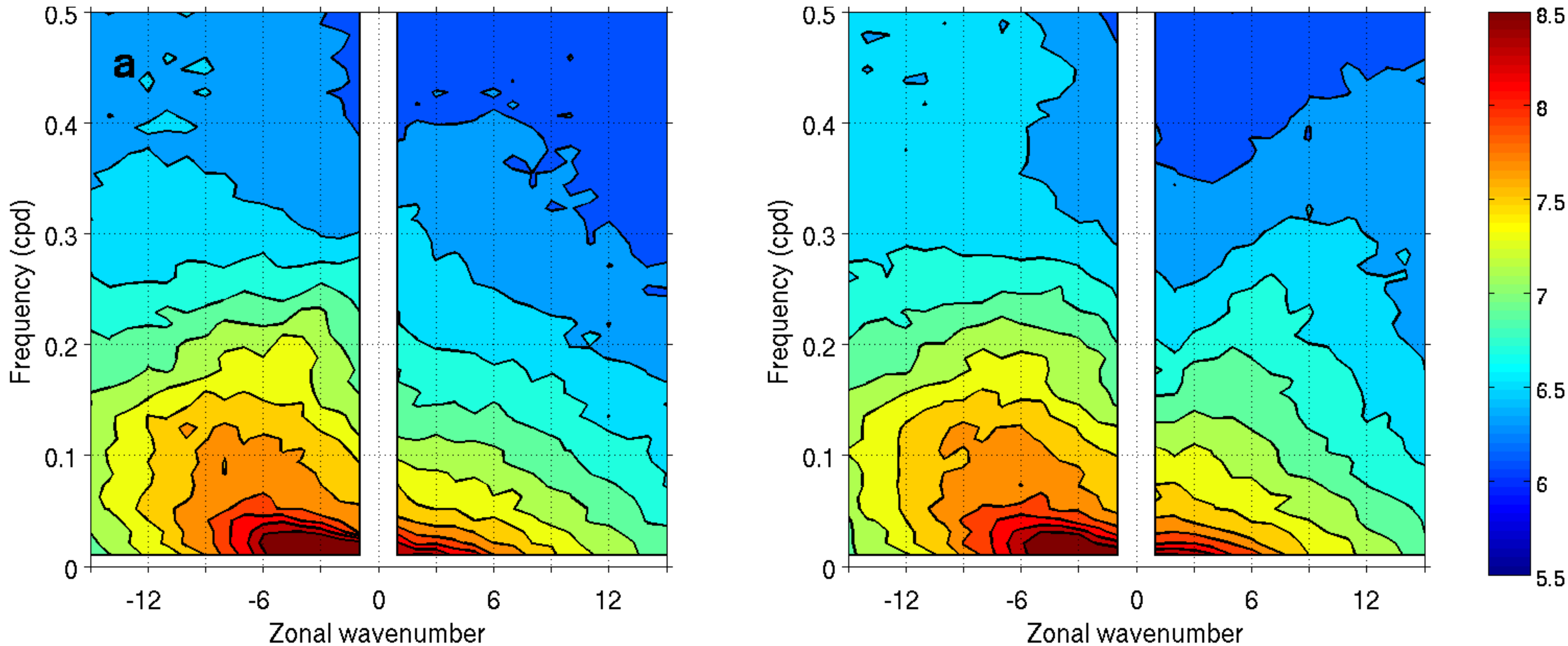
No feedback from surface heat flux or radiation (full advection)



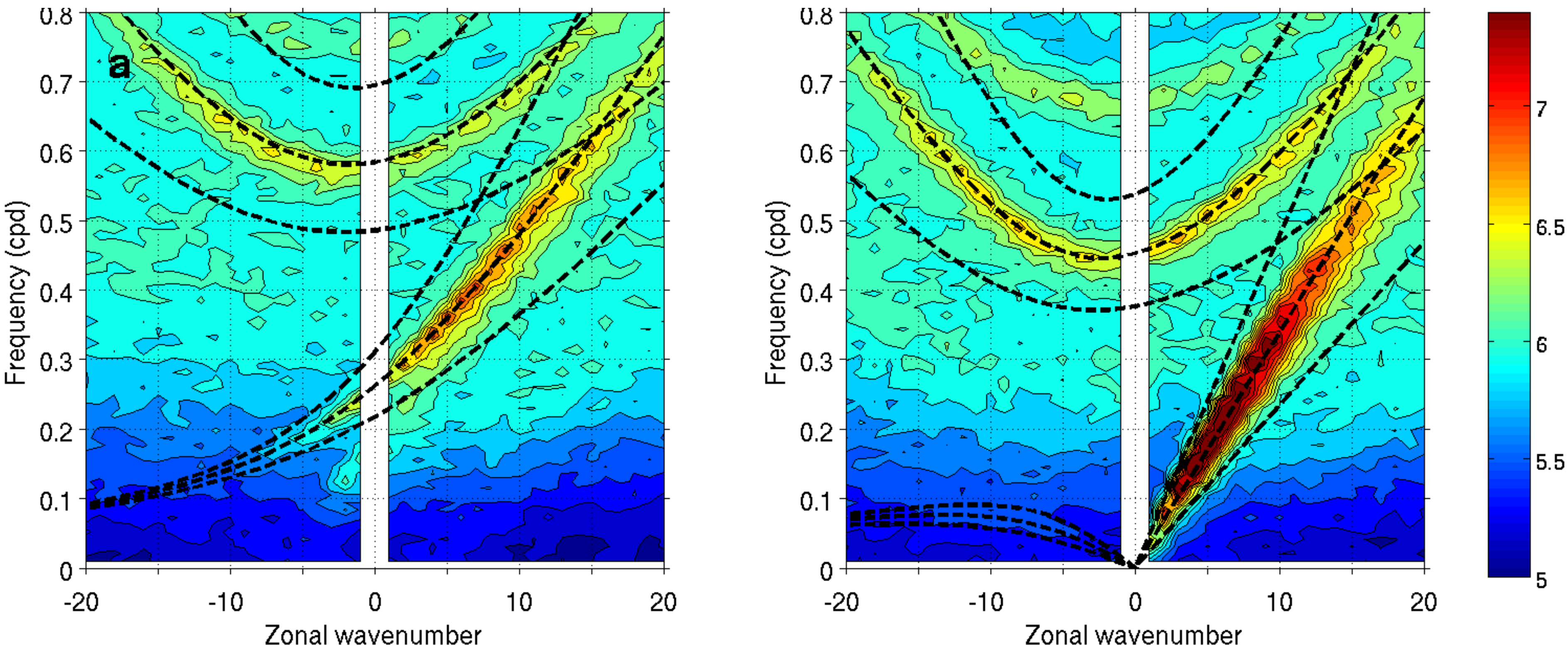
Radiative feedback only (full advection)



Surface heat flux feedback only
(full advection)



Damping column MSE anomalies with a 3hr timescale (full advection)

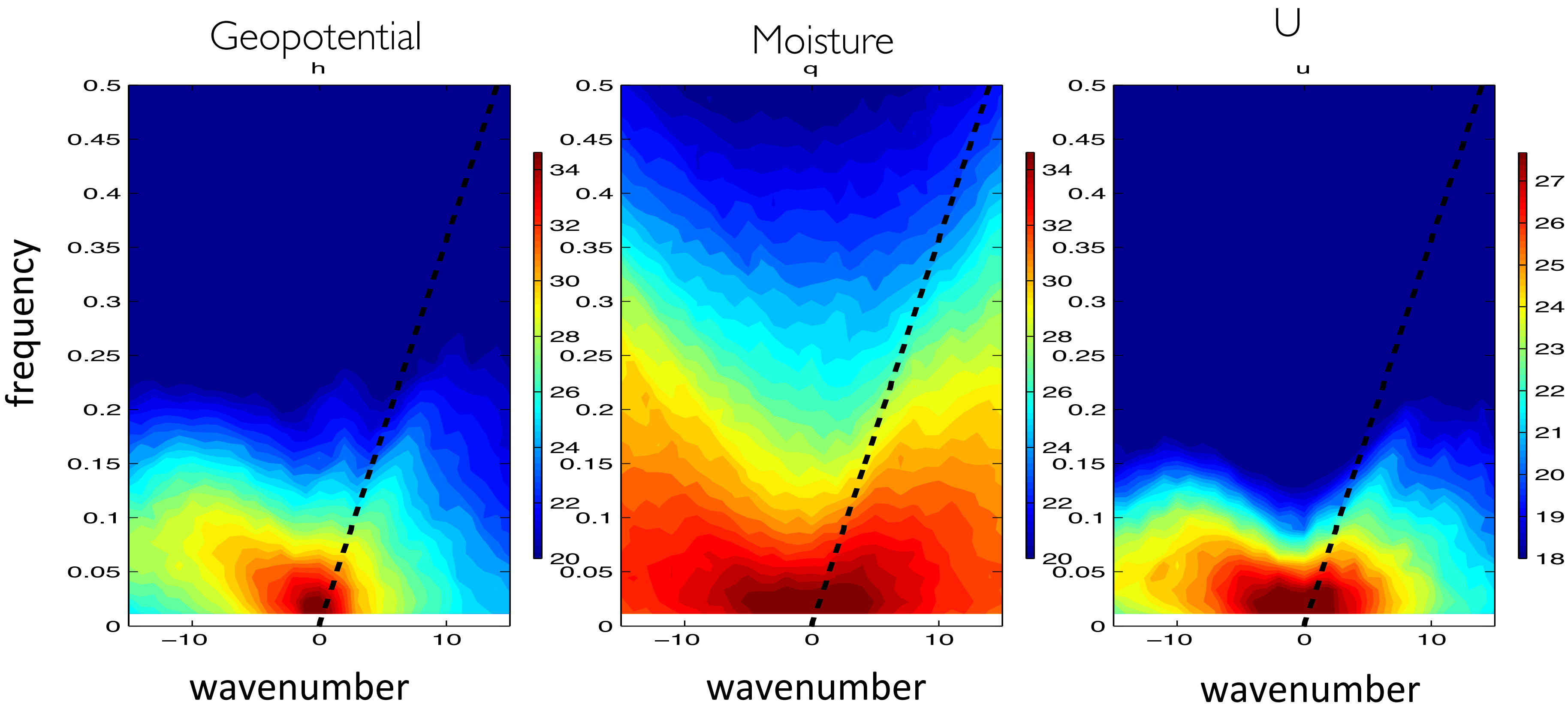


What causes the red noise background?

- Long memory in column integrated moist static energy anomalies provided by the low efficiency in removing such anomalies and sources that enhance them
- Stirring from horizontal advection of moisture

A shallow water model with a moisture equation

1. Precipitation anomaly proportional to q anomaly
2. negative gross moist stability
3. (nonlinear) horizontal moisture advection



Work with Ding Ma

Summary

- We have some understanding on the basic mechanisms of convectively coupled waves.
- Viewing the MJO in terms of column integrated MSE is a promising framework but constraining the MSE budget observationally is a challenge.
- The red noise background appears to result from the long memory in column MSE anomalies and stirring by horizontal advection of moisture