Convective self-aggregation and the Madden-Julian oscillation

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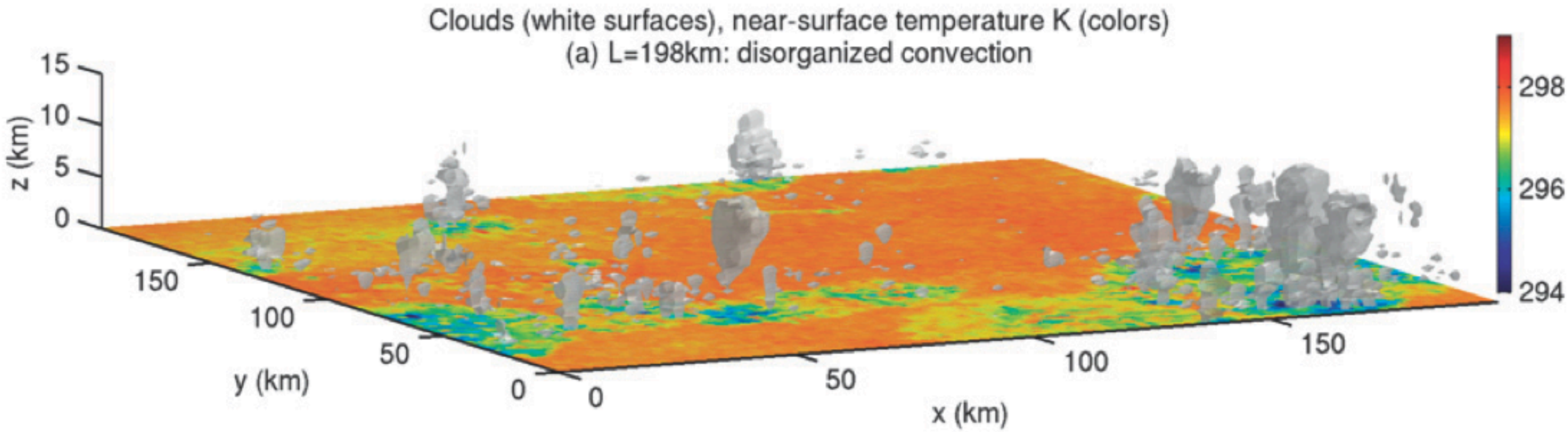
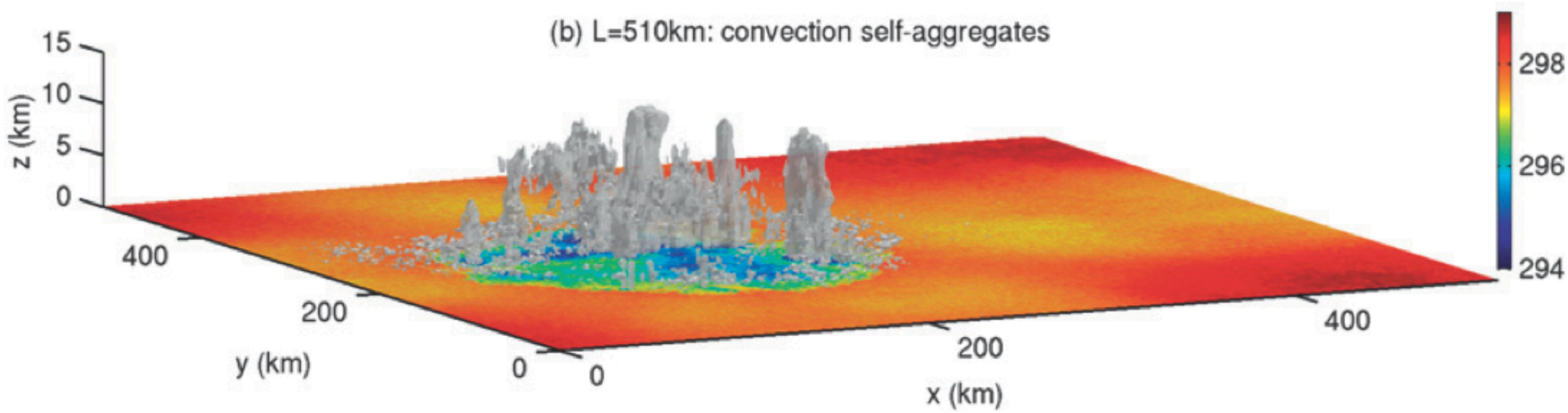
Convective Aggregation in Cloud Permitting Models



Muller and Held 2012

Expectation: random popcorn convection in Radiative-Convective Equilibrium (RCE) state.

Convective Aggregation in Cloud Permitting Models



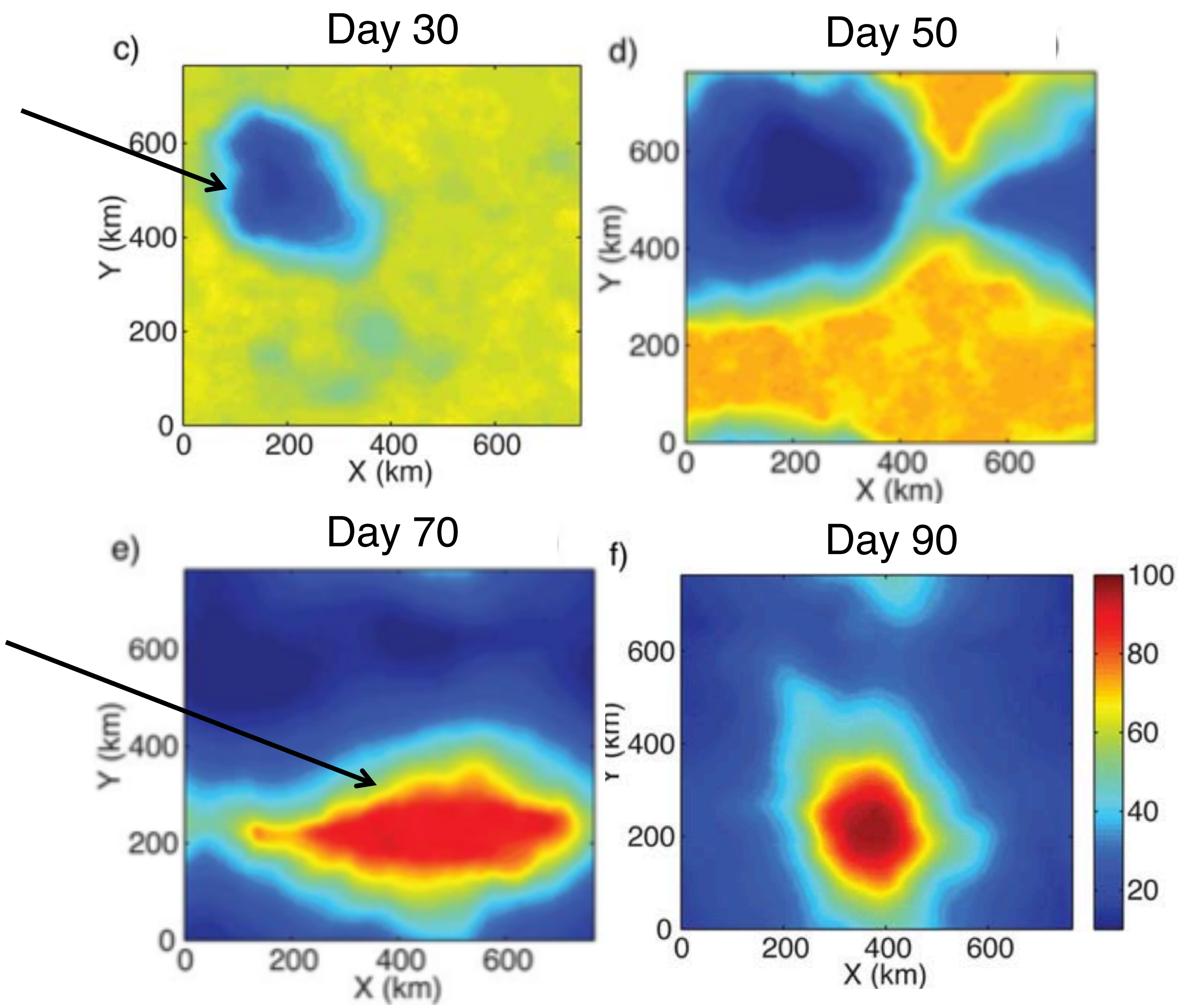
Muller and Held 2012

Under some conditions, convection aggregates into single humid region.

Convective Aggregation in Cloud Permitting Models

- Aggregation typically begins with dry patch.

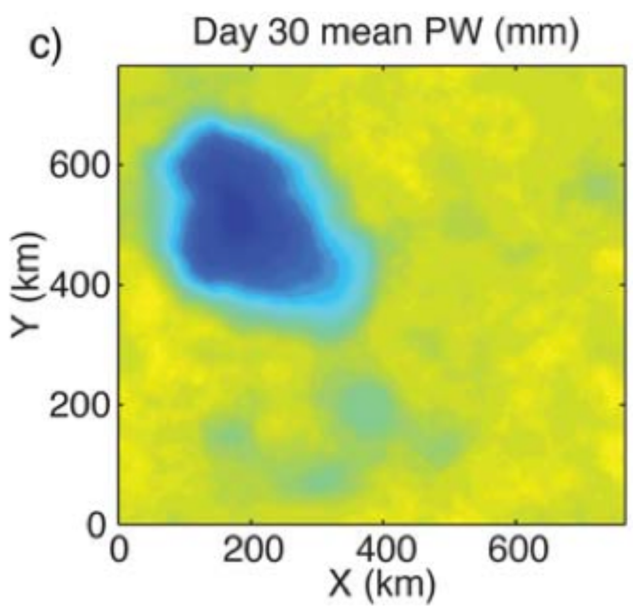
Dry patch expands, and feedbacks drive convection into an isolated moist region.



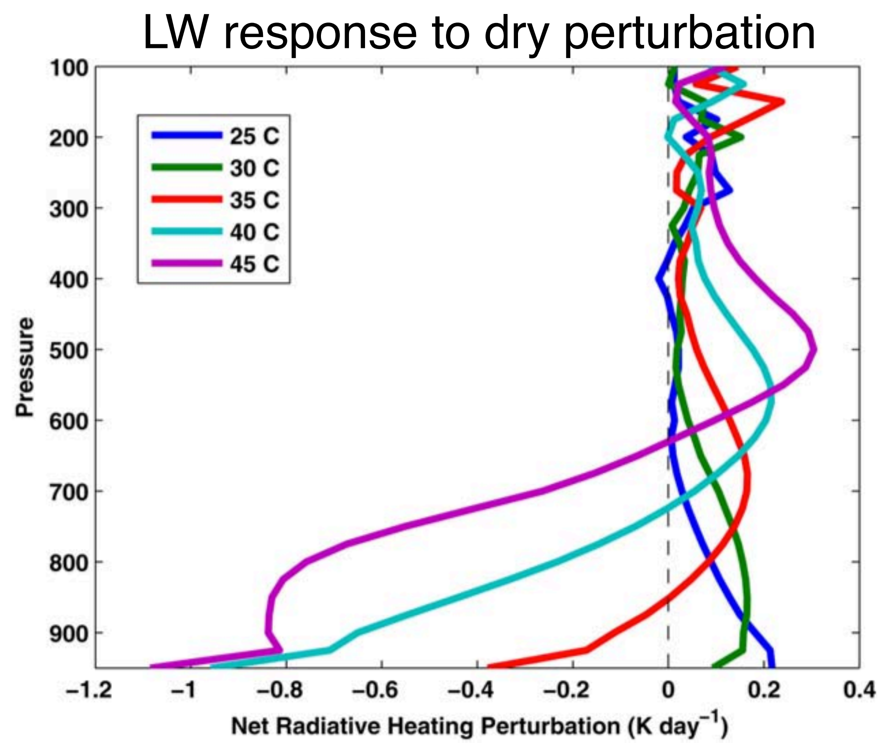
Wing and Emanuel 2014

Triggered by clear-sky radiative instability?

Emanuel et al: initial instability is a clear-sky radiative feedback.



Wing and Emanuel 2014

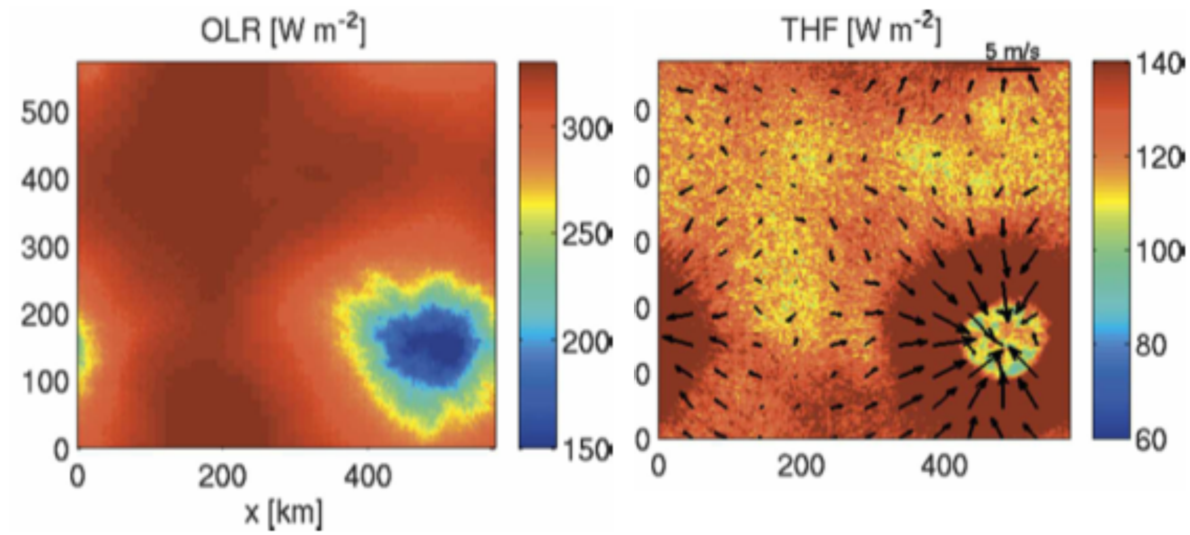


Emanuel et al., 2014

Temperature dependent!
Critical temperature is 30-35°C.

Diabatic feedbacks are generally required

Bretherton et al 2005:
turn off either interactive longwave or surface fluxes, and aggregation doesn't occur.



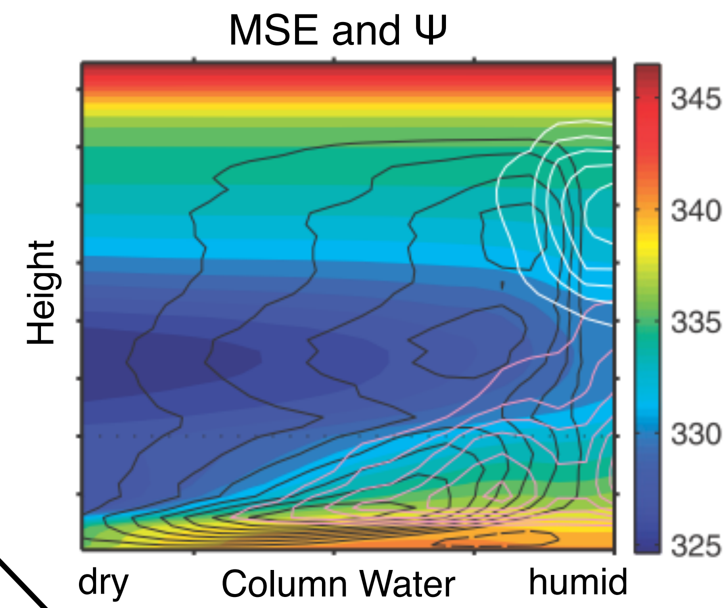
In other studies, surface flux feedback can be optional.

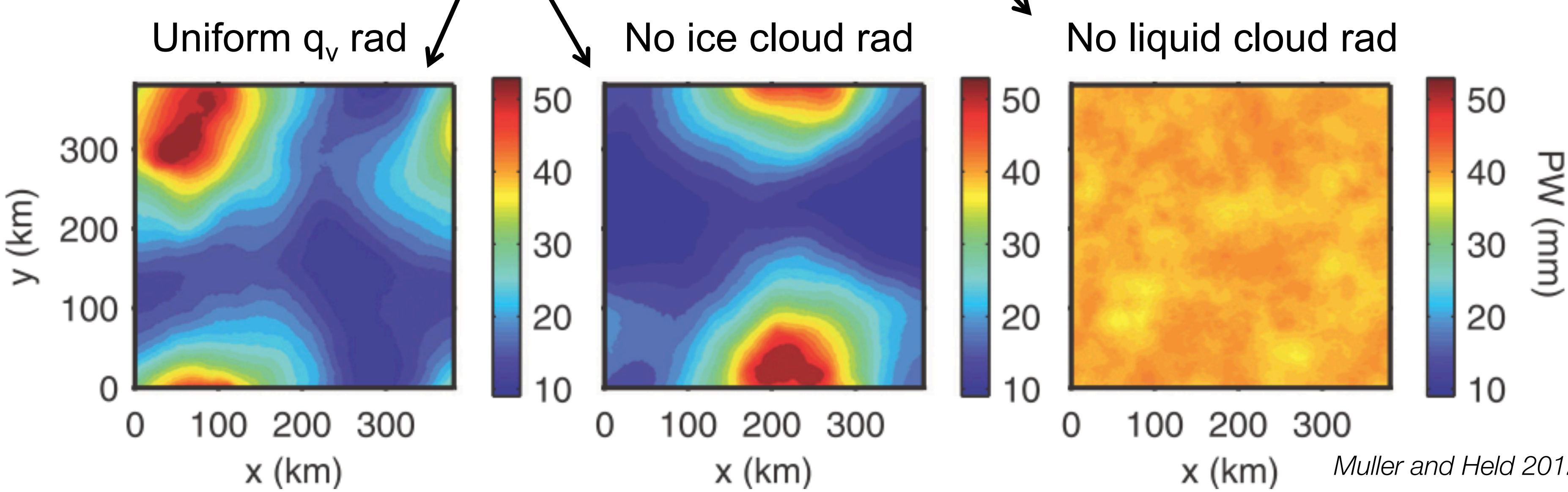
Longwave associated with high clouds in convecting region.

Bretherton et al 2005

Radiative effect of low clouds also essential?

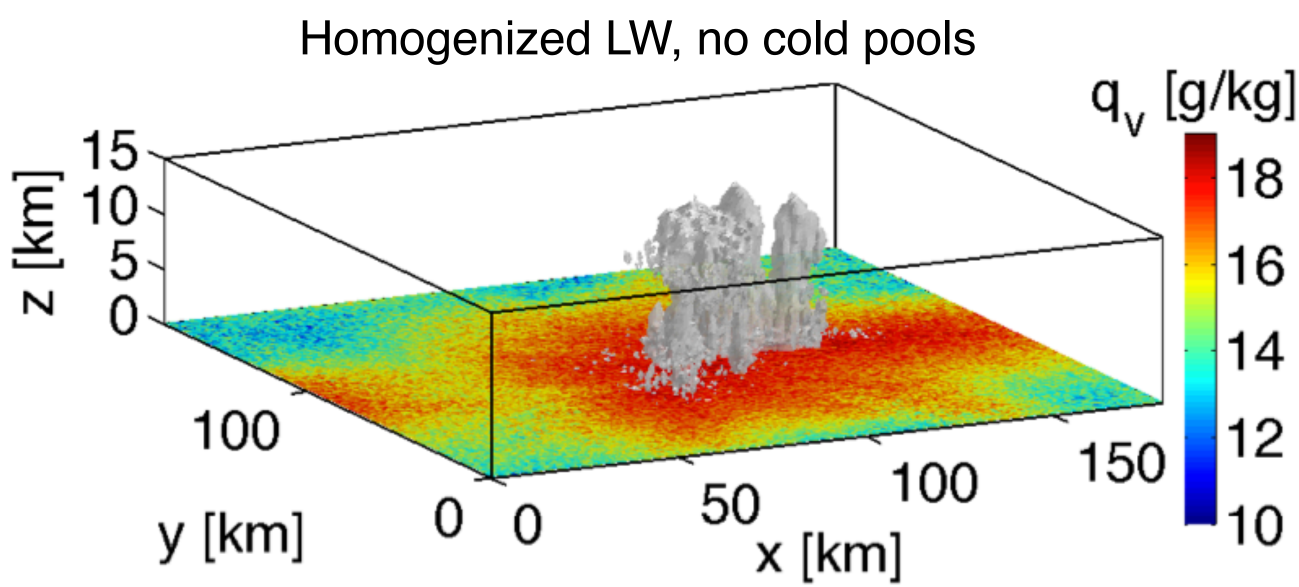
- Shallow circulation transports MSE up-gradient, driven by **low clouds.**
- If low cloud rad removed, no aggregation!
- Clear-sky and high clouds apparently less important.





Muller and Held 2012

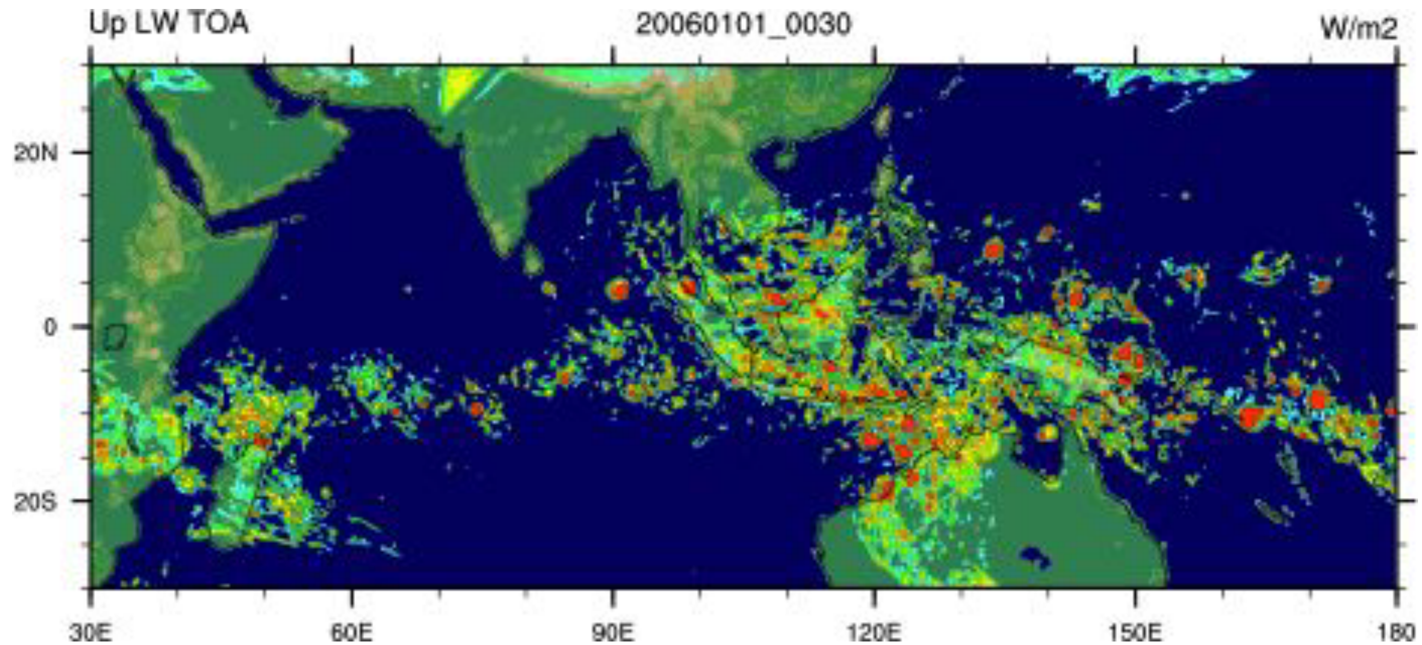
Anti-social cold pools



Muller and Bony 2015

Without cold pools, aggregation doesn’t require LW feedback:
“Moisture memory”

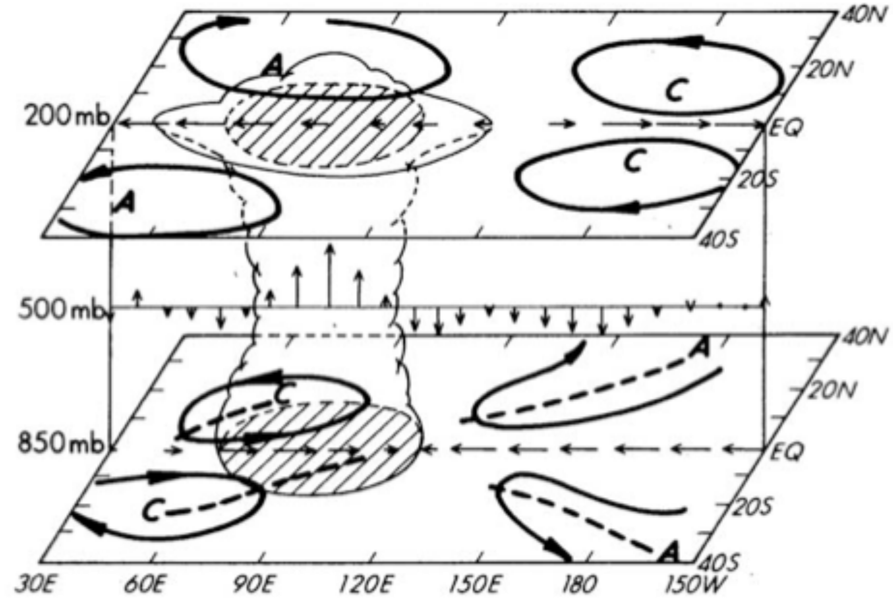
Aggregation in nature?



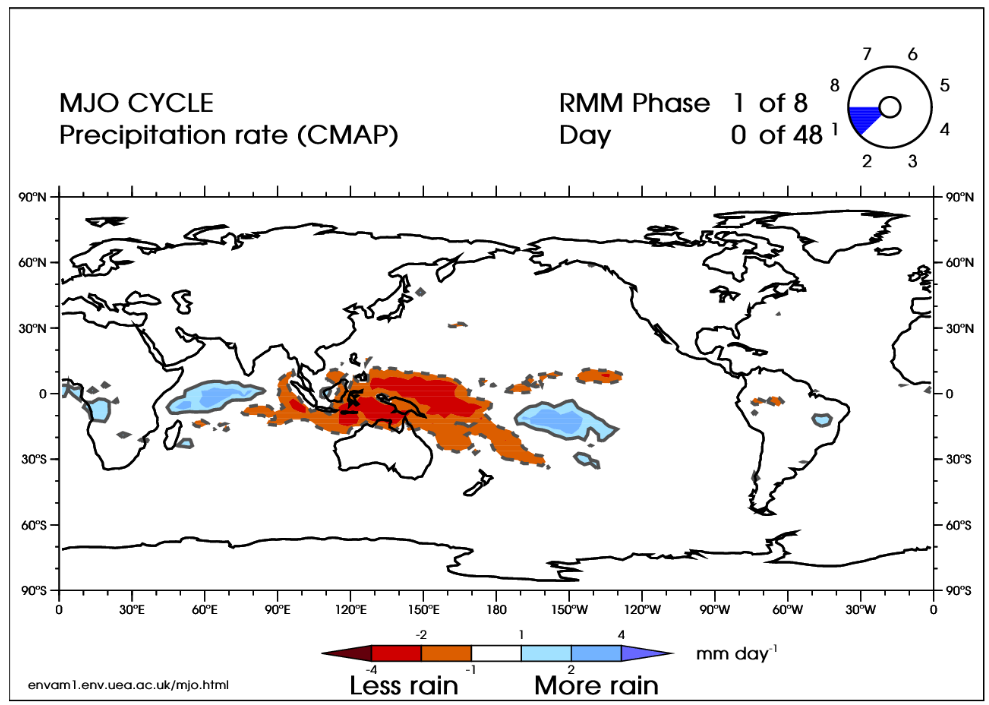
- Limited evidence for mesoscale aggregation as seen in CRMs
- Time-scale for aggregation is long; most mesoscale systems would be sheared apart in the real world.
- Aggregation processes as tendencies for/against clumping?

The Madden-Julian Oscillation (MJO)

(an example of aggregation?)

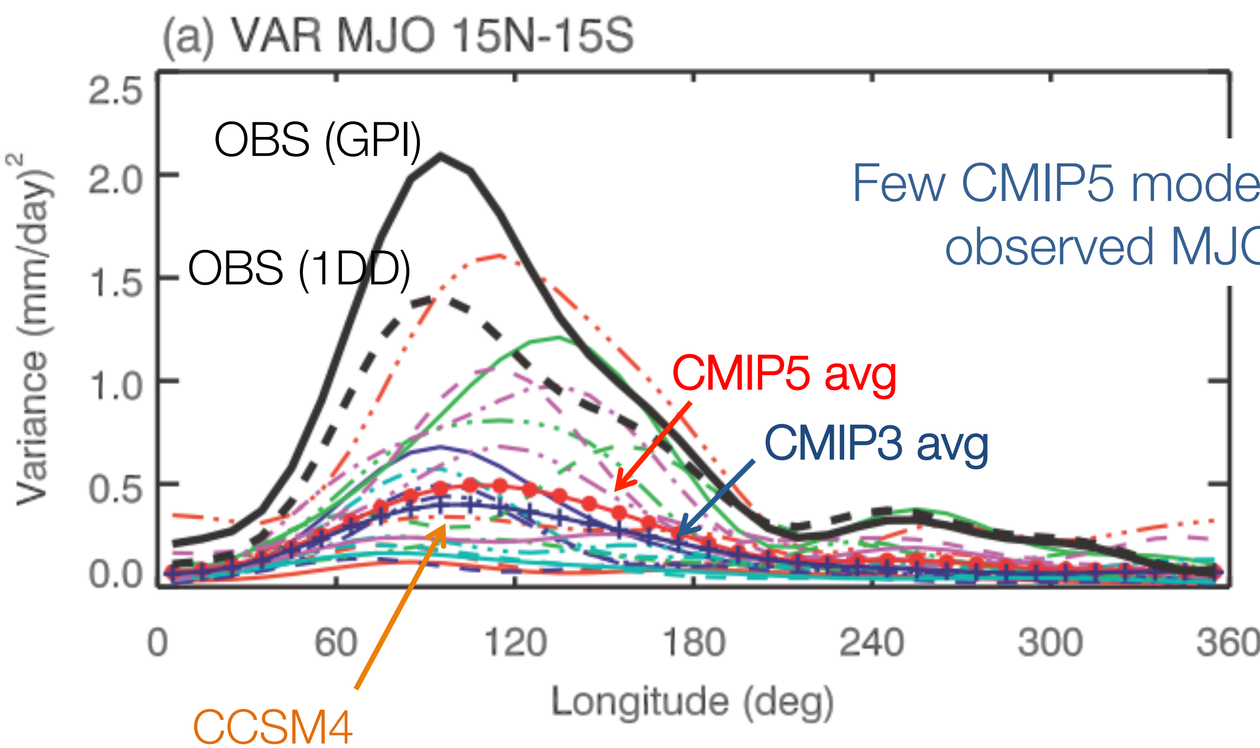


- Large-scale disturbance of wind and precipitation with ~50-day timescale.
- Forms episodically over Indian ocean, propagates eastward at 4-6m/s.
- Region of enhanced convection coupled to suppressed regions through large-scale circulation.
- Poorly understood.



Matthews 2013

MJO is poorly understood, poorly simulated in GCMs



Few CMIP5 models are close to observed MJO variance

Hung et al (2013)

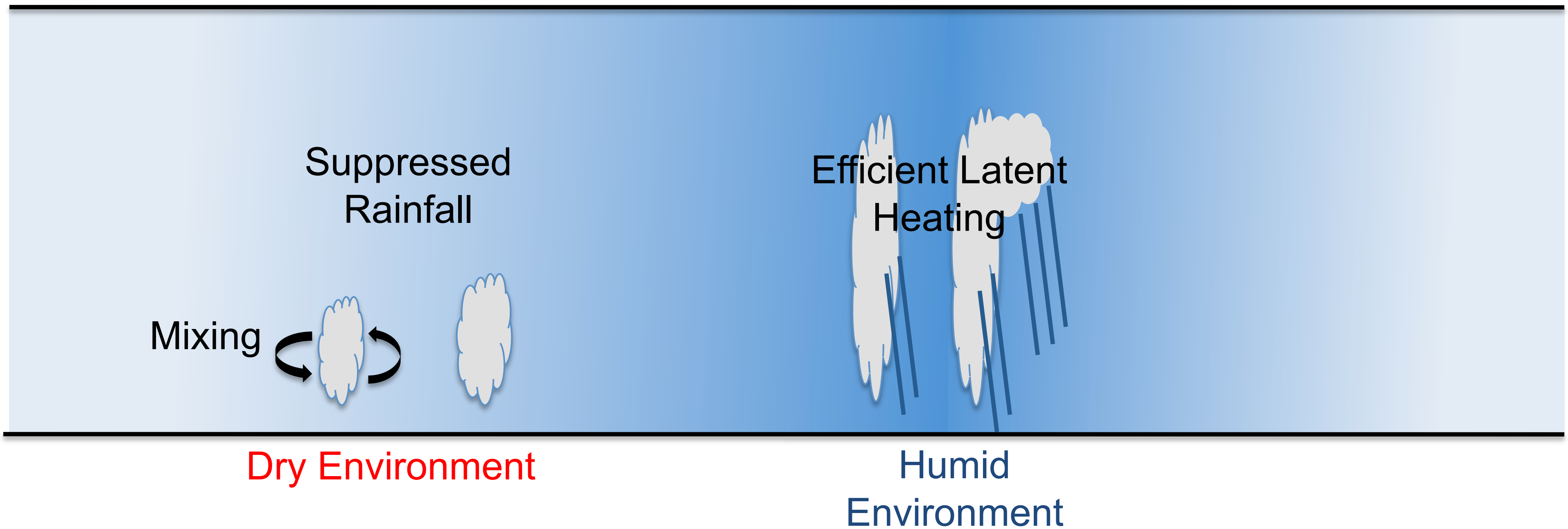
MJO is effectively nonexistent in most models

The Holy Grail of Tropical Meteorology

40+ years of MJO theories…

- **W**ind-Induced **S**urface **H**eat **E**xchange
  - Emanuel (1987); Neelin et al. (1987)
- Frictional coupled K-R waves
  - Wang and Rui (1990)
- Cloud-radiative interaction
  - Hu and Randall (1994); Raymond (2001)
- Multi-scale interaction
  - Majda and Biello (2004); Liu and Wang (2011)
- Triggered convection, IG wave interference
  - Yang and Ingersoll (2014)
- Moisture mode
  - Sobel et al (2001); Bony and Emanuel (2005); Sugiyama (2009); Raymond and Fuchs (2009); Sobel and Maloney (2012)

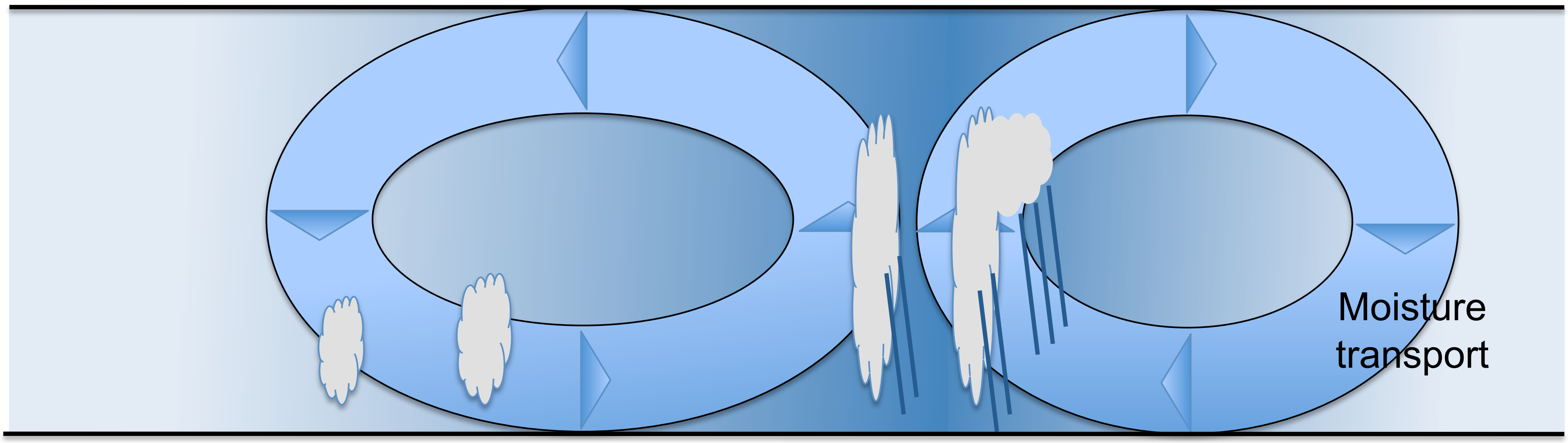
Water vapor as rainfall regulator



Efficient latent heating in humid environments.
Suppressed heating in dry environments.

e.g., Bretherton et al. 2004, Derbyshire et al. 2004

Water vapor as rainfall regulator



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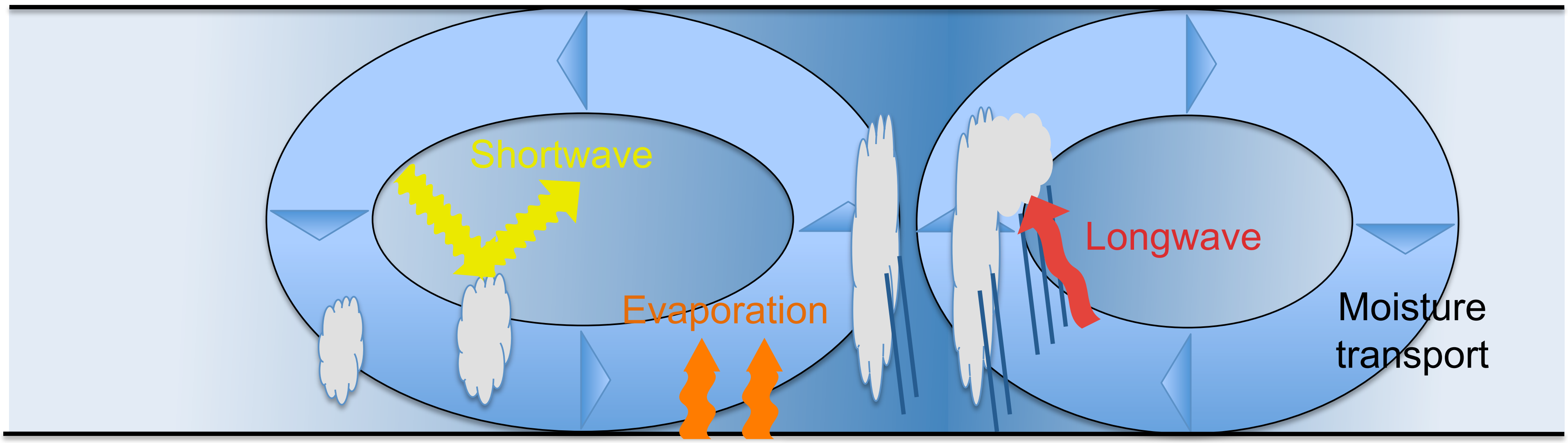
Water vapor as rainfall regulator



"Moisture mode instability" occurs when net feedbacks increase the original moisture anomaly.

e.g., *Sobel et al (2001); Raymond and Fuchs (2009)*

Looks very similar to CRM aggregation!

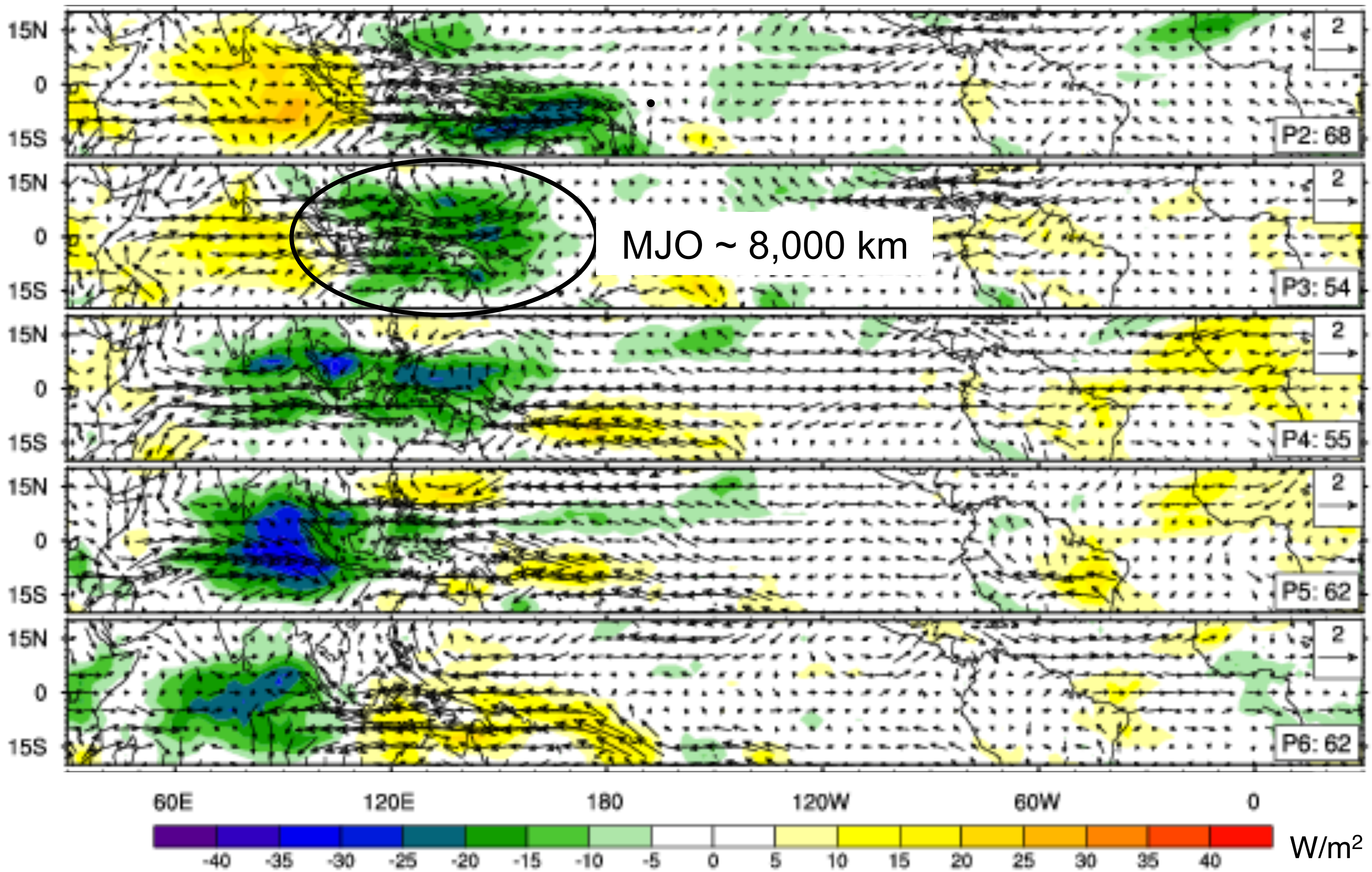
- Feedbacks amplify moisture anomalies
- Enhanced convection/rainfall co-located with moisture

On the other hand…

"There is little evidence that feedbacks between convection and moisture play an important role in self-aggregation in this model…" ~ Emanuel et al., 2014

Muller and Bony (2015) argue for separate "radiative" and "moisture memory" pathways to aggregation.

Difference in scale



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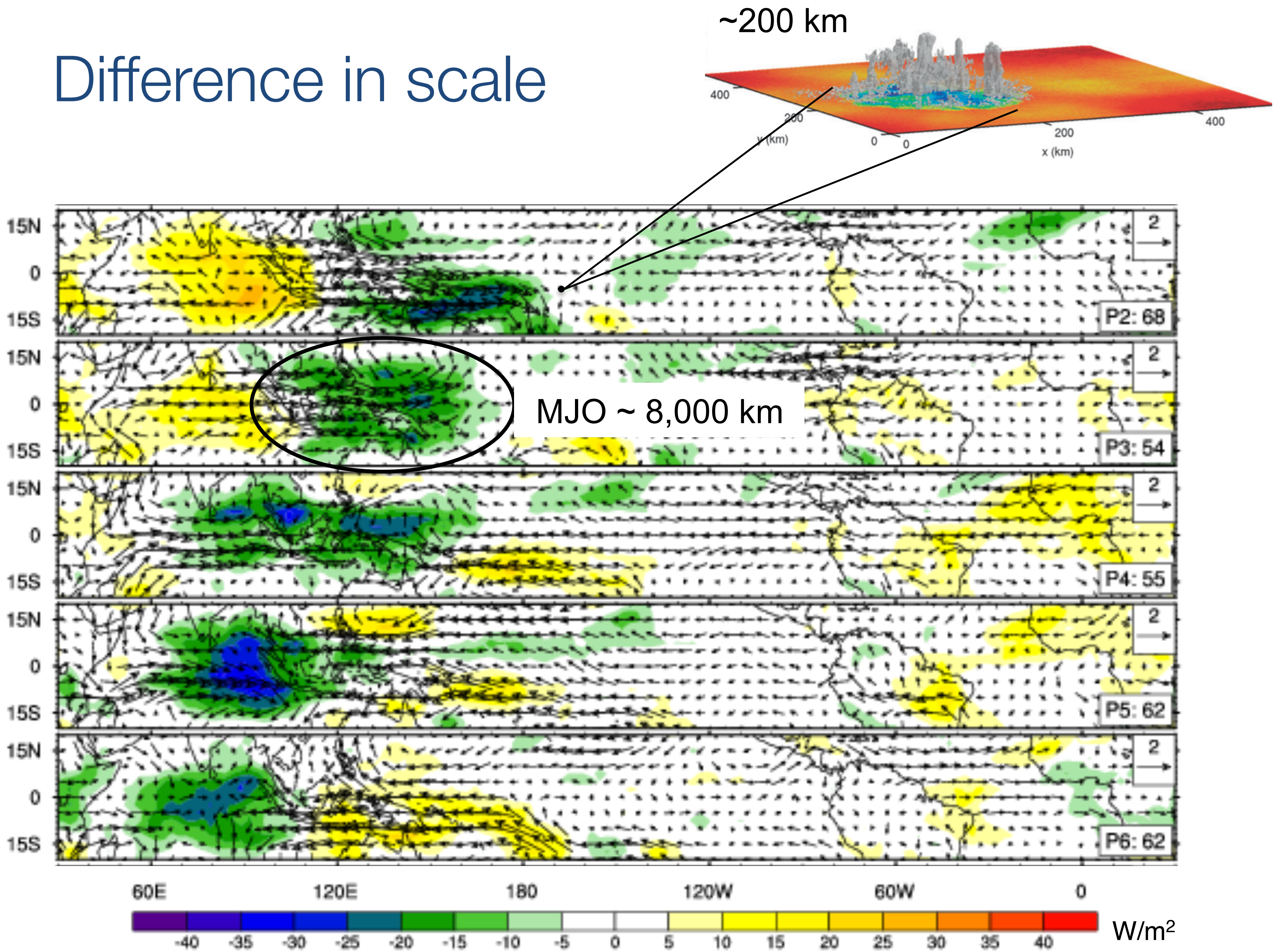
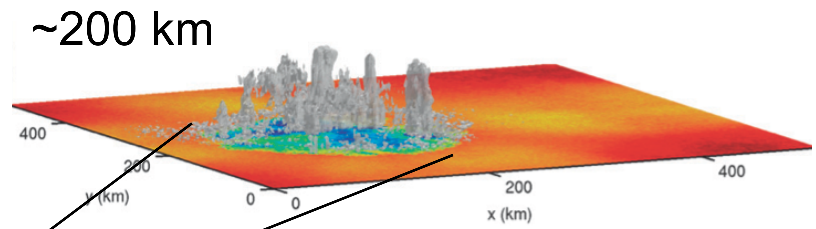
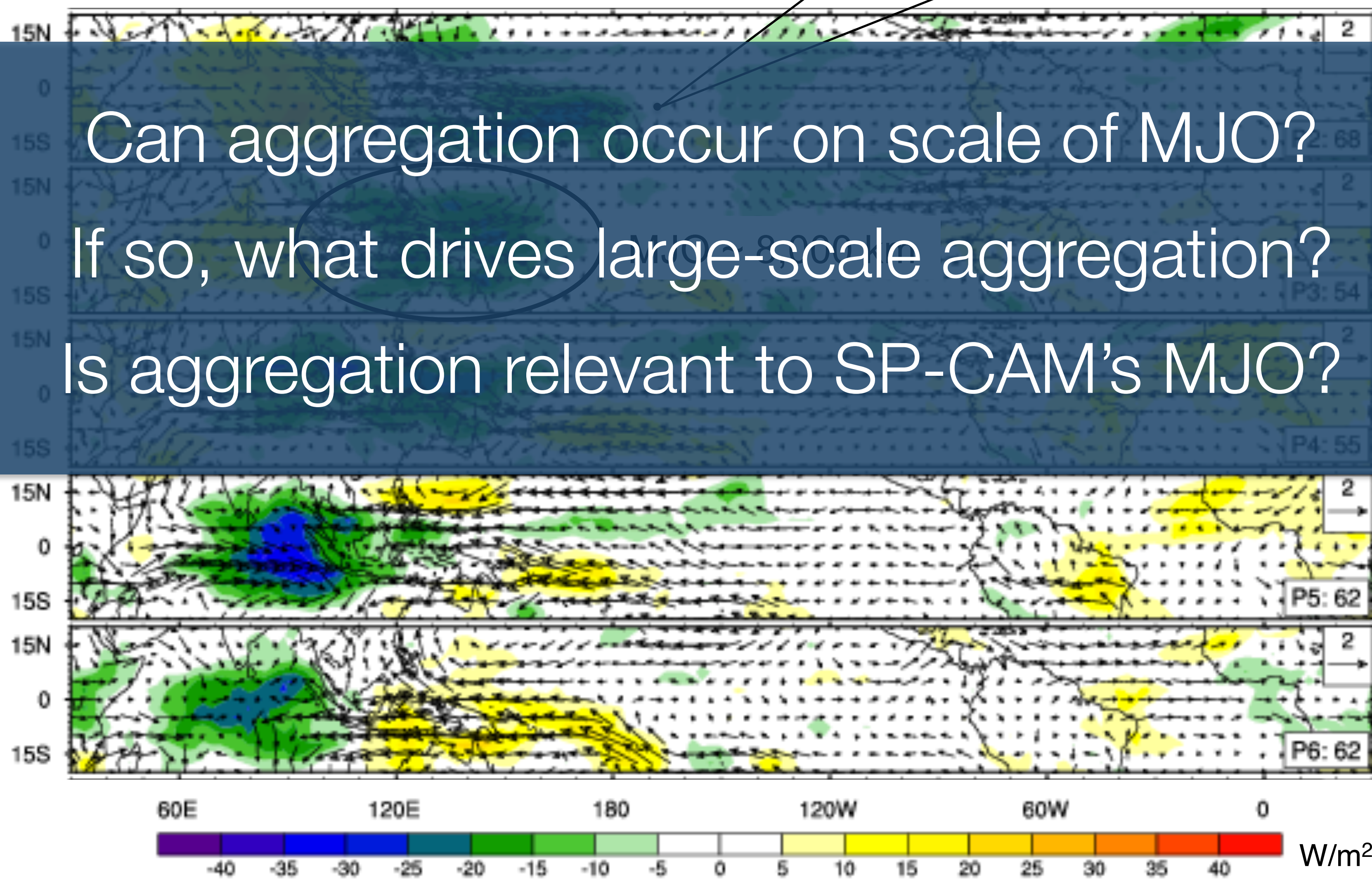


Difference in scale



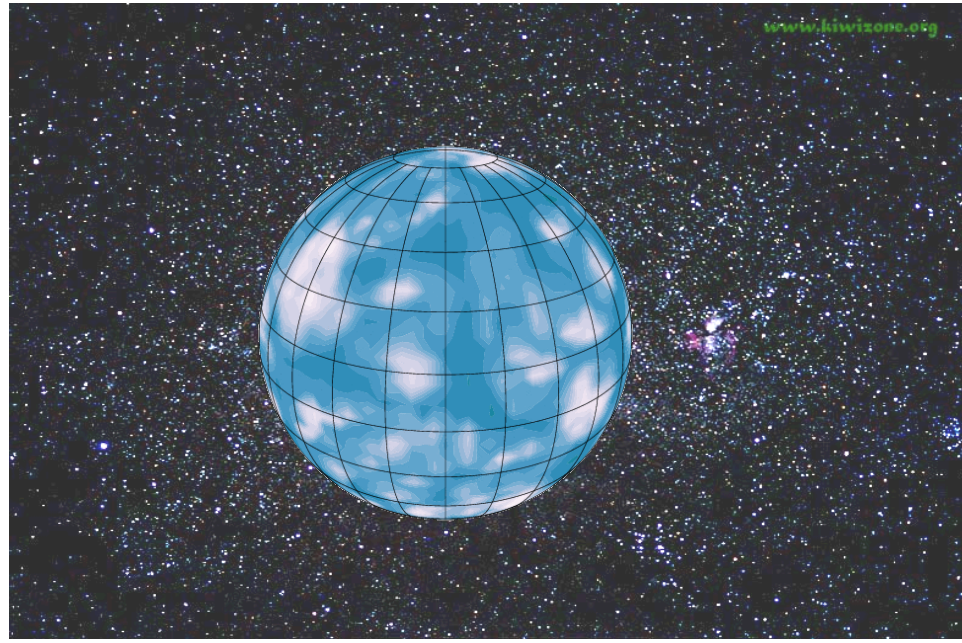


Can aggregation occur on scale of MJO?

If so, what drives large-scale aggregation?

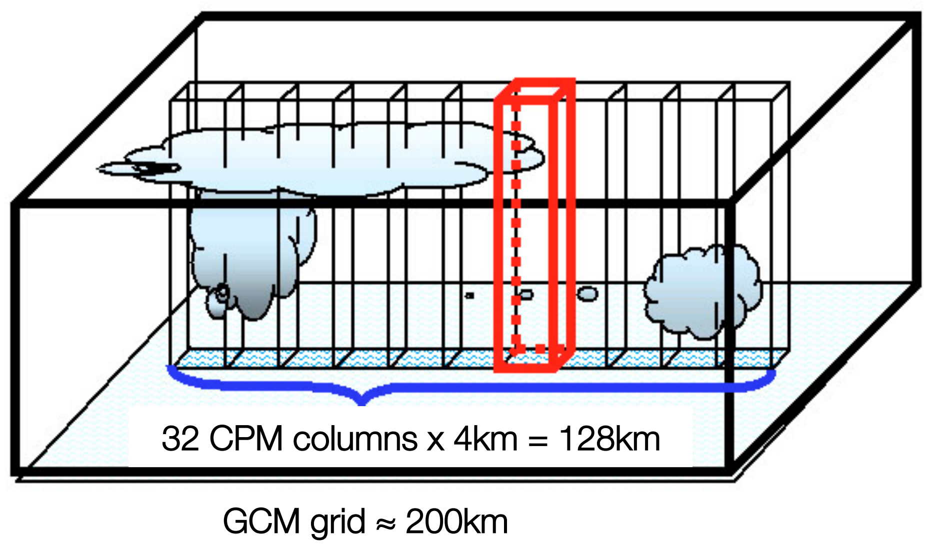
Is aggregation relevant to SP-CAM's MJO?

Very idealized setup:
A non-rotating planet powered by starlight

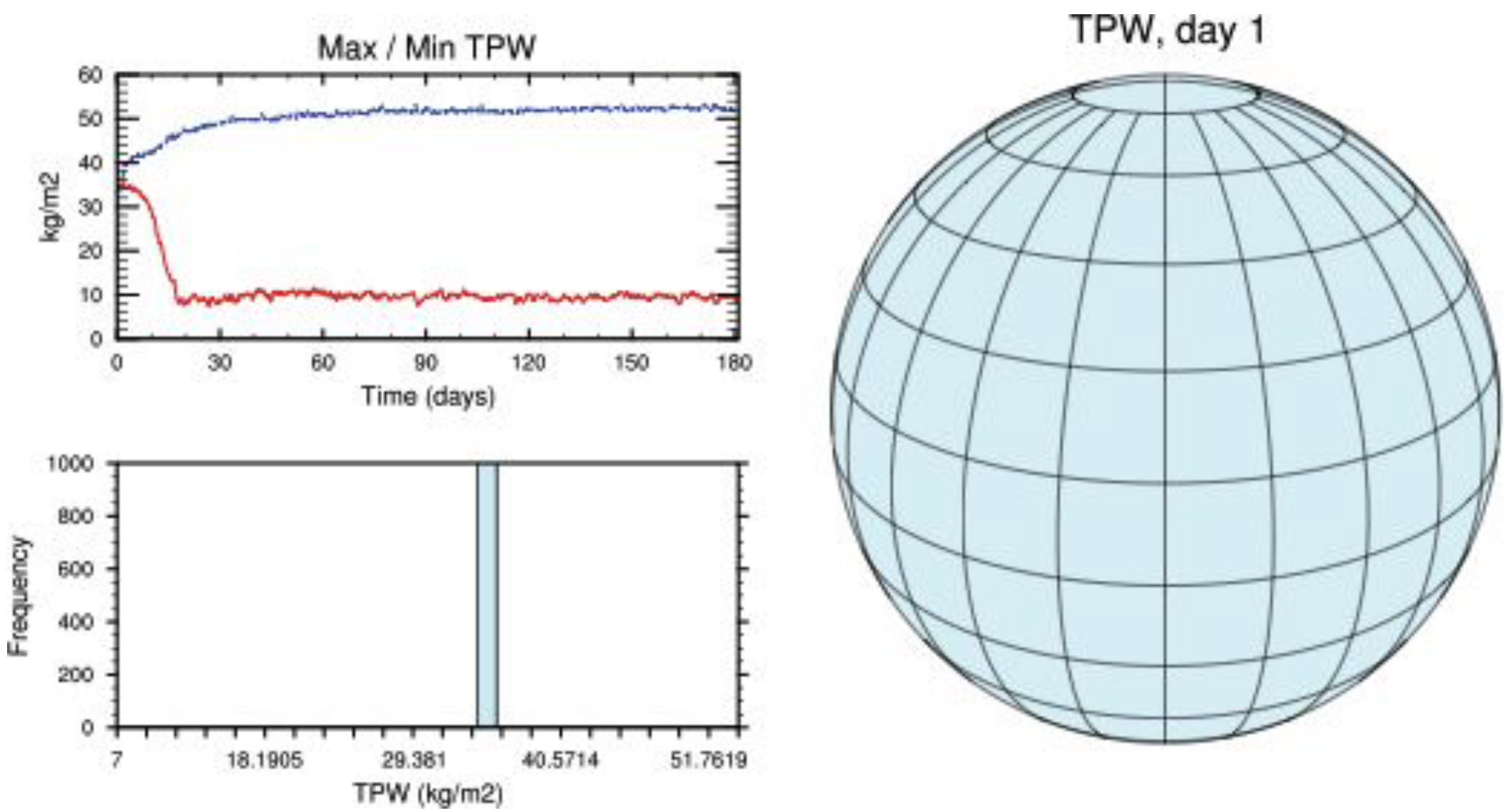


- No Rotation.
- Uniform downwelling shortwave:
  z= 50.5°, S = 650.83W/m^2
  (following Bretherton et al 2005)
- Uniform SST, fixed at 27°C.
- No seasonal or diurnal cycle.
- Running SP-CAM3.5 / 3.0
  - SLD dycore, T42
  - CPMs: 32x4km columns
  - Known to have realistic MJO

Super-parameterized convection:
embedded Cloud-Permitting Models

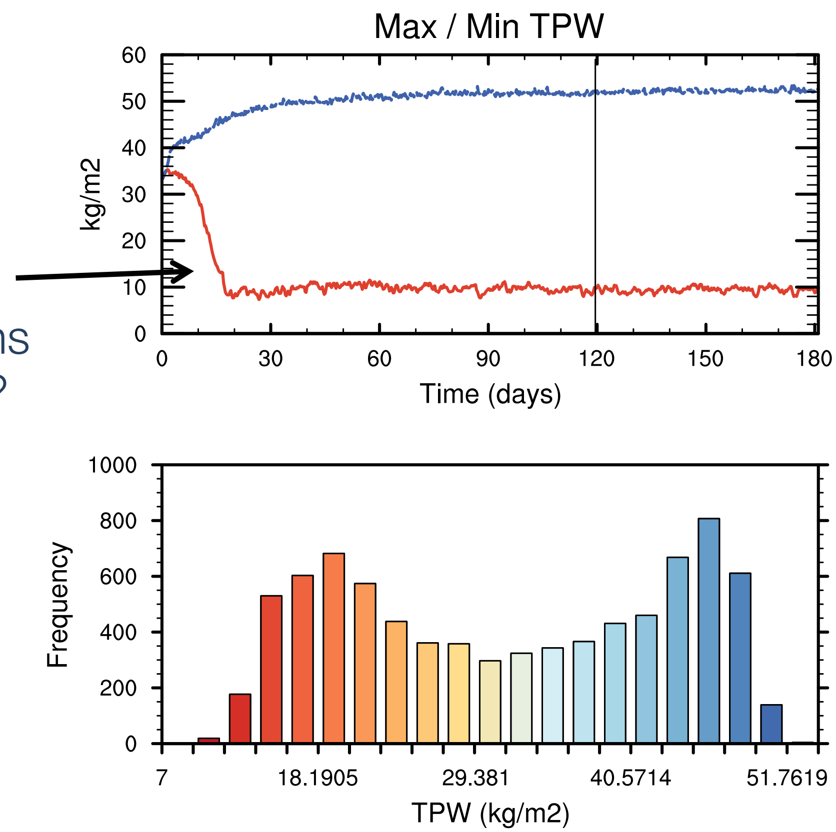


Aggregation from a uniform state of rest

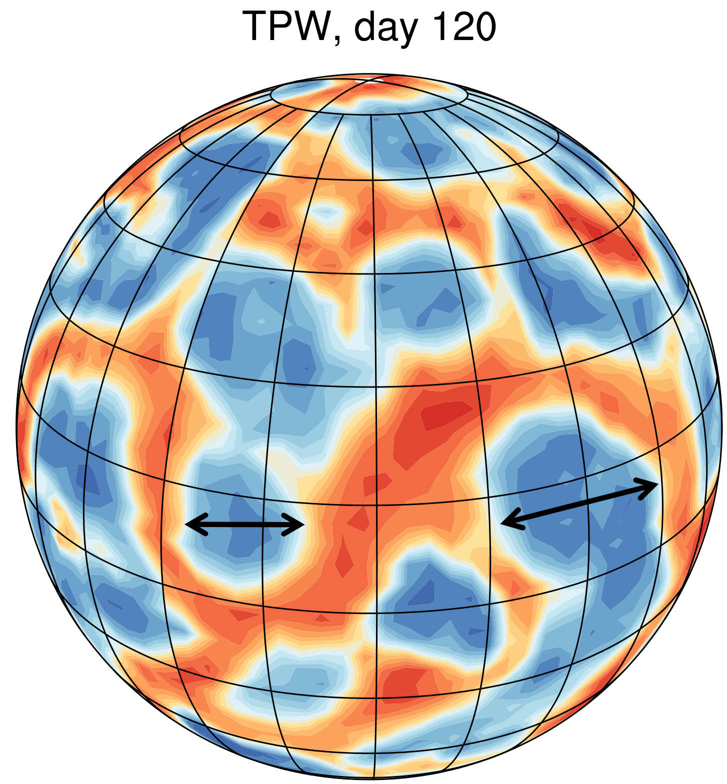


Aggregation from a uniform state of rest

Hints that dry regions form first?

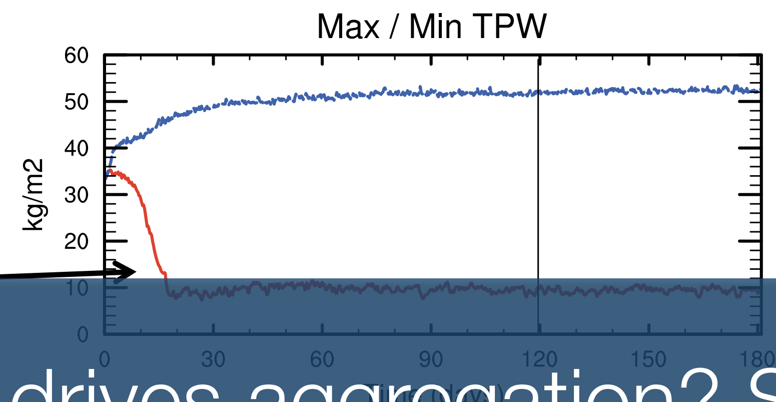


Distribution is strongly bi-modal.



Moist regions are 2000-4000km across.

Aggregation from a uniform state of rest



Hints that
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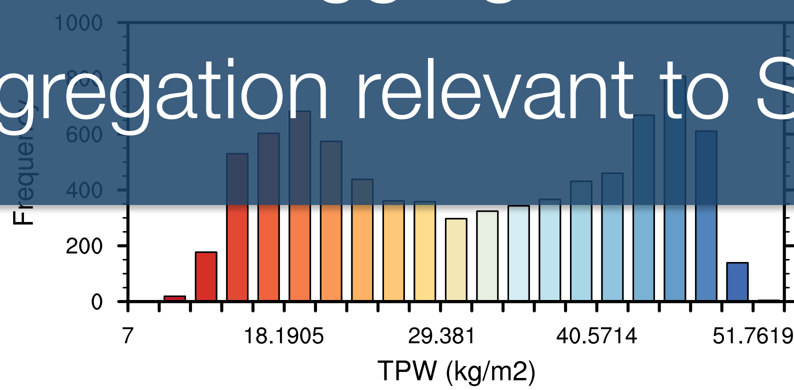

What drives aggregation? Same as in CPMs?

Is aggregation relevant to SP-CAM's MJO?

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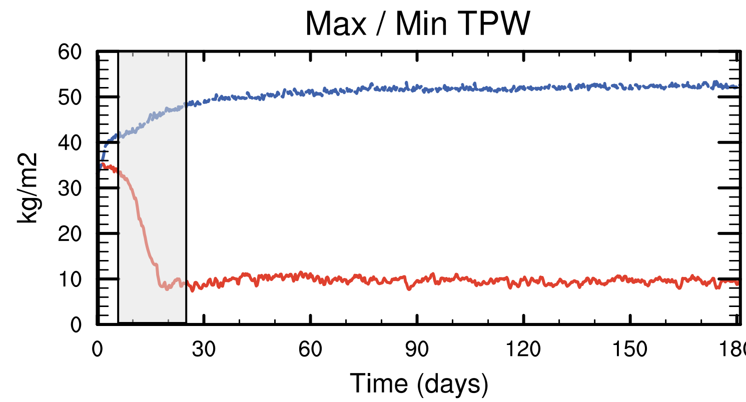
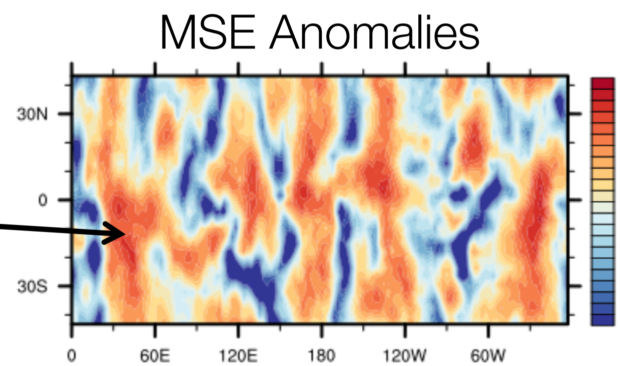
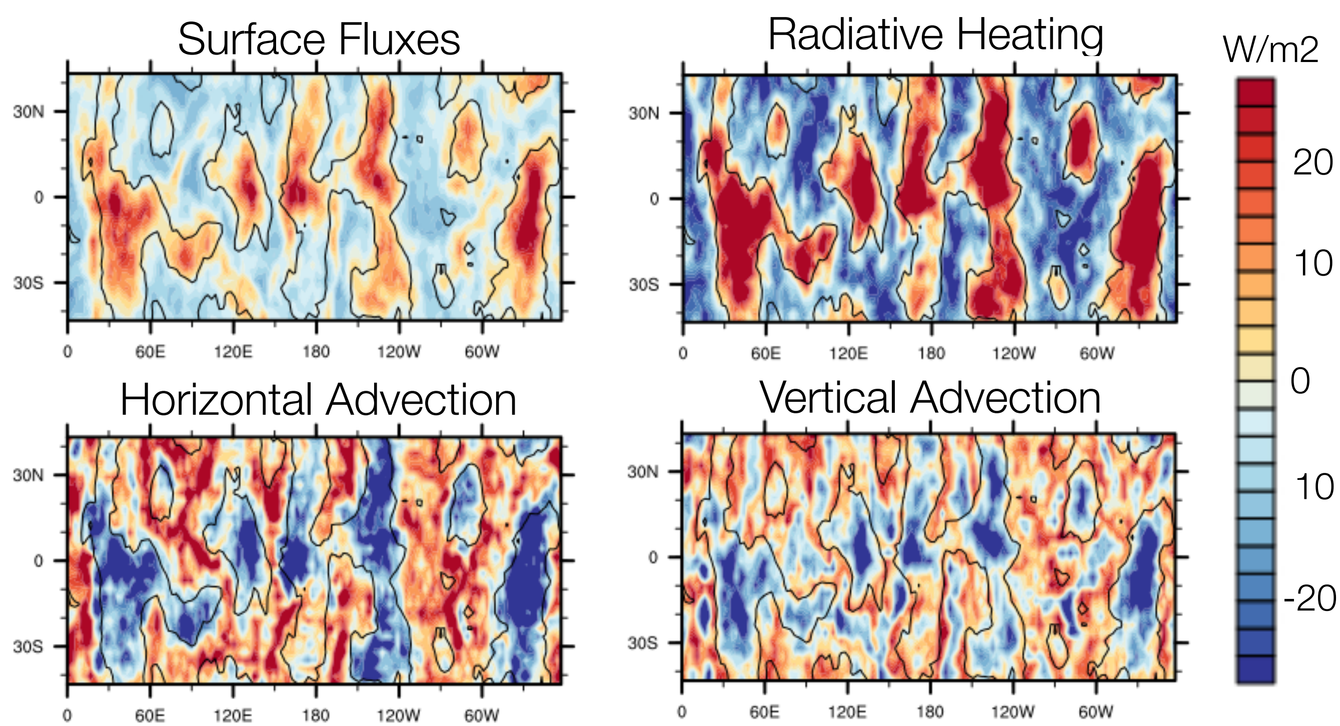
Aggregation Moist Static Energy Budget (days 5-25)



Red = humid, high MSE





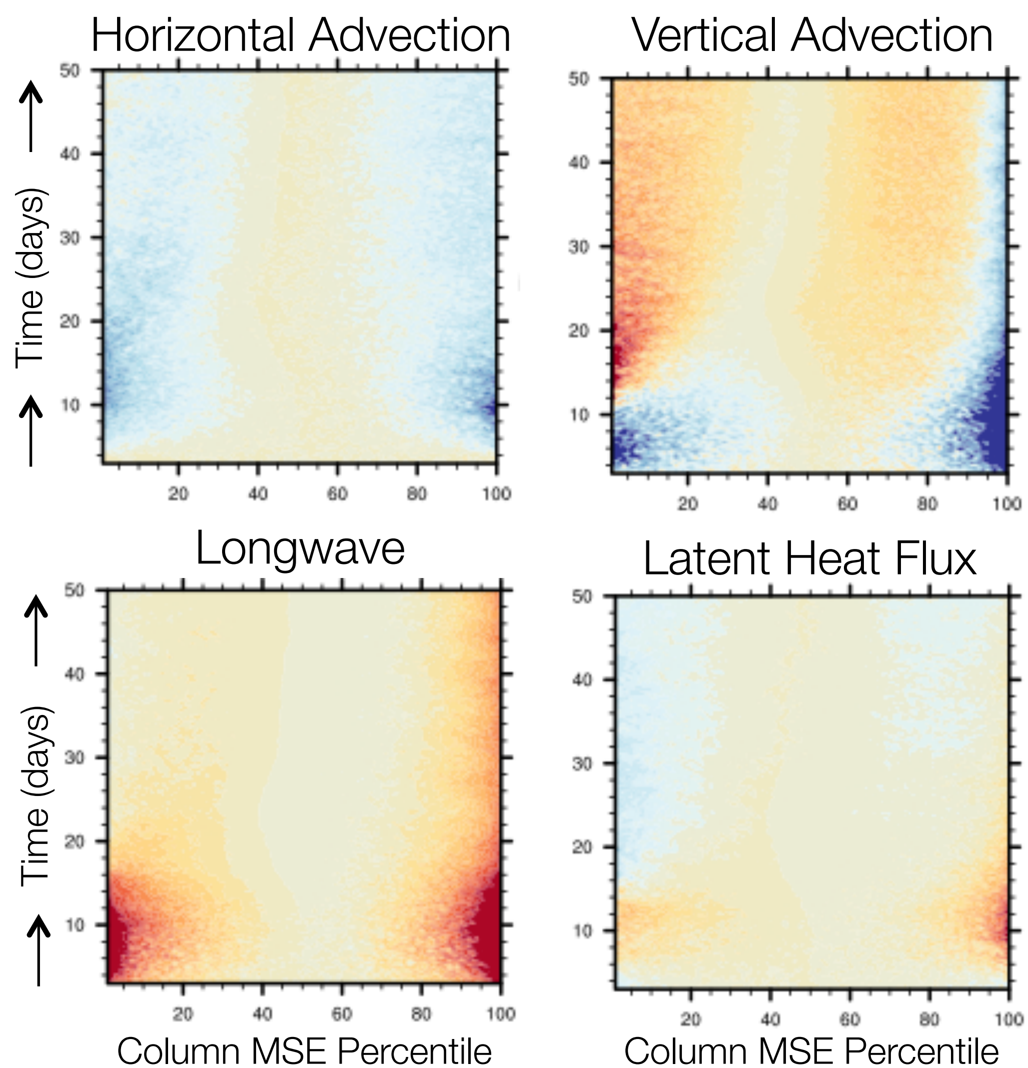
Initial aggregation driven by diabatic terms, opposed by advection.

MSE Variance Budget, binned by column MSE

$$\frac{1}{2\langle h'^2 \rangle}\frac{\partial}{\partial t}h'^2 = \frac{LW'h'}{\langle h'^2 \rangle} + \ldots$$

- Product of budget term and MSE anomalies = measure of anomaly growth rate due to term.
- Sort into 100 bins, ranked by column MSE.
- Yields growth rates in time-moisture space.

Red = amplifies anomaly
Blue = weakens anomaly



Following Wing and Emanuel (2014)

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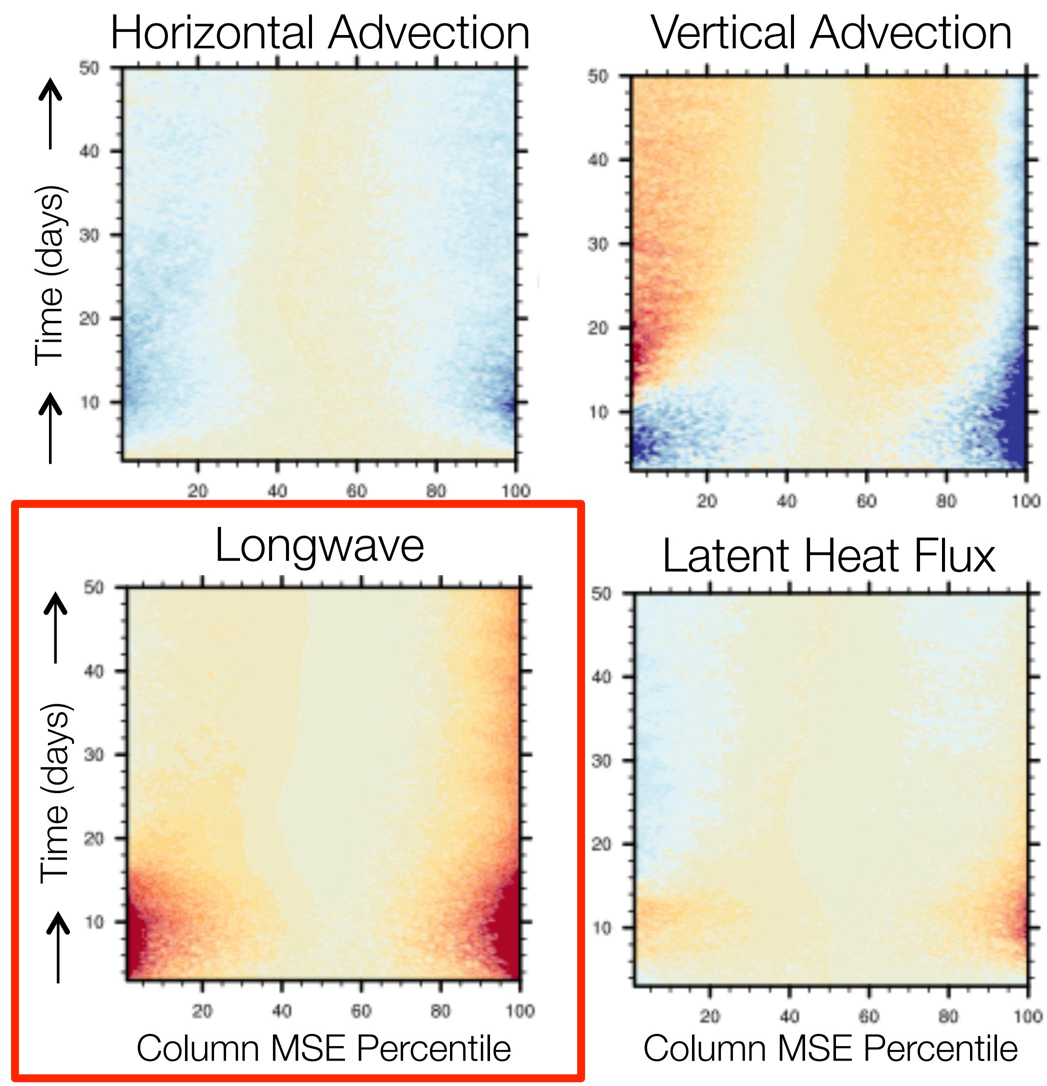
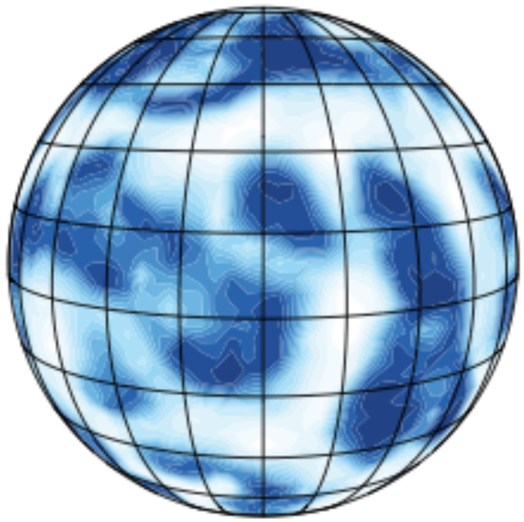


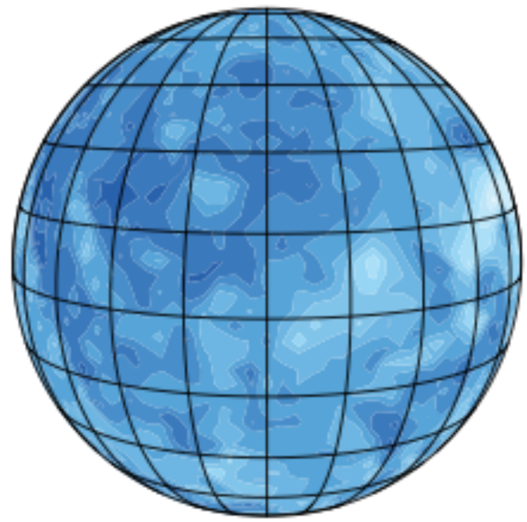
Following Wing and Emanuel (2014)

“Mechanism Denial” Experiments

Default



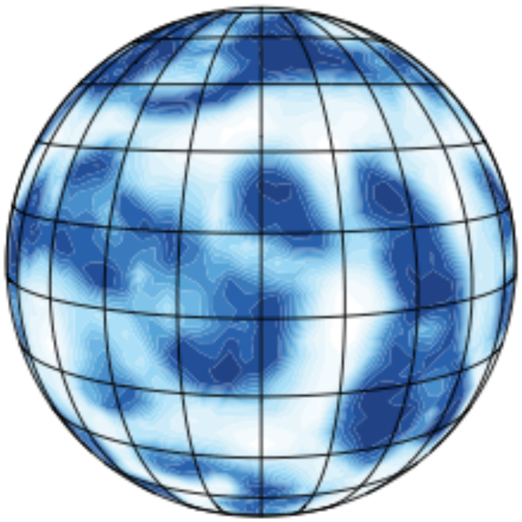
Uniform longwave heating



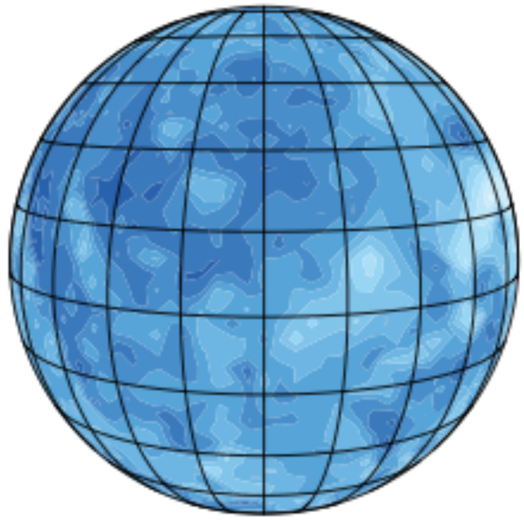
Aggregation does not occur
without interactive longwave!

“Mechanism Denial” Experiments

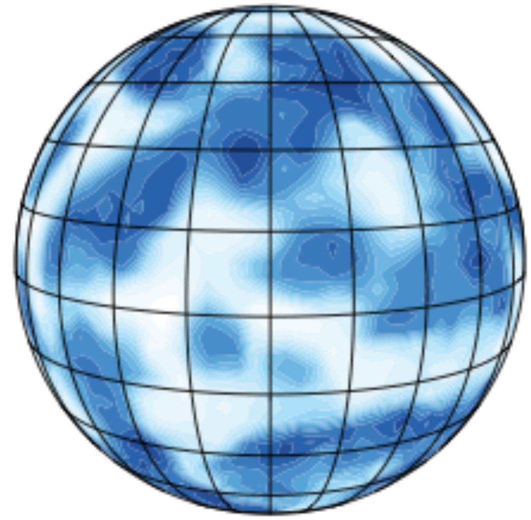
Default



Uniform longwave heating

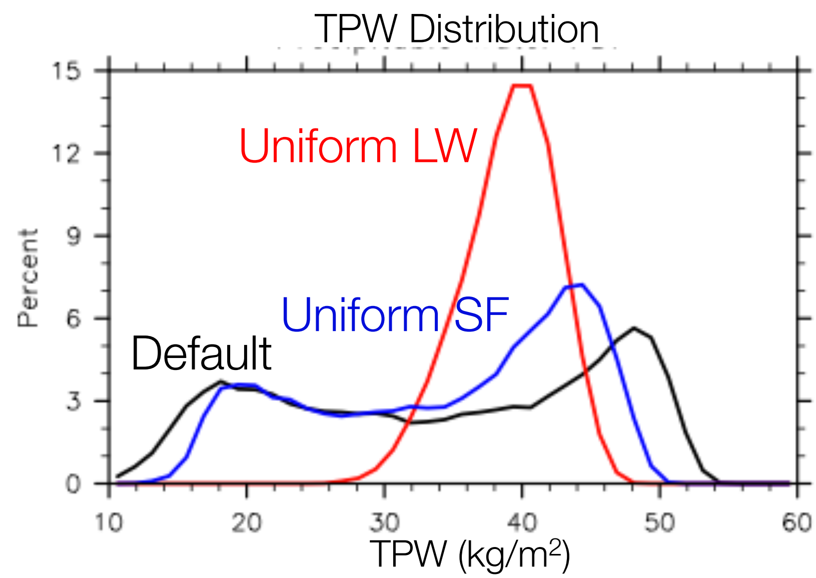


Uniform surface fluxes

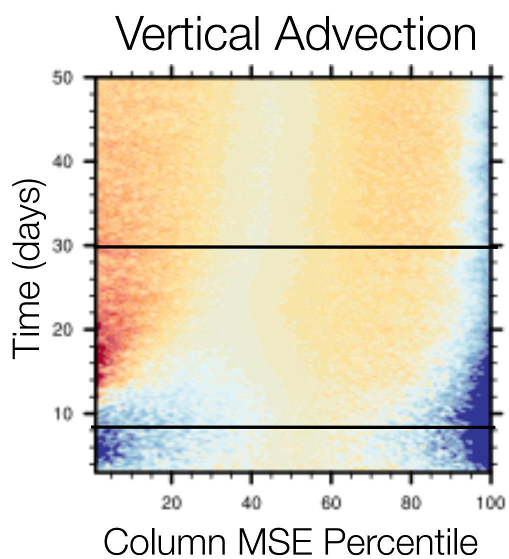


Aggregation does not occur
without interactive longwave!

Surface fluxes help,
but are not essential.



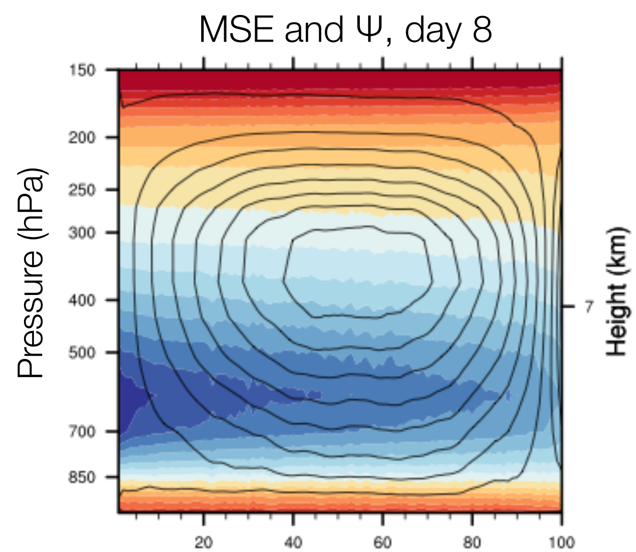
Why does vertical advection contribution reverse?

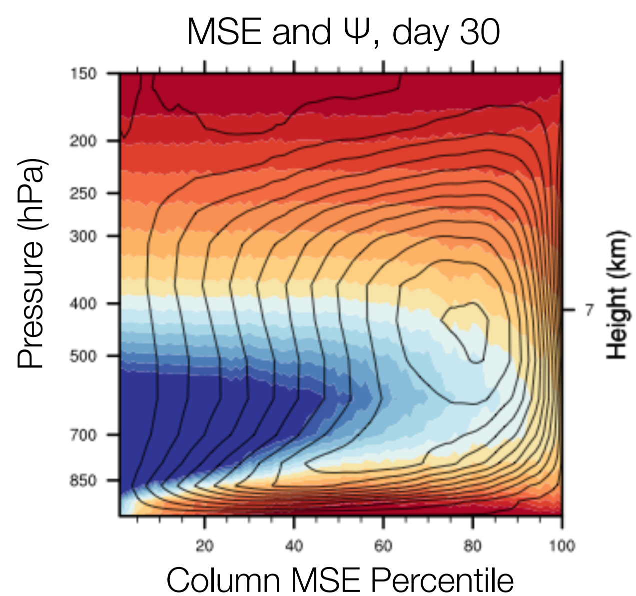


Day 8:
Top-heavy circulation, reduces MSE anomalies.

Day 30:
Dry-region subsidence more bottom heavy.

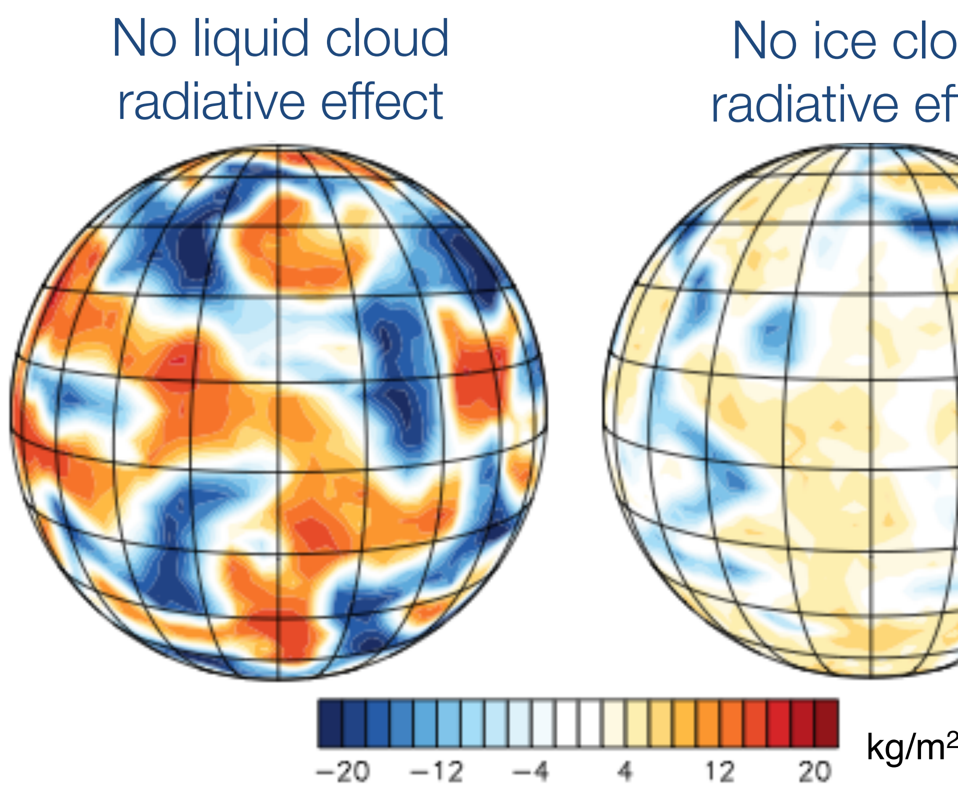
Shallow circulation provides up-gradient transport.





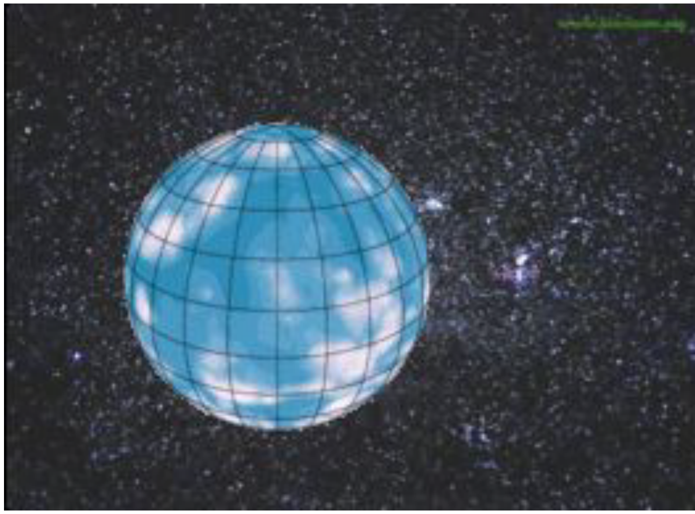
This is similar to the shallow circulation found in CPMs by Bretherton et al (2005) and others.

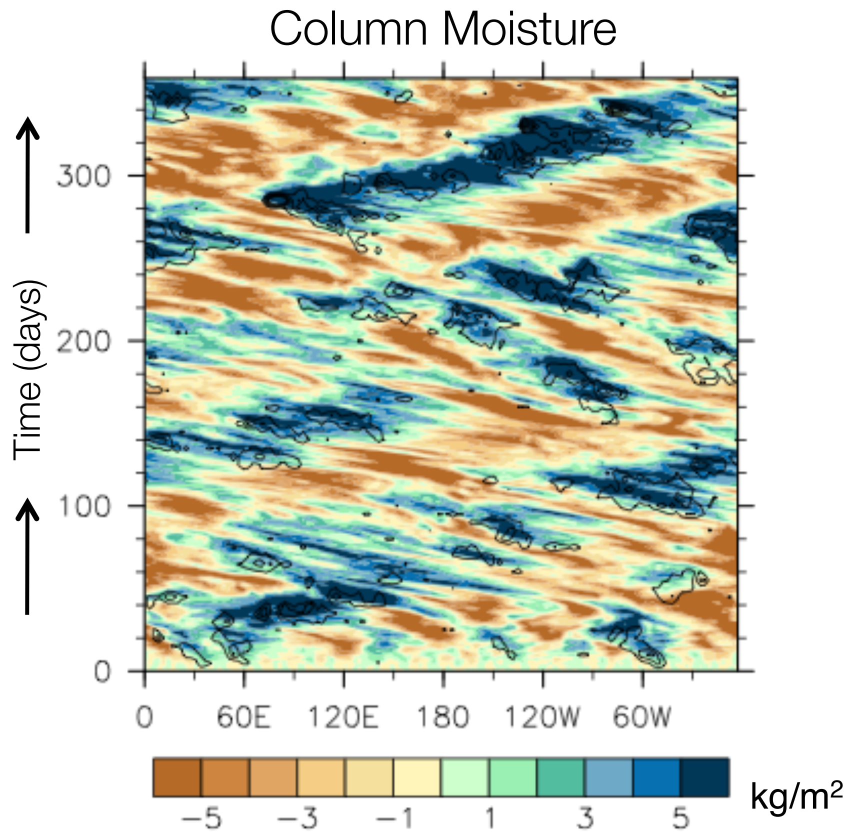
Distinguishing low vs high clouds

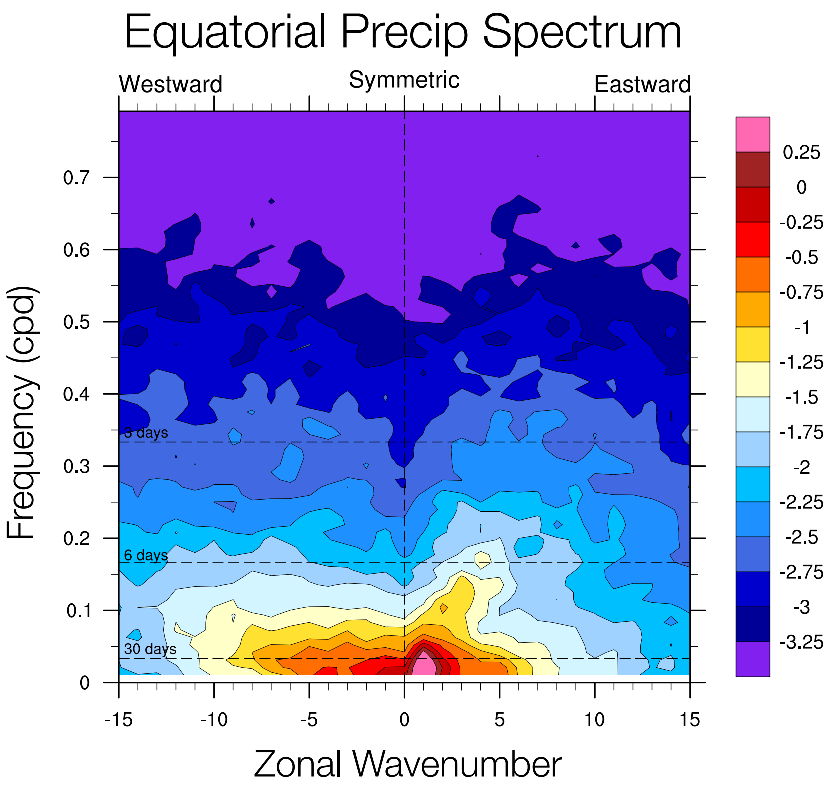


Aggregation does not occur without high cloud LW effect.
Removing low cloud feedback has little impact.
Differs from Muller and Held (2012) CRM aggregation.

Restoring full rotation: Model produces an "MJO"

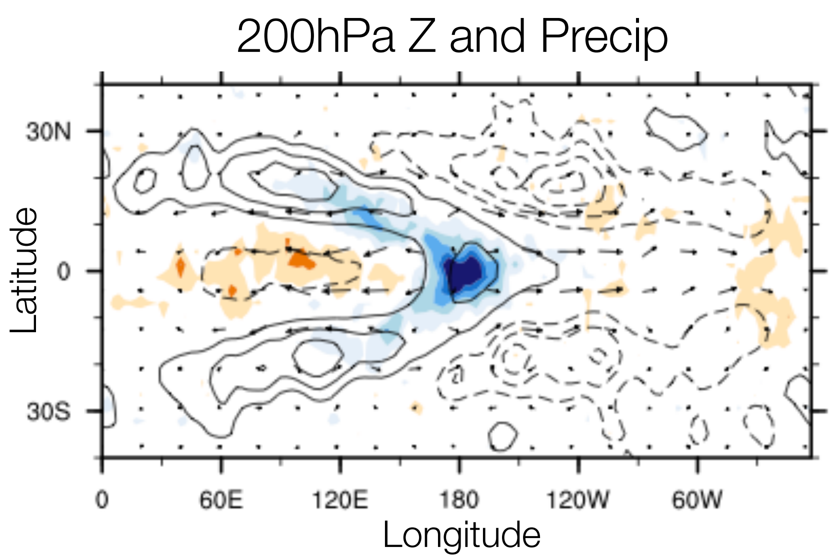


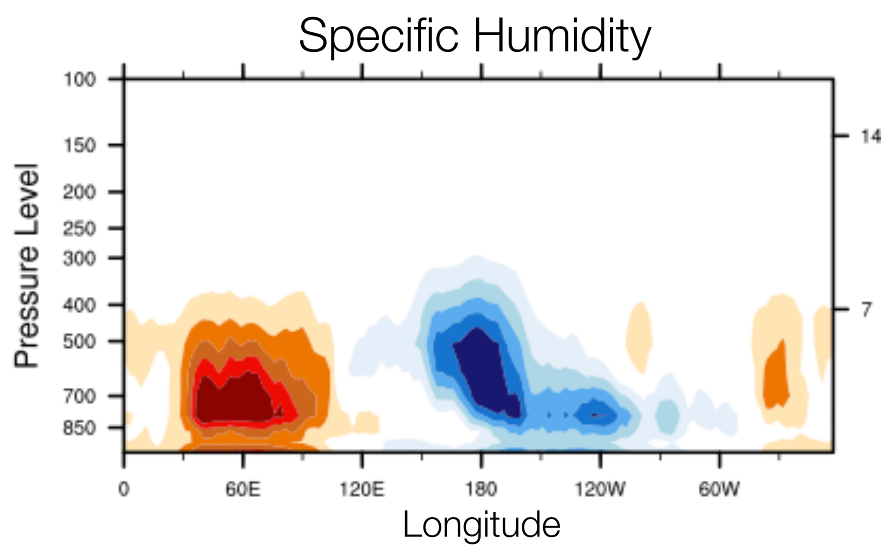


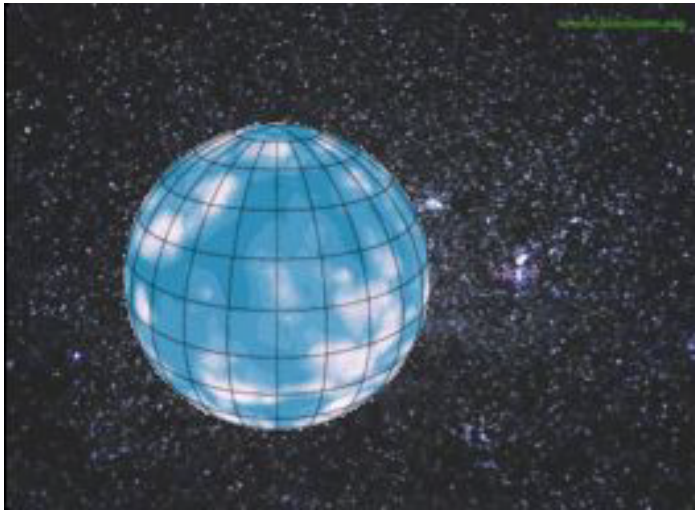


See also: Grabowski (2003/04)

Restoring full rotation: Model produces an “MJO”





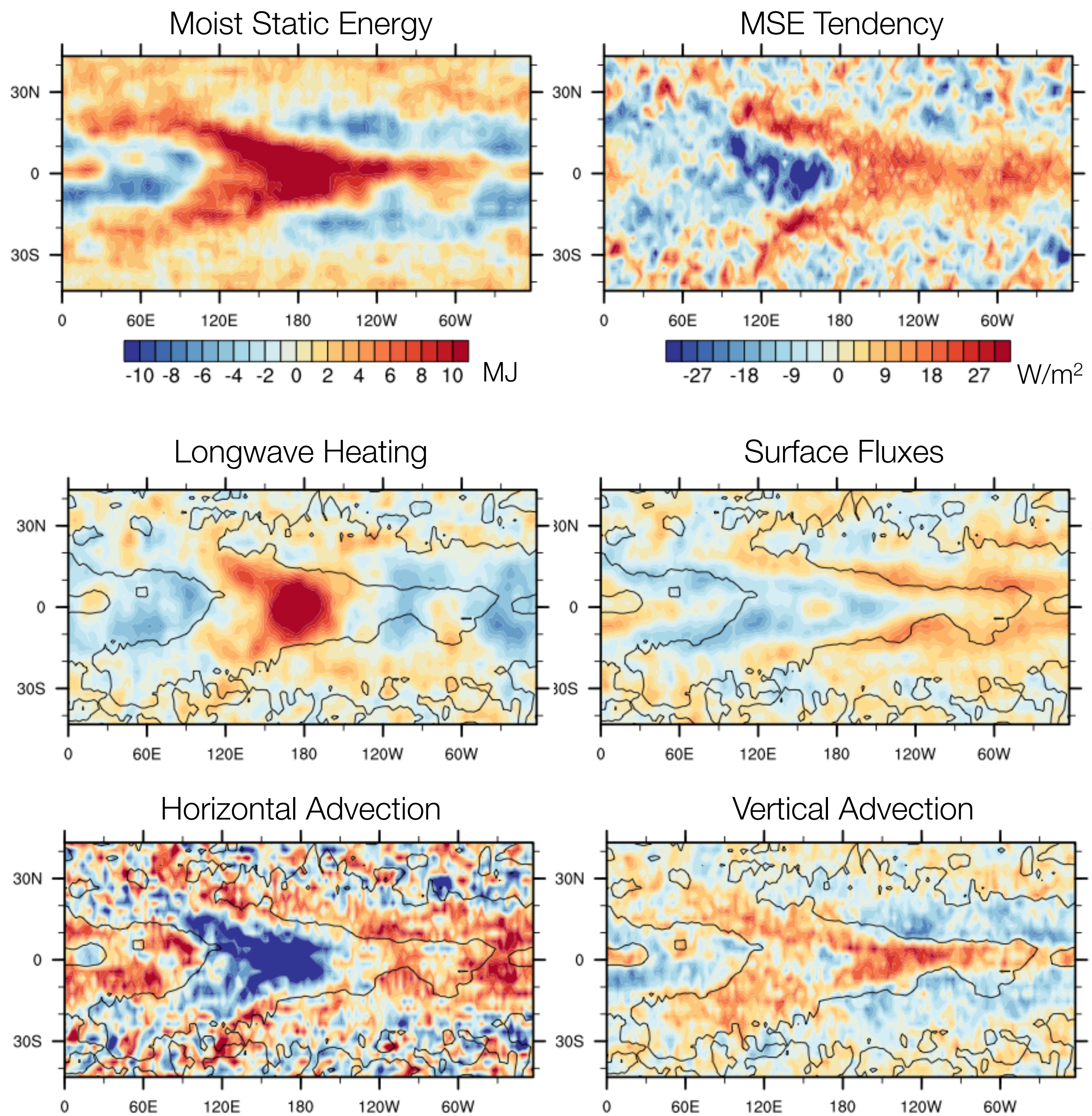


Upper level wind and vertical development of humidity anomalies resemble the real-world MJO.

See also: Grabowski (2003/04)

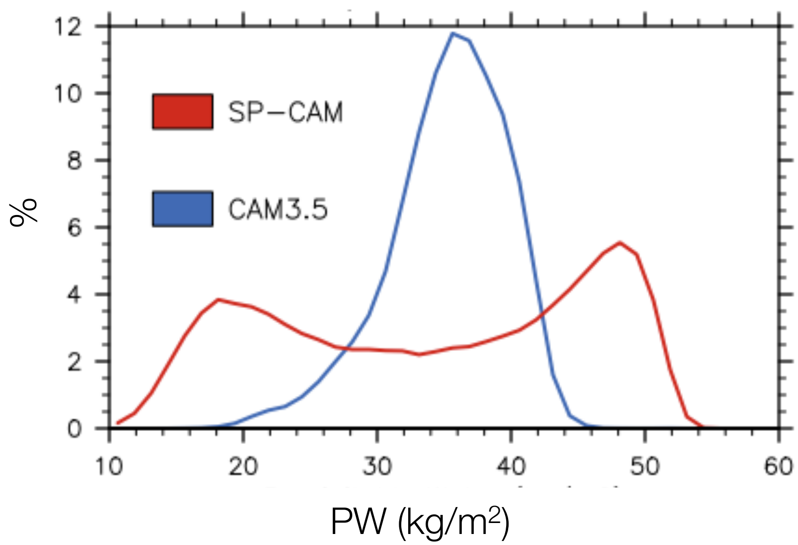
MJO MSE budget similar to aggregation

- Supported by longwave.
- Strong damping from horizontal advection.
- Surface fluxes weakly damp MSE anomalies.
- Vertical advection supports anomalies except in core of moist region.

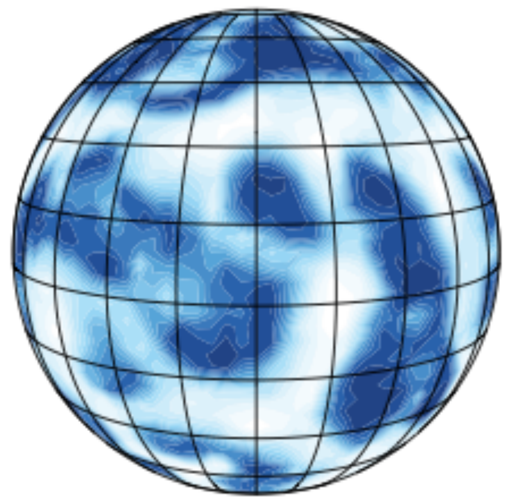


Comparison with conventional CAM: Weaker MJO, weaker aggregation

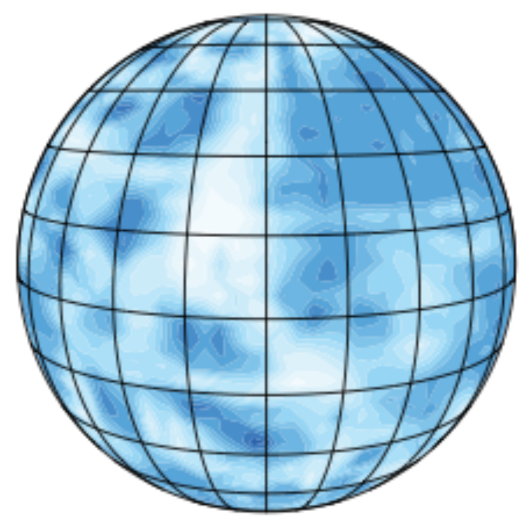
Precipitable Water PDF



SP-CAM PW

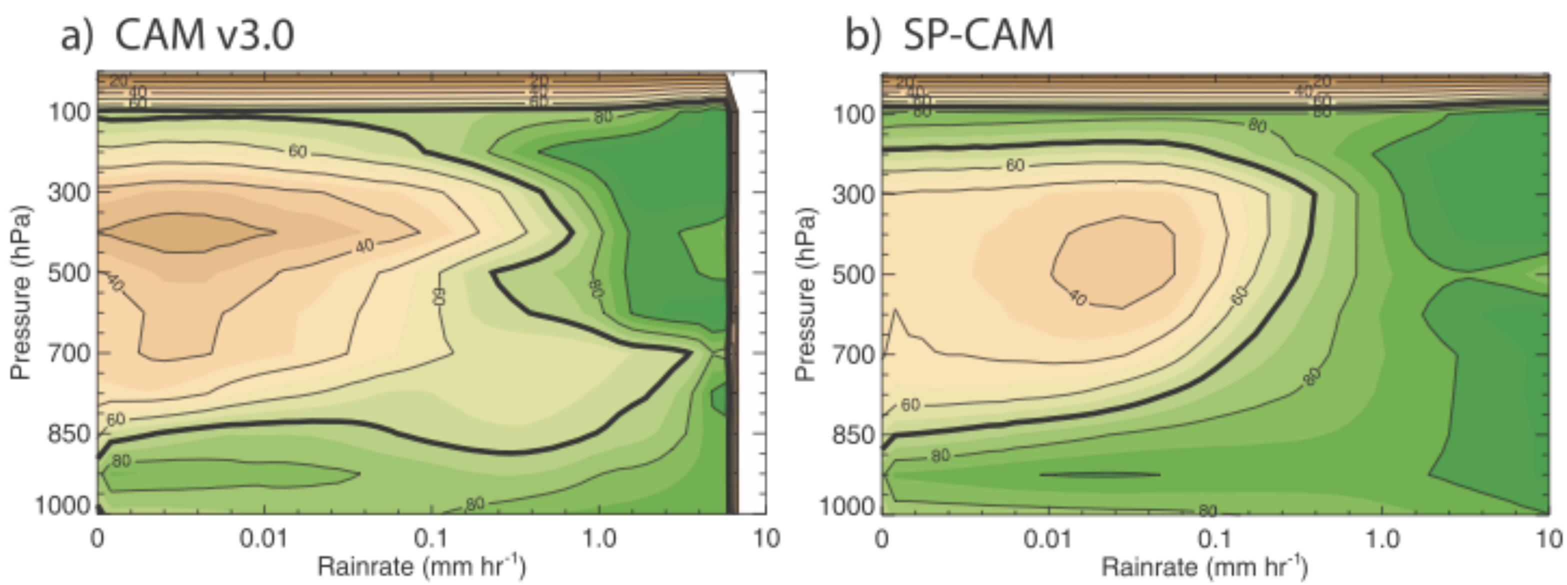


CAM PW



CAM has trouble generating moisture variance

Why doesn't CAM form humid regions?



One likely reason: CAM rainfall is insensitive to humidity.

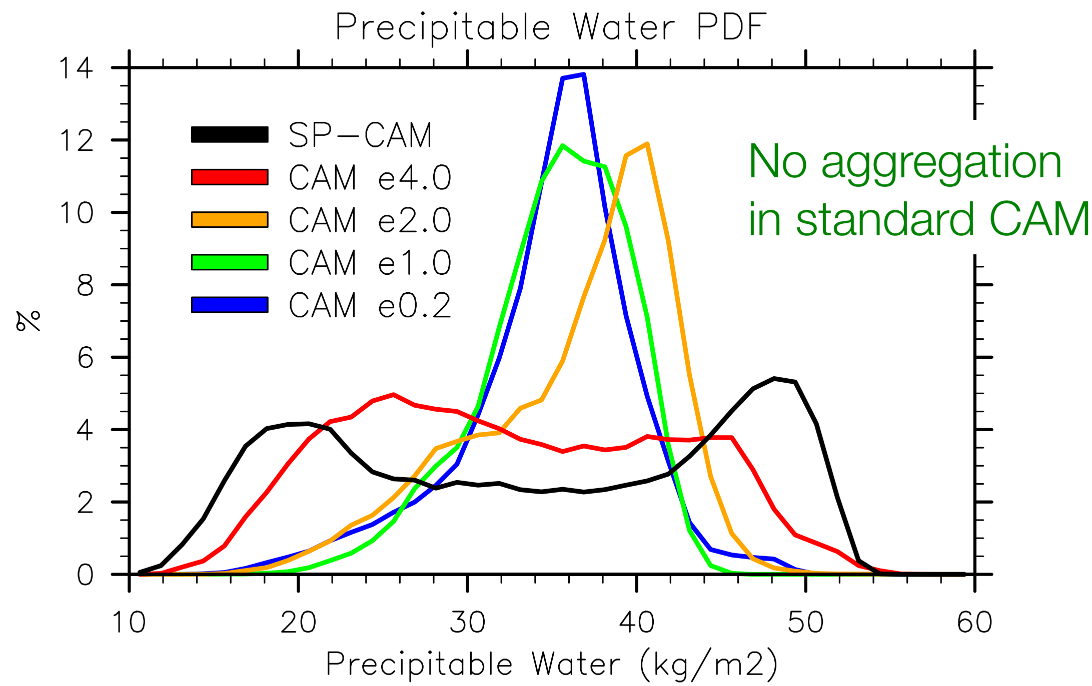
Exhibits high rainrates with relatively low humidity, can't build up moisture anomalies.

Thayer-Calder and Randall (2009)

Increasing moisture sensitivity via entrainment

In CAM3.5, the deep convection scheme uses a dilute plume to estimate CAPE.

This can increase sensitivity to mid-level humidity.



As entrainment is increased, aggregation becomes stronger.

Summary so far

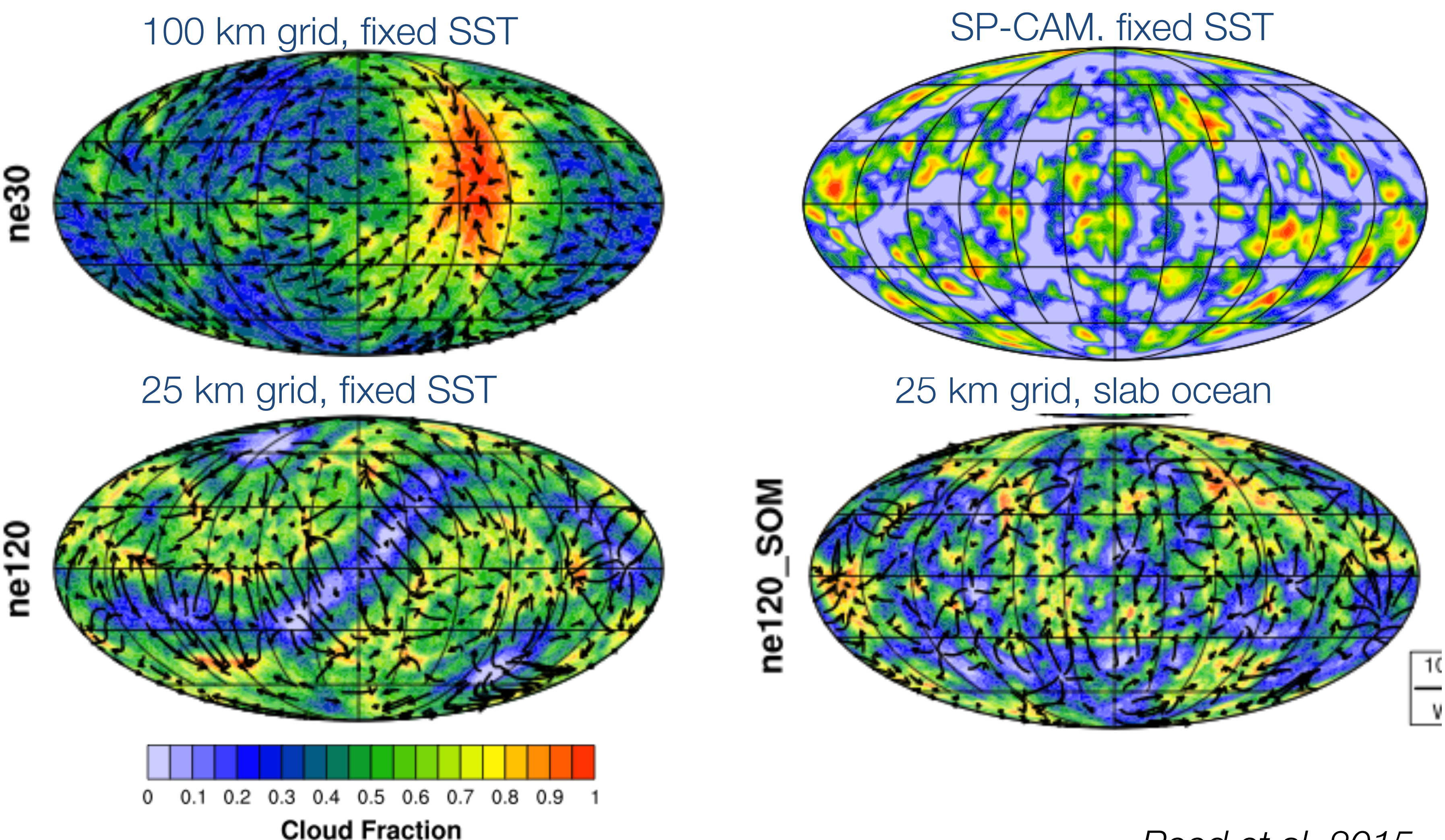
- In uniform non-rotating simulations with SP-CAM3.0, convection aggregates into ~4000km clusters.
- An MSE budget and mechanism denial experiments show the SP-CAM aggregation is driven by processes similar to CPMs:
    - Initially driven by longwave, with help from surface fluxes.
    - Shallow circulation develops and supports aggregated state.
- When rotation is added the model produces an MJO, with an MSE budget similar to the non-rotating aggregation.
- In the conventional CAM, aggregation is much weaker, consistent with its weaker MJO. Increasing the convective entrainment rate increases both MJO activity and aggregation.
- Consistent with "moisture mode" theories, less consistent with others, e.g. multi-scale model or IG wave interference.

Scale Selection

Why is the MJO envelope ~10000 km across?

Why are the non-rotating blobs ~4000 km across, rather than 500 km or 20000 km?

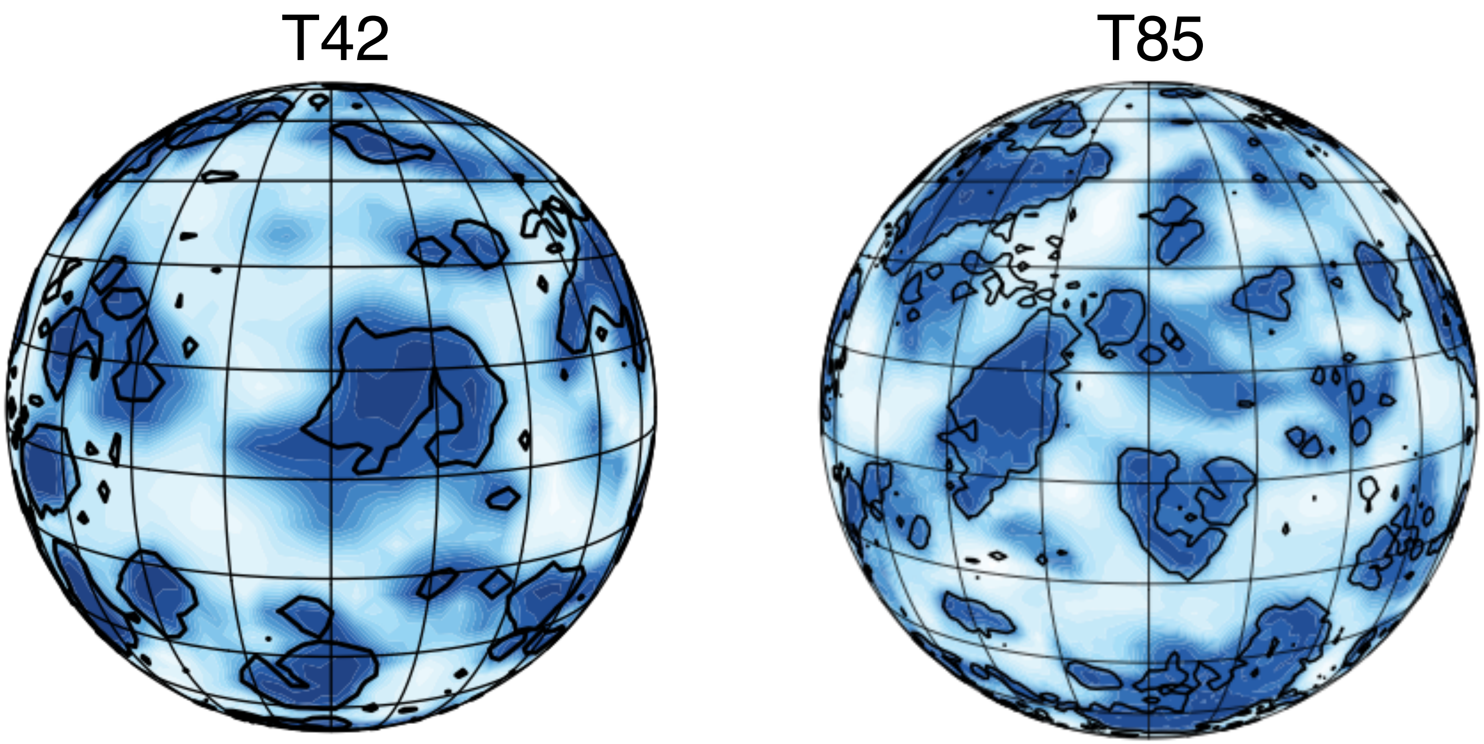
Structure varies with model / setup



Reed et al. 2015

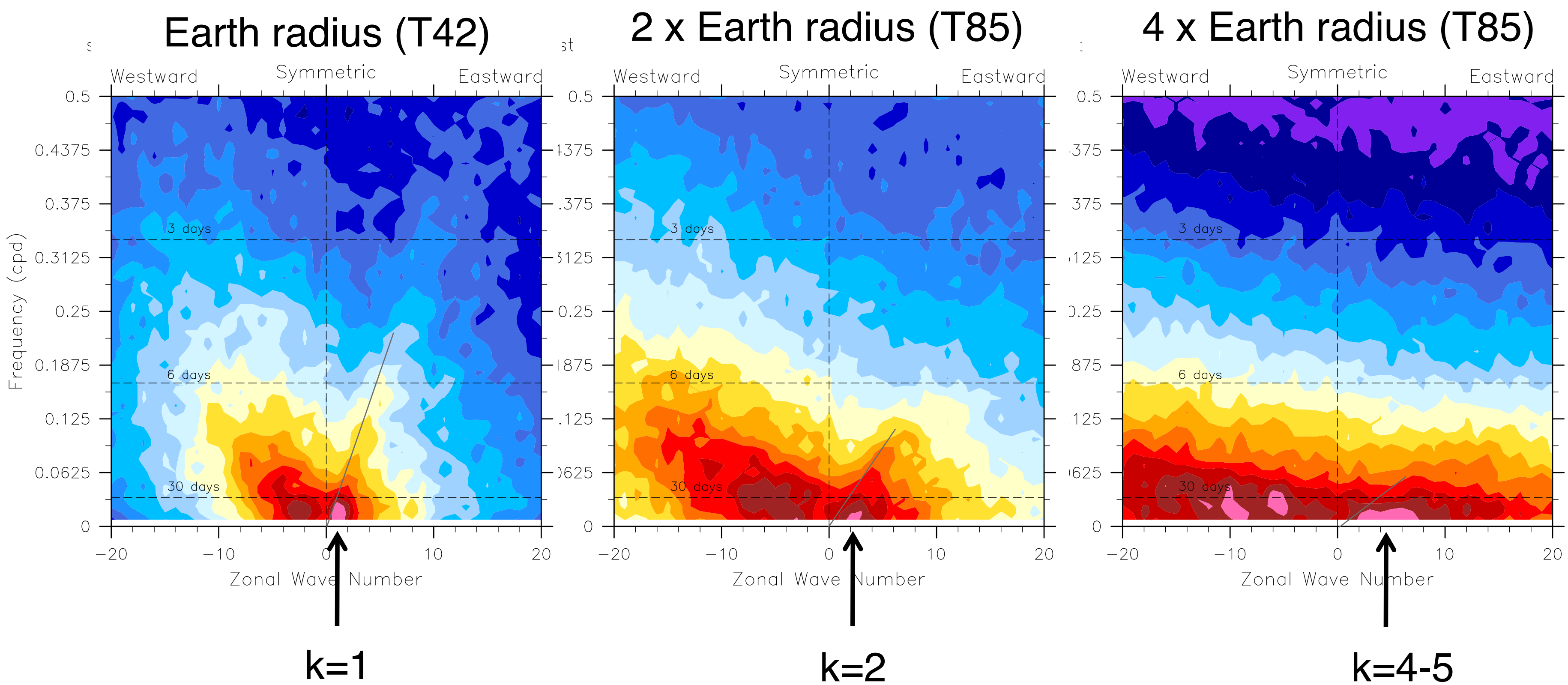
In CAM5, very sensitive to setup and physics!

In SP-CAM, scale insensitive to resolution



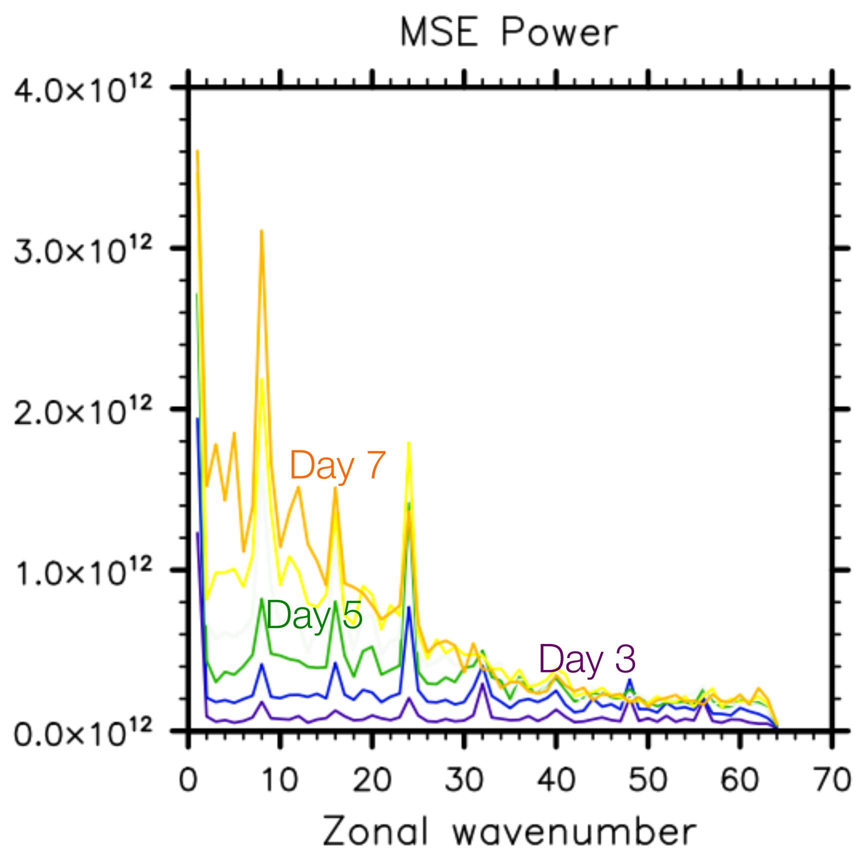
Little difference between T42 and T85.

MJO scale is independent of planetary radius



Convective zonal extent remains at ~10000 km on larger planets.

MSE zonal wavenumber spectrum



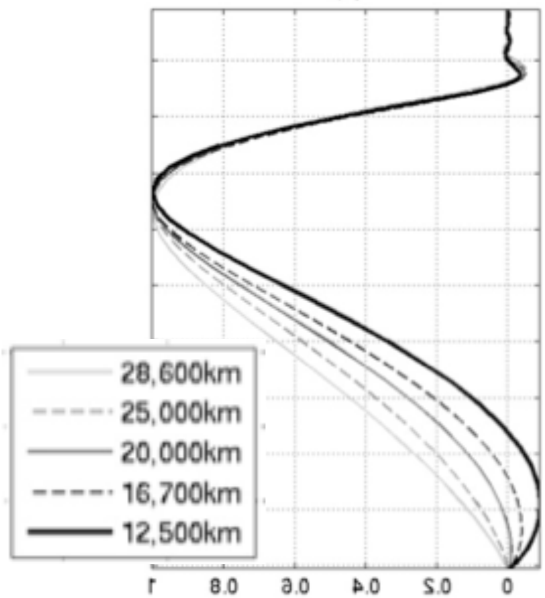
Spectrum is still white on day 3,
but scale selection noticeable by day 5.

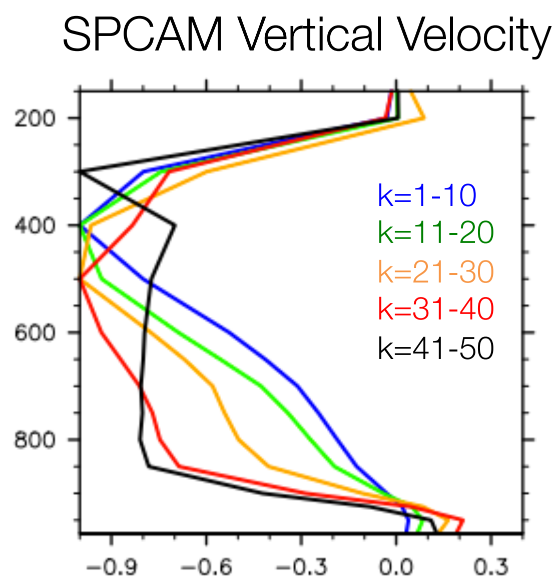
Some published ideas…

- Kuang (2008): Vertical structure wavelength dependence

Support from SAM run:

$$\{\varepsilon[\bar{\rho}w'(x_0, z, t)]_z\}_z = -k^2 \frac{\bar{\rho}g}{\bar{T}} T'(x_0, z, t)$$



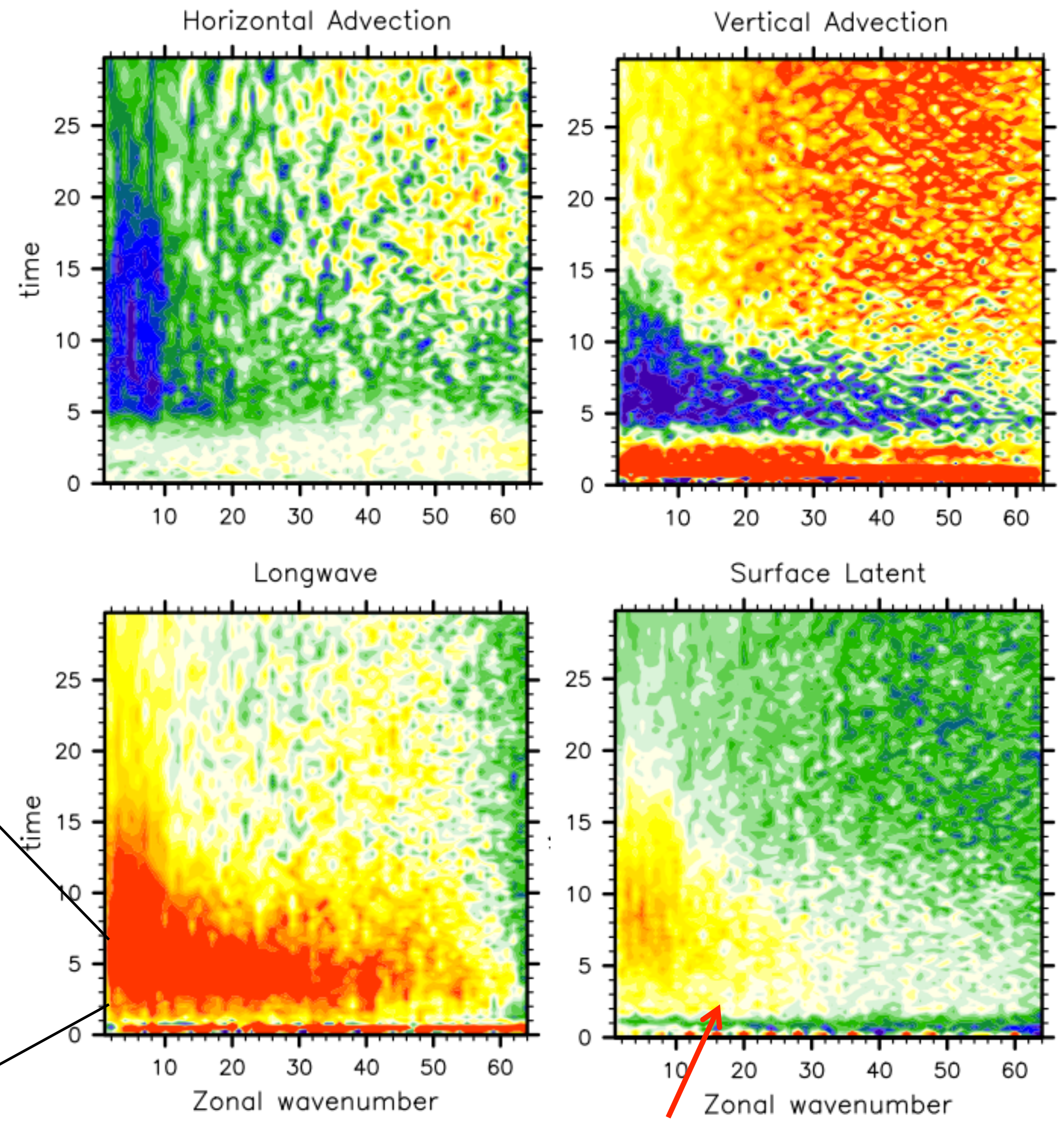


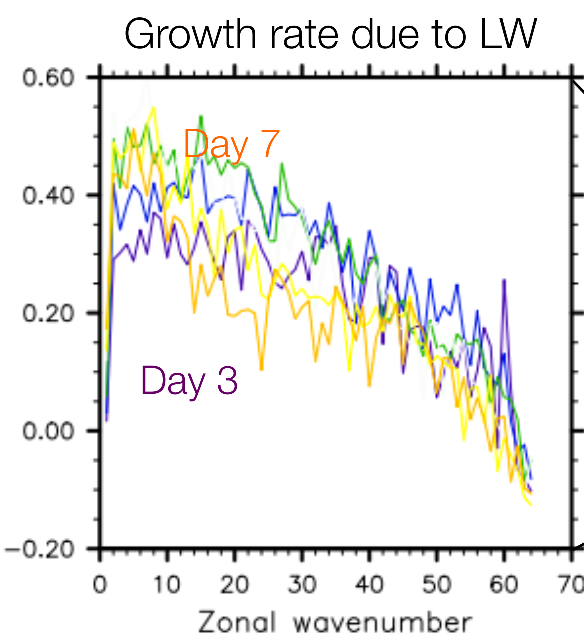
But in SP-CAM, larger scales have more top-heavy profiles!

Clues from the spectral MSE budget

$$\hat{\Psi}(k) = Re\left\{\frac{\hat{h}^*(k)\hat{X}(k)}{\hat{h}^*(k)\hat{h}(k)}\right\}$$

Fractional growth rate of MSE anomalies due to budget term X.

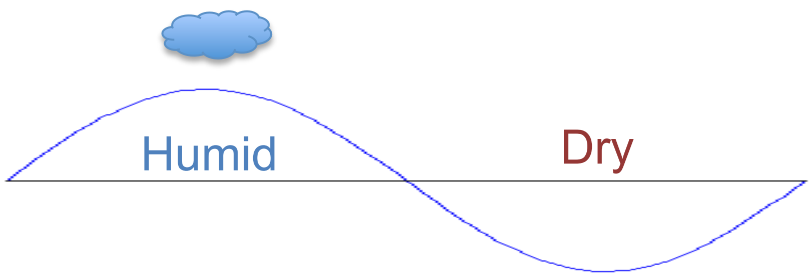


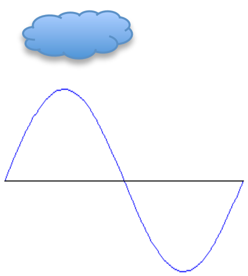


Selective, but apparently unnecessary?

Shear as a scale selection mechanism

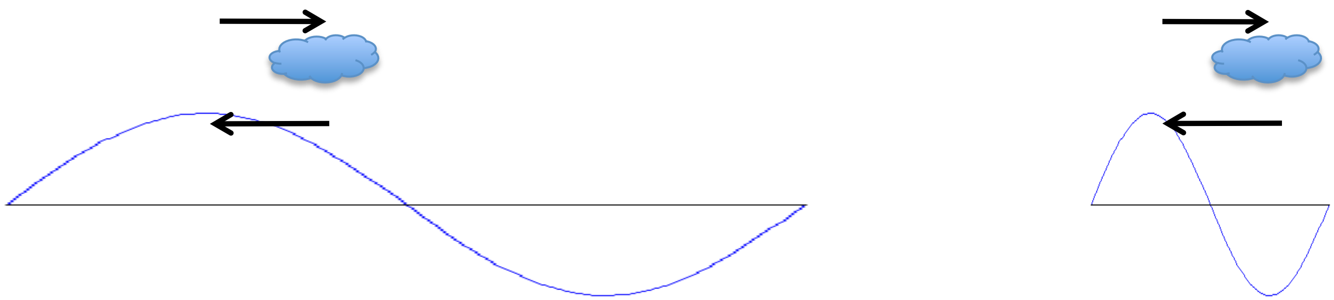
Advection of high clouds by horizontal winds:





Shear as a scale selection mechanism

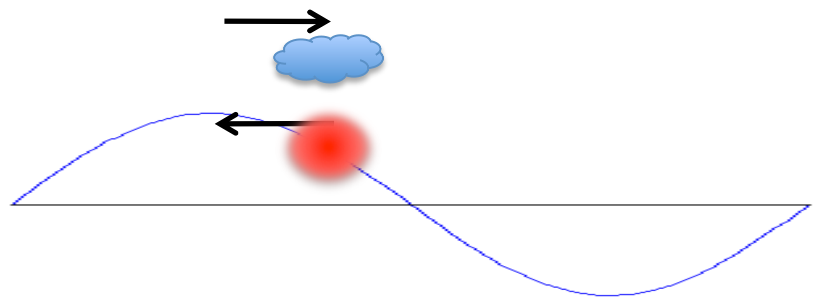
Advection of high clouds by horizontal winds:

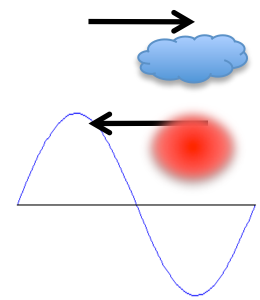


Not direct advection of moisture that matters, but the varying correlation between high clouds and column moisture.

Shear as a scale selection mechanism

Advection of high clouds by horizontal winds:

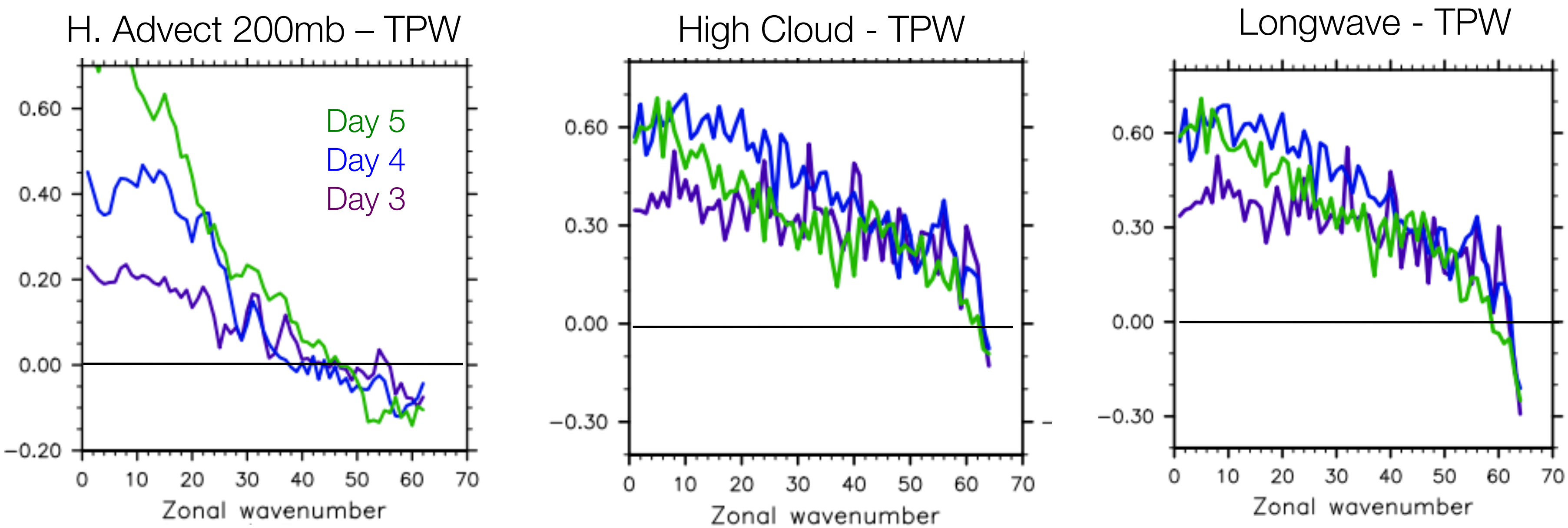




Not direct advection of moisture that matters, but the varying correlation between high clouds and column moisture.

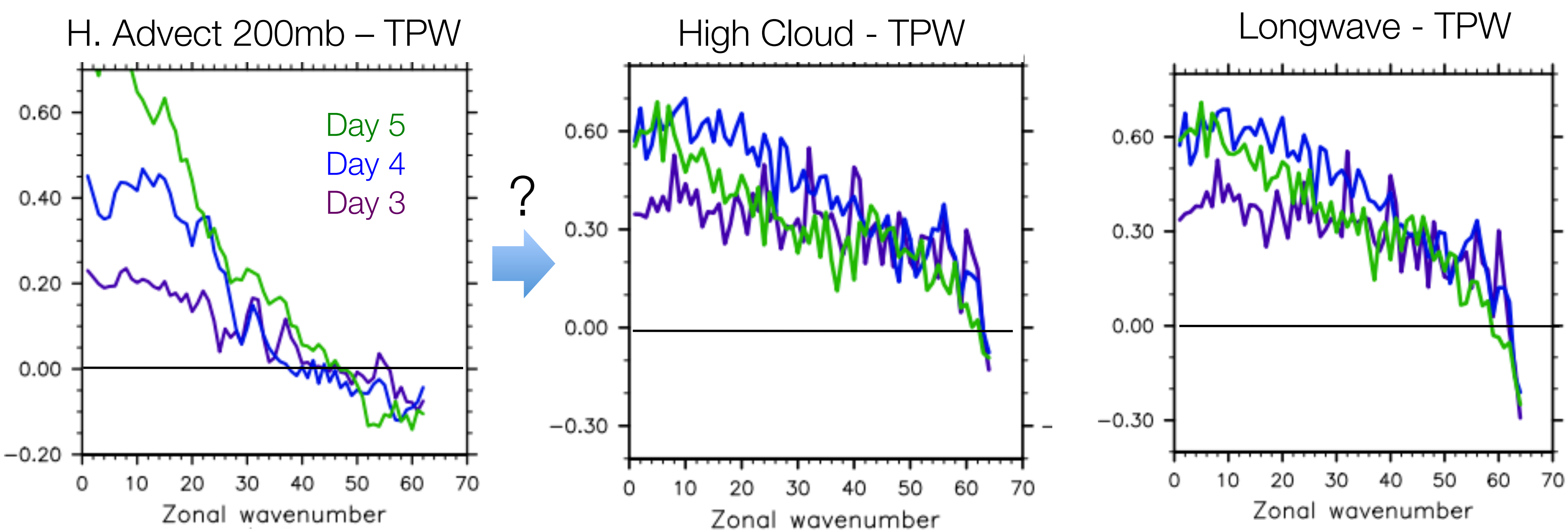
Longwave anomalies would only be positively correlated with moisture at long wavelengths.

Coherence Spectra



Total water tendency from horizontal advection is positively correlated with total column water at long wavelengths.

Coherence Spectra



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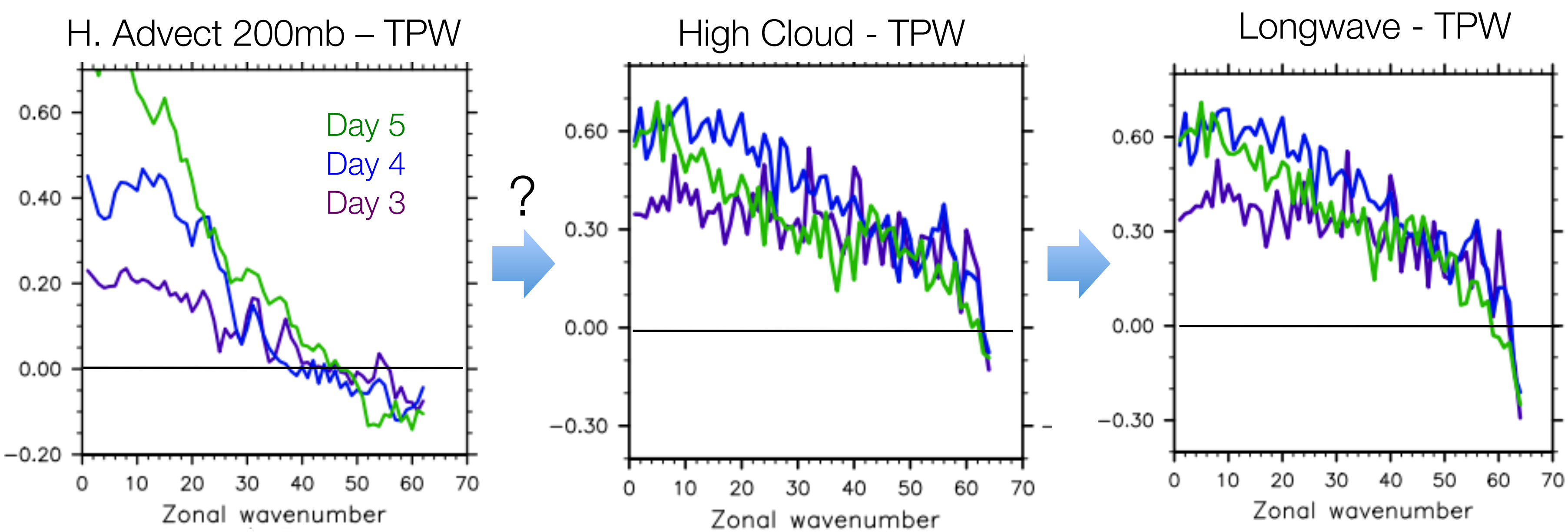
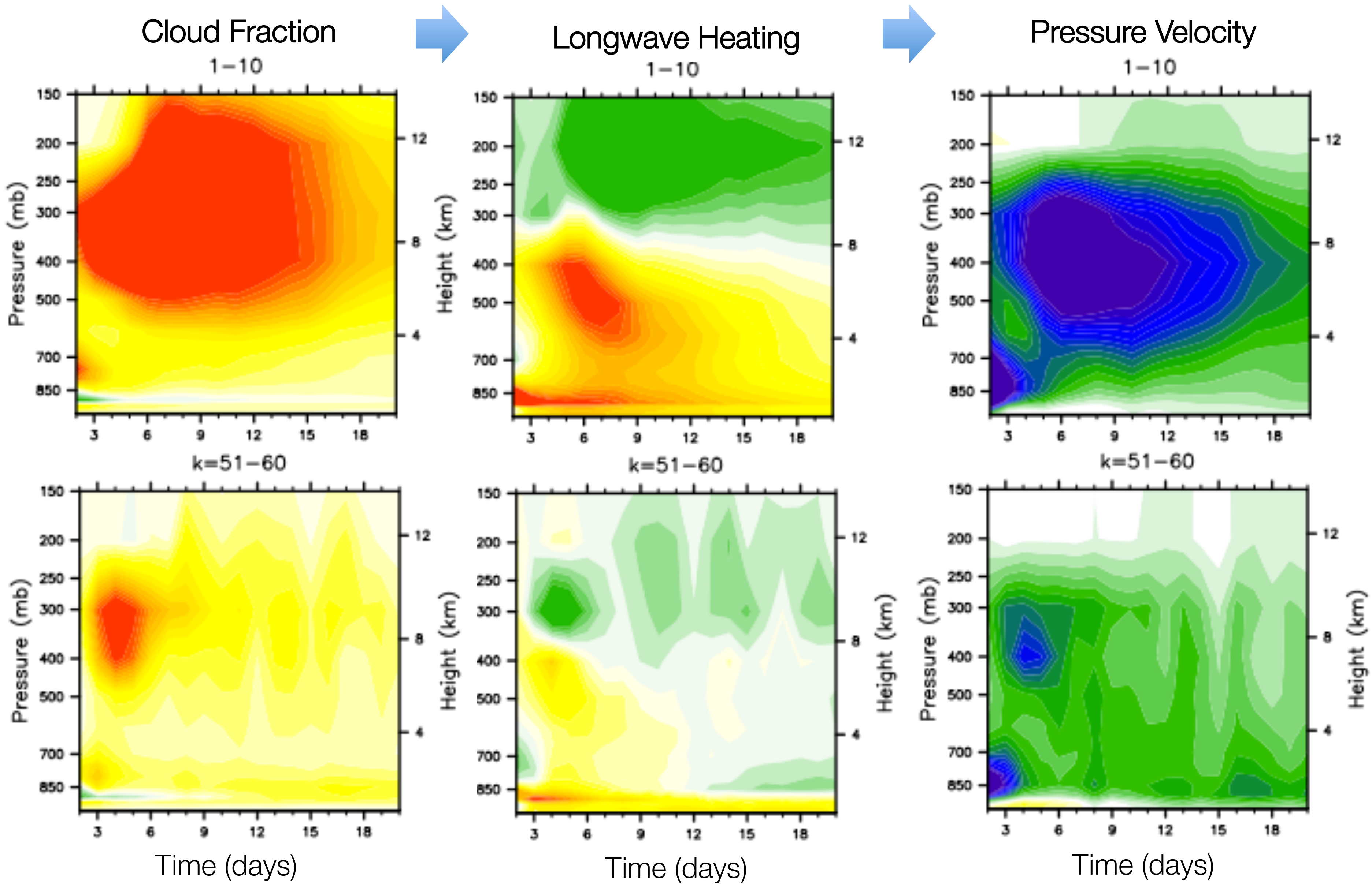
Coherence Spectra



Total water tendency from horizontal advection is positively correlated with total column water at long wavelengths.

Vertical profiles over time, by wavenumber



Conclusions II

- Aggregation spatial patterns depend on model parameters, resolution, SST interactivity.
- In SP-CAM, non-rotating aggregation and the MJO both have preference for a specific physical scale.
- In SP-CAM, diabatic feedbacks are primary source of MSE "coarsening."
- Longwave scale selection may be explained by shearing of low moisture and high clouds.