New Insights on the Madden-Julian Oscillation from Models, and a Preview of the Upcoming DYNAMO Field

Eric D. Maloney, Colorado State University

With help from Walter Hannah, Adam Sobel, Marat Khairoutdinov

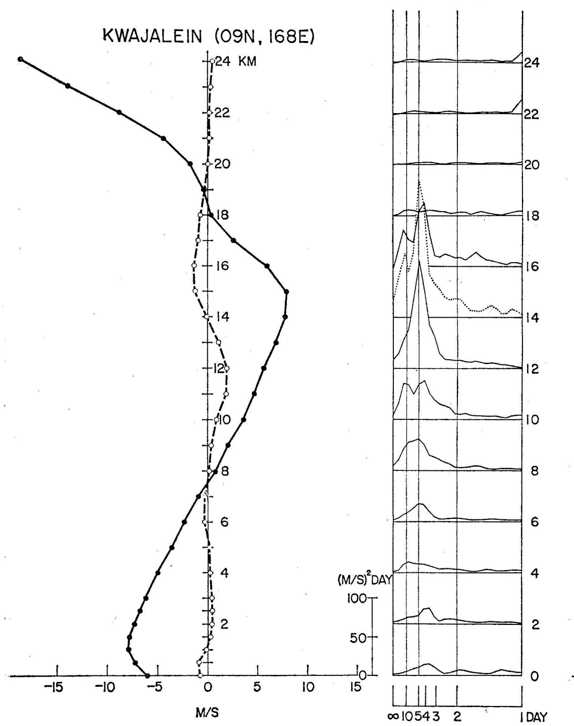
Funded by: CMMAP, NSF Climate and Large-Scale Dynamics Program, NOAA Climate Program Office

Power Spectra of Large-Scale Disturbances over the Tropical Pacific*

By M. Yanai, T. Maruyama, Tsuyoshi Nitta and Y. Hayashi

Geophysical Institute, Tokyo University, Tokyo

(Manuscript received 26 February 1968, in revised form 14 June 1968)



(c) Kwajalein

- Yanai et al. (1968) analyzed westward propagating disturbances with 4-5 day timescales in the upper troposphere and lower stratosphere during 1962 using spectral analysis and analysis of coherence.
- These disturbances are now known as Yanai or mixed Rossby-gravity waves
- Roland Madden was impressed by the statistical techniques employed in this paper and attempted to reproduce this behavior using data from the Line Islands Experiment in spring of 1967 (esp. tropospheric).

Results of 1967 Line Islands Study

- "I could not reproduce [these results] from the Line Islands experiment (spring of 1967) so we became interested in the time-varying characteristics of the tropospheric waves ….. We got distracted from that work when we saw the large 40-50 day signal." –Rol Madden, Summer 2010
- "In the course of an investigation of tropical wind data …. to study non-stationary aspects of the aforementioned wave modes, we stumbled upon an apparent long-period oscillation in station pressure and zonal wind at Canton Island (3S, 172W)." Madden and Julian (1971)

Canton Island Spectral Variance

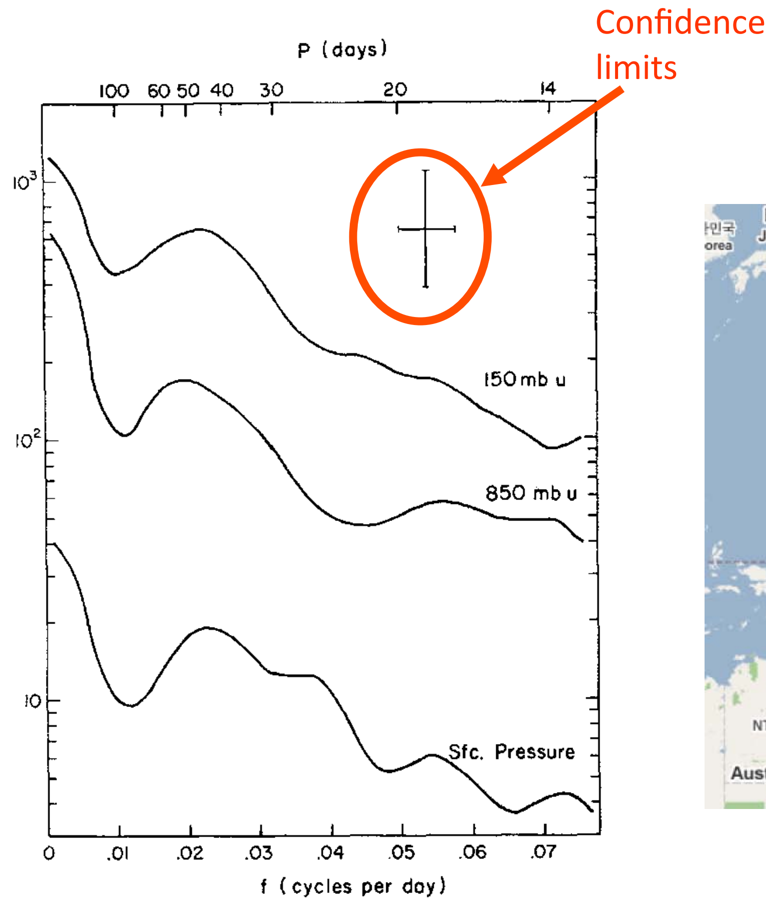
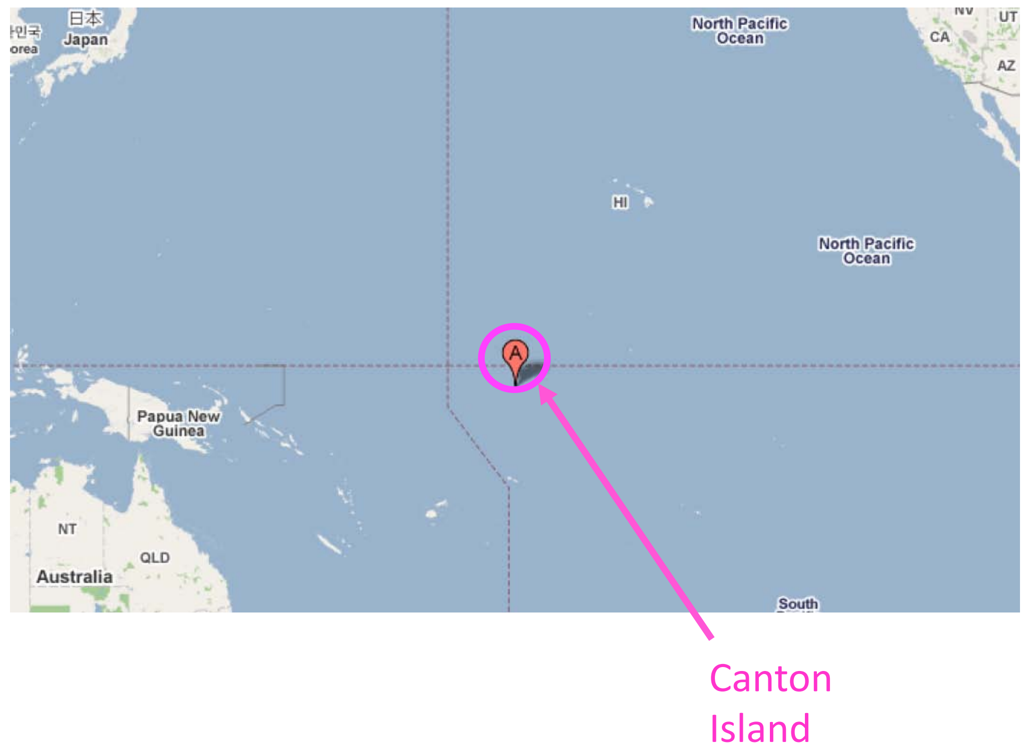
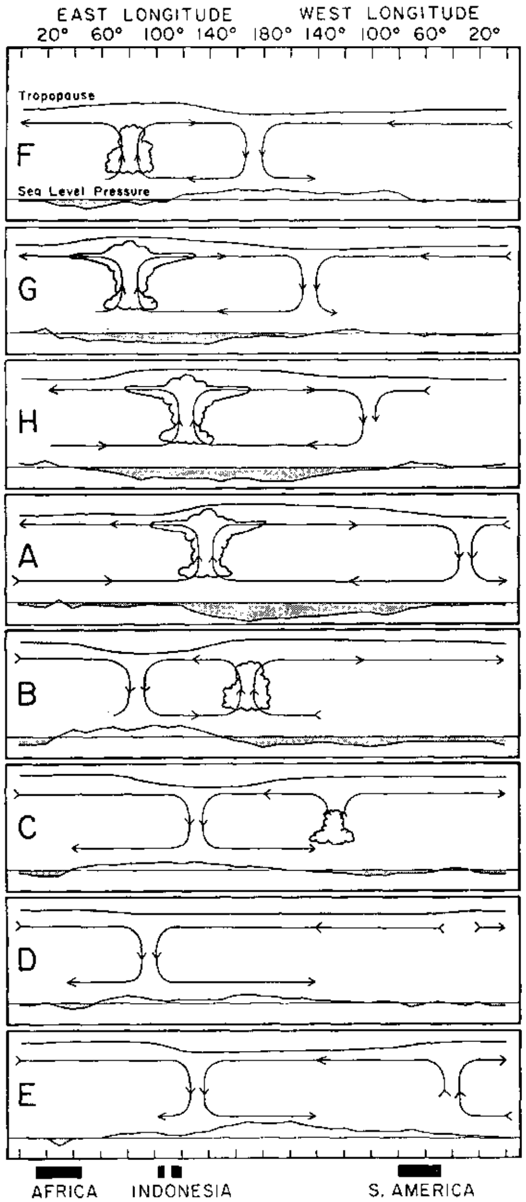


FIG. 2. Individual variance spectra for the 850- and 150-mb zonal wind component and station (sfc) pressure for the Canton Island record. The use of a logarithmic ordinate permits a constant scaling to be used for the chi-square degrees of freedom sampling analysis. This scaling [$\chi^2(0.1\%)/51$] and the bandwidth of the analysis, $\Delta f=0.0081$ day^{-1}, are shown by the cross. Spectral densities are normalized to unit bandwidth (m^2 sec^{-2} day^{-1}).



Madden and Julian 1971

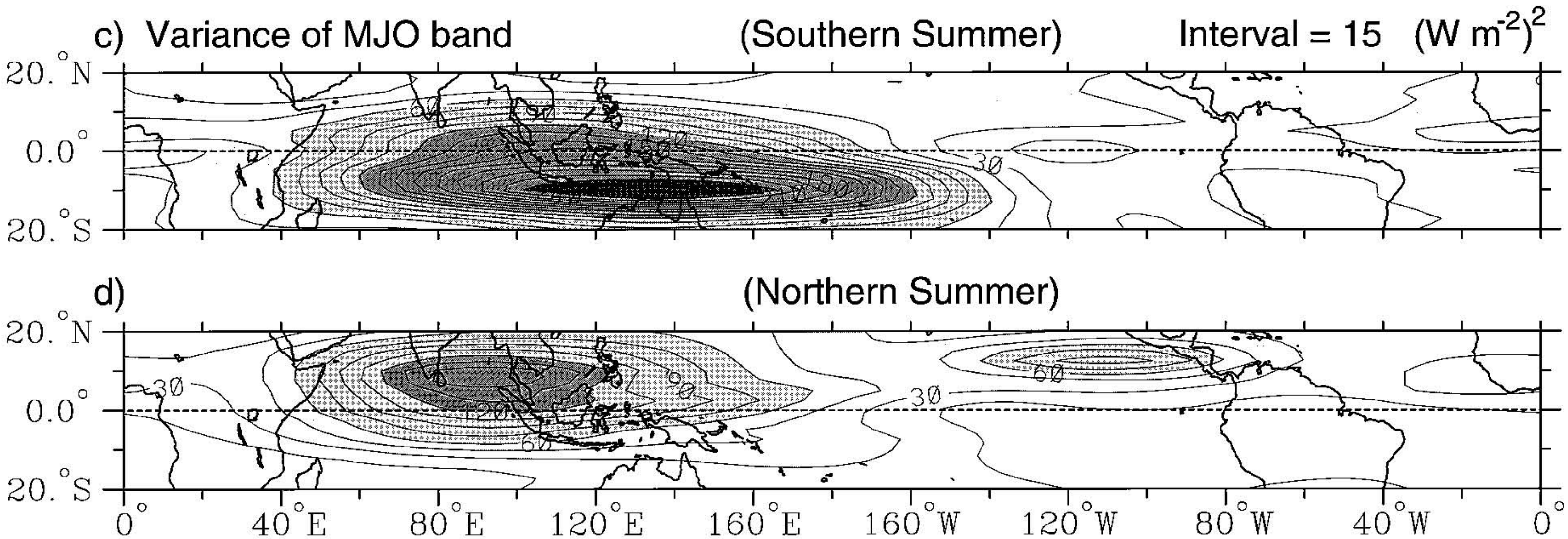
The Madden-Julian Oscillation (MJO)



- Broad features described by Madden and Julian, further refined in subsequent work:
  - A disturbance characterized by precipitation coupled to wind variations that propagates eastward across the Tropics
  - 5-10 m s^{-1} propagation speed in the Indian and west Pacific, where MJO precipitation variability is strongly coupled to the large-scale flow.
  - Simple baroclinic wind structure, with upper troposphere and lower troposphere wind perturbations 180^{o} out of phase
  - Characteristic timescales of 30-90 days.

Madden and Julian 1972

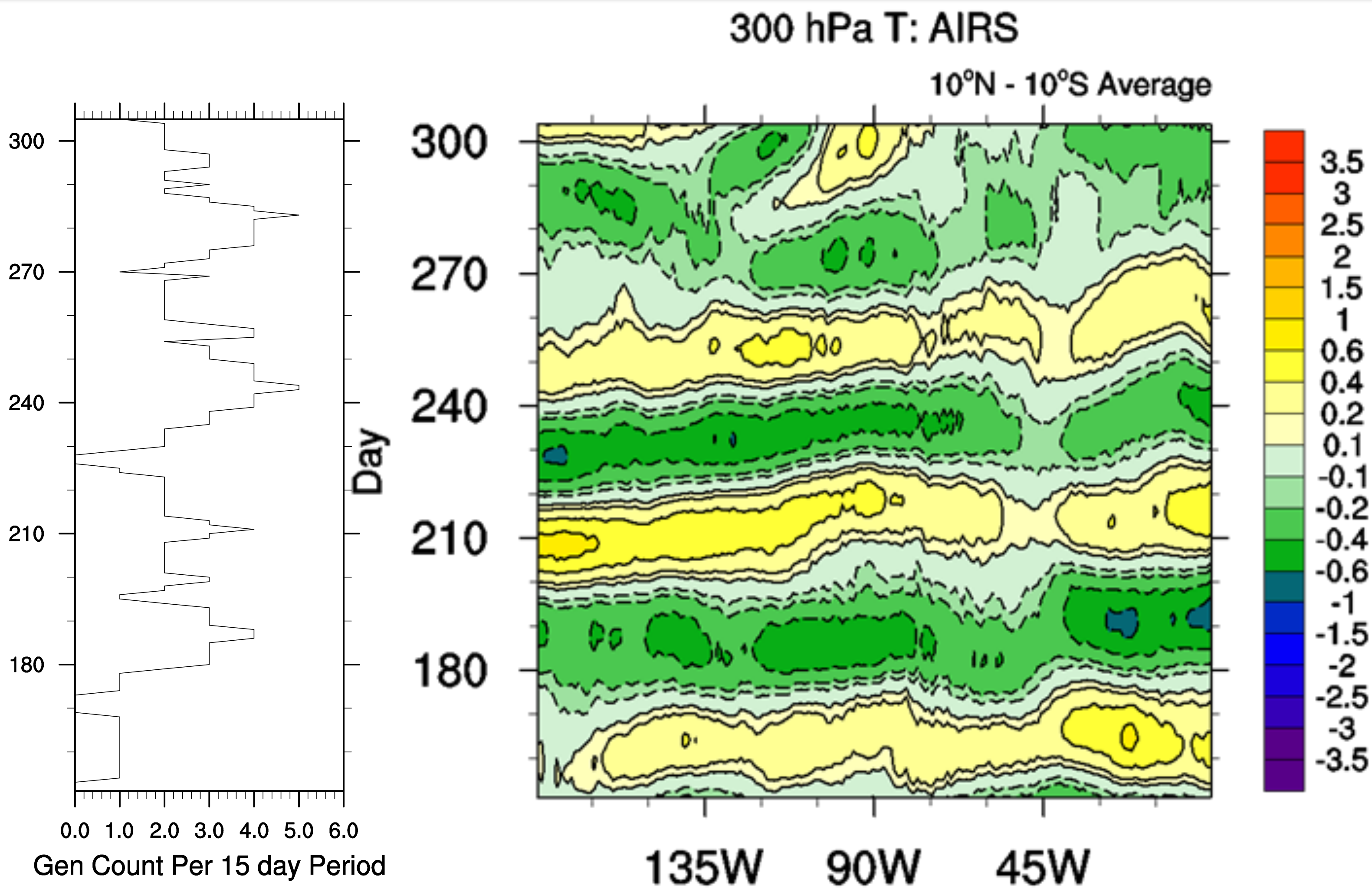
The Madden-Julian Oscillation (MJO): Geographical Distribution of Activity



- Eastward-propagating variability centered along 10°S during December-May, and 10°N during June through November.
- East Pacific variability during Northern summer.

Wheeler and Kiladis (1999)

2005 Intraseasonal Temperature and Atlantic Tropical Cyclone Genesis Counts



Items to Be Addressed in this Talk

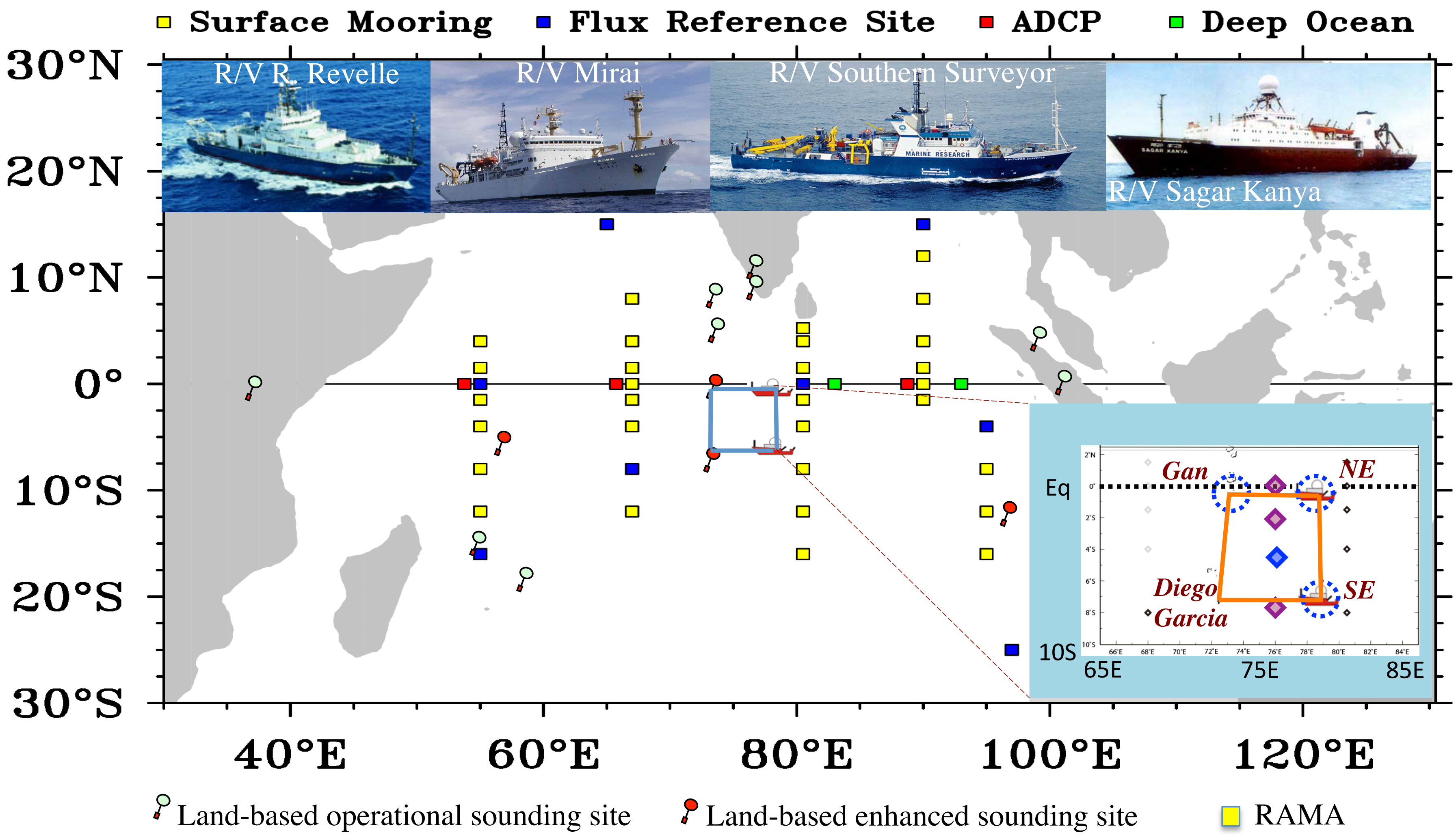
- Part I: MJO Initiation
  - Upcoming DYNAMO field program
- Part II: MJO Dynamics
  - Recent research results

Even though the MJO was discovered around 1970, no consensus yet exists as to its underlying dynamics.

Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011 (CINDY2011) and Dynamics of the MJO (DYNAMO)

Field Campaign

October 1, 2011 – March 31, 2012



Goal: Expedite our understanding of MJO initiation processes and efforts to improve simulation and prediction of the MJO

Objectives:
– Collect observations (*field campaign*)
– Establish empirical statistics; prepare data for model constraints, validation, and evaluation (*analysis*)
– Test hypotheses; identify model deficiencies; provide better physical basis for model improvement (*modeling*)
– Develop prediction indices for MJO initiation; benchmark improvement in MJO prediction (*forecast*)

Hypotheses: Three essential factors for MJO initiation
I. Interaction between convection and its environmental moisture
II. Distinct roles of different types of convective clouds at each MJO initiation stage
III. Upper ocean processes and air-sea interaction

DYNAMO/CINDY2011 Observation Periods

Long-Term Monitoring (LTM): IndOOS, RAMA

Extended Observing Period (EOP): island-based radar (SMART-R) and radiation package (AMF2), surface/upper-ocean moorings, drifters, enhanced RAMA moorings

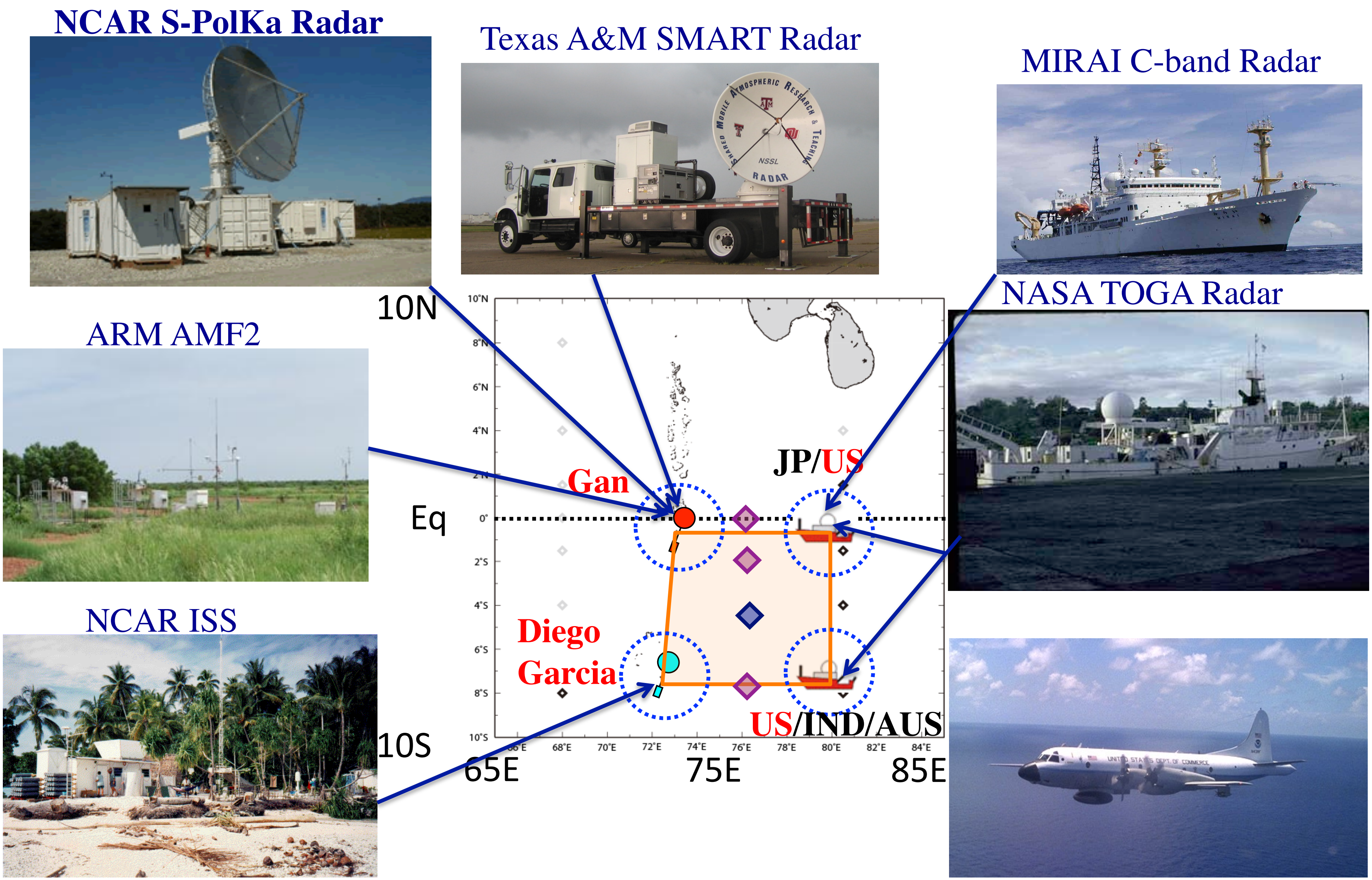
Intensive Observing Period (IOP): sounding-radar array, ship-based measurement of air-sea fluxes, atmospheric boundary layer and upper-ocean mixing/turbulence profiles, aerosol

SOP: enhanced soundings

September October November December January February

2011 2012

DYNAMO Sounding-Radar Network
(4 soundings per day for IOP; 8 per day for SOP)



DYNAMO Modeling Activities

Process-oriented studies and model improvement proposed by DYNAMO modeling group

- Global AGCMs, OGCMs, CGCMs (inc. SP-CAM, CAM5)
- Tropical channel model (nested to cloud resolving resolution)
- Global cloud system resolving models (inc. WRF, NICAM)
- Coupled regional mesoscale model (ONR)
- Limited domain cloud system resolving models (WRF, SAM): conventional and WTG forcing methods
- Single column atmospheric model and ocean mixing-layer model (e.g. various versions of SCAM)

DYNAMO forcing dataset for SCMs, limited domain CSRM

- integrated flux dataset (buoy, aircraft, ship)
- advective tendencies from array (large array!)

RADAR

- integrated dataset of cloud statistics (reflectivity, echo-top height, cloud width and depth, precipitation rate, etc) that can constrain CSRMs. Include non-precipitating clouds

Integrated water vapor dataset (microwave radiometer, sounding, X/Ka band radar, aircraft, et al)

Hindcast experiments

NSF Student Travel Fellowships for the DYNAMO Field Campaign

- The field campaign will provide an excellent opportunity for young scientists to gain firsthand experience in a modern, international field experiment, broaden their scientific background, and interact with scientists outside their home institutes.

- We anticipate several DYNAMO NSF Student Travel Fellowships available to support participation in the DYNAMO field campaign by advanced graduate students and recently graduated postdoctoral associates, especially those from underrepresented groups.

- Fellowship recipients will provide needed assistance to the field operation, including, but not limited to, sounding launches, radar operation and data retrieval, and in-field data analysis. Each fellowship recipient will work closely with a senior mentor during the field campaign.

- Application deadline: January 30, 2011.
  Decision deadline: late February

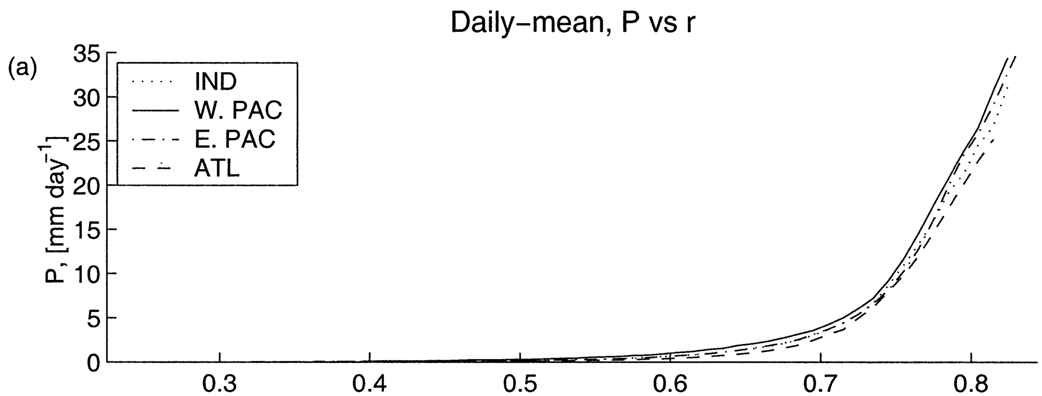
- Contact: czhang@rsmas.miami.edu or me
  for more information.

Understanding MJO Dynamics Using Climate Models

Results from three papers:

1) Hannah, W. M., and E. D. Maloney, 2011: The role of moisture-convection feedbacks in simulating the Madden-Julian oscillation. *J. Climate*, accepted pending revisions.
2) Maloney, E. D., A. H. Sobel , and W. M. Hannah, 2010: Intraseasonal variability in an aquaplanet general circulation model. *J. Adv. Modeling*. *Earth*. *Sys*, **2**, Art. #5, 24 pp.
3) Landu, K., and E. D. Maloney, 2011: Understanding intraseasonal variability in an aquaplanet GCM. *J. Meteor. Soc. Japan*, accepted pending minor revisions.

Heavy Precipitation is Only Supported When the Atmosphere Nears Saturation

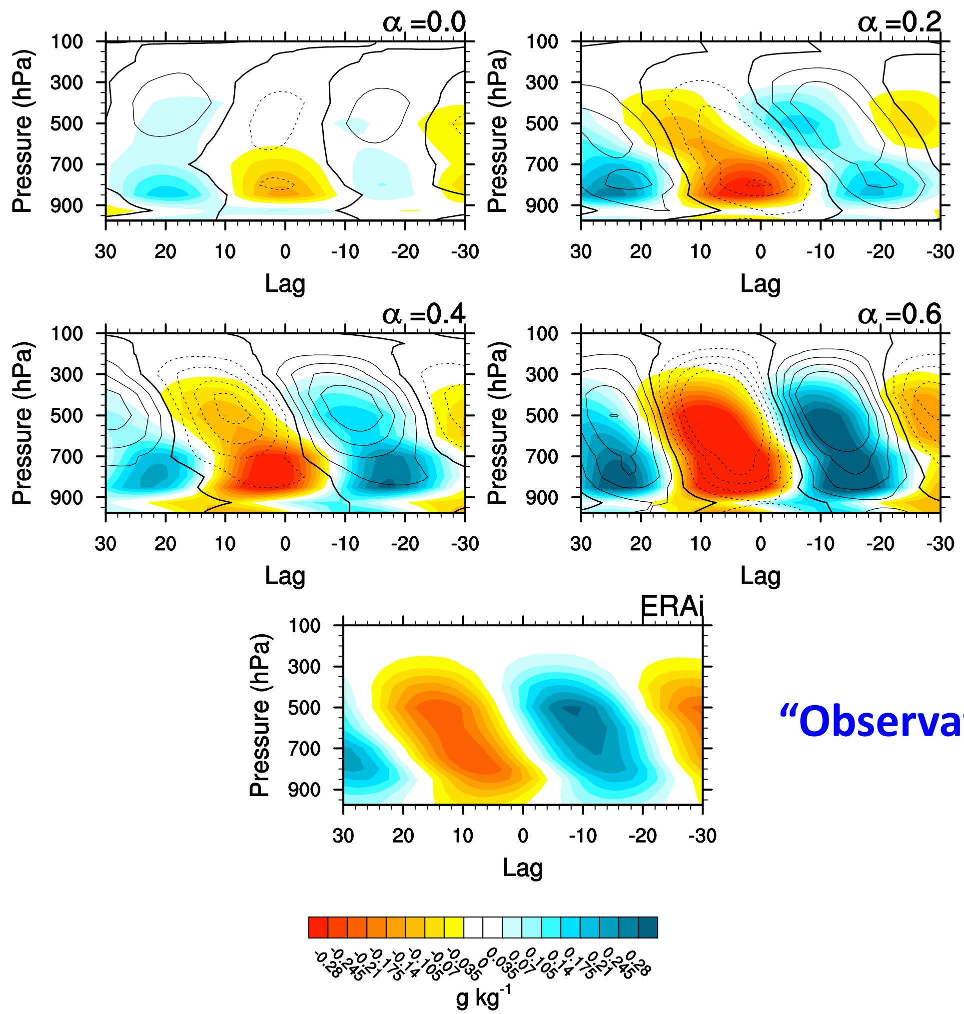


Bretherton et al. (2004)

- Many climate model convection parameterizations are not sensitive enough to dry atmospheres.
- Walter Hannah used a version of the NCAR CAM3 to demonstrate that the MJO simulation can be improved by making tropical convection more sensitive to environmental humidity
- This was done in a related way to Tokioka et al (1988) by suppressing weakly entraining deep convective plumes in dry atmospheres.

Increasingly Realistic MJO with Increased Moisture Sensitivity

Winter (Nov-Apr) Filtered Specific Humidity and Diabatic Heating Lag Composite

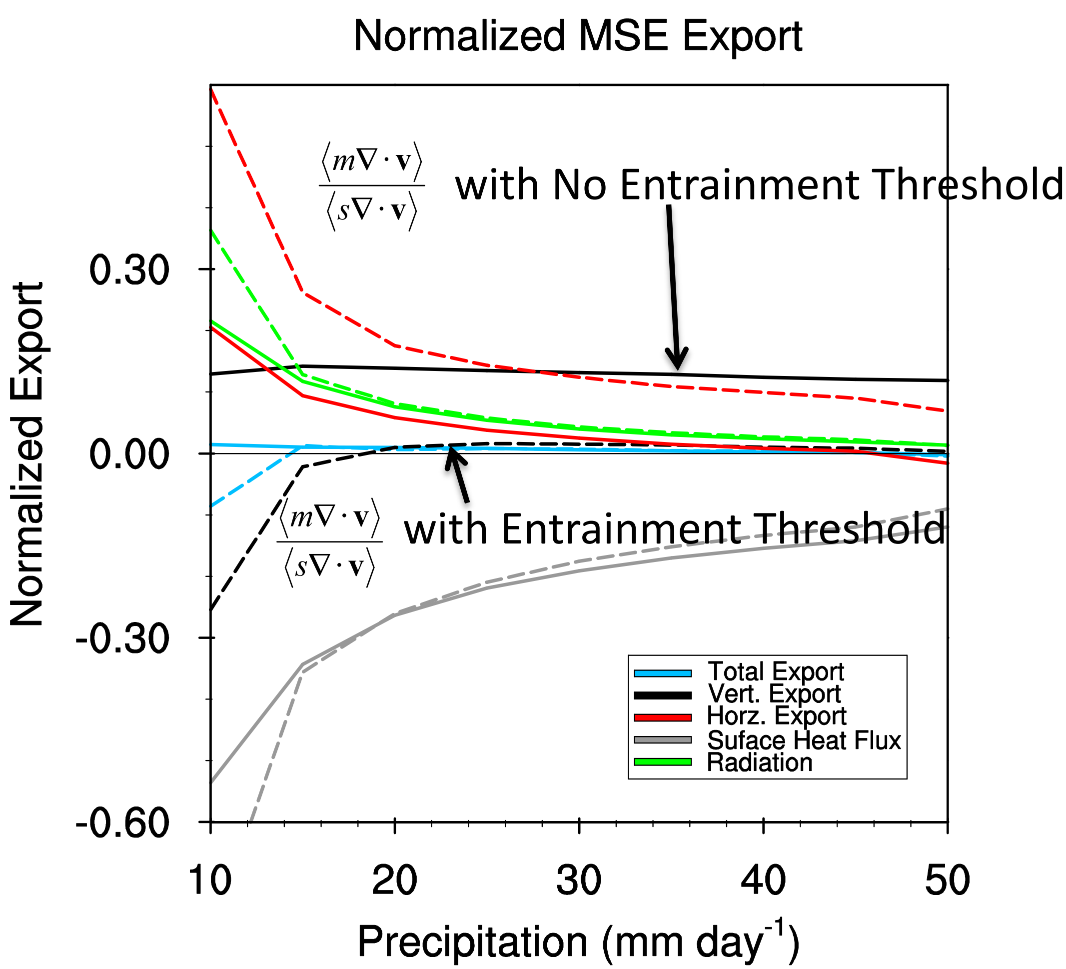


"Observations"

- Amplitude of the MJO and vertical tilted structure moisture structure becomes more realistic as moisture sensitivity is increased in the model
- We'll get back to this tilt later

Hannah and Maloney (2011)

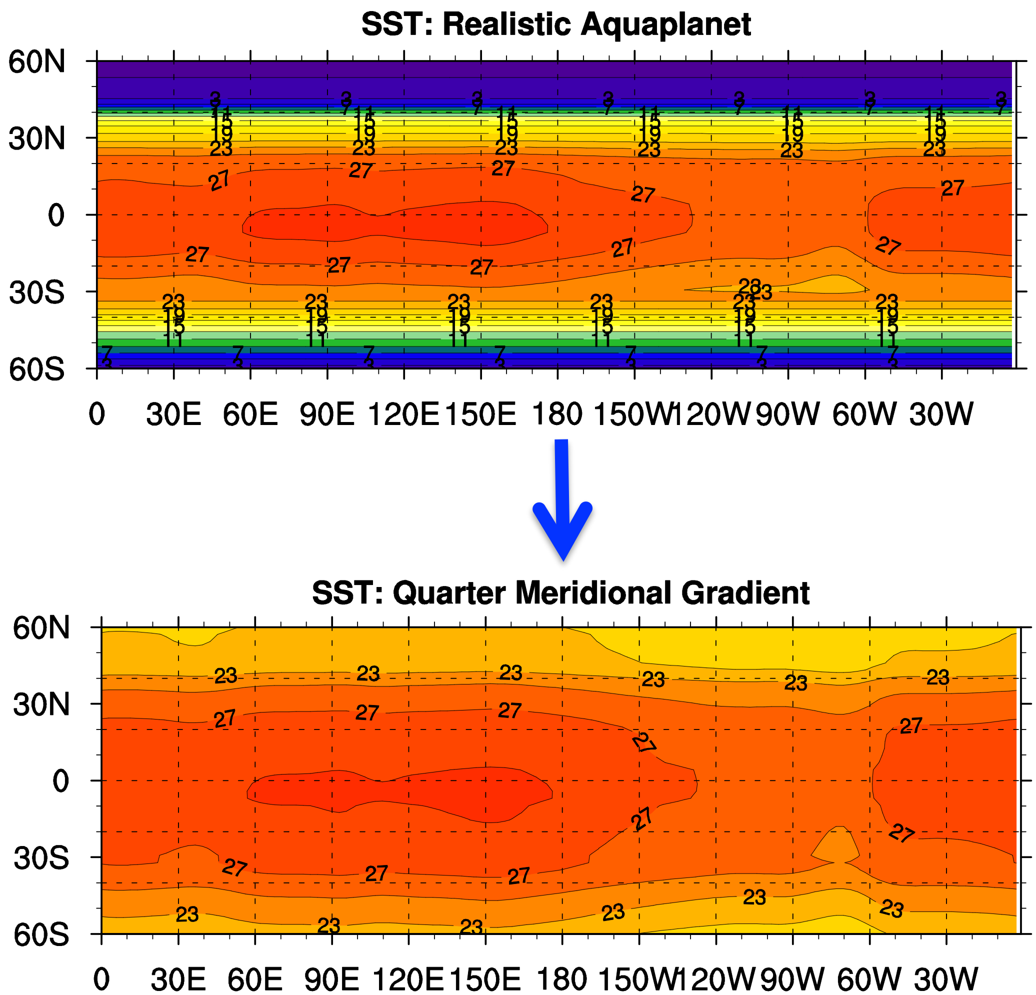
Why Is MJO Improved by Suppressing Weakly Entraining Clouds?



- Convection is in general less effective at drying the atmosphere, which means that atmospheric moisture anomalies can grow in the presence of sources like surface evaporation.
- In dry regions, shallow clouds are now dominant that directly moisten the column.

Hannah and Maloney (2011)

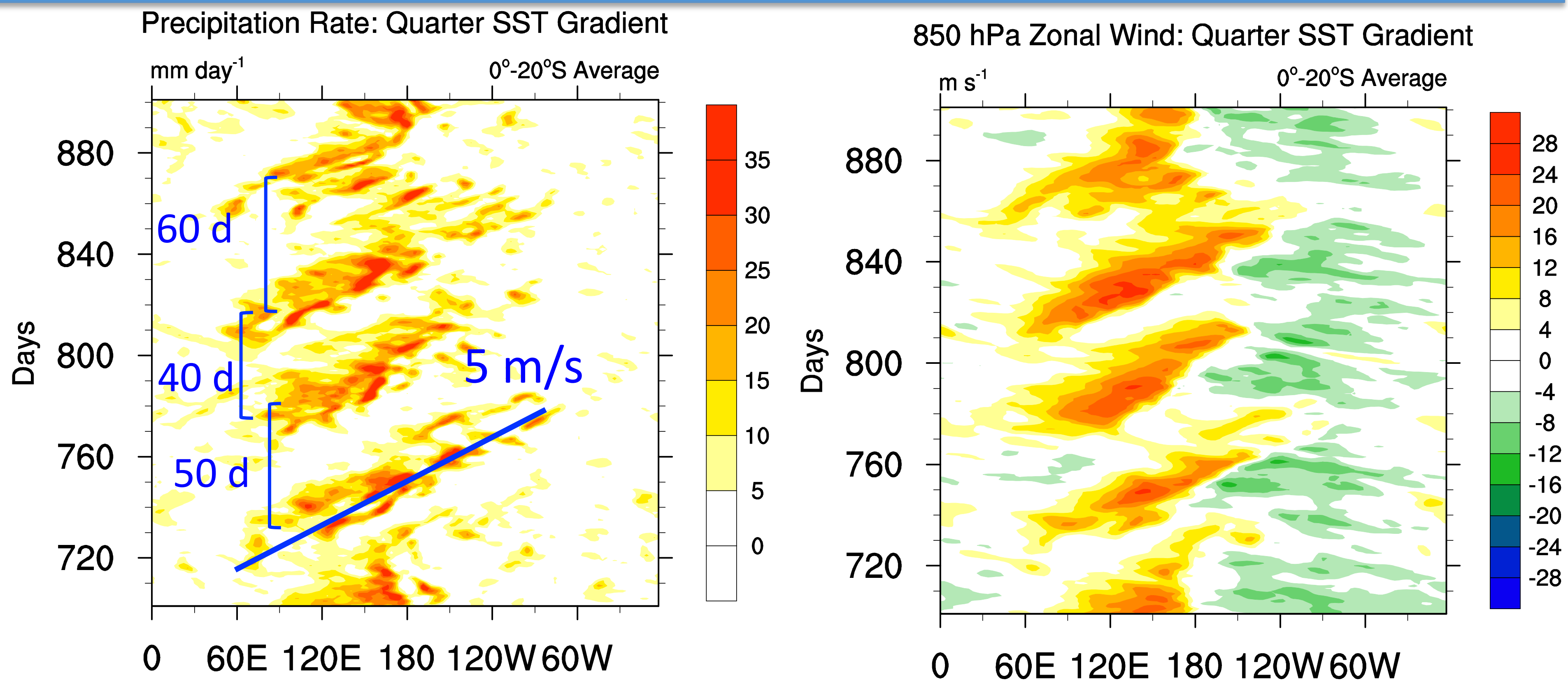
We Now Dig into the Dynamics of the Model MJO with Some Idealized Runs



- Starting from an aquaplanet ocean surface temperature distribution that produces results similar to those in Walter's study with enhanced moisture sensitivity employed, 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

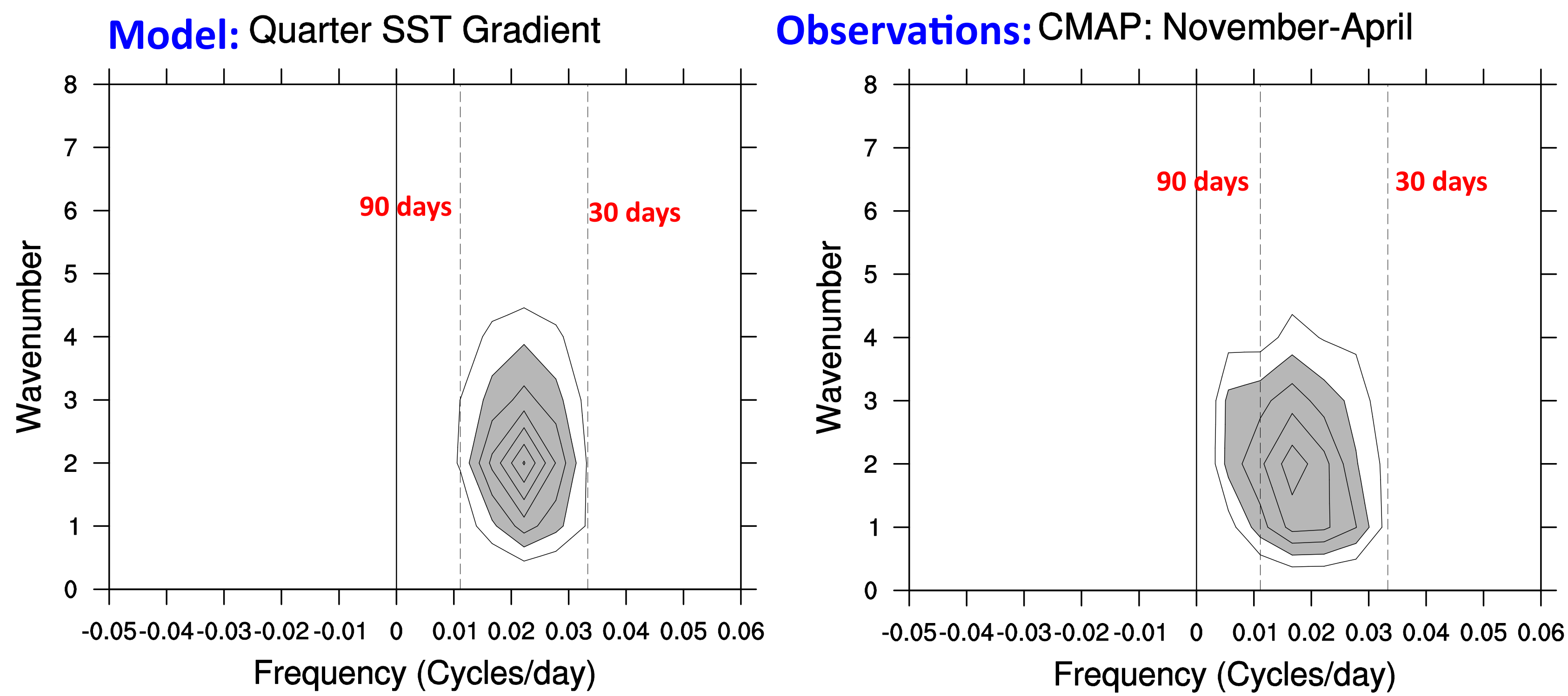
Maloney et al. (2010)

Robust MJO: Unfiltered Precipitation and Winds vs. Longitude



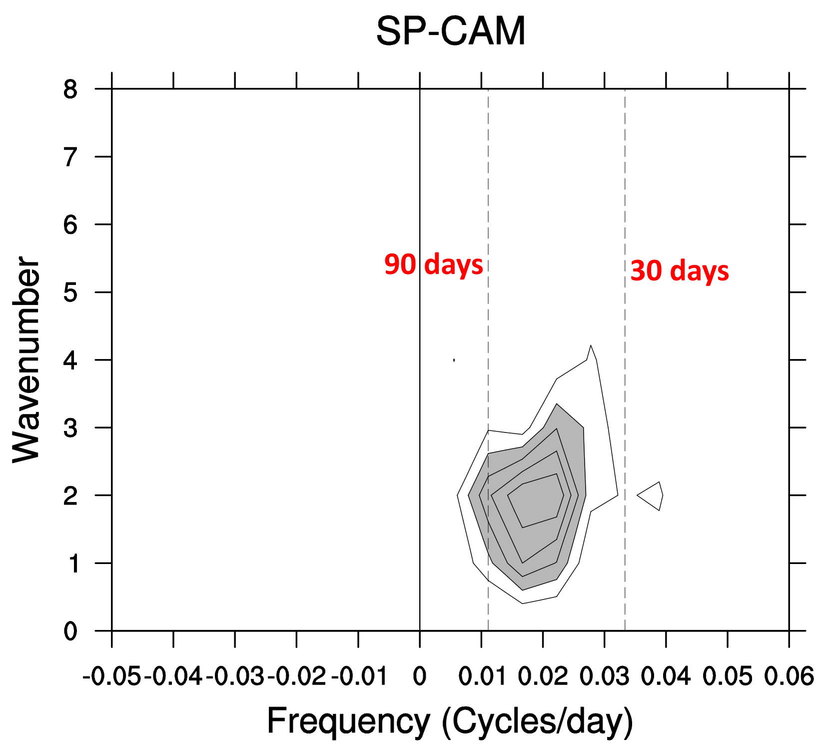
Even in unfiltered data, many salient features of the MJO apparent, including 5 m s^{-1} eastward propagation, and a period of 40-60 days.

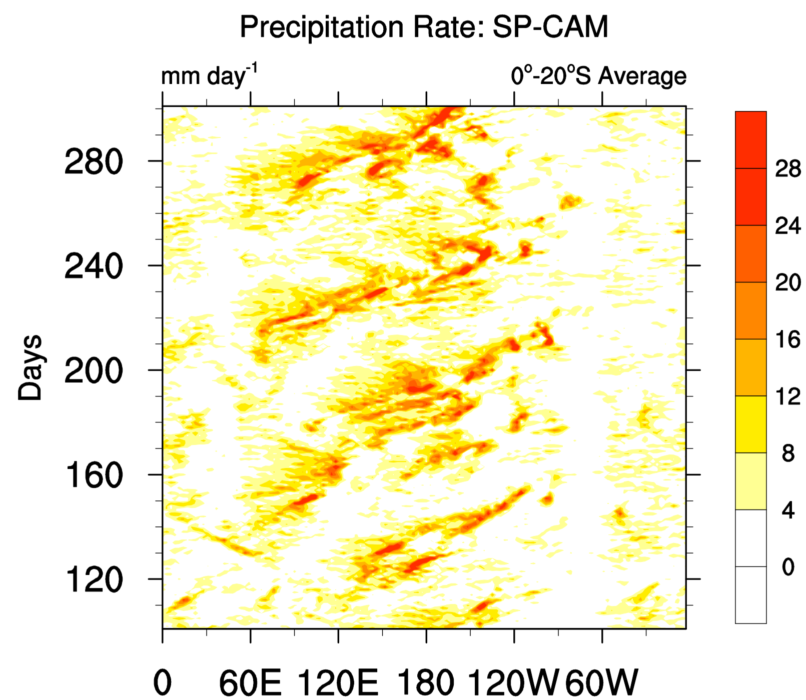
Model Captures Correct Space and Time Structure of Precipitation Variability



A strong spectral peak exists in the model at same zonal wavenumber and frequency as observations.

Given the Same SST Distribution, SP-CAM Generates Variability with the Same Character

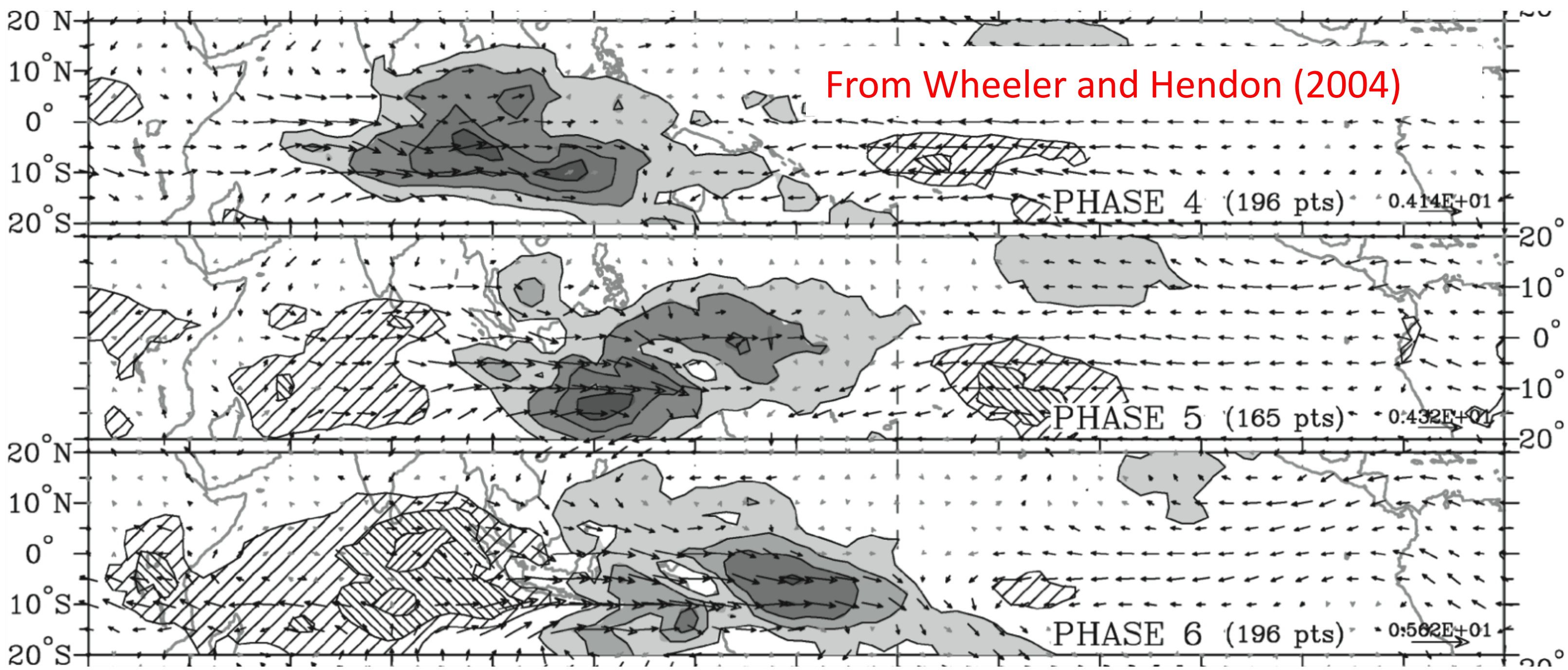




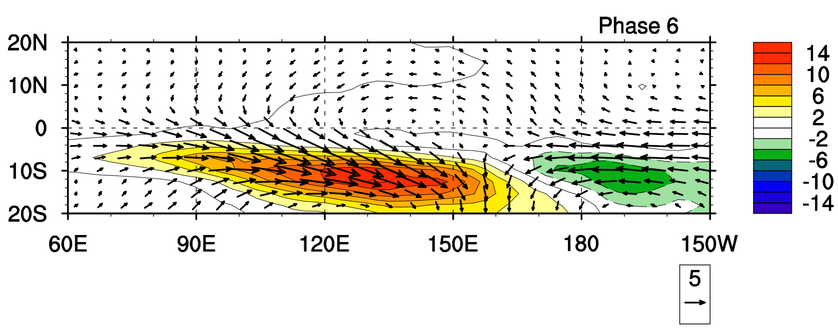
More multiscale convective variability, but the nature of the MJO is very similar .

Composite Precipitation and Winds

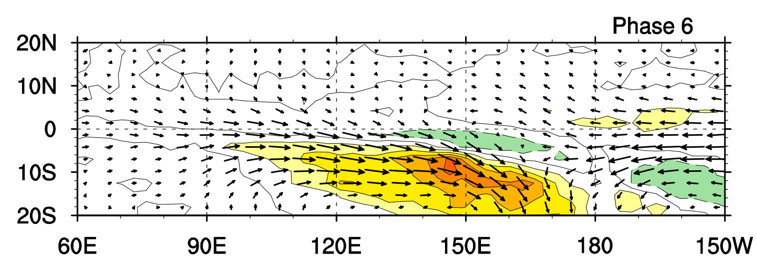
Observations



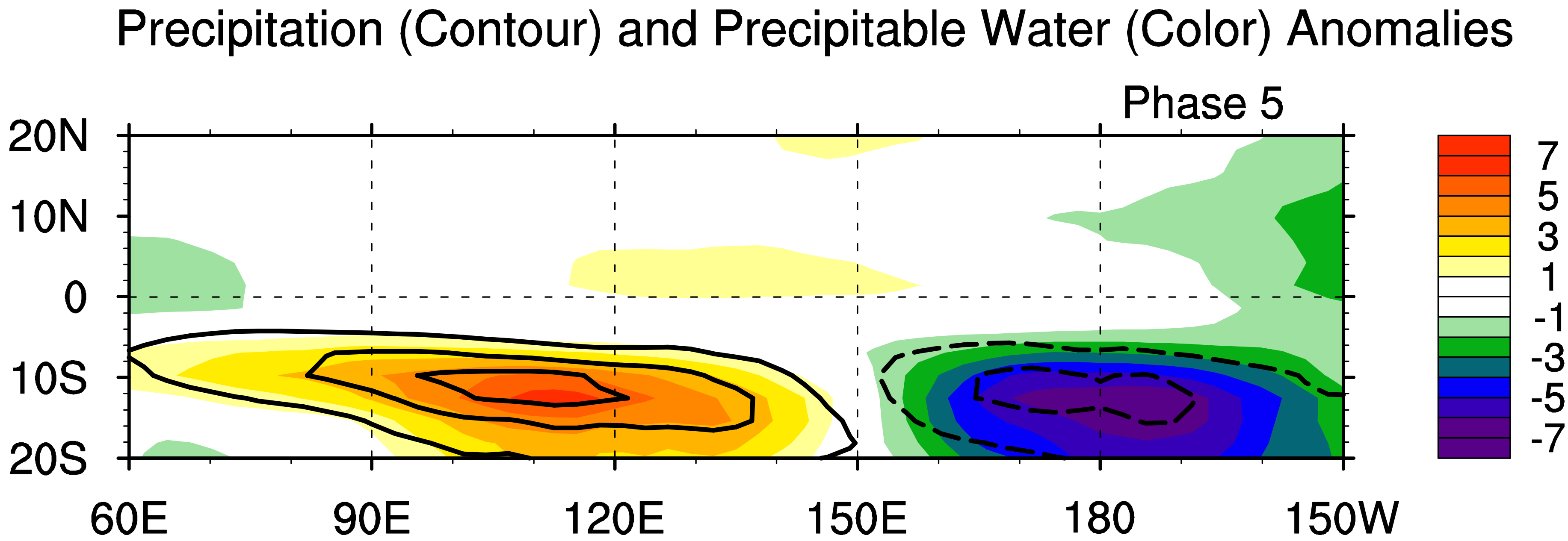
Conventional Model



SP-CAM



Composite Column Water Vapor Anomalies



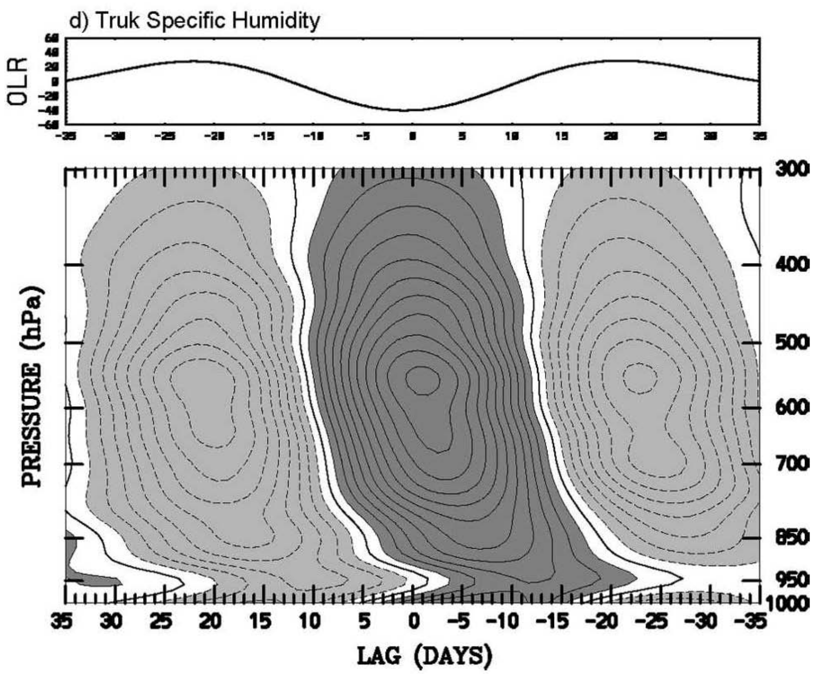
PW Units: mm

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}.

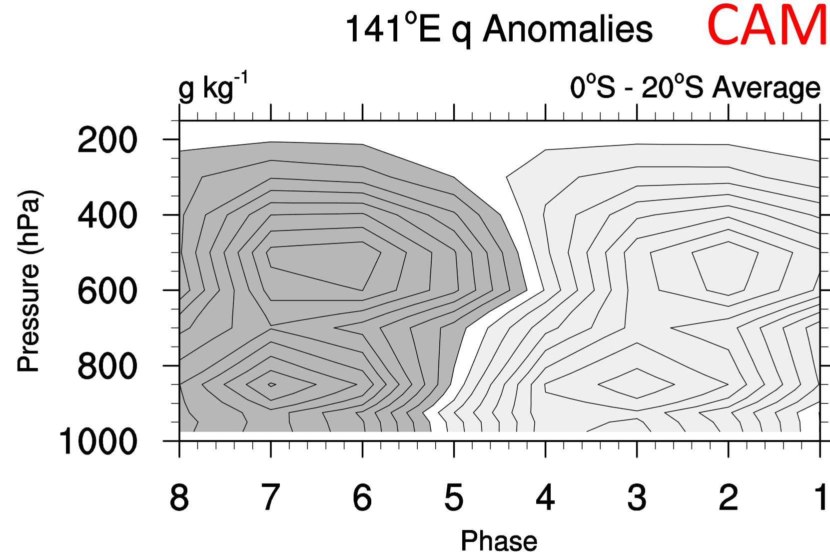
Vertical Structure of Humidity Anomalies

Observations

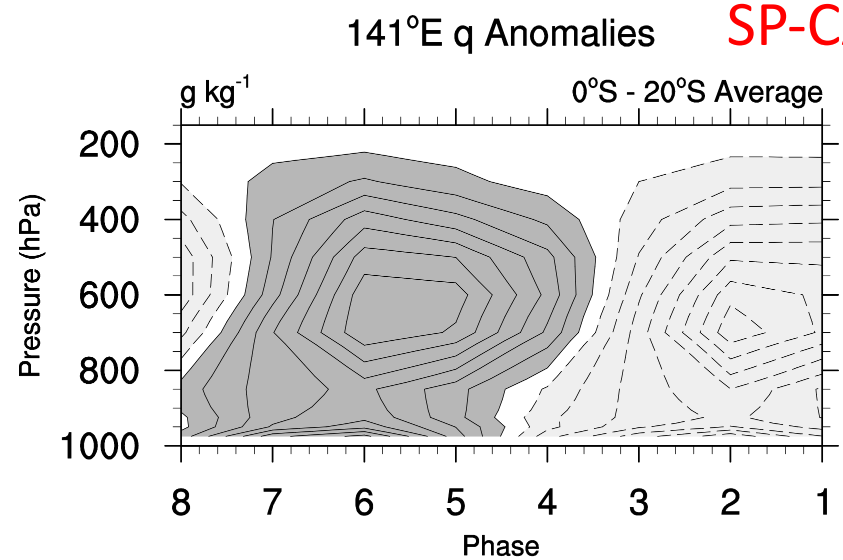


From Kiladis et al. (2005)

CAM/RAS

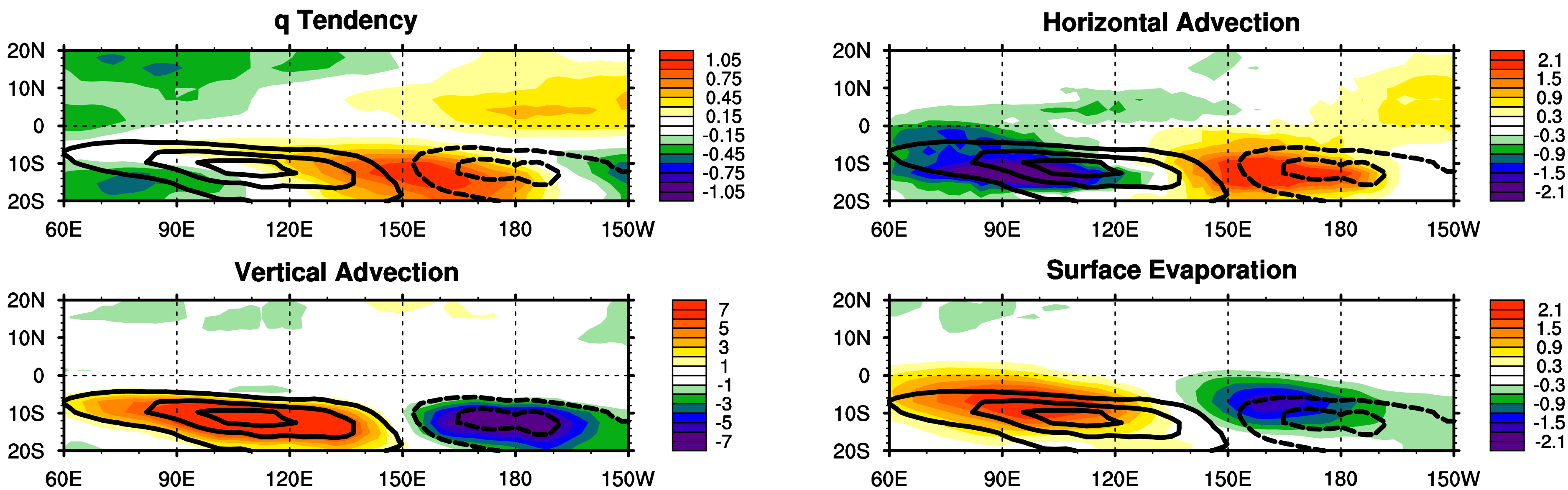


SP-CAM



What Is Supporting Water Vapor Anomalies in the Model, and What is Moving Them Eastward?

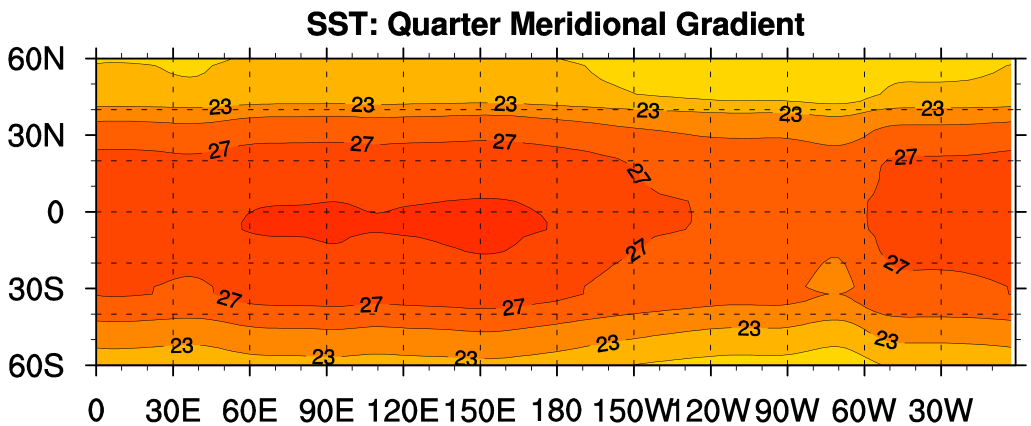
Precip (Contour) and q Budget Terms: Phase 5 (Vertical Integral)

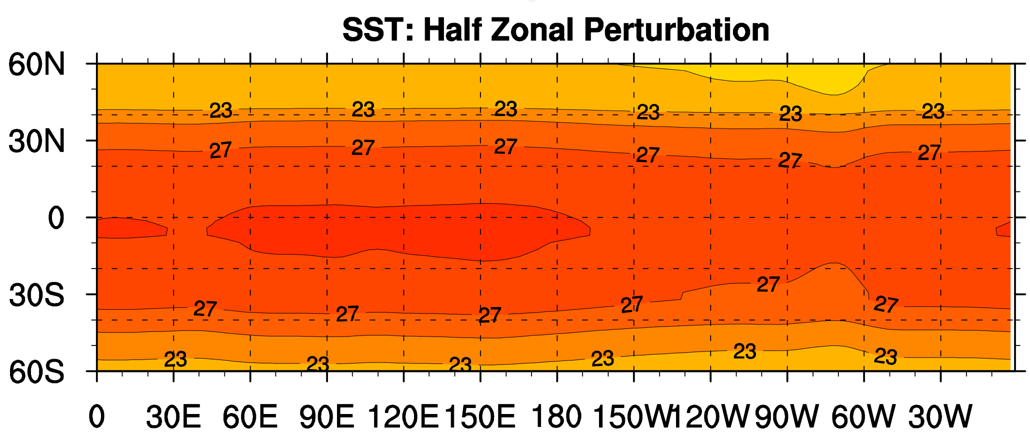


$$\left\langle \frac{\partial q}{\partial t} \right\rangle \approx -\langle q \nabla \cdot \vec{v} \rangle - \langle \vec{v} \cdot \nabla q \rangle + E - P$$

- 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

What Happens When We Weaken the Background Zonal (East-West) Winds?

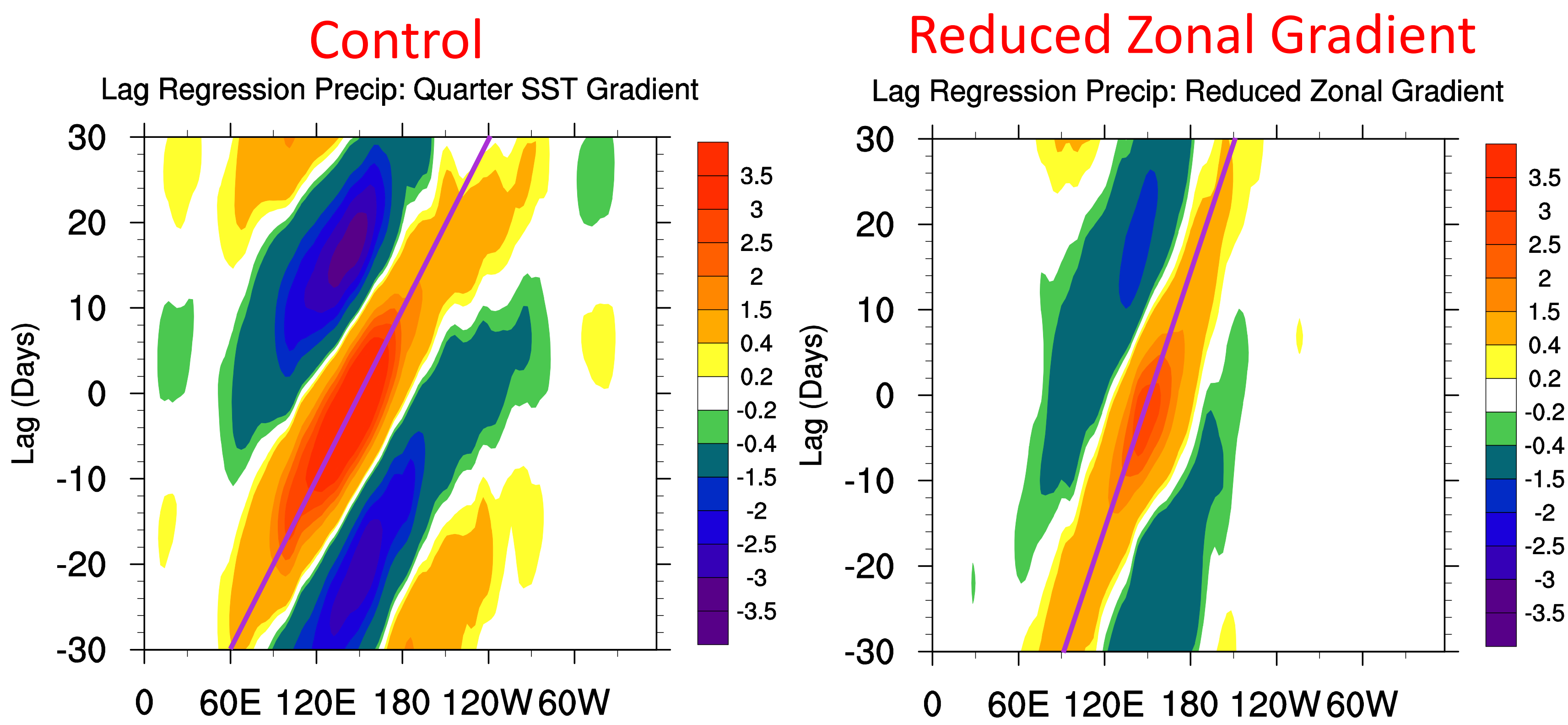




- East-west gradients in SST are reduced by ½,
- This approximately reduces the strength of low-level westerly winds in the warm pool by ½.
- We hypothesize that this should slow down the model MJO propagation speed

Maloney et al. (2010)

Propagation of Signals Along Equator is Slowed with Reduced Background West Winds

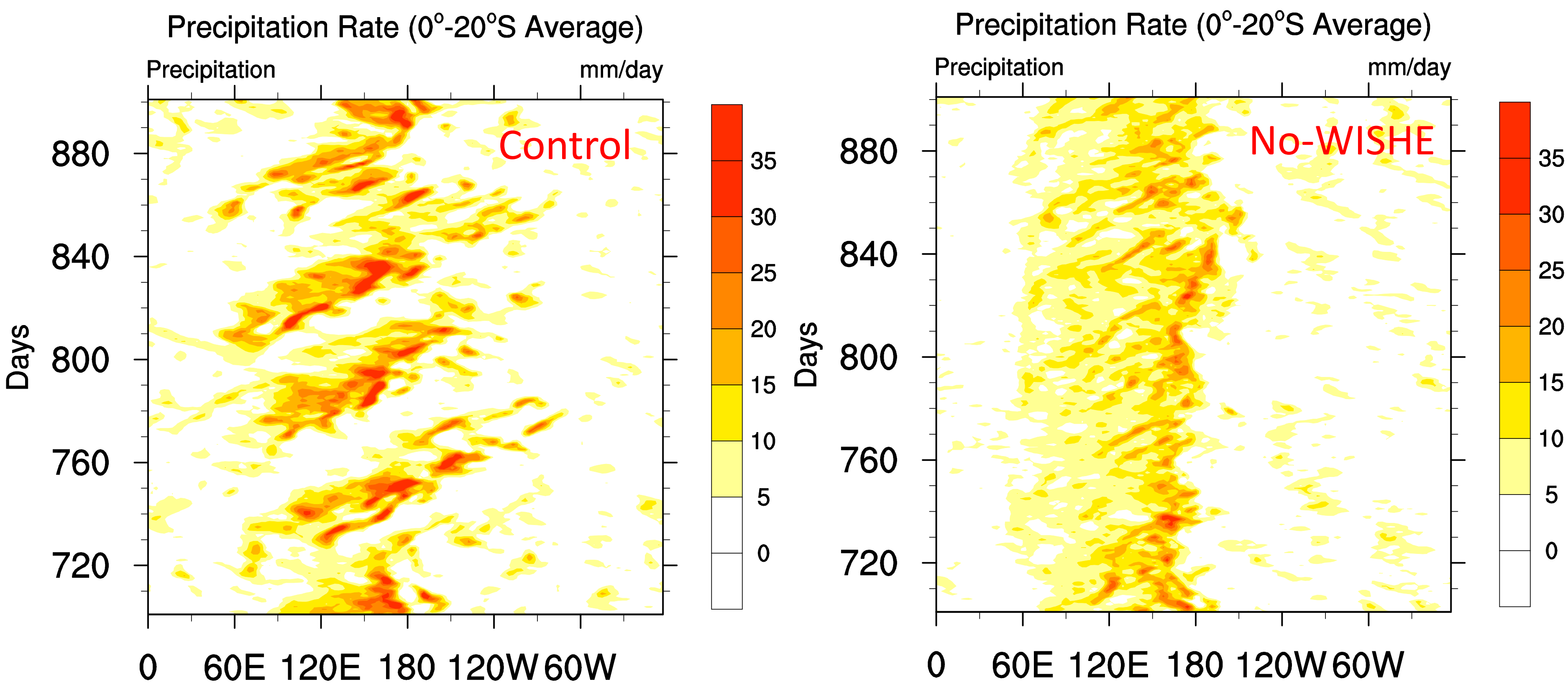


- Propagation speed slowed from 4-5 m s^{-1} to about 2.5 m s^{-1} in going to the simulation with reduced zonal gradient and reduced westerlies.

Further Sensitivity Tests

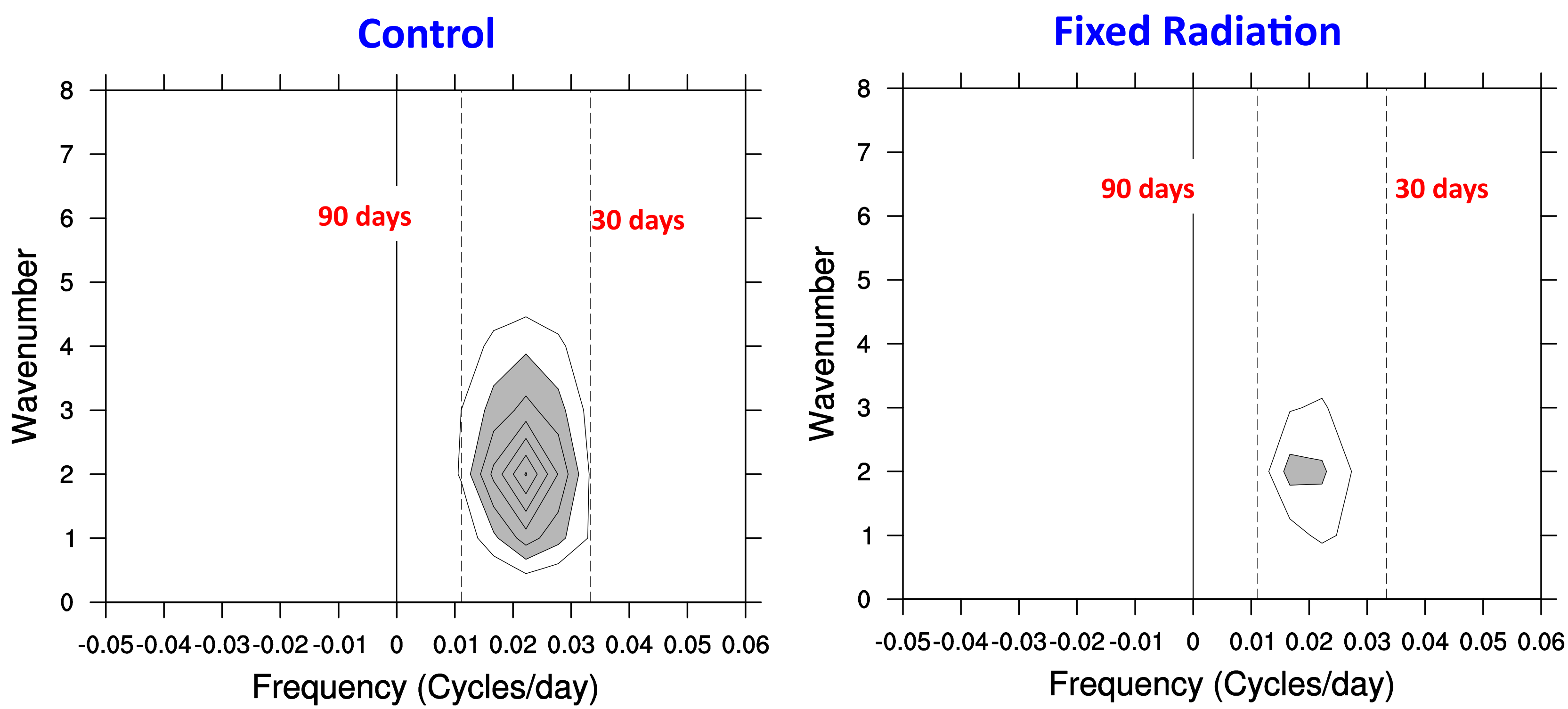
- It was shown before that a positive covariance exists between anomalous precipitation and surface evaporate fluxes in the model MJO
- We hypothesized before that this extra vapor source provided by surface evaporation anomalies may be able to destabilize the model MJO (support and/or grow water vapor anomalies in convective regions), as long as model convection is not too effective at drying the atmosphere
- We will fix surface evaporative fluxes to their climatological mean and not allow them to vary to test the importance of this hypothesis.
- We will also do the same for radiative heating

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

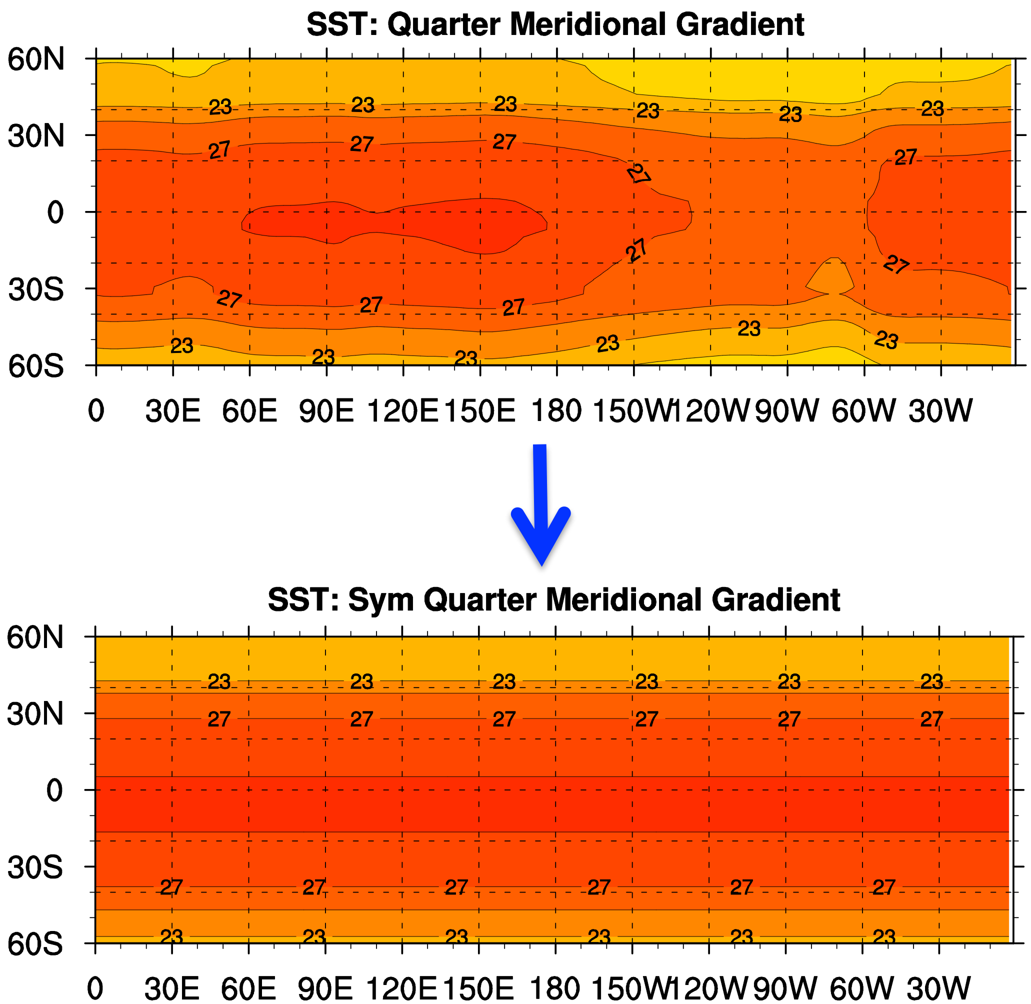
Effect of Prescribing Radiative Heating



Cloud-radiative feedbacks contribute to destabilization of the MJO in the model, although the spatial structure and propagation characteristics are the same.

Landu and Maloney (2011)

Can a Zonally Symmetric Simulation Produce a Realistic MJO?

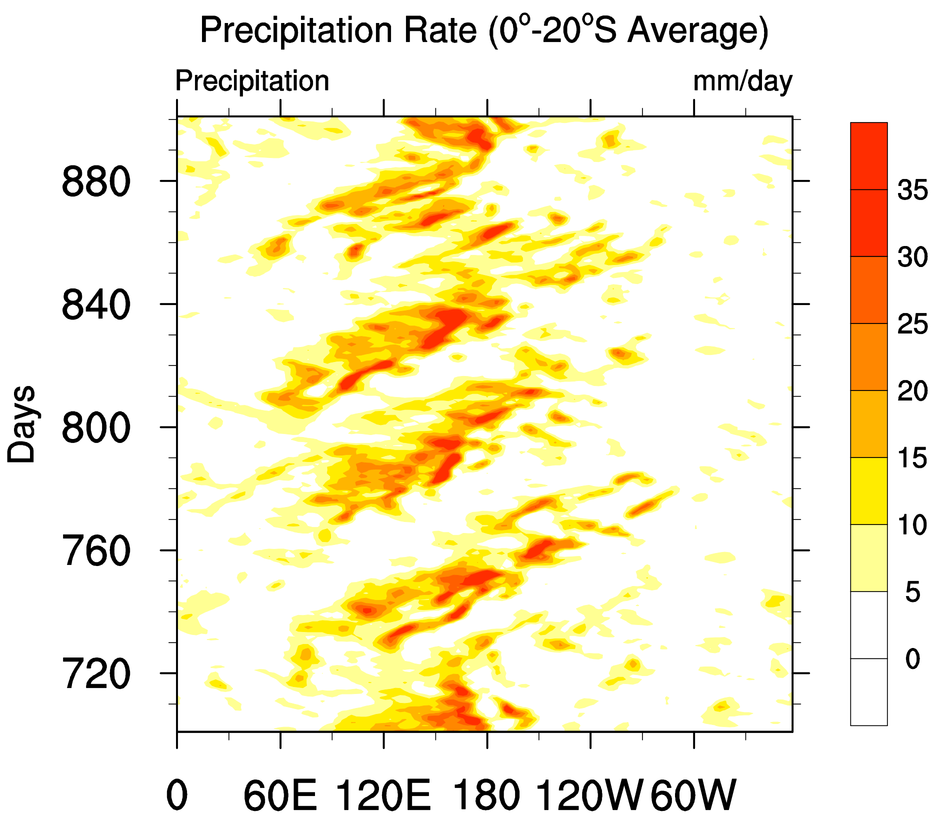


- SST at every longitude is equal to that over the warm pool from the control simulation
- Now, low-level winds in the tropics are easterly everywhere, and do not contain a region of westerlies like in the control simulation

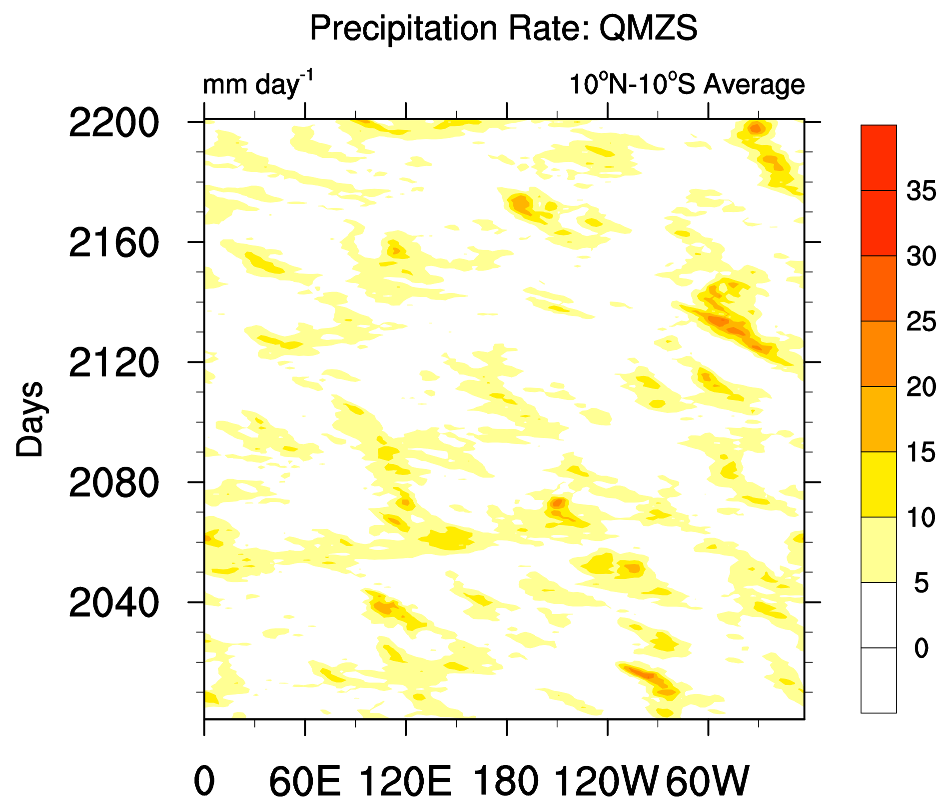
Landu and Maloney (2011)

Can a Zonally Symmetric Simulation Produce a Realistic MJO? Not in this Model

Control



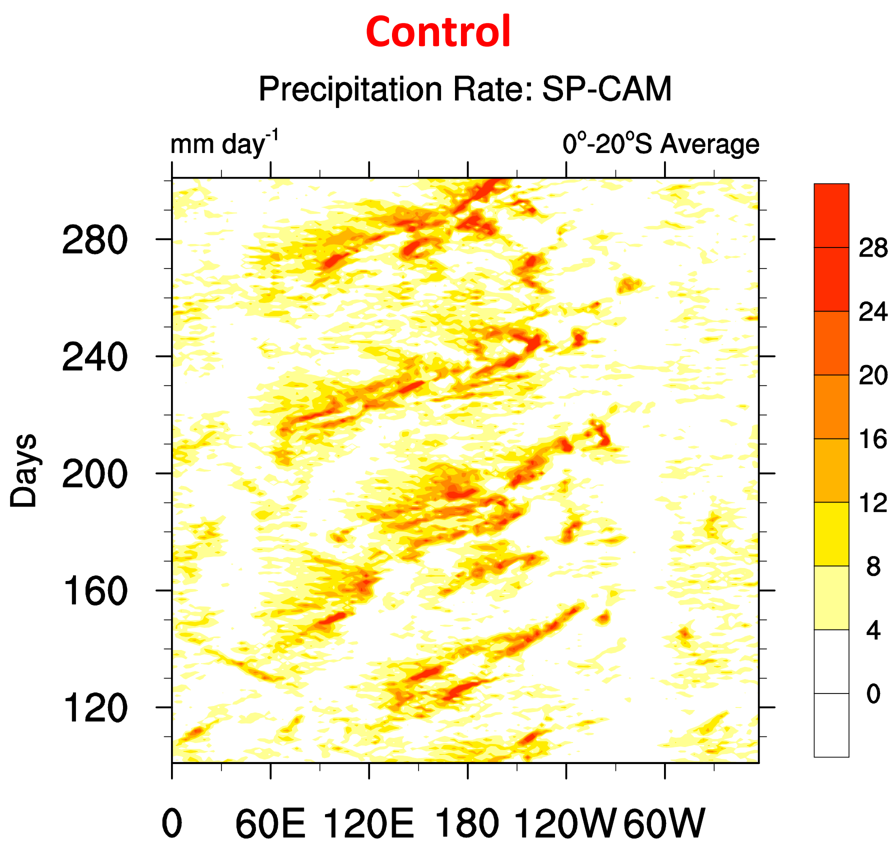
Zonally Symmetric

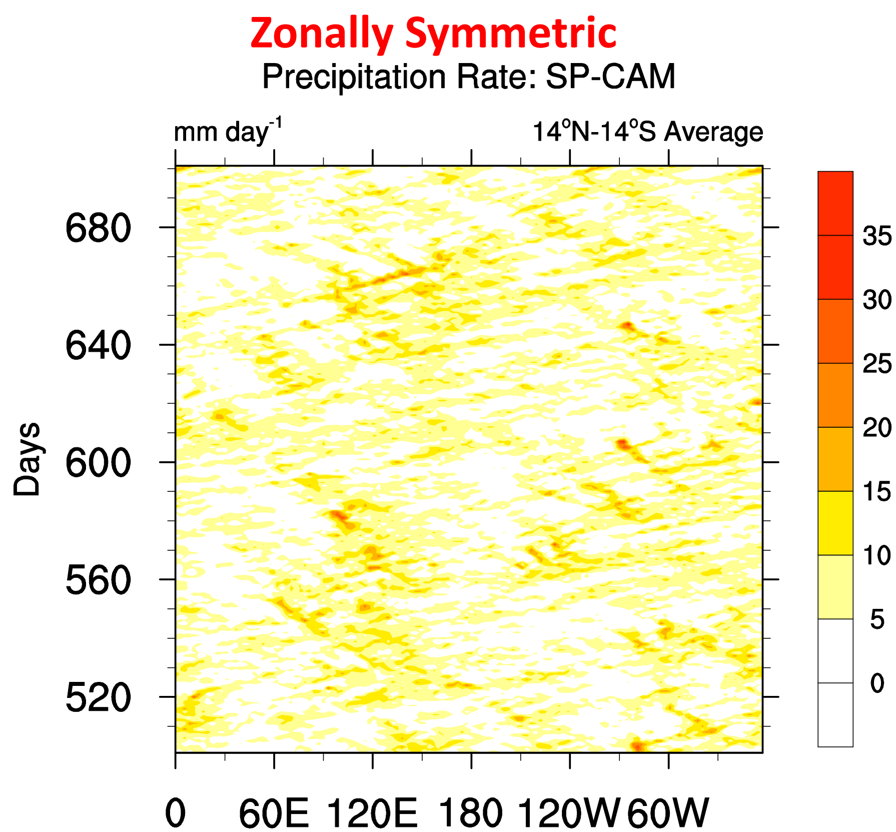


- Suggests importance of basic state westerlies to destabilization and propagation characteristics in the model

Landu and Maloney (2011)

How About SP-CAM?

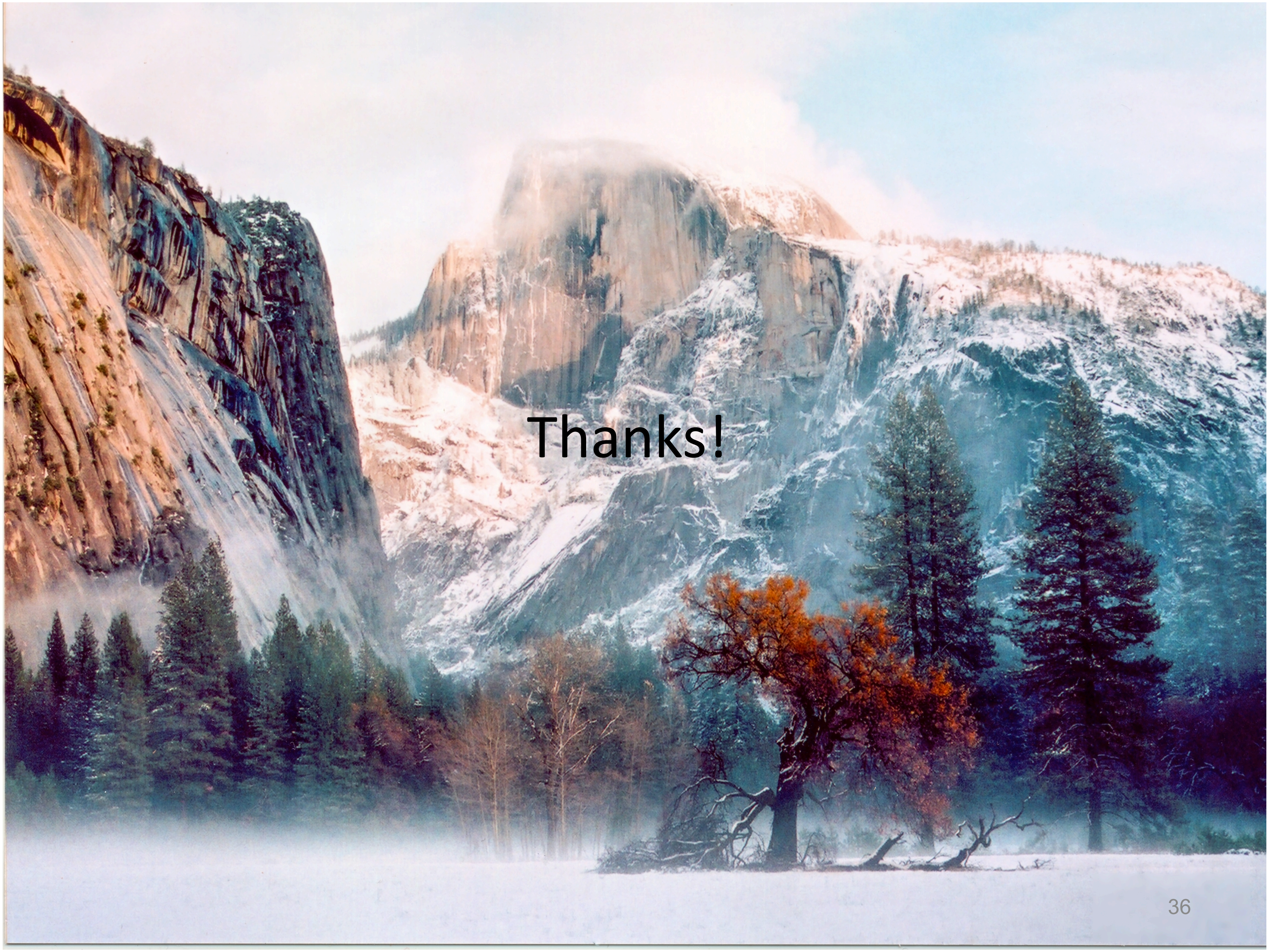




SP-CAM similarly has a problem producing robust intraseasonal variability with a zonally-symmetric SST distribution.

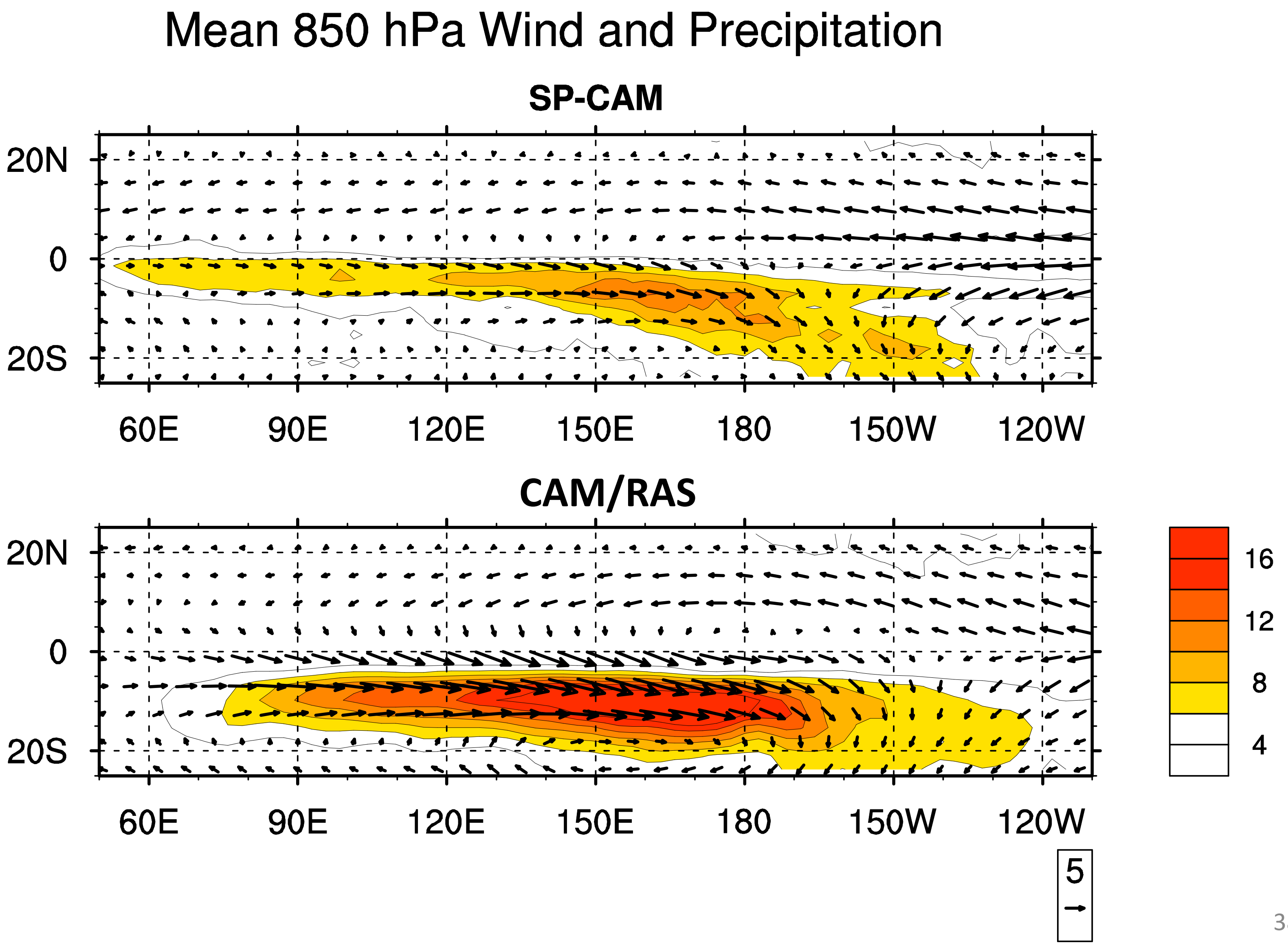
Summary

- Upcoming DYNAMO field program to study MJO initiation
- Modeling studies suggest that MJO is destabilized by wind-evaporation feedbacks and cloud-radiative feedbacks, and eastward propagation is aided by horizontal moisture advection
- Model MJO resembles “moisture mode”
- Zonal asymmetry needed to produce realistic MJO simulation

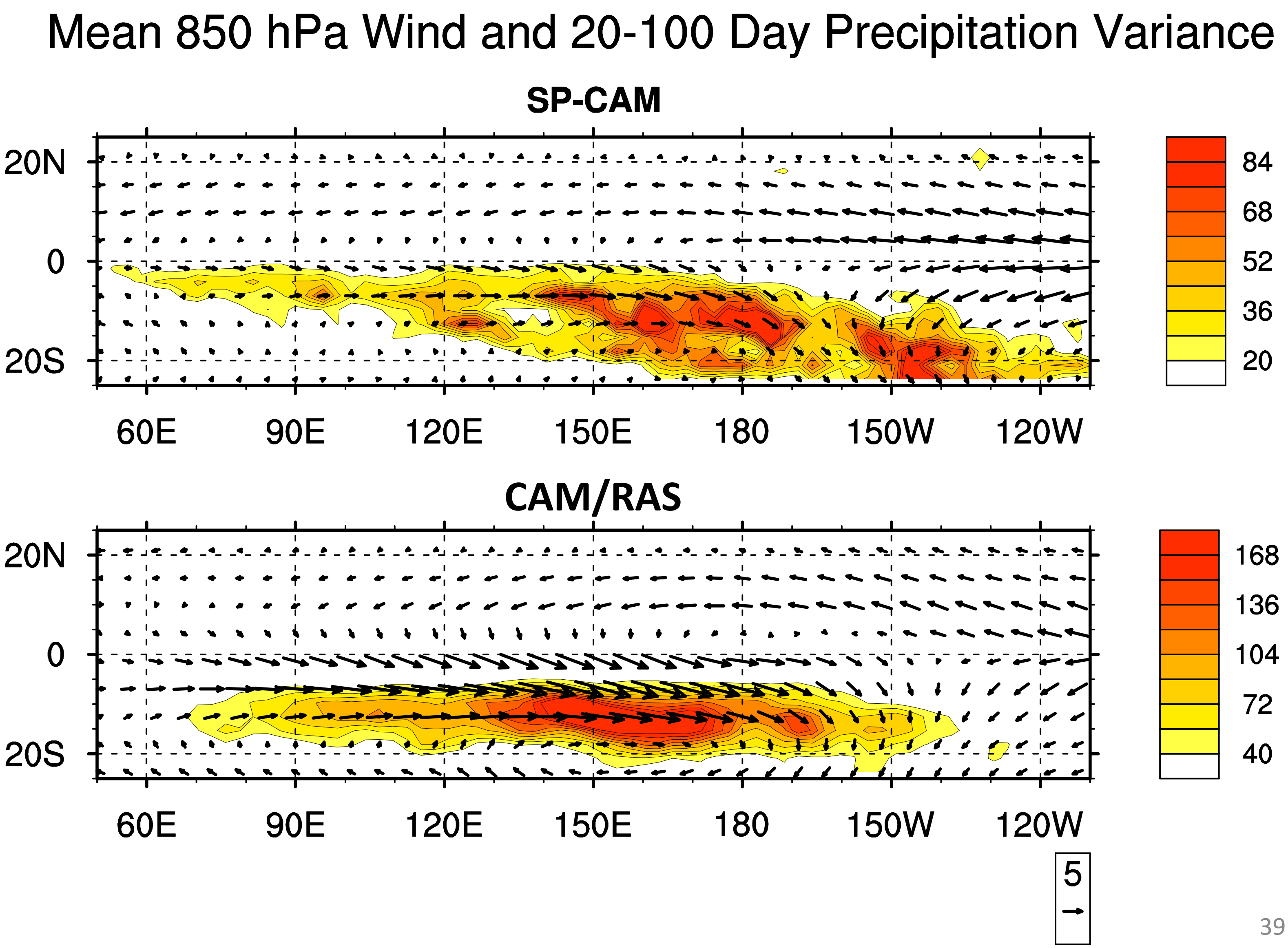

Thanks!

Extra Slides

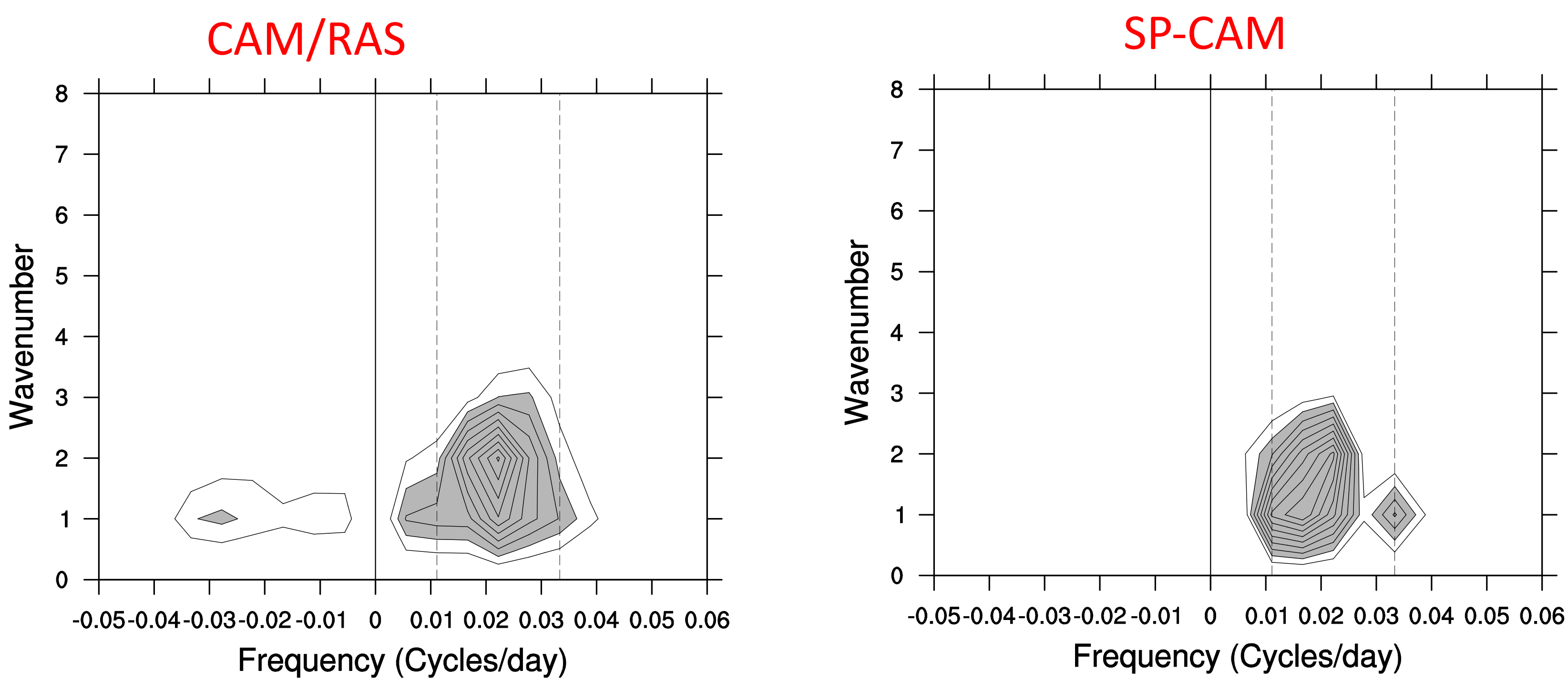
Mean Precip and 850 hPa Winds



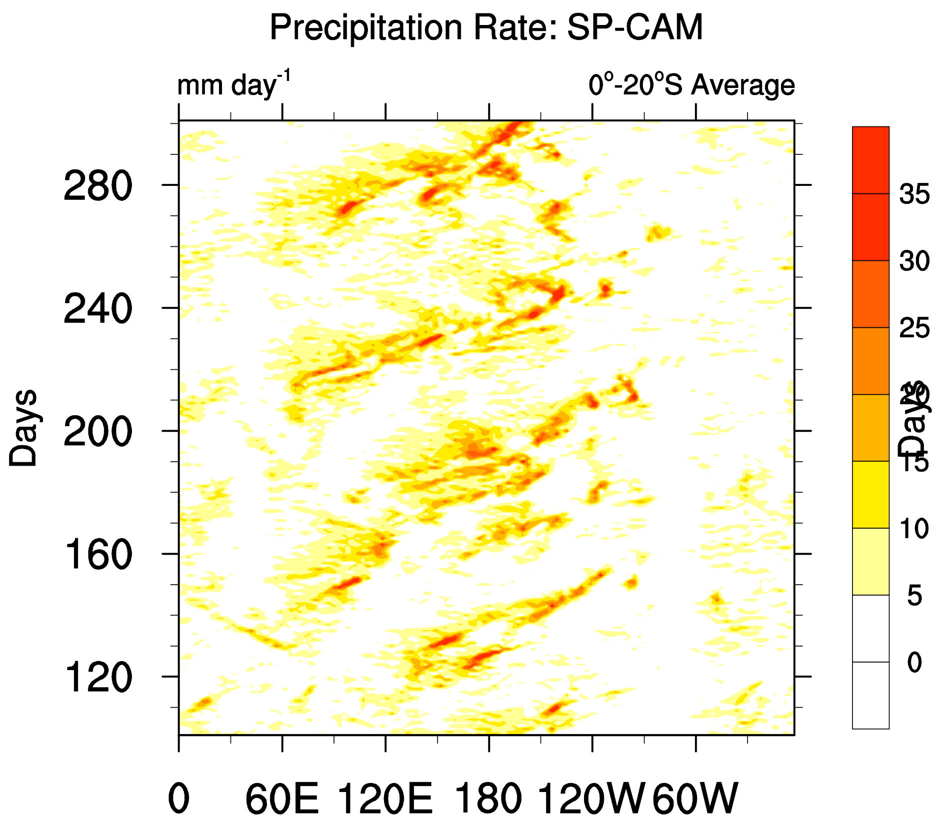
20-100 Day Precip Variance

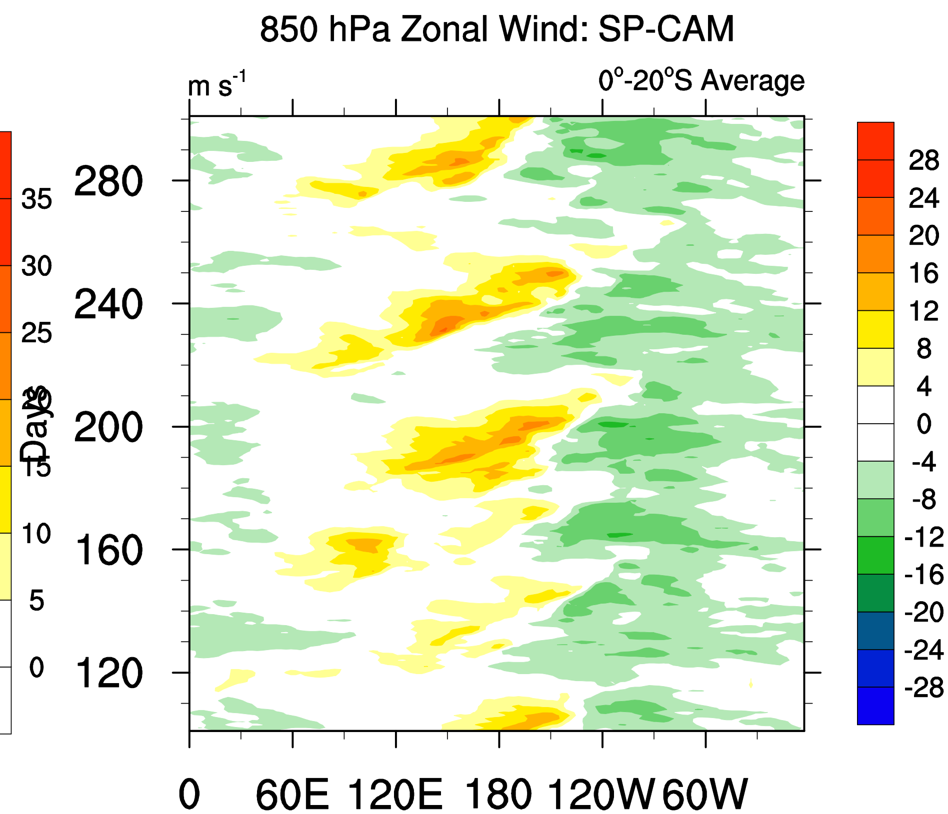


Wavenumber-Frequency Spectra (U850)



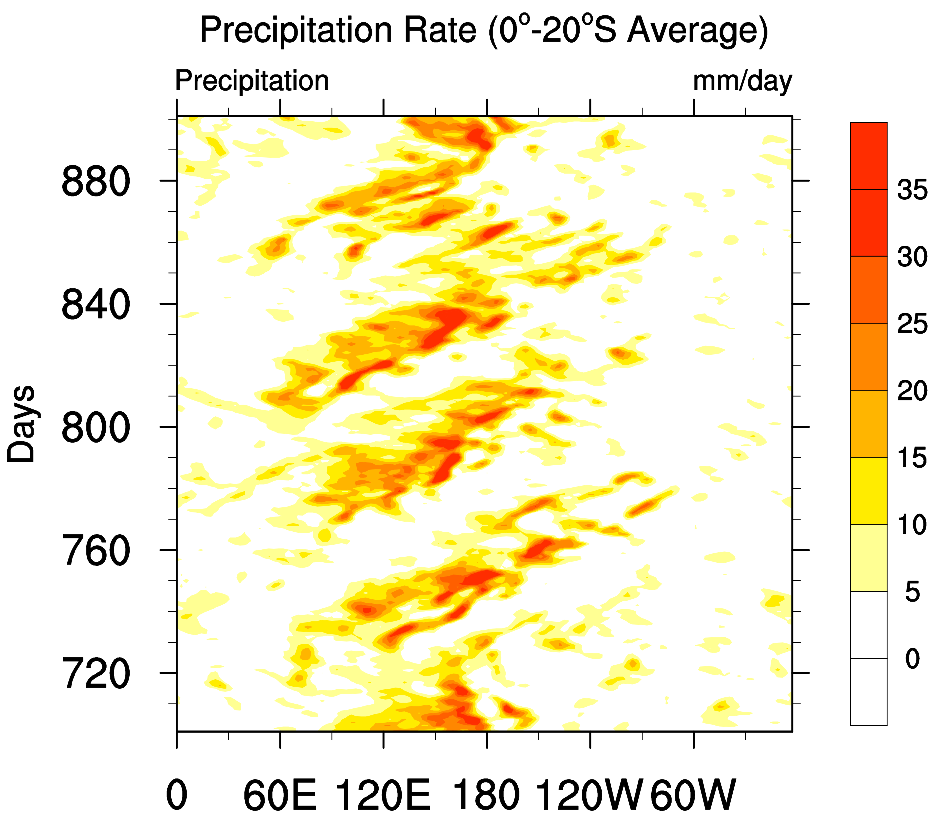
SP-CAM: Unfiltered Precipitation and Winds vs. Longitude



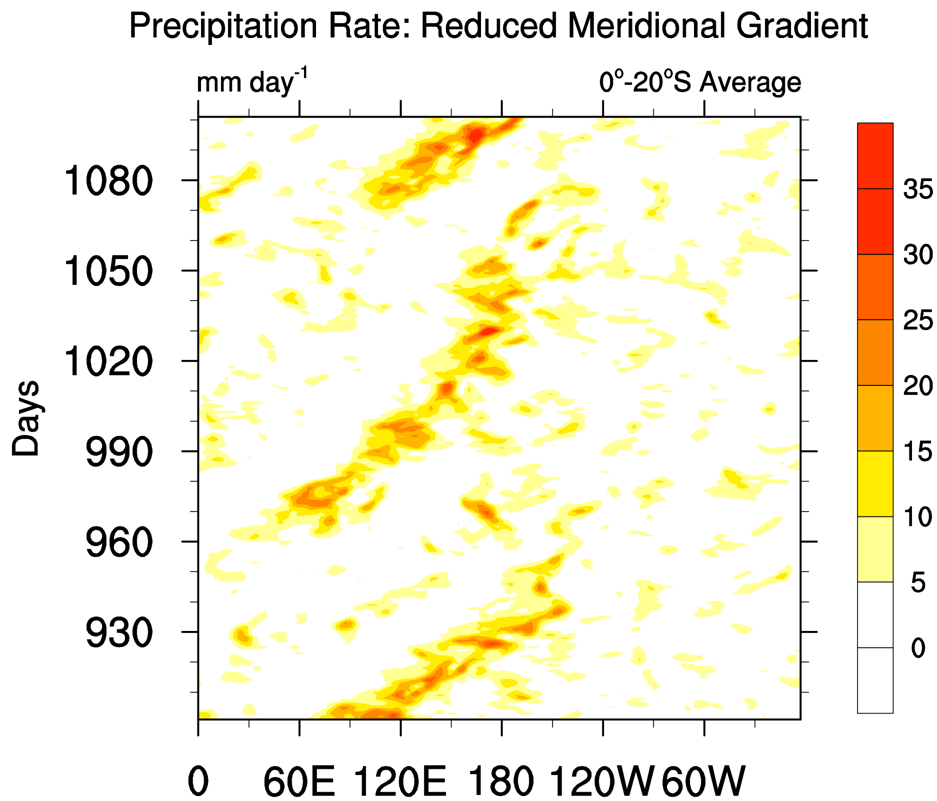


Effect of Reduced Westerly Basic State

Control



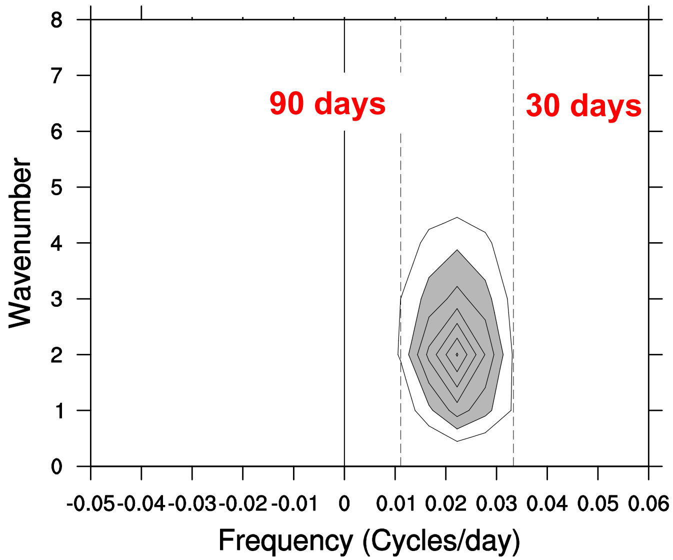
Reduced Zonal Gradient



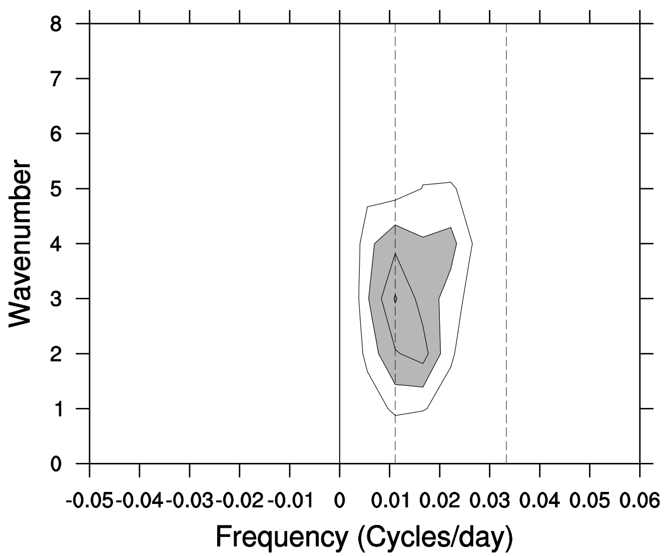
- Get the sense right away that eastward propagation is slower when the basic state westerlies are changed, supporting the role of $-(u' + \overline{u})\frac{\partial q'}{\partial x}$ in eastward advection.

Effect of Reduced Westerly Basic State

Control



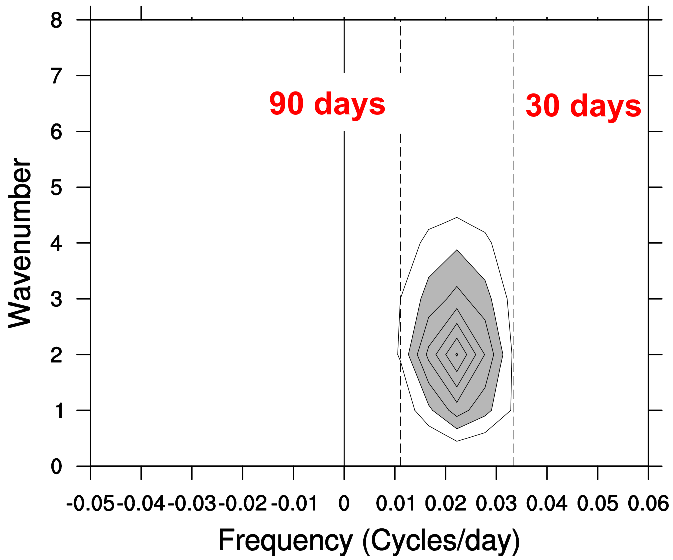
Reduced Zonal Gradient



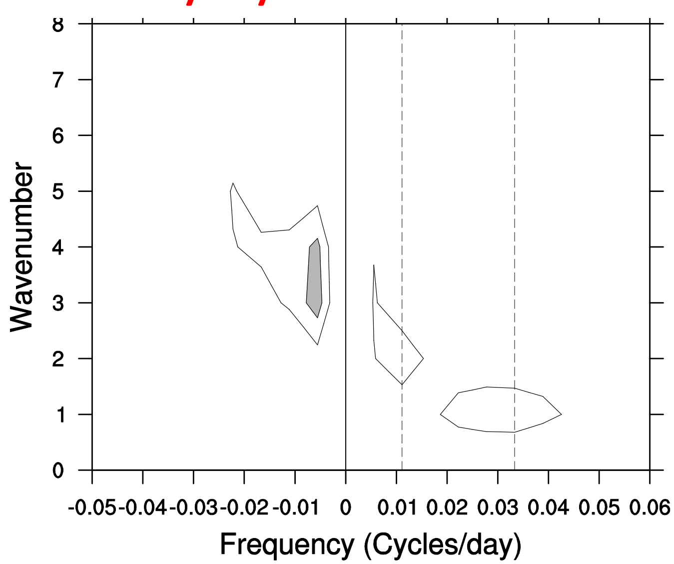
- Consistent with the slowing of eastward propagation suggested in the previous plot, the space time-spectrum of precipitation still indicates a concentrated spectral peak, but now it occurs near 100 day period rather than 40-50 days.

Zonally Symmetric Model

Control



Zonally Symmetric Model



- MJO variability strongly decreases, consistent with the importance of mean westerlies for producing realistic phase relationship between precipitaiton and latent heat flux.
- Faster propagation