Recent Advances in Understanding MJO Dynamics

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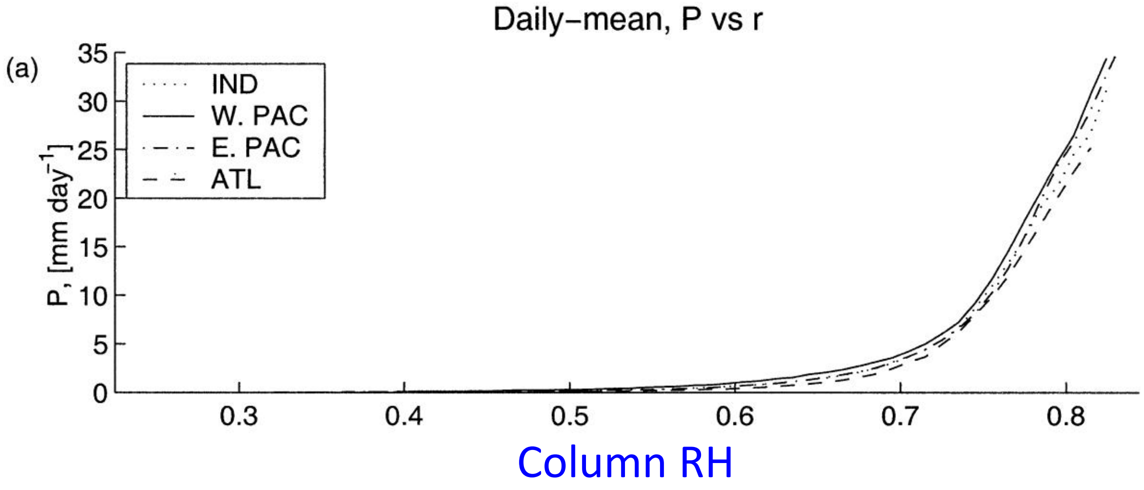
Heavy Precipitation is Only Supported When the Atmosphere is Moist



Bretherton et al. (2004)

- Precipitation is a strong, non-linear function of tropospheric relative humidity
- Suggests that processes regulating the tropospheric moisture field control where convection occurs, and hence associated divergence.

Spectral Gap Between MJO and Convectively Coupled Kelvin Waves

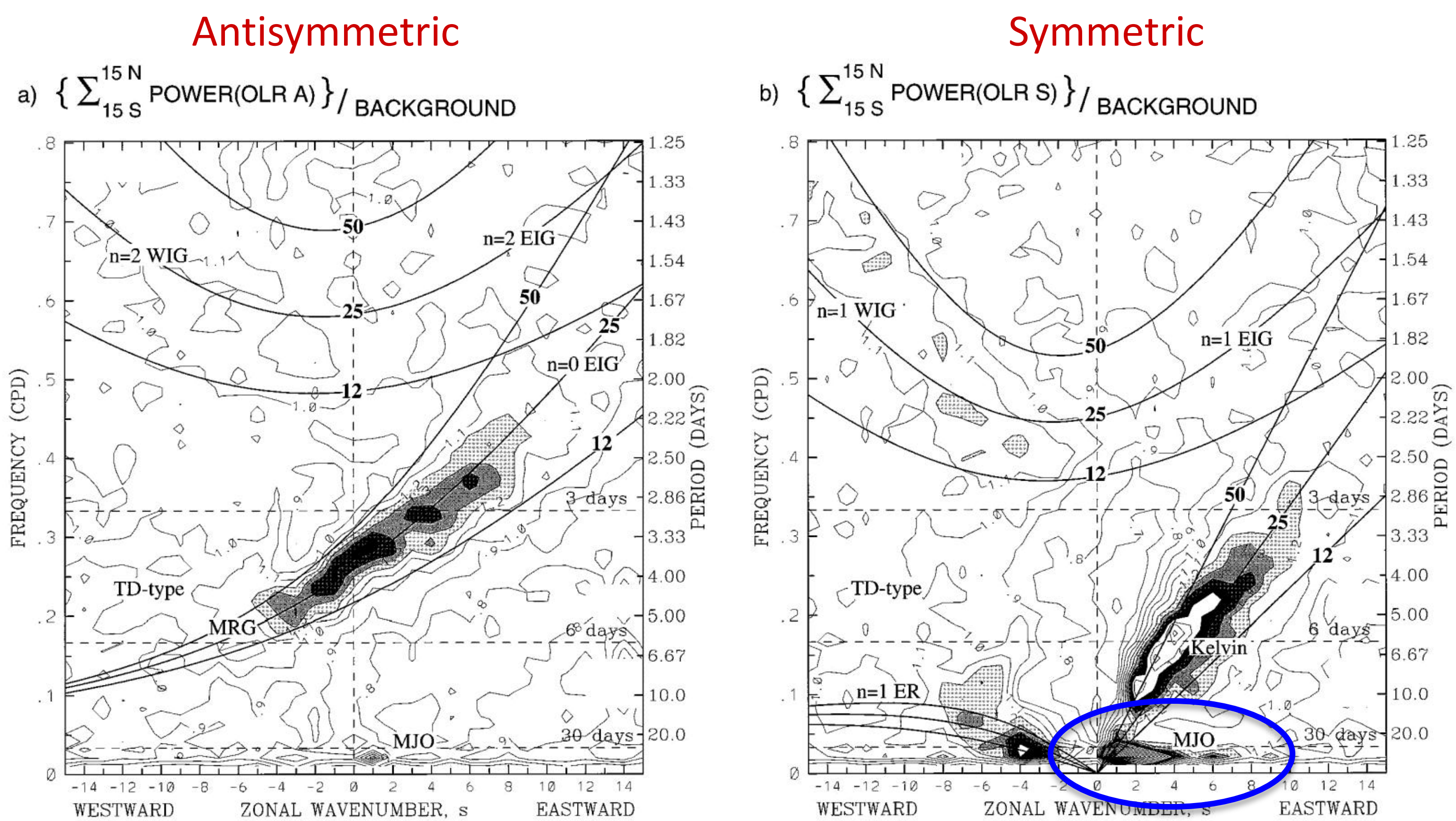
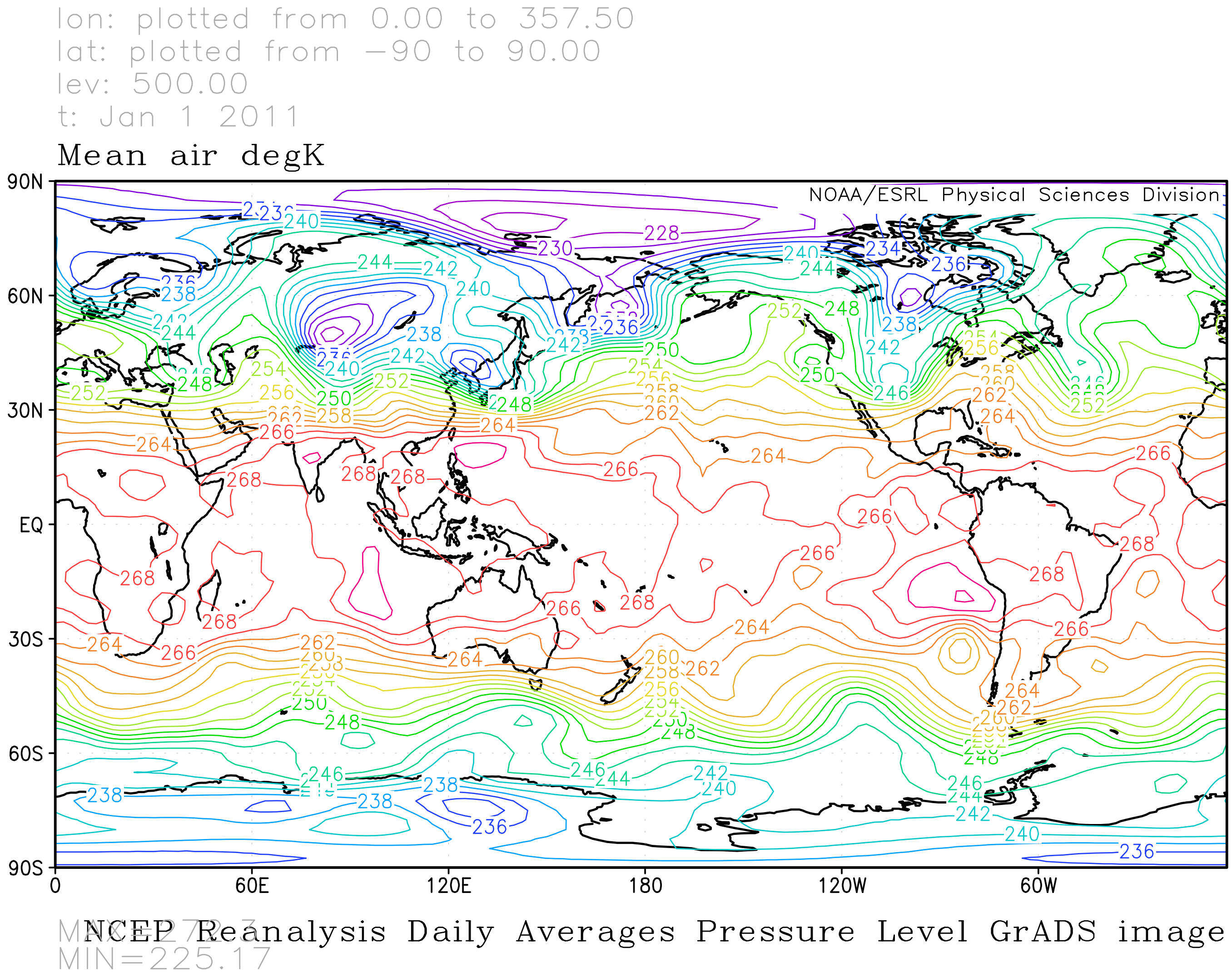


FIG. 3. (a) The antisymmetric OLR power of Fig. 1a divided by the background power of Fig. 2. Contour interval is 0.1, and shading begins at a value of 1.1 for which the spectral signatures are statistically significantly above the background at the 95% level (based on 500 dof). Superimposed are the dispersion curves of the even meridional mode-numbered equatorial waves for the three equivalent depths of h = 12, 25, and 50 m. (b) Same as in panel a except for the symmetric component of OLR of Fig. 1b and the corresponding odd meridional mode-numbered equatorial waves. Frequency spectral bandwidth is 1/96 cpd.

Wheeler and Kiladis (1999)

Another disturbance is not predicted by shallow water theory

Tropical Atmosphere is Dominated by Weak Temperature (and Geopotential) Gradients (WTG)



Concept of Moisture Modes

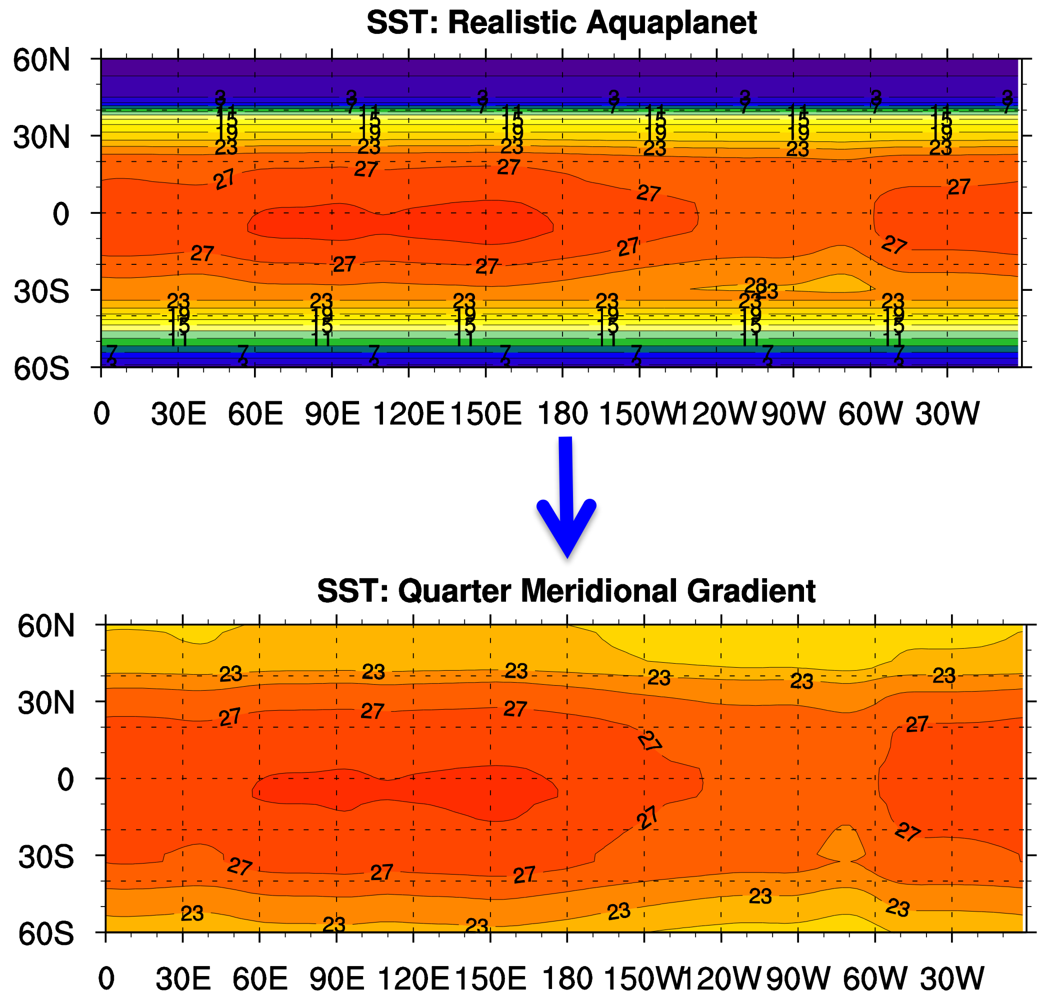
- Major thermodynamic balance at sufficiently long timescales (>10 days):

$$\omega \frac{\partial \bar{\theta}}{\partial p} \approx \frac{Q_1}{c_p}\left(\frac{p_o}{p}\right)^{\kappa}$$

Q_1=apparent heat source
(diabatic heating and unresolved processes)

- Under such conditions, gravity wave solutions are not admitted.
- Modes are admitted in which the dynamics are strongly regulated by processes that control the growth and propagation of moisture (and convection) anomalies (e.g. Sobel et al. 2001; Raymond et al. 2009; i.e. ***moisture modes***)
- Convection only occurs where the troposphere is moist, and resulting convection regulates the divergence (and subsequently vorticity) field through the mandated WTG thermodynamic balance

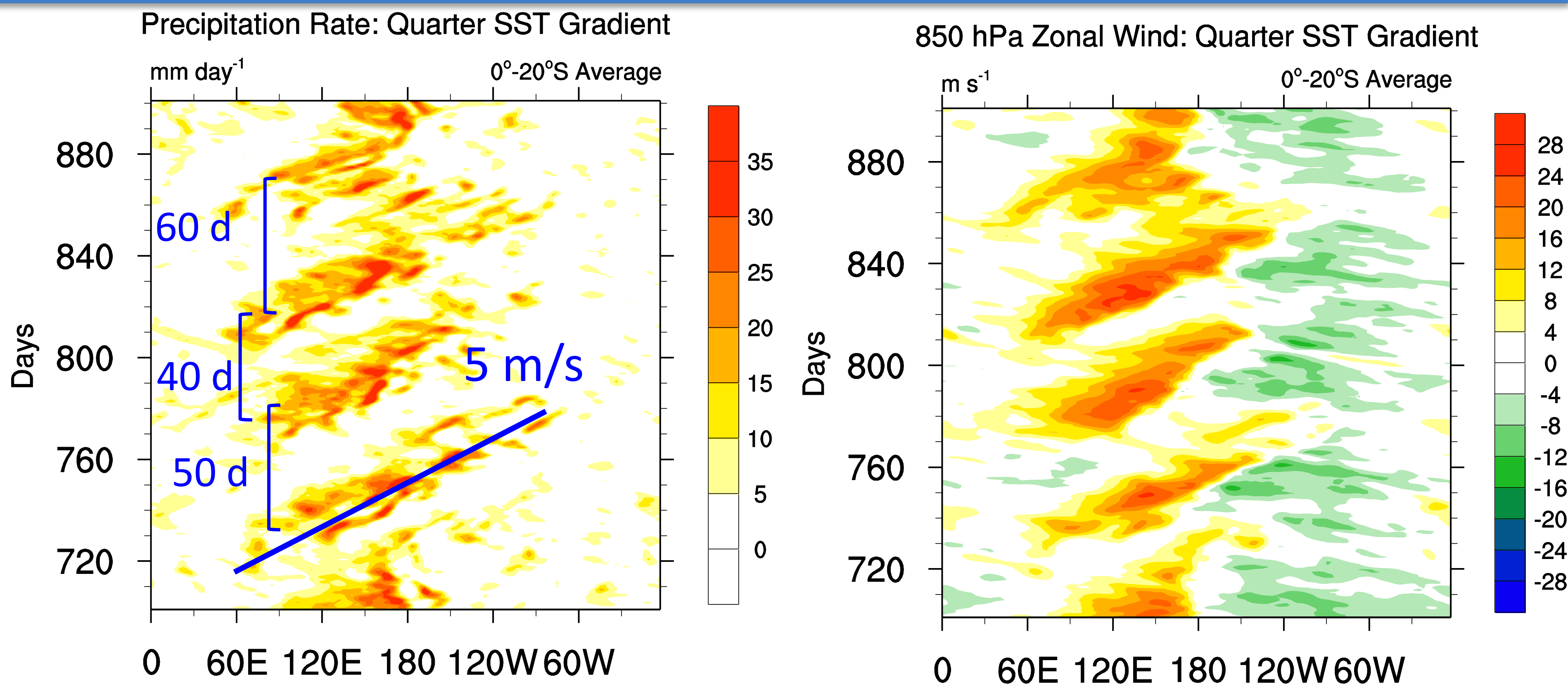
We Now Dig into the Dynamics of the Model MJO with Some Idealized Runs



- Version of NCAR CAM
- Starting from an aquaplanet ocean surface temperature distribution, we transition to a more idealized SST distribution with reduced meridional gradient.
- This distribution produces a very clean model MJO, as will be shown below.
- Varying idealized distributions may allow us to learn something about MJO physics

Maloney et al. (2010)

Robust MJO: Unfiltered Precipitation and Winds vs. Longitude

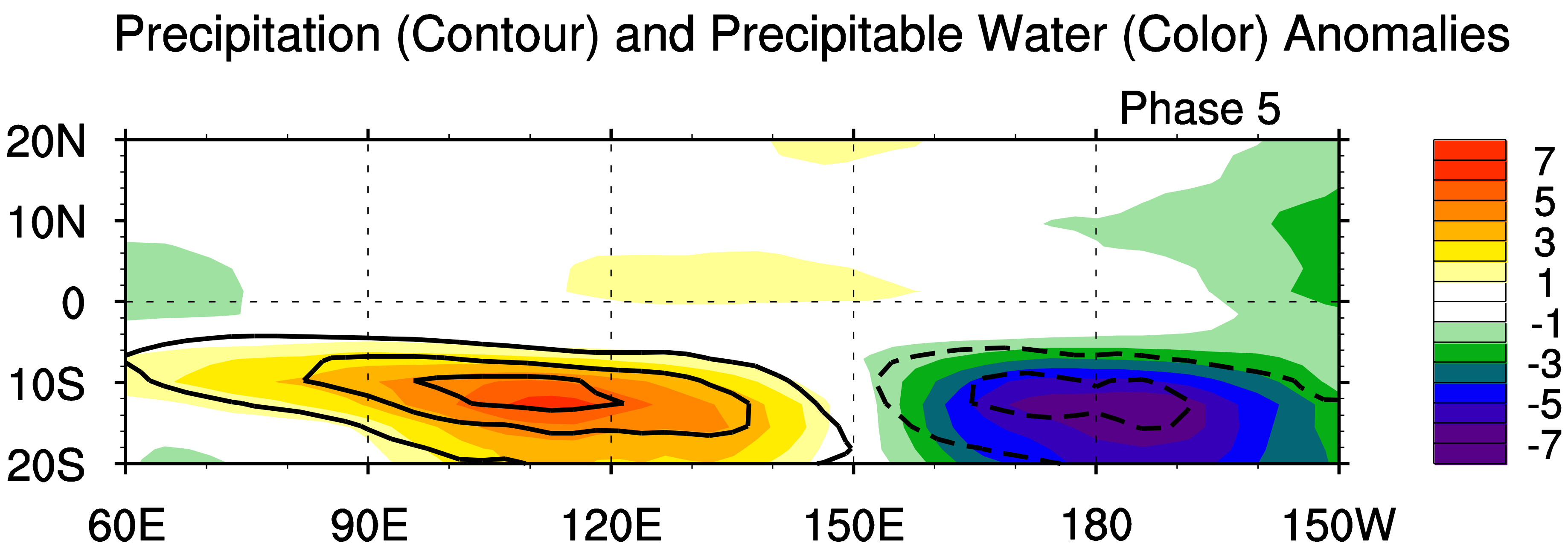


Even in unfiltered data, many salient features of the MJO apparent, including 5 m s^{-1} eastward propagation, and a period of 40-60 days.

Evidence for Applicability of Weak Temperature Gradient Theory to Model MJO

- Strong relationship between precipitation and column saturation fraction
- Positive temperature anomalies occur in regions of westerly lower tropospheric wind anomalies (i.e. doesn't resemble a Kelvin wave)
- Approximate cancelation between adiabatic cooling and diabatic heating (residual at least an order of magnitude smaller)
- Moist static energy anomalies dominated by humidity anomalies

Composite Column Water Vapor Anomalies

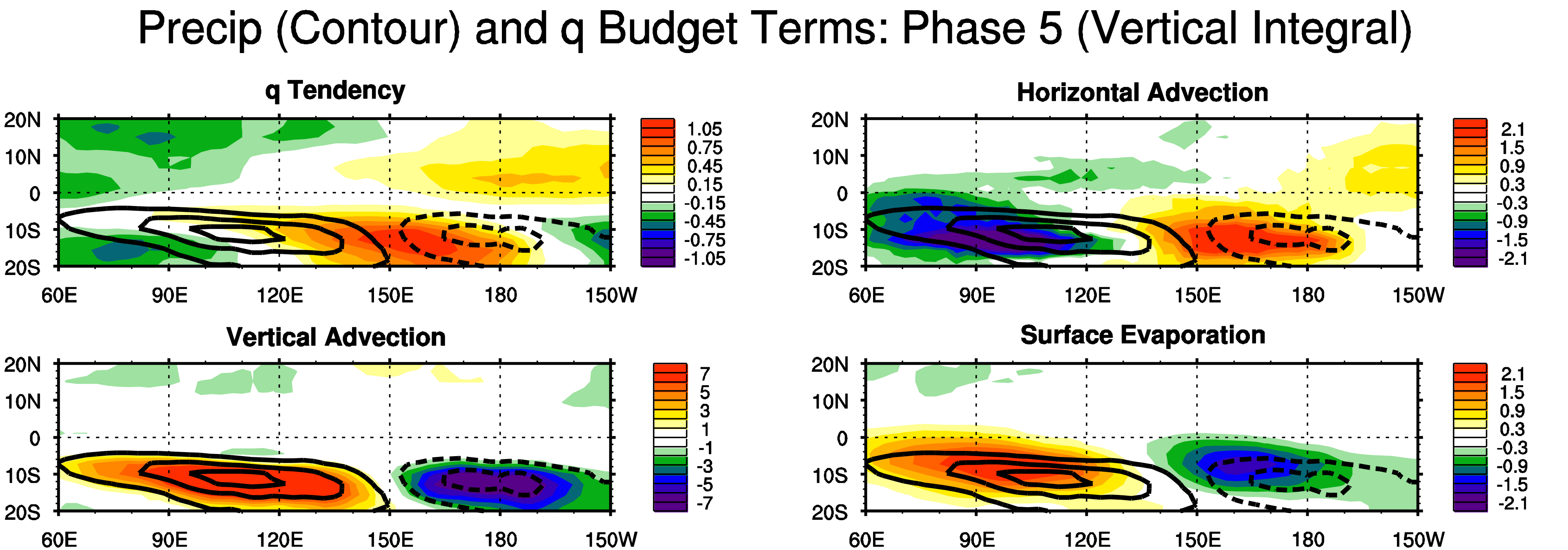


PW Units: mm

Column precipitable water anomalies are sizeable, and in phase with precipitation anomalies, as would be expected given the strong relationship between model saturation fraction and precipitation.

Precipitation contour interval 4 mm day^{-1}.

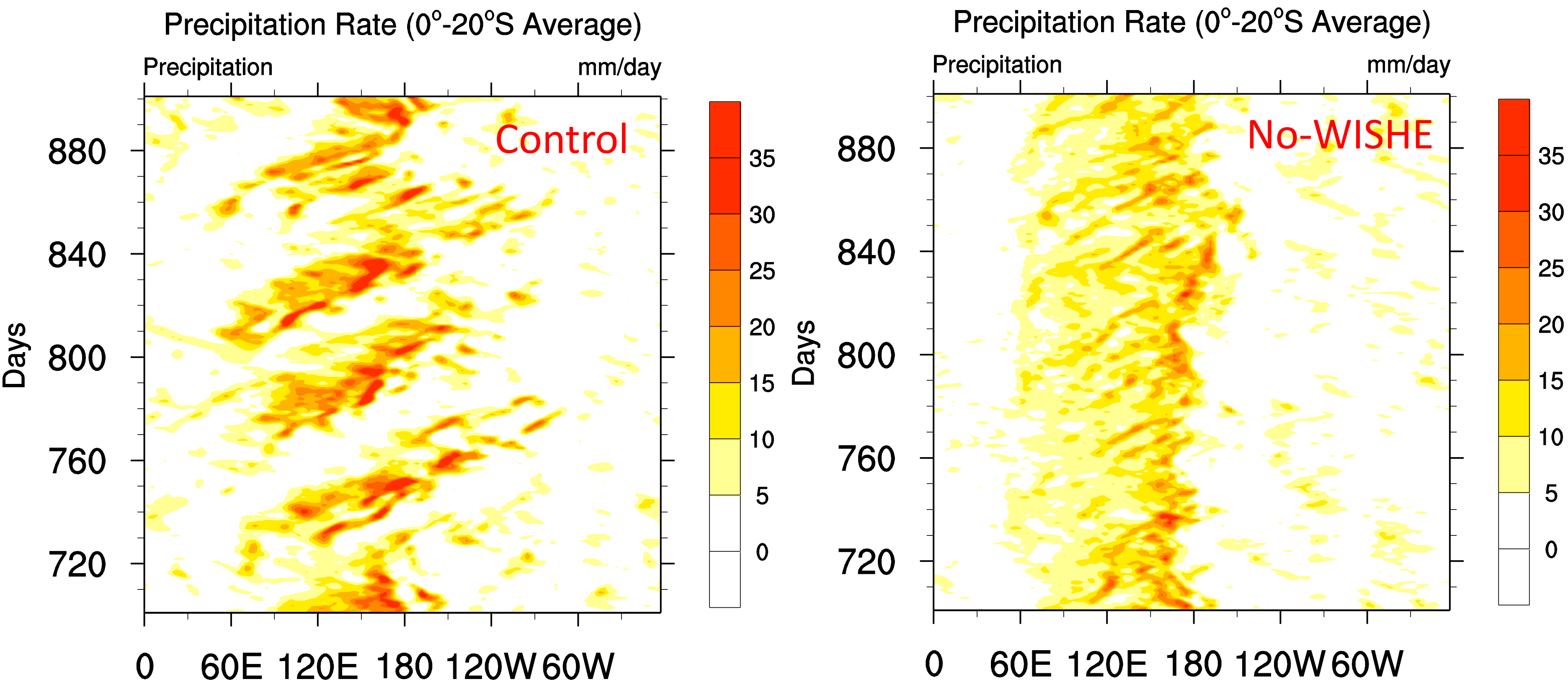
How Are Water Vapor Anomalies Supported, and What is Moving Them Eastward?



$$\left\langle \frac{\partial q}{\partial t} \right\rangle \approx -\left\langle q\nabla\cdot \vec{v} \right\rangle - \left\langle \vec{v}\cdot \nabla q \right\rangle + E - P$$

- Horizontal advection is (nearly) in quadrature with precipitation (and PW) and in phase with the humidity tendency.
- Surface evaporation slightly lags the precipitation anomalies, with a strong positive covariance

Effect of Fixing Surface Evaporation



- Wind-evaporation feedbacks appear to destabilize the MJO in the model. 30-90 day, zonal wavenumber 1-3 variance decreases dramatically without WISHE
- Small spatial scale precipitation variability that moves slowly east is still apparent in the model. Radiative feedbacks appear similarly important

Conclusions from Recent Modeling Work

- The MJO resembles a moisture mode that is destabilized by cloud-radiative feedbacks and/or surface flux feedbacks, and propagated eastward by horizontal advection (e.g. Raymond 2001; Raymond and Fuchs 2009; Maloney 2009; Maloney et al. 2010; Andersen and Kuang 2012; and others)
- Models in which convection is less efficient at discharging tropospheric moisture tend to produce stronger MJOs (Hannah and Maloney 2011; Benedict et al. 2012).

Under WTG, Vertically-Integrated MSE Budget Becomes a Moisture Equation

- For WTG:

$$\left\langle L\frac{\partial q}{\partial t}\right\rangle + \langle \vec{v}\cdot\nabla m\rangle + \left\langle w\frac{\partial m}{\partial p}\right\rangle = LE + SH + \langle R\rangle$$

m=moist static energy
LE= Latent heat flux
SH=sensible heat flux
R= radiative heating

- Vertical advection terms implicitly (and approximately) accounts for the cancelation of moisture convergence and condensational drying

- Vertically-integrated MSE budget thus becomes a convenient way of diagnosing and modeling MJO dynamics, assuming MJO is regulated by WTG theory

Simple 2-D Linear Model in Longitude (Sobel and Maloney 2012a,b)

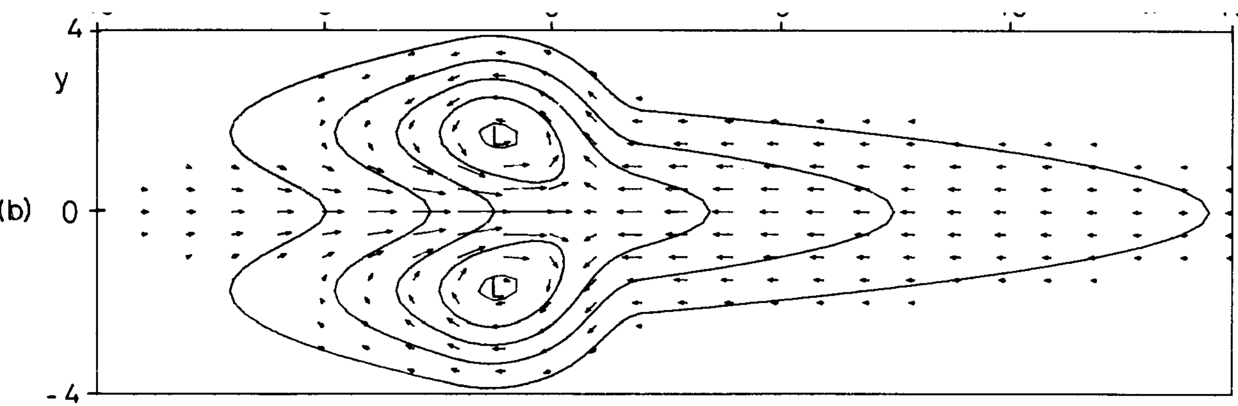
$$L\frac{\partial q'}{\partial t} + U\frac{\partial m'}{\partial x} = -\hat{M}P' - ku' + E' - (1-\hat{M})R'$$

- m' is perturbation column moist static energy;
- U is constant background wind;
- $P' = P'(m')$
- $E' \sim u'$, zonal wind; is computed diagnostically
- $R' = rP'$
- Normalized gross moist stability ($\hat{M}$) is constant
- $-ku'$ is the effect of eddy moistening/drying (e.g. Maloney 2009; Andersen and Kuang 2012).

Projection Operator to Determine Winds

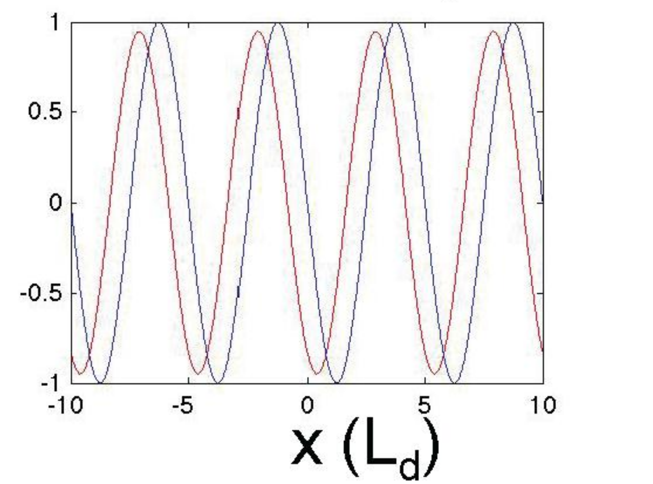
$$u'(x,t) = \int G(x|x')P'(x',t)\,dx'$$

- From precipitation anomaly, wind perturbation is determined using a projection operator to mimic the Gill (1980) model



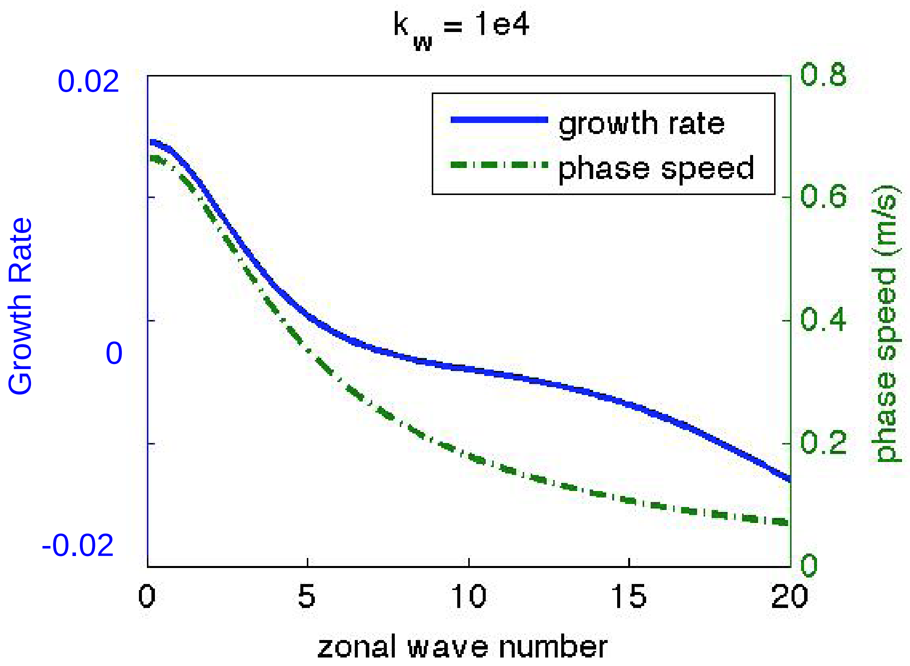
Sobel and Maloney (2012a,b)

Equatorial zonal wind response (red) to sinusoidal heating (blue) - westerlies lag heating



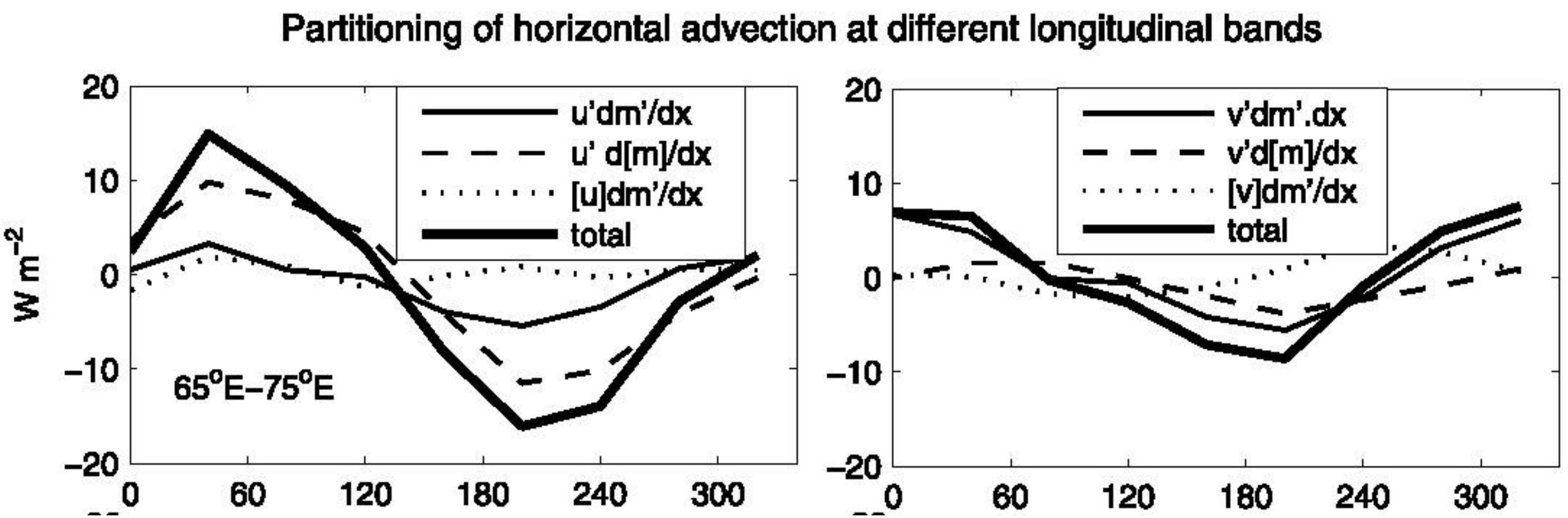
Growth Rate and Phase Speed

- Linear stability analysis shows that with a small amount of horizontal diffusion, growth rate maximizes at largest scales, and disturbance propagates eastward relative to the mean flow.
- Radiative and/or surface flux feedbacks are necessary to destabilize the mode
- Eastward propagation due to eddy-mediated impacts, or zonal advection if we have a mean humidity gradient (i.e. DYNAMO)



Sobel and Maloney (2012a,b)

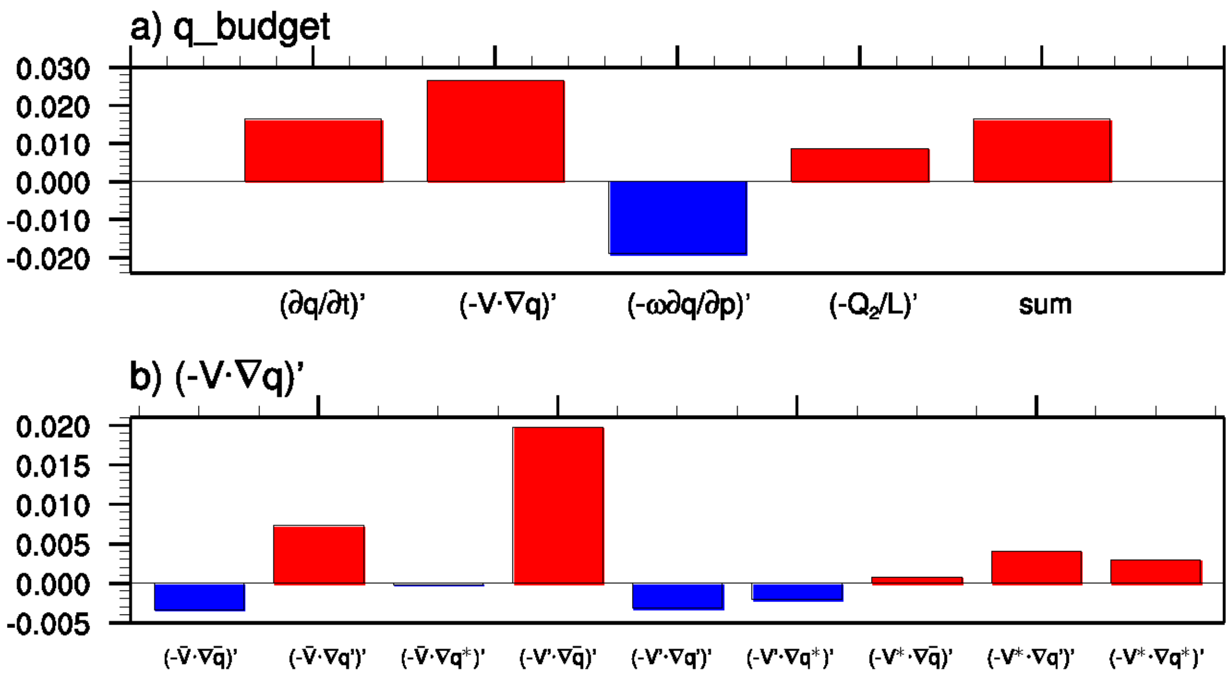
MJO Initiation Region: Anomalous Moisture Advection in Easterly Perturbations

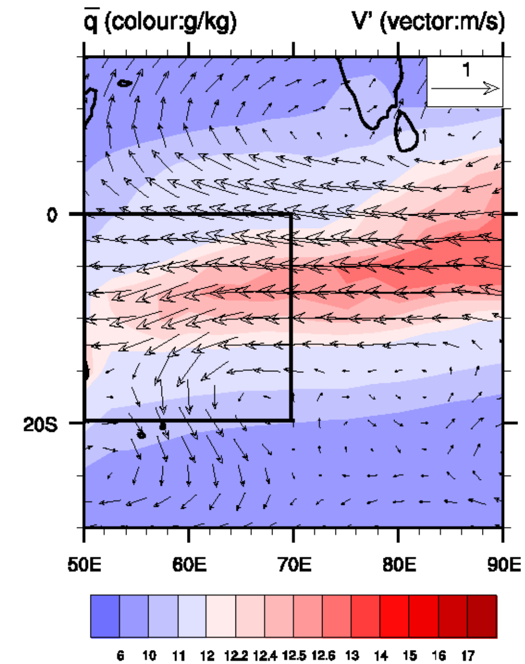


Kiranmayi and Maloney (2011)

- $-Lu'\frac{\partial q}{\partial x}$ is the largest term in the ERA-I MSE budget (and moisture budget considering the cancellation of vertical advection and *P*) in the MJO initiation region.

Recent Analysis from Zhao et al. (2012)

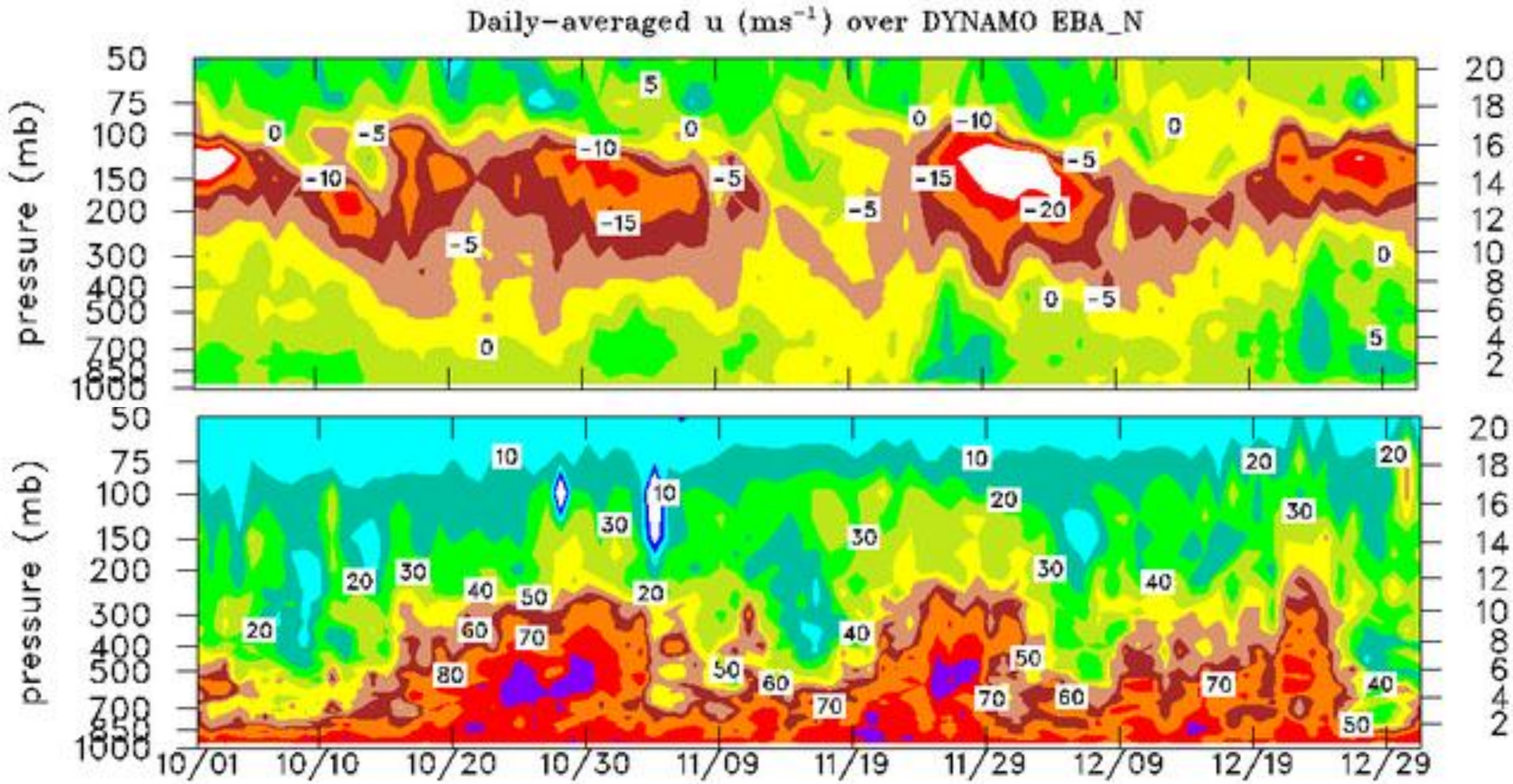




Zhao et al. (2012)

- Anomalous horizontal advection is largely responsible for moistening in the MJO initiation region (mainly $-\vec{v}\cdot\nabla\bar{q}$), with strong contributions from both meridional and zonal components.

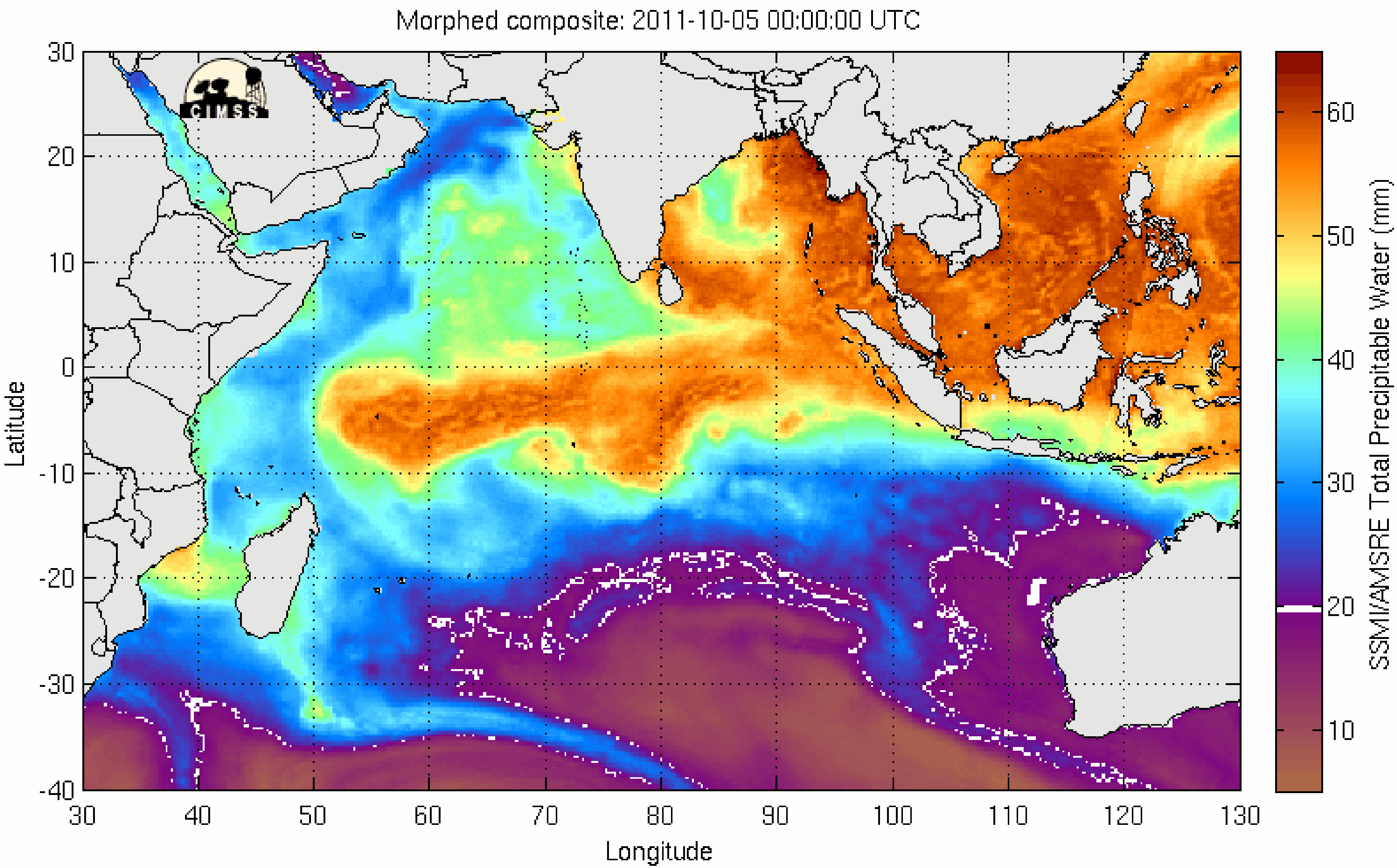
DYNAMO MJO Events: Wind and Humidity Fields within the DYNAMO sounding array



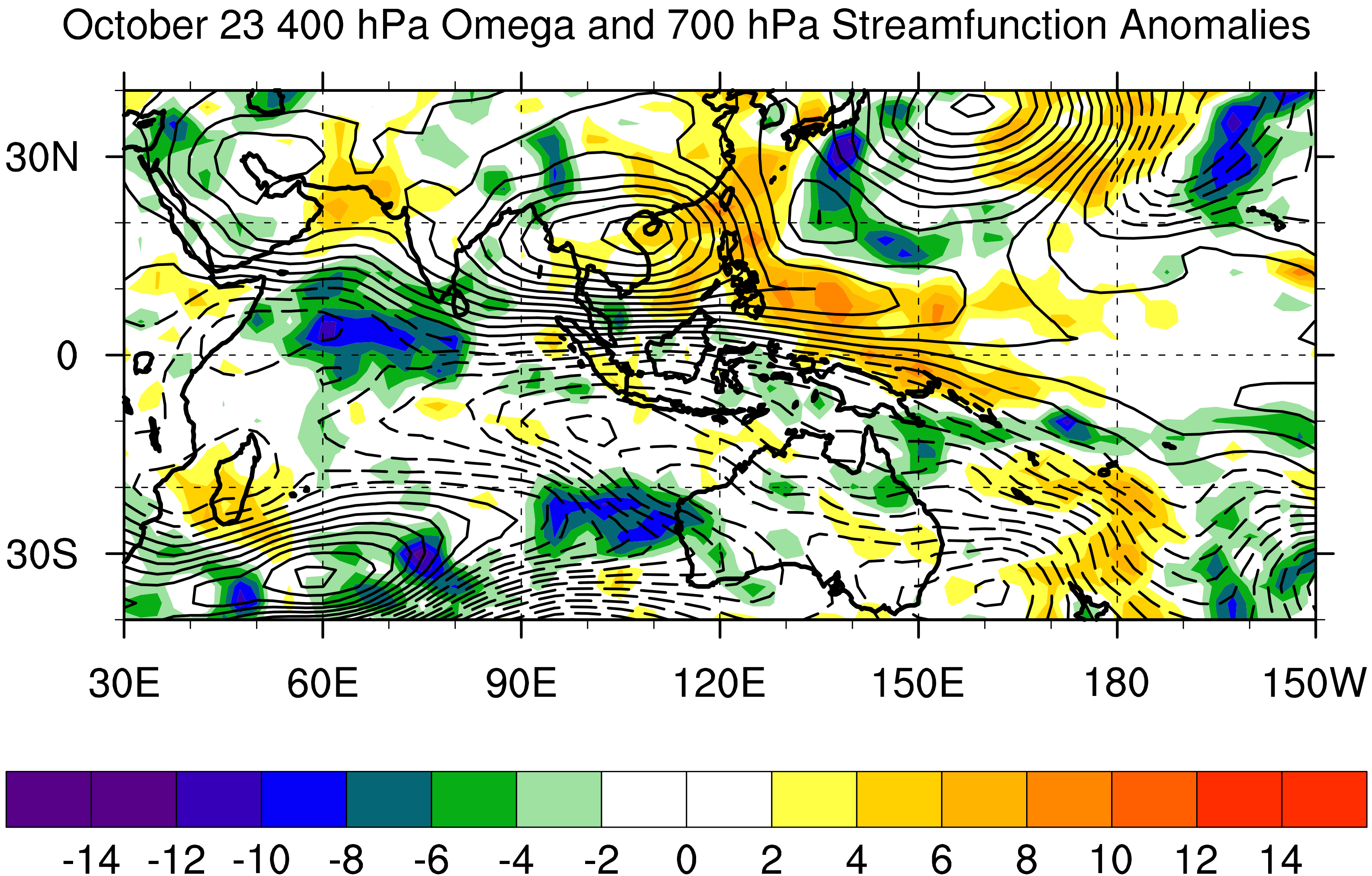
Courtesy of Richard Johnson and Paul Ciesielski

Enhanced MJO Convection occurs during the three moist periods shown here

Total Precipitable Water First DYNAMO MJO Event

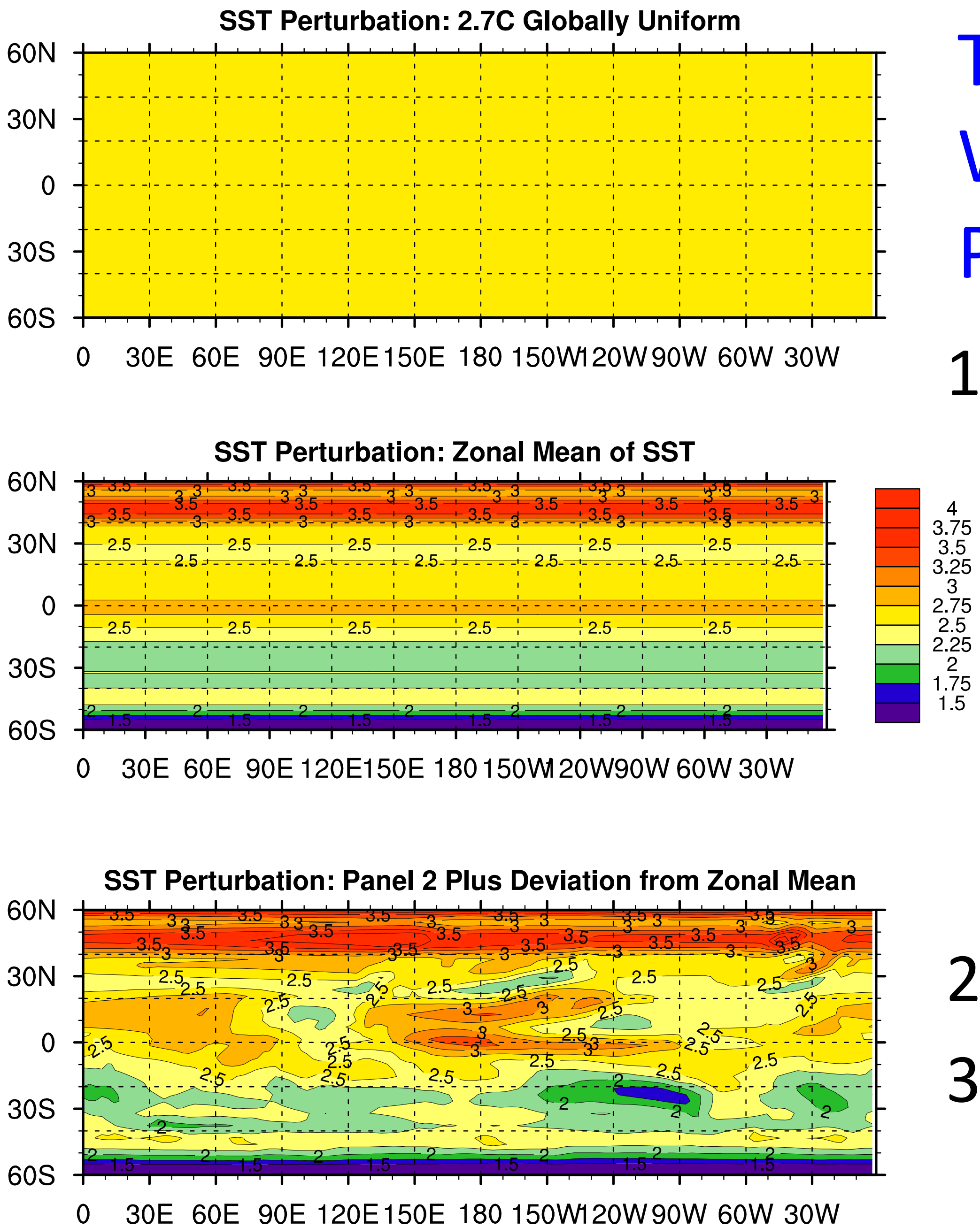


DYNAMO Case Study (Rossby Gyre Moistening?): ERA-I



How Does the Model MJO Change with Climate Warming?

- Does change in MJO depend on pattern of SST warming?
- Compare homogeneous warming versus patterned warming
- Not necessarily a prediction of how MJO activity will change in future
- However, does suggest that future MJO activity ***may*** be sensitive to pattern of SST warming.
- Details found in Maloney and Xie (2012)

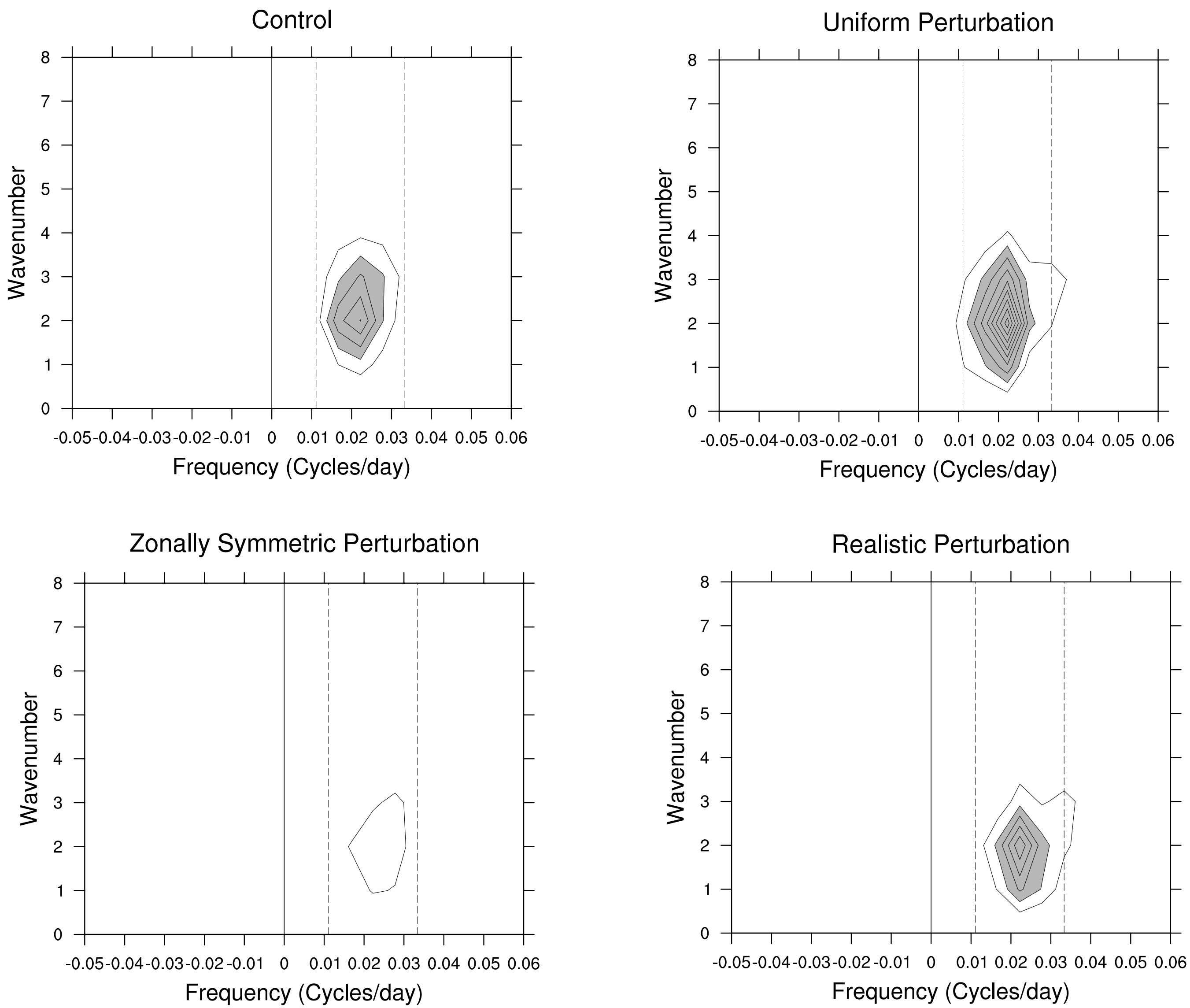


Three Different SST Warming Perturbations

1) Realistic oceanic SST warming perturbation for 2080-2100 taken from GFDL CM2.1 for mid-range scenario.
2) Zonal mean of #1
3) Global mean of #1

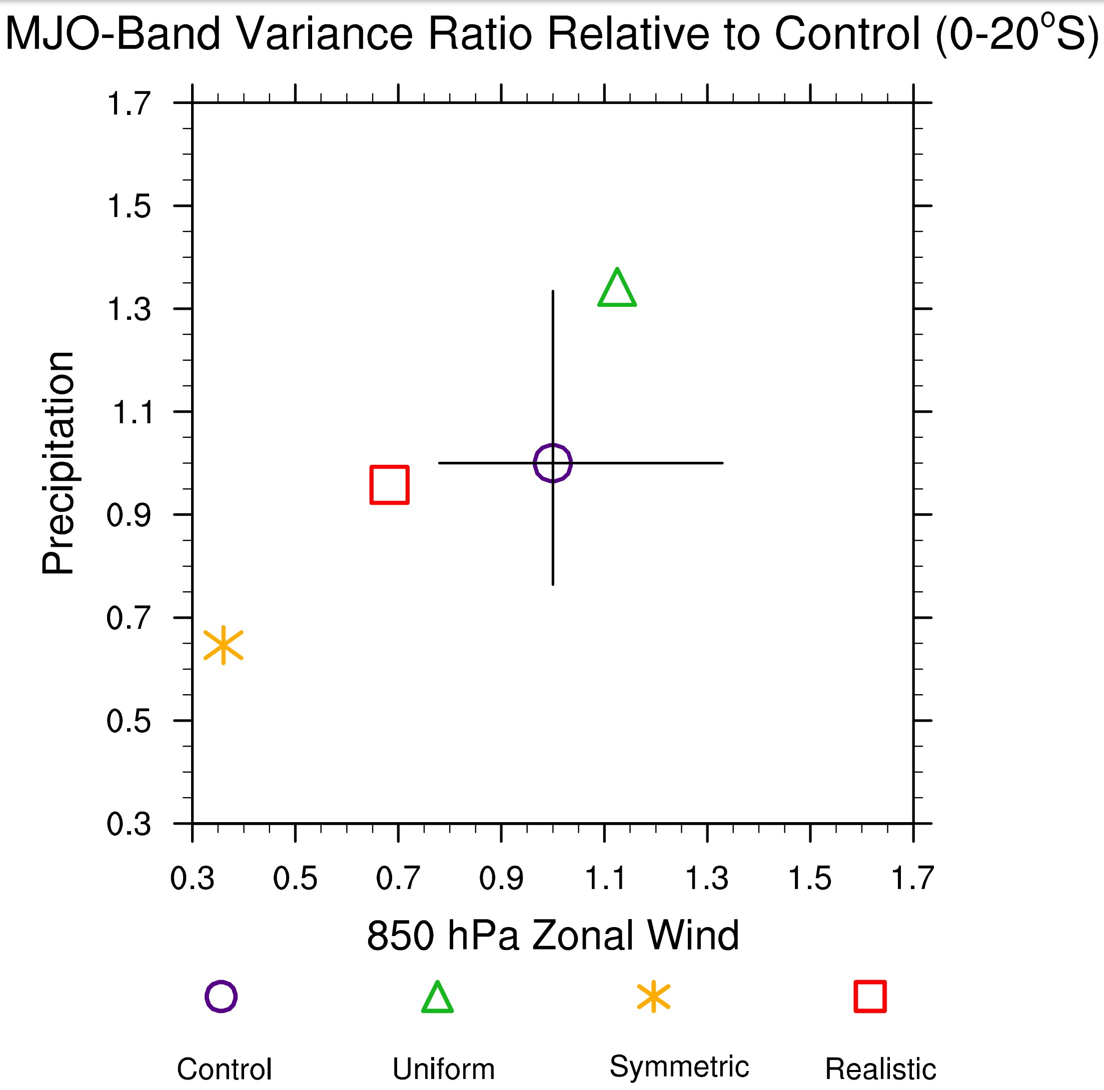
Maloney and Xie (2012)

Precipitation Spectra



Maloney and Xie (2012)

Variance in MJO Band Relative to Control (Wave#1-4, Eastward 30-90 Day), 0-20ºS.



Confidence intervals 95% determined from Chi-squared Distribution.

Maloney and Xie (2012)

Conclusions

- Modeling and observational evidence suggests that the MJO is a “moisture mode” destabilized by radiative and wind-evaporative feedbacks and propagated eastward by horizontal advection
- A semi-empirical model based on such principles is able to predict the correct scale and propagation speed for the MJO
- Horizontal advection is hypothesized to be a leading moistening process in advance of MJO initiation
- Future changes in MJO activity are likely to be sensitive to the pattern of SST warming.