Water vapor as an active scalar

Adam Sobel, Columbia U.

Jim Benedict, Daehyun Kim, Eric Maloney, Shuguang Wang

and many of you here…

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Water vapor as an active scalar in tropical atmospheric dynamics

Adam H. Sobel[a)]
Department of Applied Physics and Applied Mathematics and Department of Earth and Environmental Sciences, Columbia University, New York, New York 10027

(Received 16 November 2001; accepted 4 April 2002; published 20 May 2002)

Water vapor is a constituent of the tropical atmosphere which, though to a significant extent locally controlled by vertical advection, precipitation, and surface evaporation, is also affected by horizontal advection. Water vapor affects the flow in turn, because a humid atmosphere supports deep, precipitating convection more readily than a dry atmosphere. Precipitation heats the atmosphere, and this heating drives the flow. Water vapor is thus a dynamically active constituent. Simplifications to the primitive equations of dynamical meteorology, based on the so-called weak temperature gradient approximation, are presented which highlight this behavior. The weak temperature gradient approximation is valid on large scales near the equator. It eliminates gravity waves, leaving only balanced dynamics, though the fundamental balance occurs in the temperature rather than the momentum equation (as is customary in most balance models of geophysical fluid dynamics). The dynamical role of water vapor is examined in a couple of idealized contexts, where either the vertical or horizontal structure of the flow is severely simplified. [DOI: 10.1063/1.1480795]

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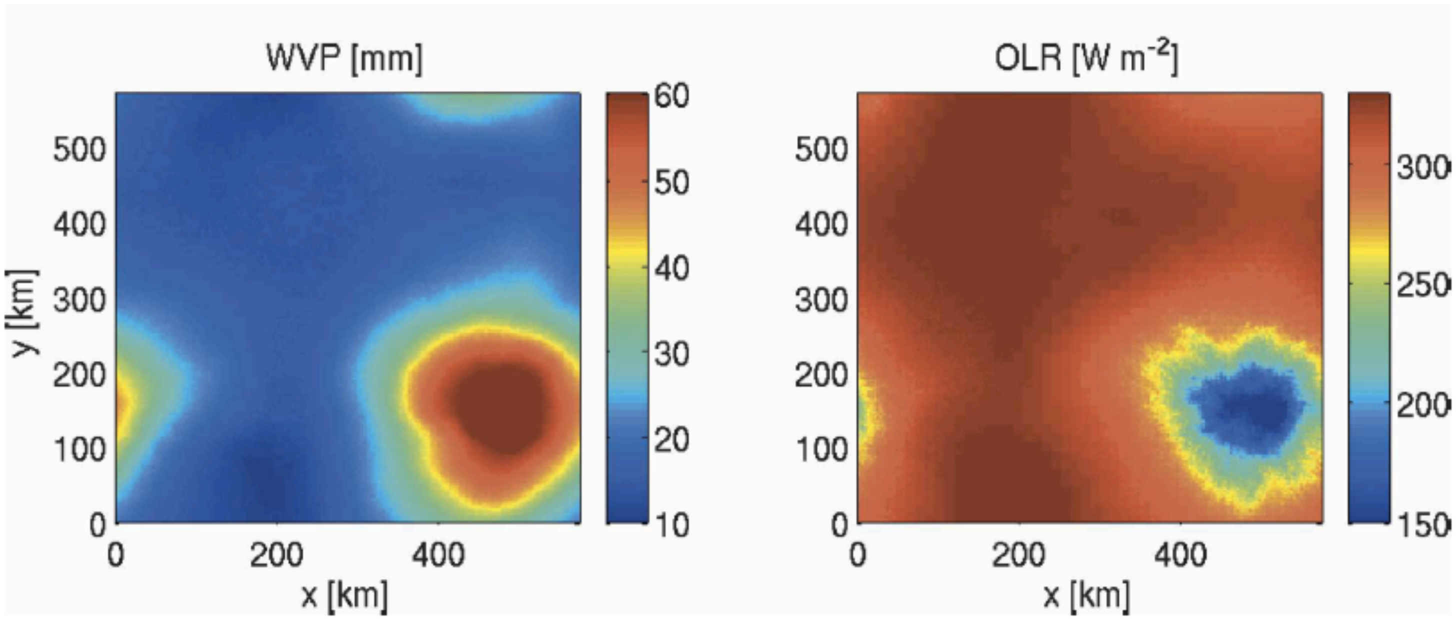
(Cited 4 times in 12 years, one of them a self-citation)

Bretherton et al. (2005): self-aggregation in a large-domain CRM in RCE



CF Muller and Held, Wing and Emanuel, and others.

The weak temperature gradient approach seems to be a useful way to think about self-aggregation. Replace the domain-averaged temp. equation by its dominant balance:

$\omega \, \partial s / \partial p$ = heating

which is diagnostic for ω , instead of prognostic for dry static energy *s* (or temperature *T*).

(For SCM/CRM applications, can substitute damped gravity wave/WPG if desired, but WTG is cleaner for the purposes of our argument here because it filters gravity waves)

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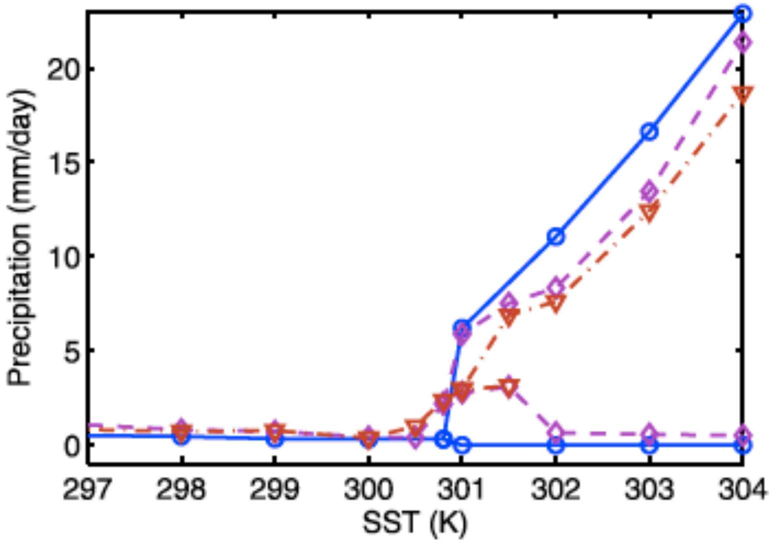
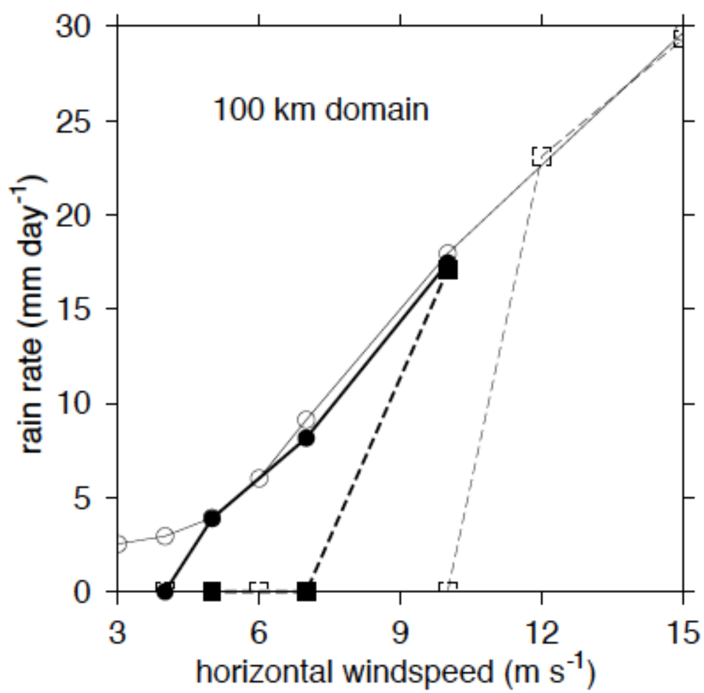
A single column model in which WTG is imposed produces multiple equilibria which we believe are analogs of self-aggregation (Sobel, Bellon & Bacmeister 2007; Emanuel & Sobel 2013)



Same thing happens in small-domain CRM under WTG (Sessions et al. 2010)



The single-column WTG view of self-aggregation leads to analysis of column-integrated budgets of moist static energy (or moist entropy). What maintains the column MSE anomalies – advection, surface fluxes, radiation?

To the extend that WTG is valid, variations in the column MSE itself are dominated by those in column-integrated water vapor.

In the presence of planetary rotation, self-aggregation leads to tropical cyclogenesis.

(Held and Zhao 2008; Khairoutdinov and Emanuel 2013; Zhou et al. 2014; Isaac Held's recent blog post, #43)

The “marsupial” theory of tropical cyclogenesis focuses on a blob of moist air as a Lagrangian entity – genesis occurs to the extent that it can hold together against both horizontal and vertical shear.

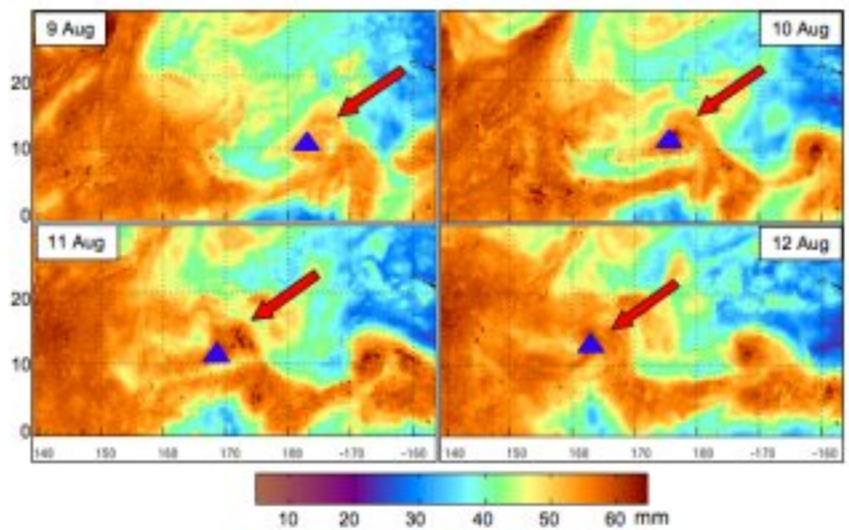
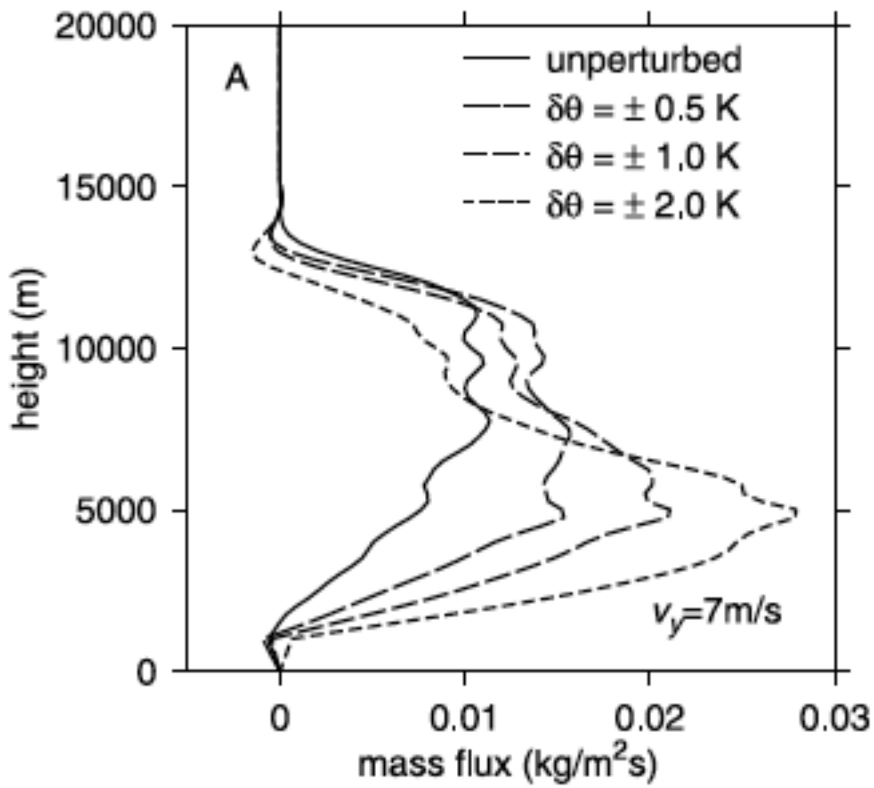


Fig. 6. Four-day time series of CIMMS Morphed TPW valid at 12:00 Z each day. Red arrows point towards the cat's eye region of the easterly wave (i.e., the wave pouch), which is hypothesized by DMW09 to be an area of increased moisture in the low to mid-troposphere and which helps protect the proto-vortex from lateral intrusions of dry air. The blue triangles indicate the position of the sweet spot as diagnosed in the GFS FNL at the 925 hPa level.

Montgomery et al 2010, *ACP*
See also Dunkerton et al. 2009 etc.

As vorticity spins up, balanced temperature anomalies can be sustained. These have an influence on convection.



Raymond & Sessions 2007, *GRL*

In the strong form of WTG, we must give up on prediction of temperature. *T* perturbations assumed negligible for purpose of computing physics tendencies.

The weak form: we can allow small temperature perturbations - impose them (e.g., Raymond and Sessions), or diagnose them from higher order balances, to see their effect on physics.

Many of us are now thinking about the MJO in broadly similar terms.

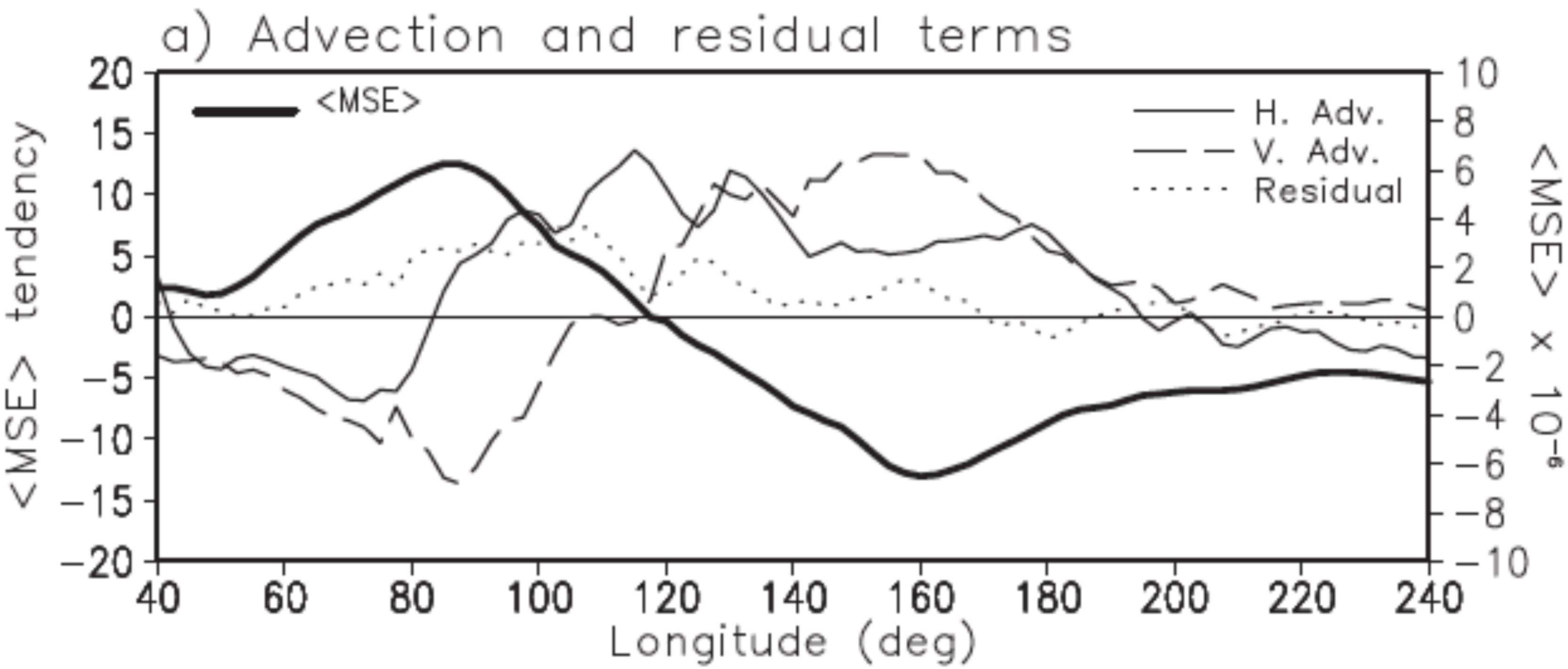
"Self-aggregation on the beta plane"

Meaning, a (large) blob of moist air encourages continued convection in one region, by moisture-convection feedback (entrainment etc.).

Some combination of surface flux and radiative feedbacks maintains the moisture anomaly - best seen through MSE (or entropy) budget.

Advection causes it to propagate. To a significant extent the advection is horizontal.

Horizontal and vertical advection are comparable in magnitude but horizontal plays a more obvious role in propagation.



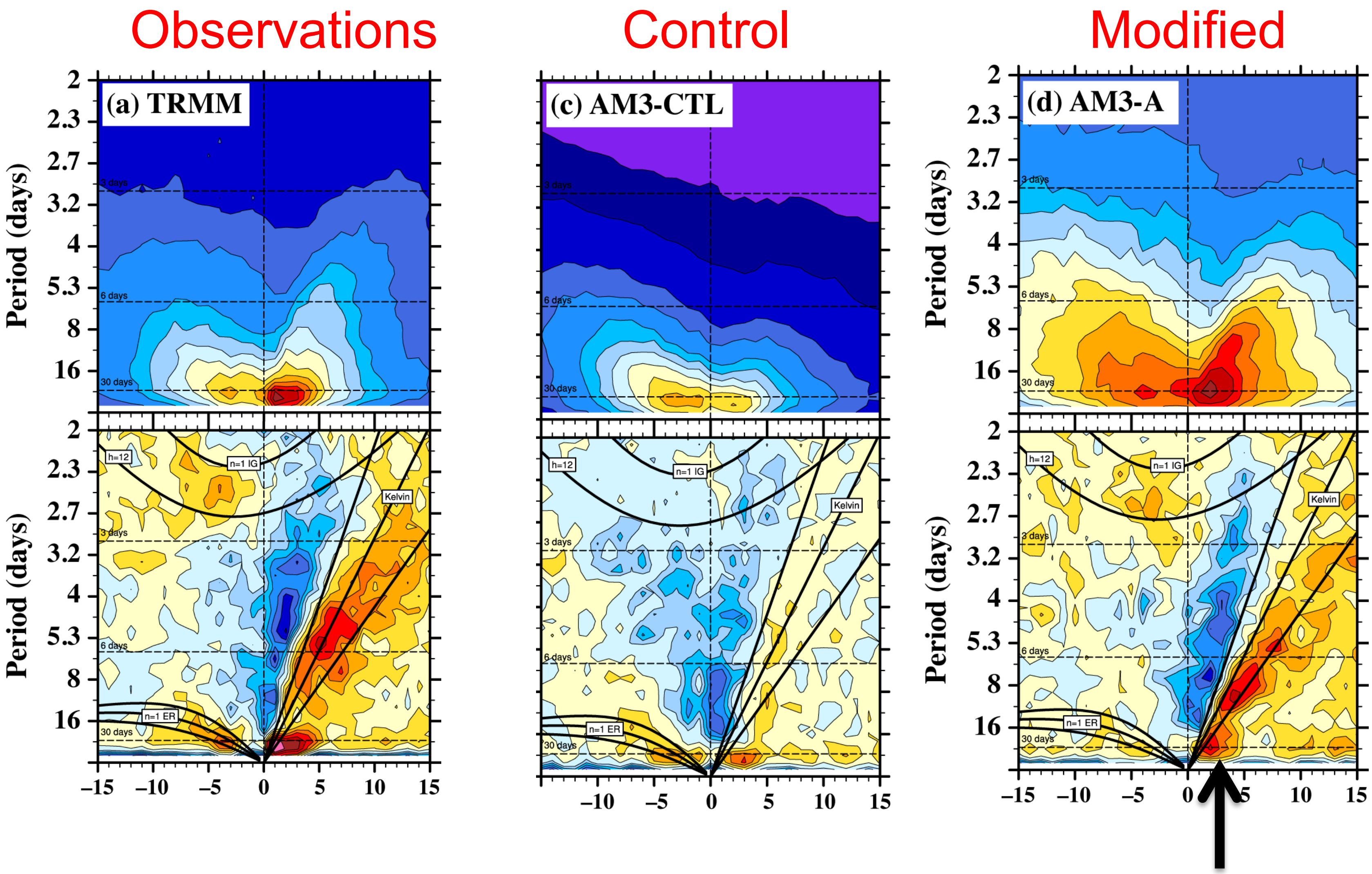
Kim, Kug, and Sobel *J. Climate* 2014

"Self-aggregation on the beta plane"

Moisture - > convection -> flow field that moves the moisture

Numerical models don't simulate a good MJO unless their deep convection is sufficiently sensitive to free-tropospheric moisture.

E.g., GFDL AM3 – Donner et al. (2011), Benedict et al. (2011)



Better MJO in model whose convection scheme has been modified to increase sensitivity to moisture

- Moisture influences convection (*active scalar*)
- Convection influences radiation
- Convection, radiationdirectly control the divergent flow (WTG)
- The divergent flow drives the rotational flow by vortex stretching
- Rotational flow controls temperature anomalies, which also feed back to convection
- The total flow controls the surface fluxes
- Surface fluxes, radiation and advection move moisture around (best viewed through budgets of entropy/MSE)

The picture that emerges has some resemblance to the theory of balanced, adiabatic motions in the extratropics (e.g., Hoskins, McIntyre and Robertson)

The picture that emerges has some resemblance to the theory of balanced, adiabatic motions in the extratropics (e.g., Hoskins, McIntyre and Robertson):

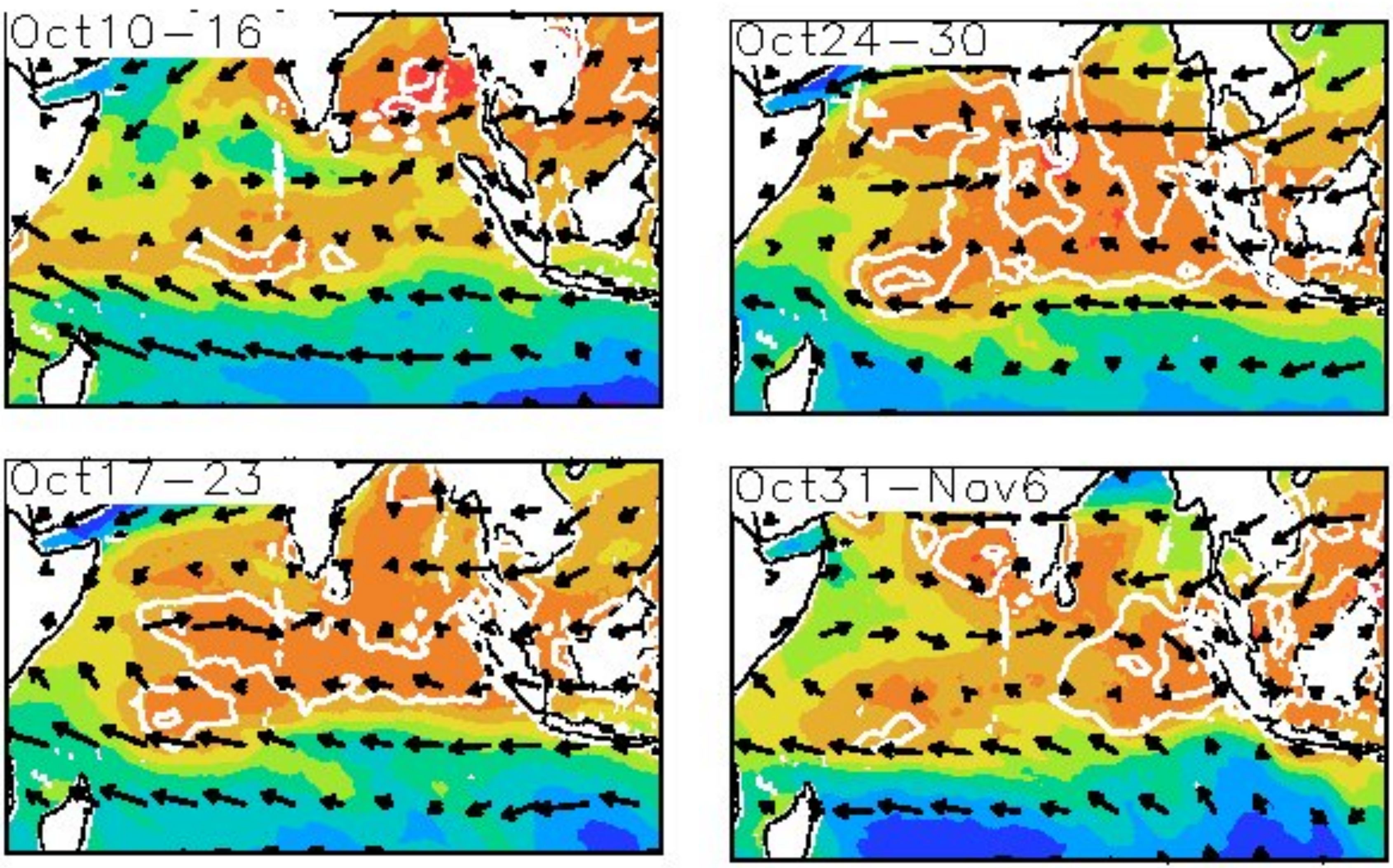
Potential temperature and potential vorticity are approximately conserved following the motion. The rotational
flow can be found diagnostically from those two fields, given boundary conditions. The divergent flow is small and inferred diagnostically at second order. The rotational flow then advects PV and theta around, etc.

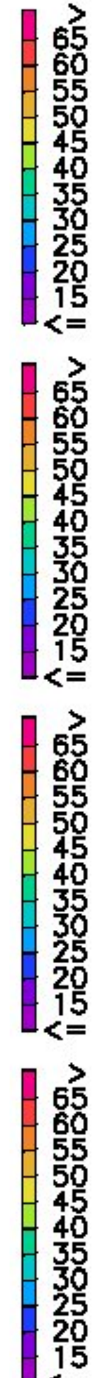
Extratropical	Tropical
PV advected on theta surfaces	Moisture advected in 3D (but horiz. component important)
Rotational flow diagnosed from PV	Divergent flow diagnosed from moisture (given physics and WTG)
Divergent flow diagnosed from second order balances	Vorticity prognosed, temperature diagnosed from second order balances
Ro, Fr $\ll 1$	Fr $\ll 1$ (Ro may or may not be)
$f \gg \beta L$	f small
Diabatic heating small (thus moisture unimportant)	Diabatic heating large, controlled by moisture

This picture of tropical dynamics is not as clean as its extratropical counterpart. Nothing is conserved all that well. The relation of moisture to convection is highly model-dependent.

But the recognition that horizontal advection is important Implies some degree of Lagrangian thinking.

Weekly means from CINDY/DYNAMO period: Column water vapor (color, mm) 850 hPa wind vector, Precipitation (mm/d, interval 10)

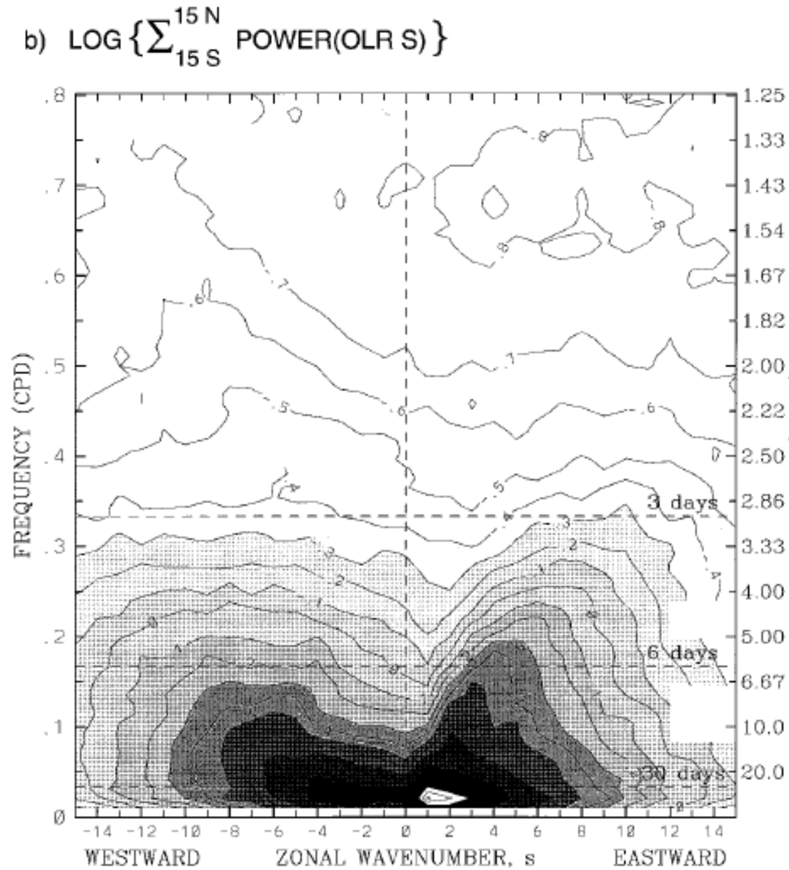




October event

How much tropical behavior might this "slow" dynamics explain? Hypothesis: MJO, ER/tropical depressions/early genesis. Not Kelvin/ IGW.

frequency



wave number

Wheeler and Kiladis 1999

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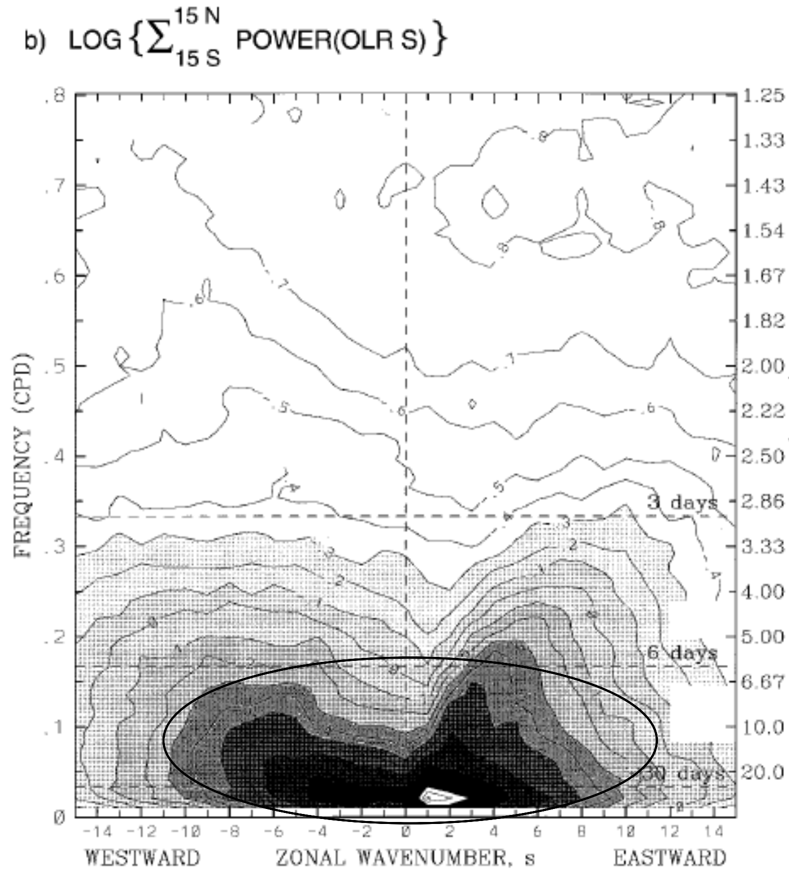

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Wheeler and Kiladis 1999

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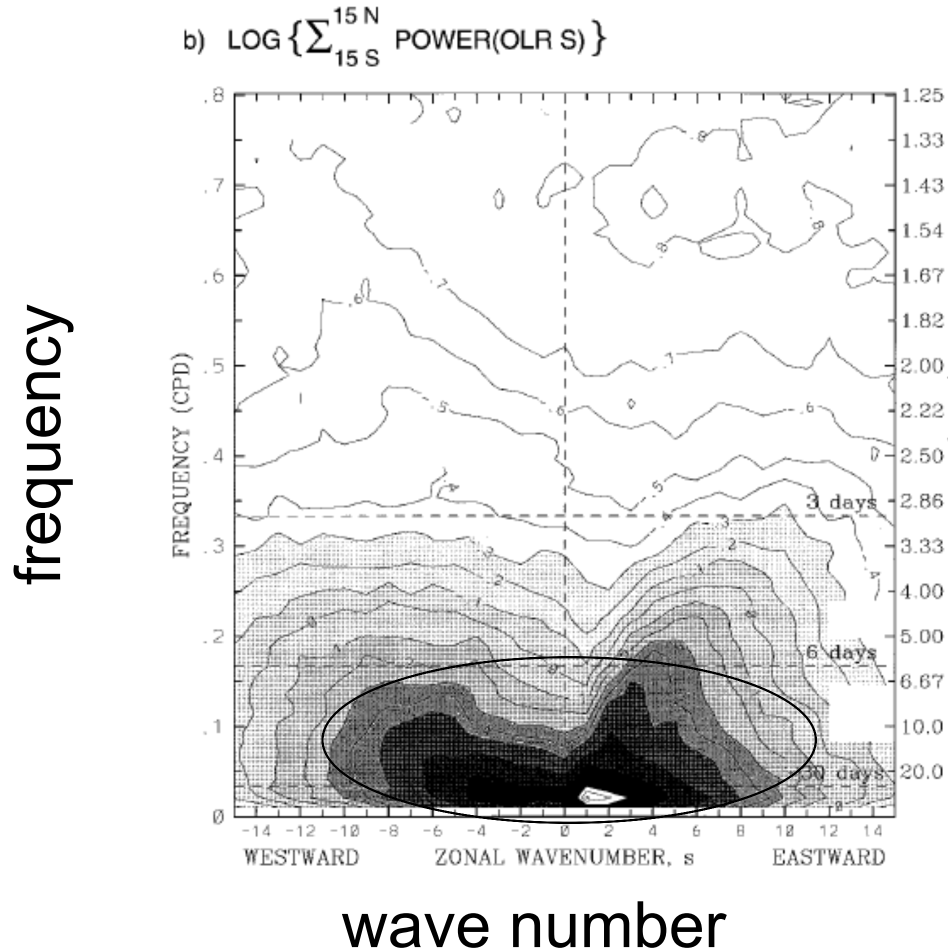
We tend to think there is no scale separation in the tropics, but maybe there is.



Wheeler and Kiladis 1999

What are the implications of this?

It means something about predictability. TC genesis and MJO are being predicted better and better by models.

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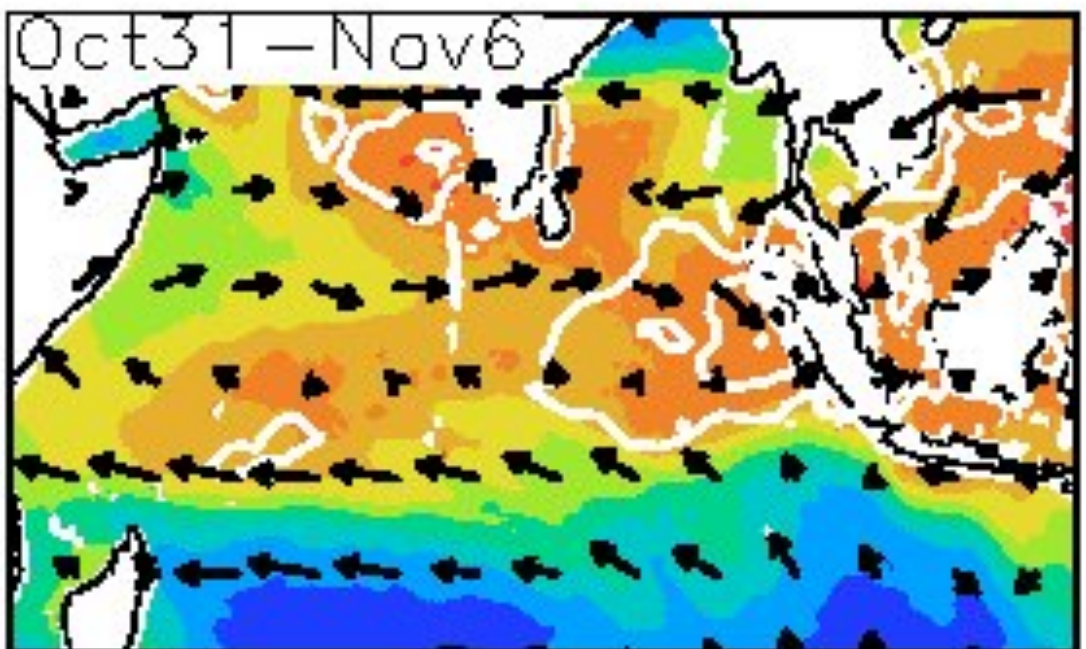
What is the equivalent of the isentropic PV map?



Surface fluxes always lag convection; would drive MJO westward.
Radiation must be important for growth; advection for propagation.