Moisture modes, cloud-radiative feedbacks and the MJO

Adam Sobel

Eric Maloney, Shuguang Wang, Daehyun Kim, also bits from Jim Benedict; thanks also Gilles Bellon, Dargan Frierson…

FDEPS, Kyoto

The Madden-Julian oscillation – a natural fluctuation of the tropical climate

Outgoing longwave radiation 15S-15N

Blue = rainy
Orange = clear

Aug 2011

Sep

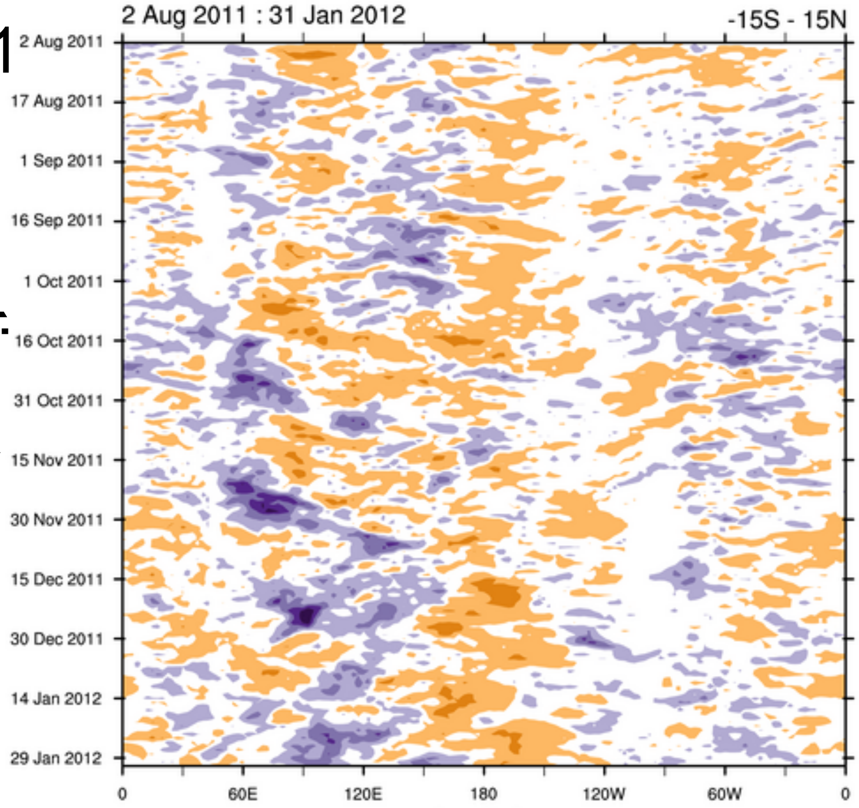
Oct

Nov

Dec

Jan

time->



longitude

Source: Matt Wheeler, Centre for Australian Climate and Weather Research
cawcr.gov.au

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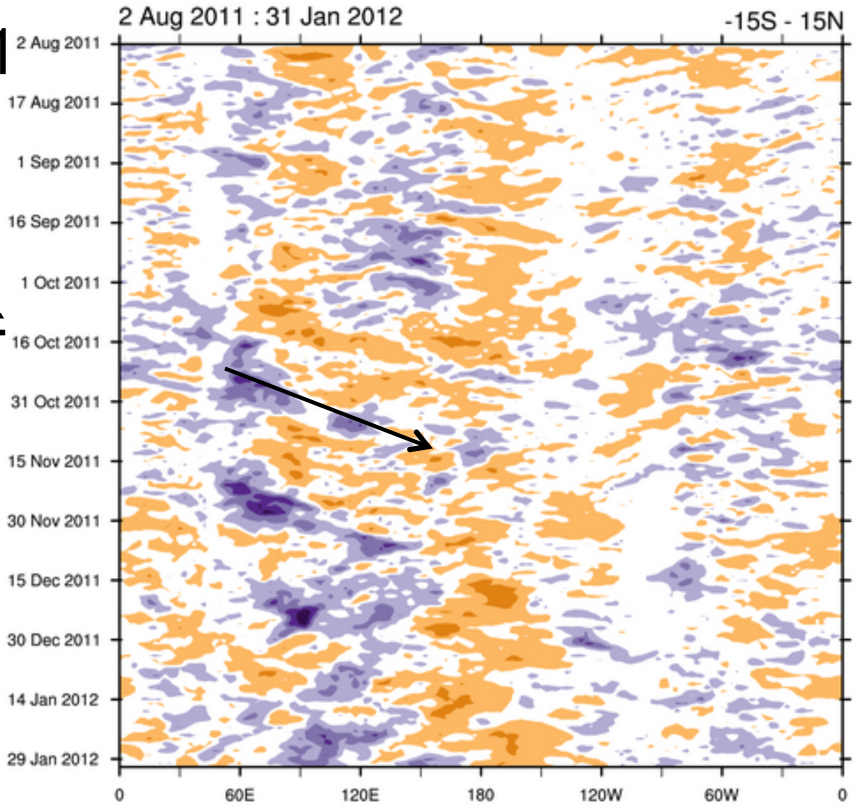

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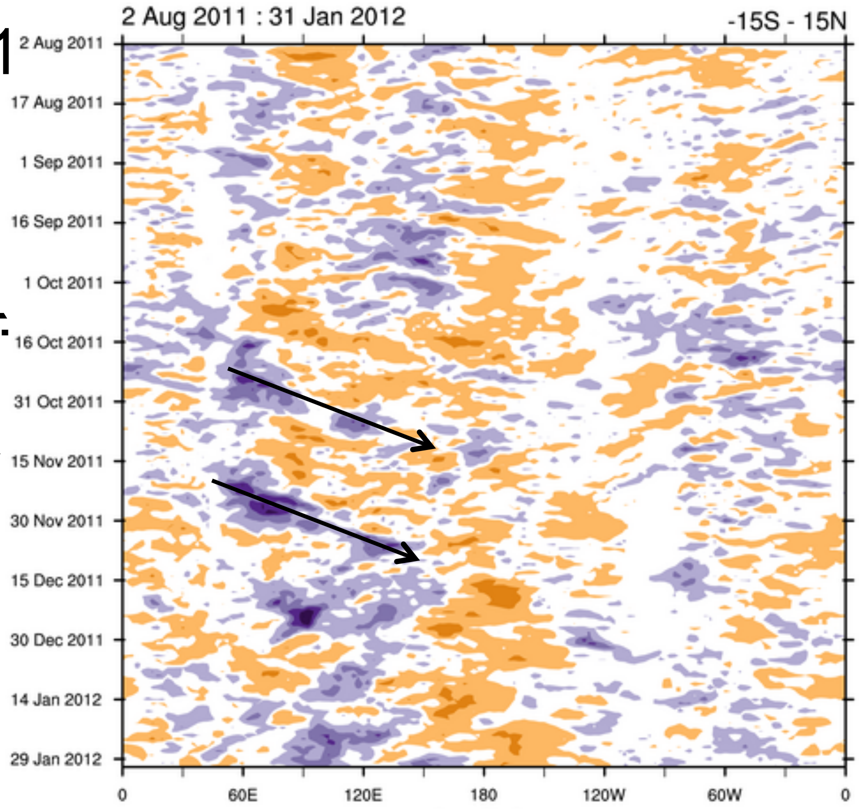

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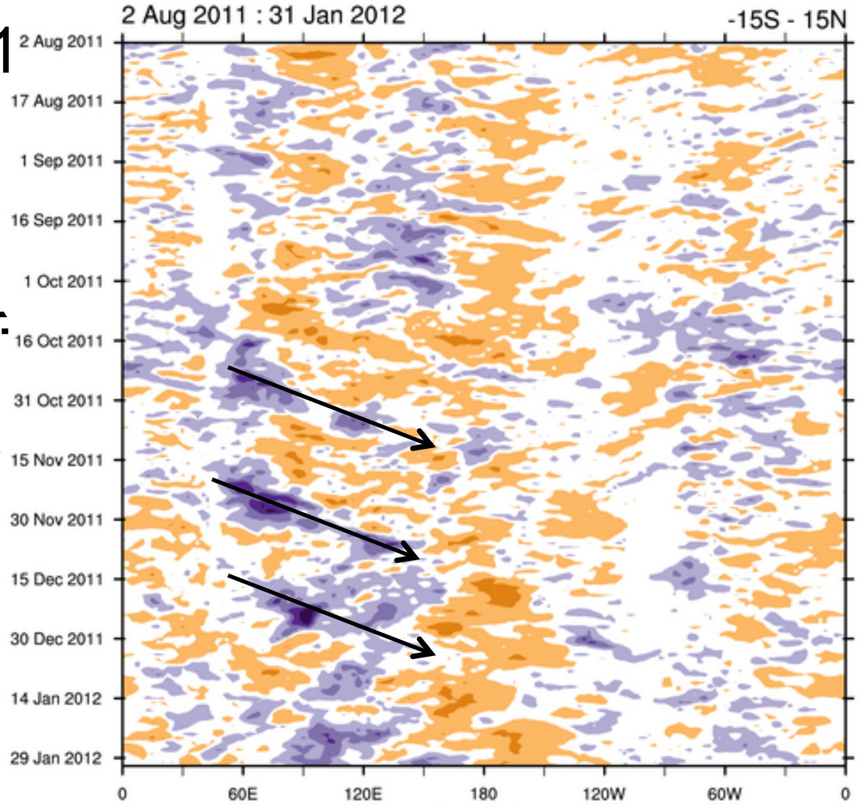

Aug 2011
Sep
Oct
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Jan

time->

longitude

Source: Matt Wheeler, Centre for Australian Climate and Weather Research
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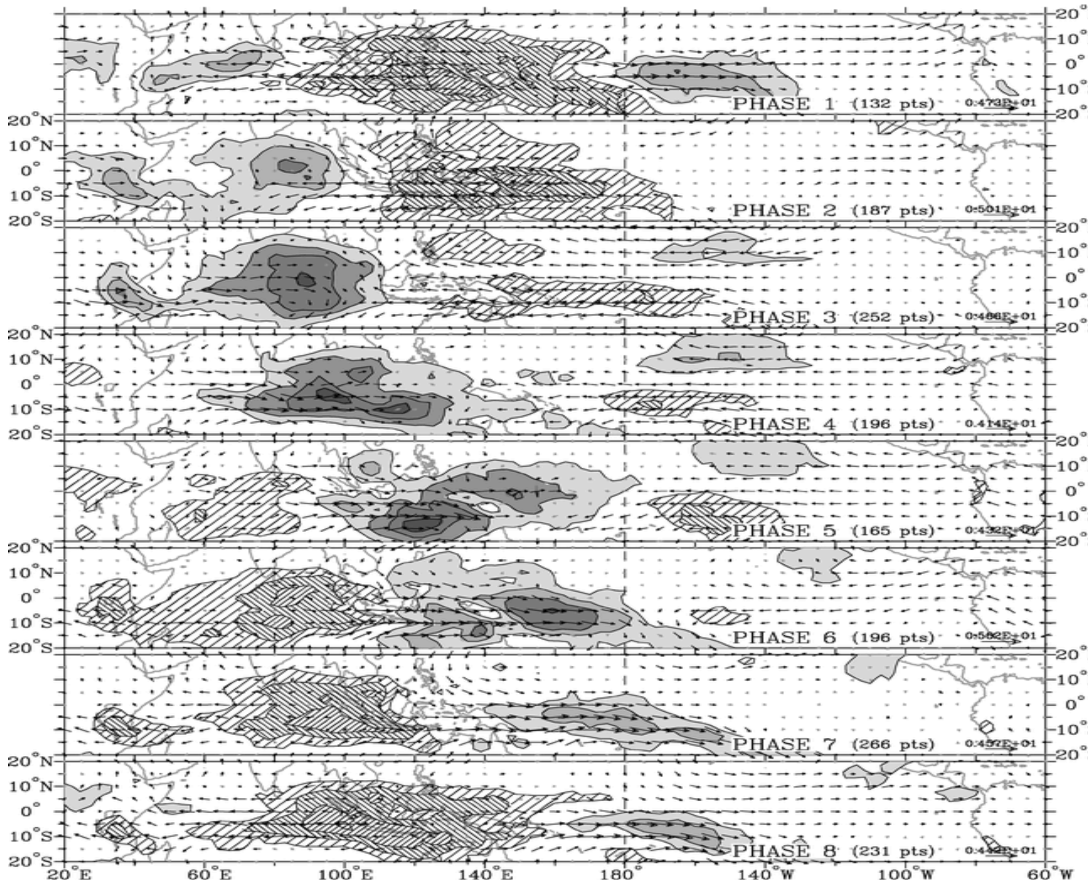
The “Madden-Julian oscillation” (MJO) propagates eastward in a belt around the equator

Statistical composite MJO in outgoing longwave radiation and lower tropospheric wind (Wheeler and Hendon 2004)

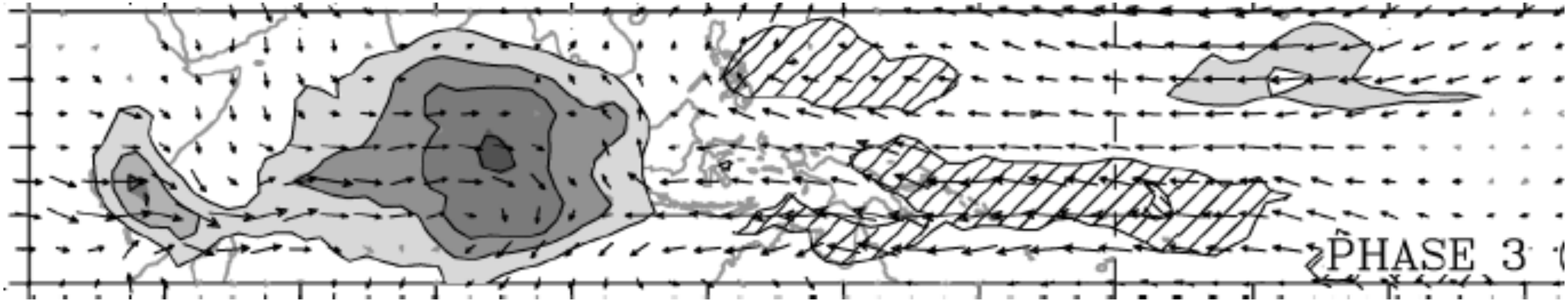


time

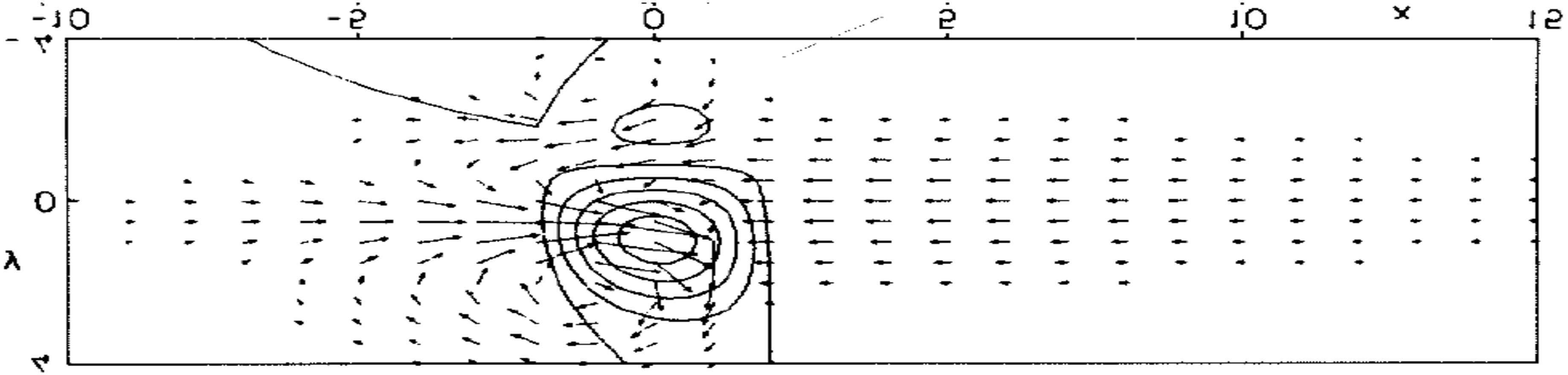
latitude

longitude

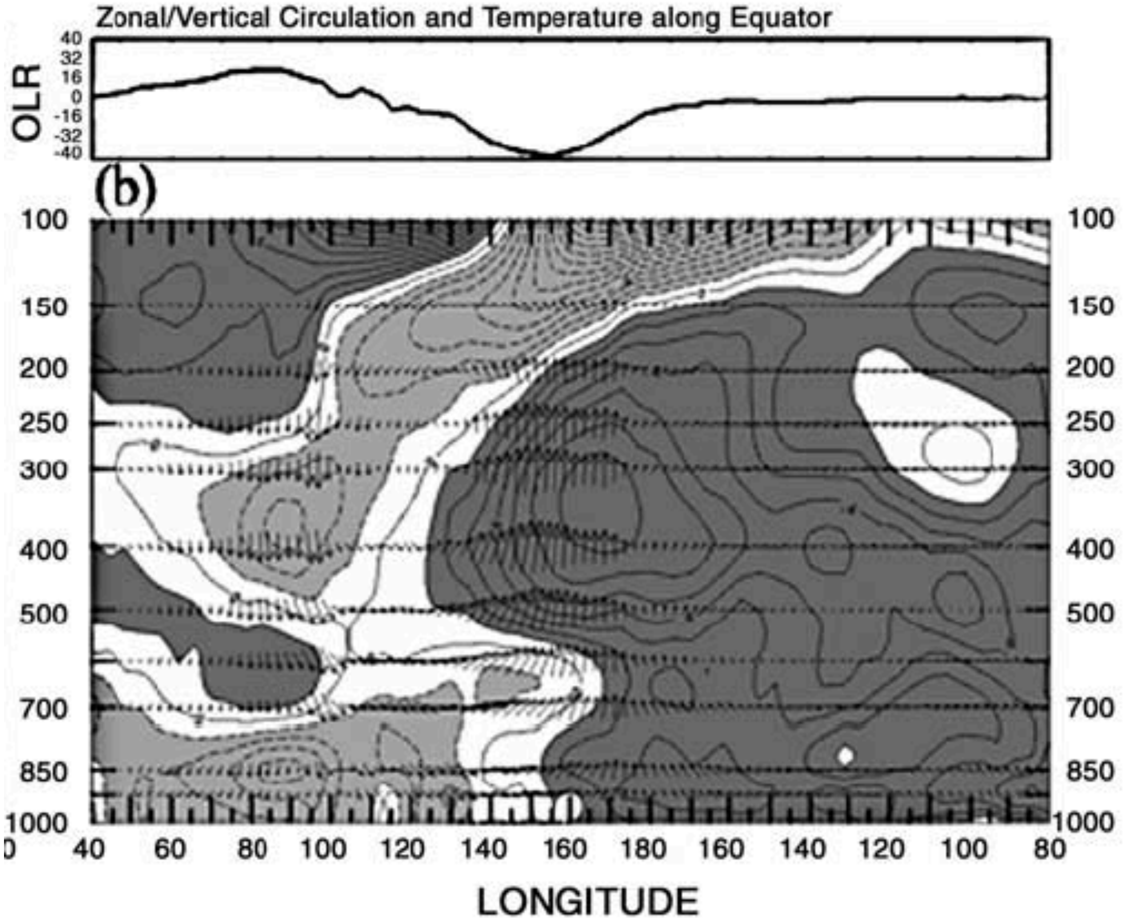
Statistical composite low-level flow (Wheeler and Hendon 2004)



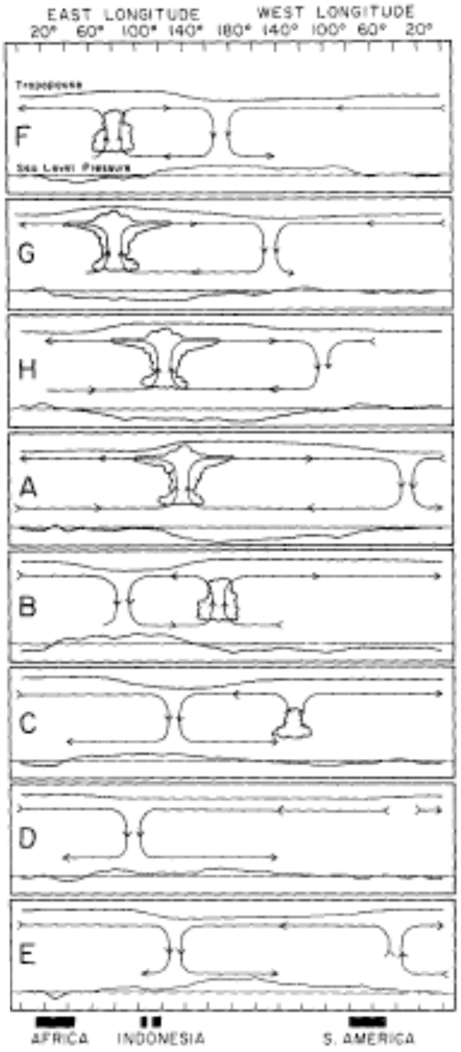
Gill (1980) low-level flow for off-equatorial heating



Zonal/vertical circulation and temperature along equator (Zhang 2005, *Rev. Geophys*.)

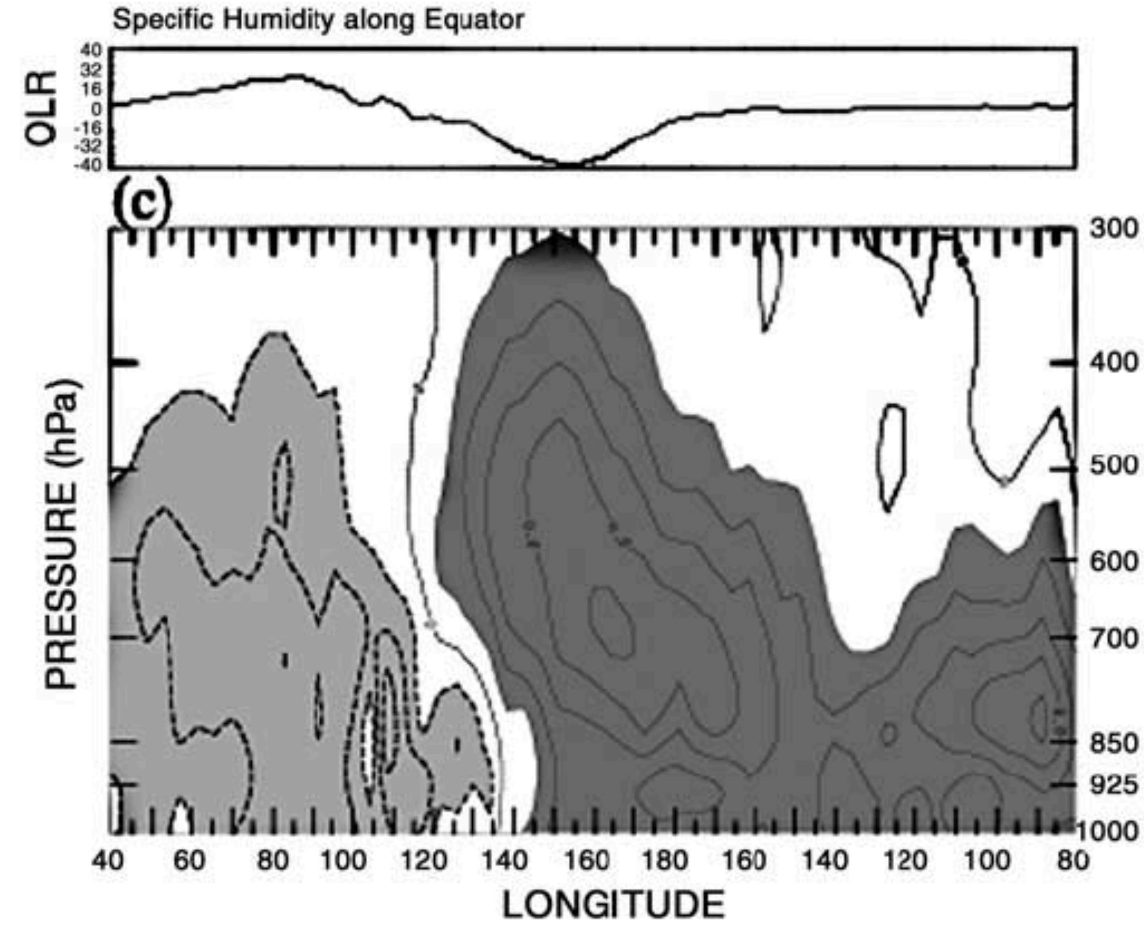


The MJO is a translation of the planetary-scale zonal overturning (Walker) circulation

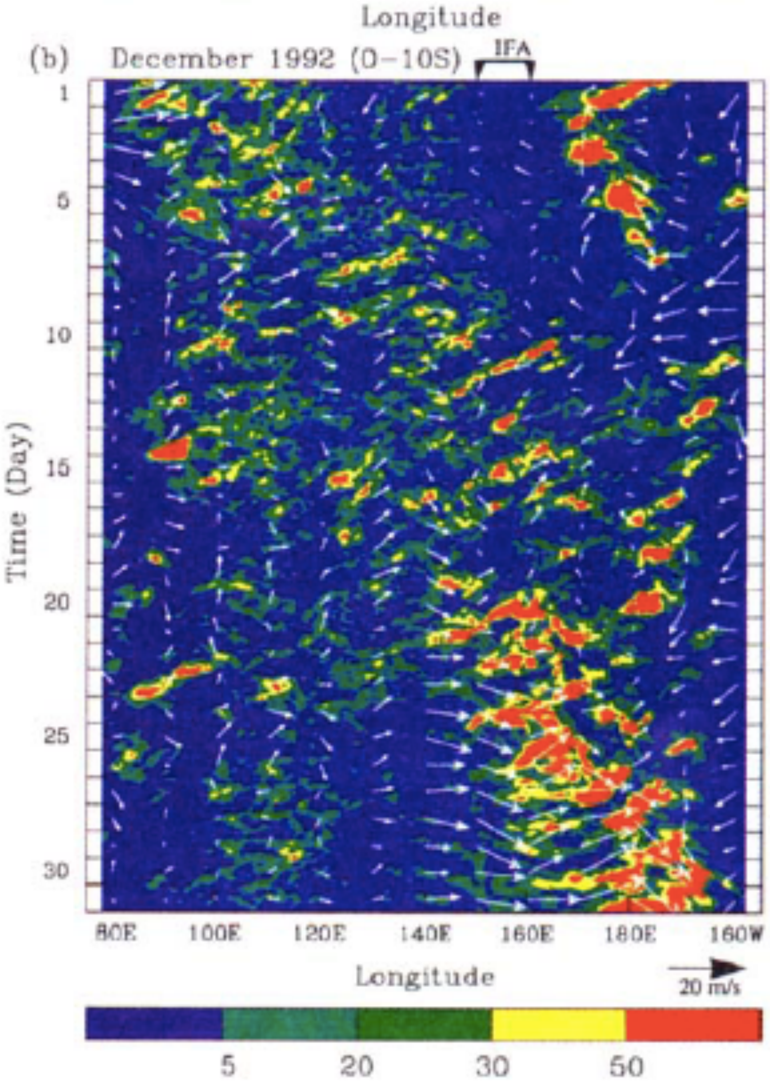


Madden and Julian ~~1971~~ 1972

Humidity structure in longitude and pressure (Zhang 2005, *Rev. Geophys*.)



The MJO is an envelope for higher-frequency disturbances



Chen et al. 1996, *J. Atmos. Sci.*

We now have significant forecast skill, with dynamical models beating statistical
(Kang and Kim ~~2009~~)
2012

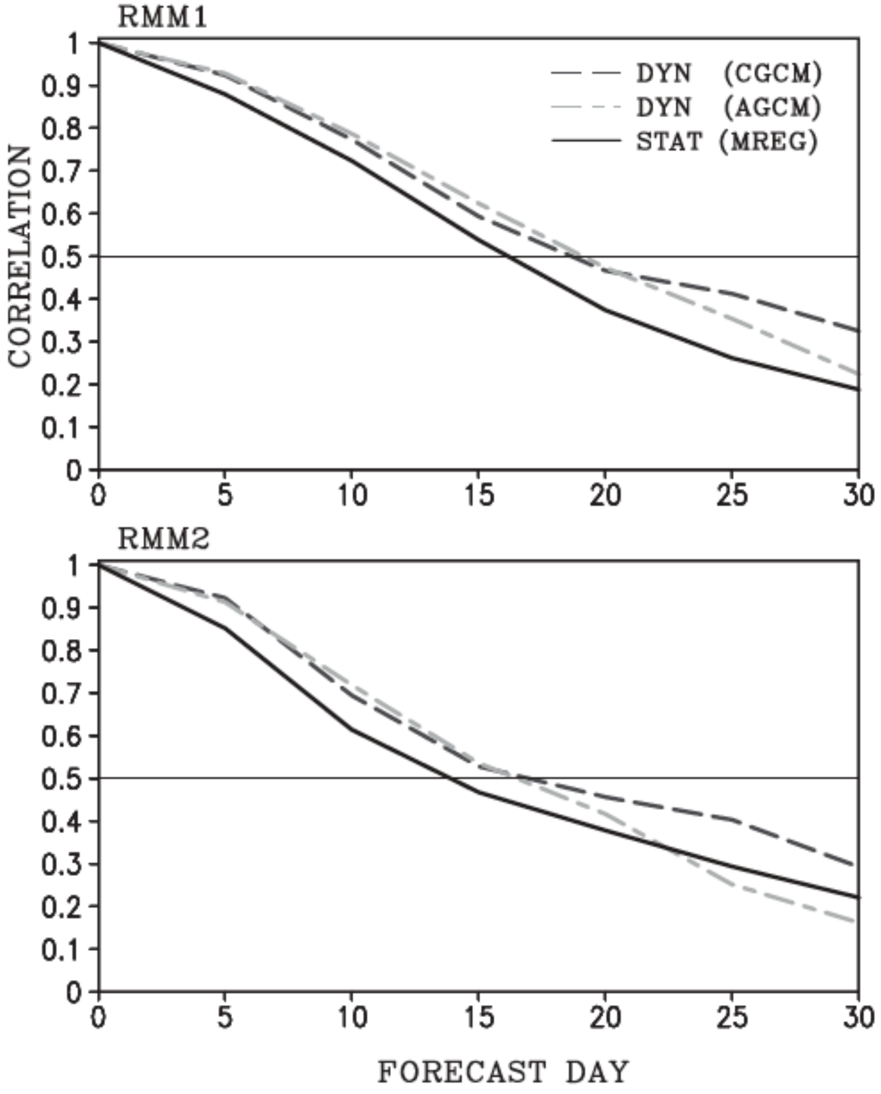
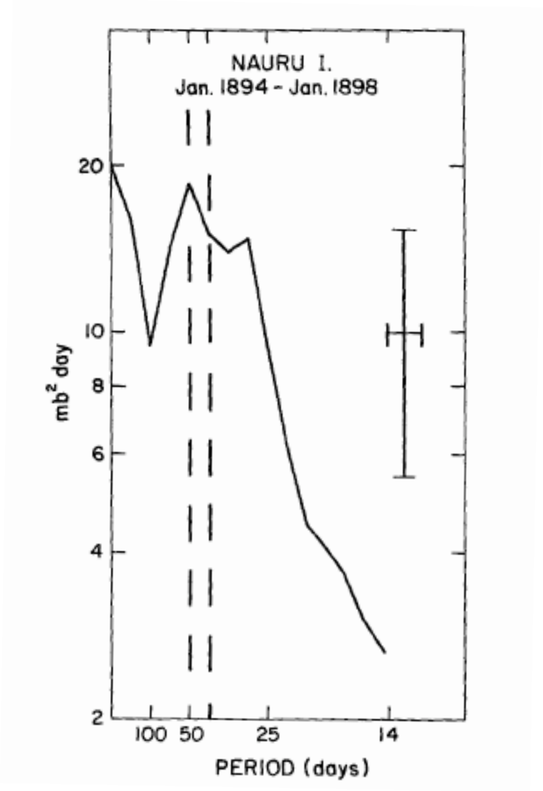


FIG. 7. Correlation skills of AGCM (long- and short-dashed line) and CGCM (dashed line) for RMM1 and RMM2 as a function of lead time, and the MREG (solid line).

Numerical simulations are not so bad any more… but there is no agreement on the basic mechanisms despite ~4 decades of study

Surface pressure spectrum,
Nauru Island, tropical Pacific

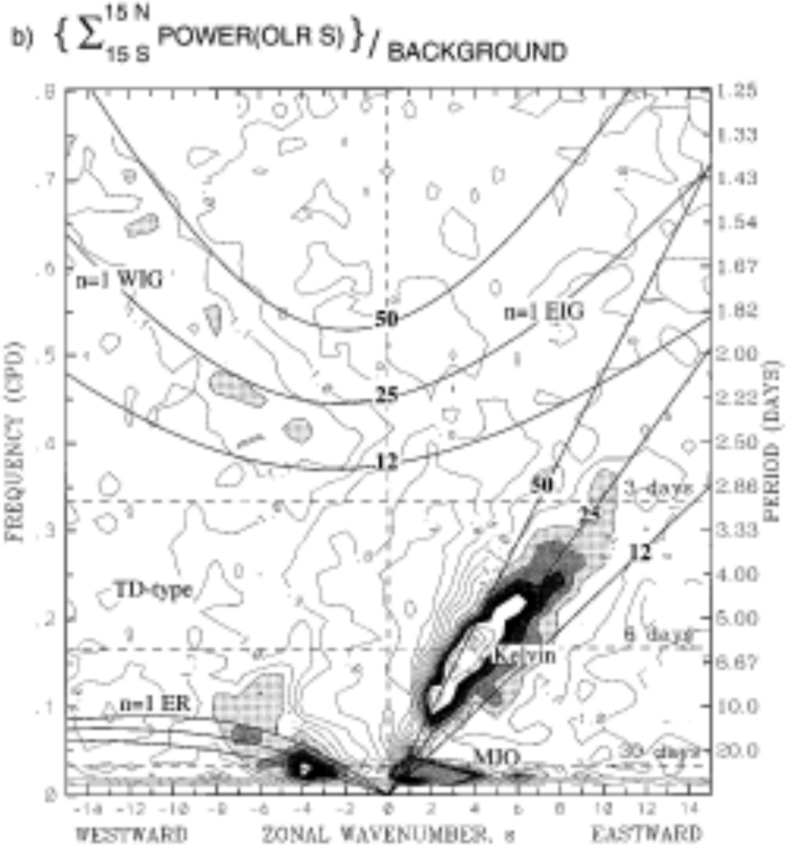


Madden and Julian 1972

Helium spectral lines

wikipedia

Spectral analysis shows that the MJO is not a Kelvin wave… so what is it?



frequency

wave number

Wheeler and Kiladis 1999

Questions

- What is the MJO? What are the fundamental dynamics?
- What sets the scales: spatial scale, and frequency or phase speed?
- Why does it go eastward?
- What is the energy source?

I will argue that cloud-radiative feedbacks are essential to the existence of the MJO.

This is not a new idea (e.g., Raymond ~~2000~~ 2001, Bony and Emanuel 2005), but is probably not broadly accepted yet.

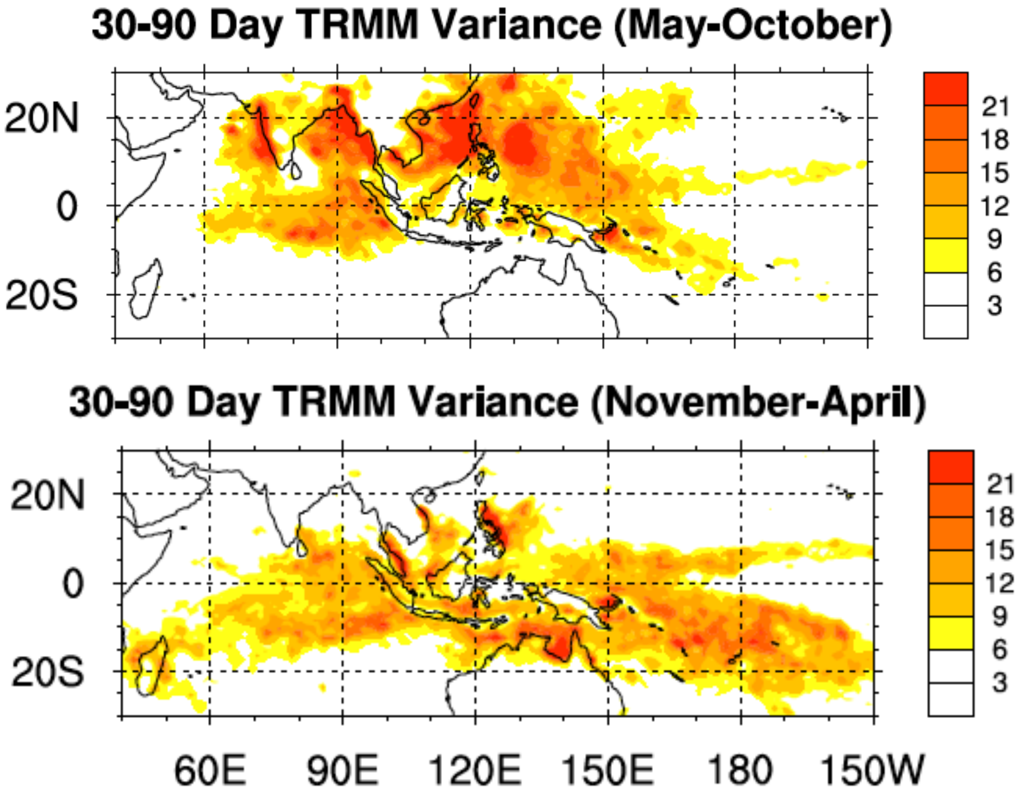
Historically nearly *all* theories of transient meteorological phenomena (MJO, waves, TCs…) over tropical oceans ignore cloud-radiative feedbacks.

Presumably this is because radiative cooling variations are << convective (condensation) heating variations.

But if conserved variables (MSE, moist entropy) are what matter then condensation heating is irrelevant!

Observation: Intraseasonal rainfall variance is greater over ocean than land. Suggests a role for net surface heat flux.

Intraseasonal rain variance



30-90 Day TRMM Variance (May-October)

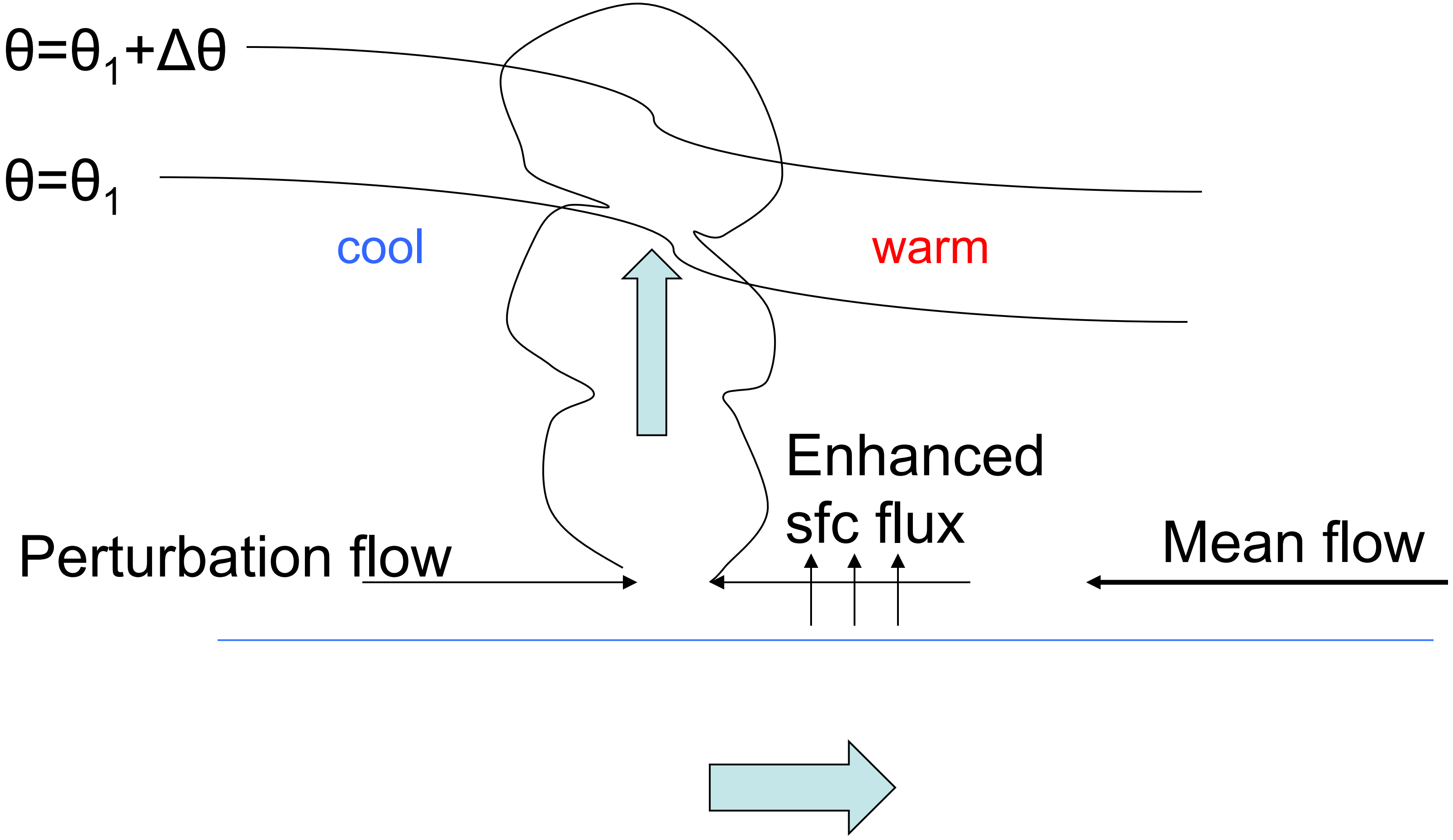
30-90 Day TRMM Variance (November-April)

Northern Summer

Southern Summer

Sobel, Maloney, Bellon, and Frierson 2008: *Nature Geosci.,* **1**, 653-657.

Emanuel (87) and Neelin et al. (87) proposed that the MJO is a Kelvin wave driven by wind-induced surface fluxes (“WISHE”)



$\theta=\theta_1+\Delta\theta$

$\theta=\theta_1$

cool

warm

Enhanced sfc flux

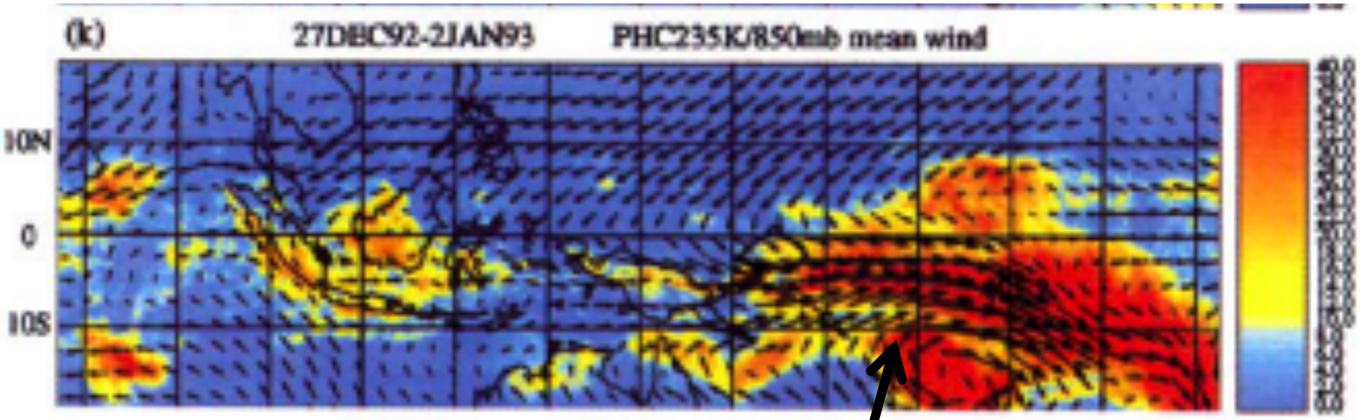
Perturbation flow

Mean flow

Wave propagation

This idea has been somewhat abandoned because the real MJO does not look quite like the original WISHE theory

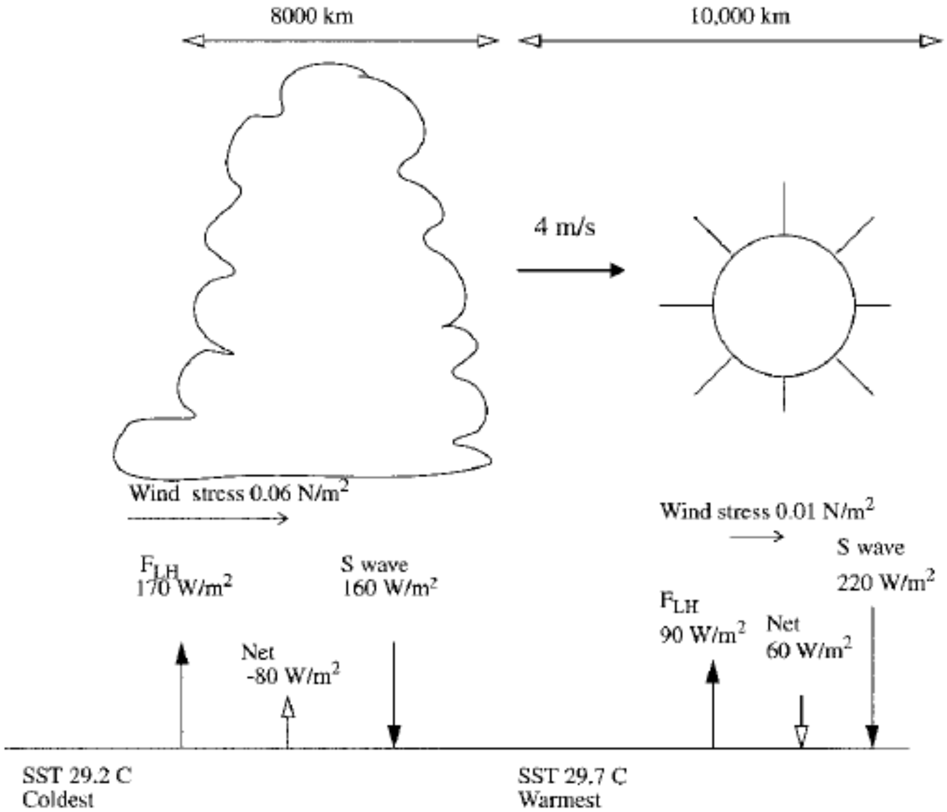
Observed cloudiness and wind from TOGA COARE



Strongest winds and fluxes are in phase with or lag precipitation, and lie in westerlies

Chen, Houze and Mapes 1996

But the real MJO does have significant net surface heat flux variations, roughly in phase with convection

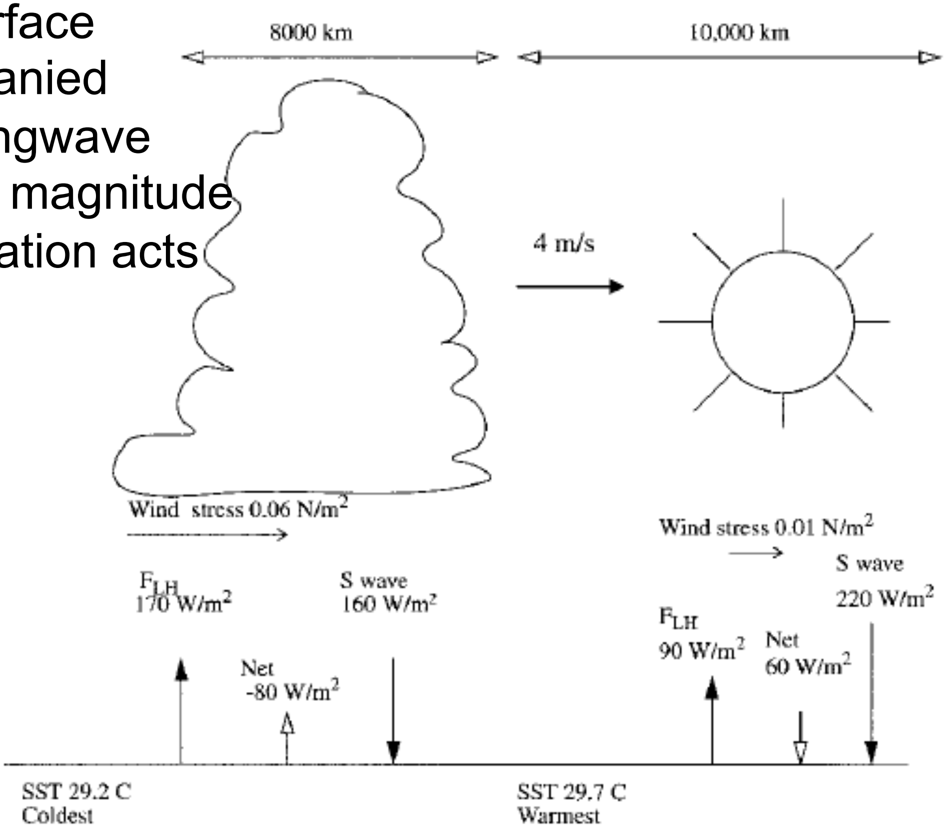


ocean

Shinoda et al. 1998

But the real MJO does have significant net surface heat flux variations, roughly in phase with convection

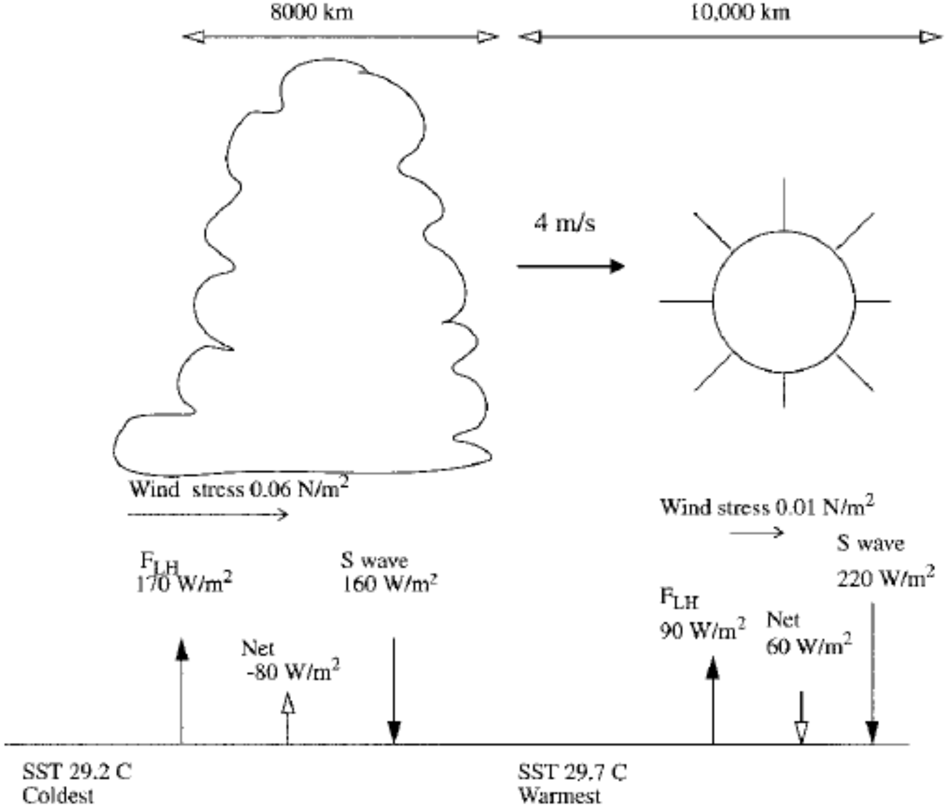
The shortwave surface cooling is accompanied by atmospheric longwave warming of similar magnitude (so in the net, radiation acts like a surface flux)



ocean

Shinoda et al. 1998

Over land, there can be no significant net flux variations on intraseasonal time scales - so if net flux were important to ISO convection, we’d expect stronger ISO over ocean



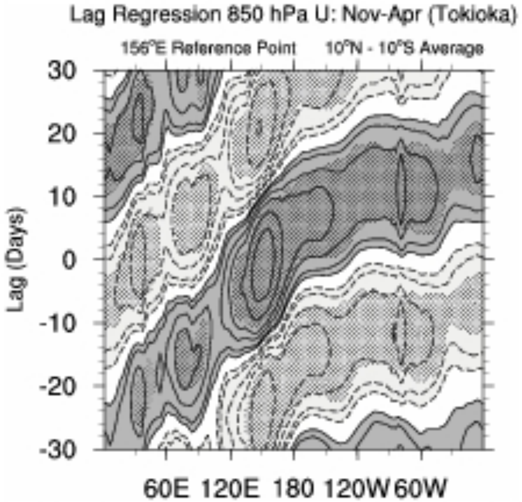
ocean

Net = 0 W/m^2

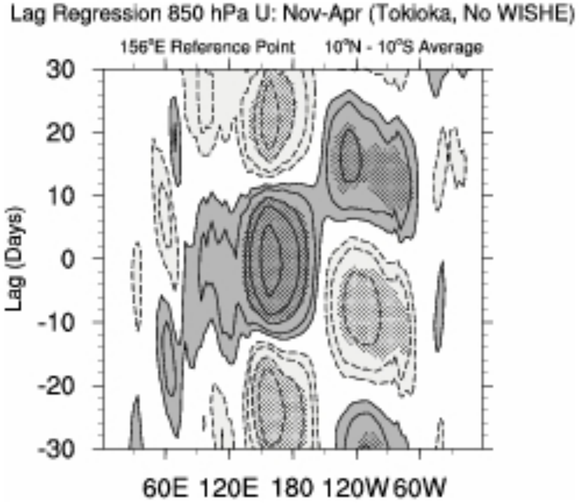
land

In a number of models, surface fluxes are important to the MJO – e.g. GFDL AM2 (after Tokioka fix)

control

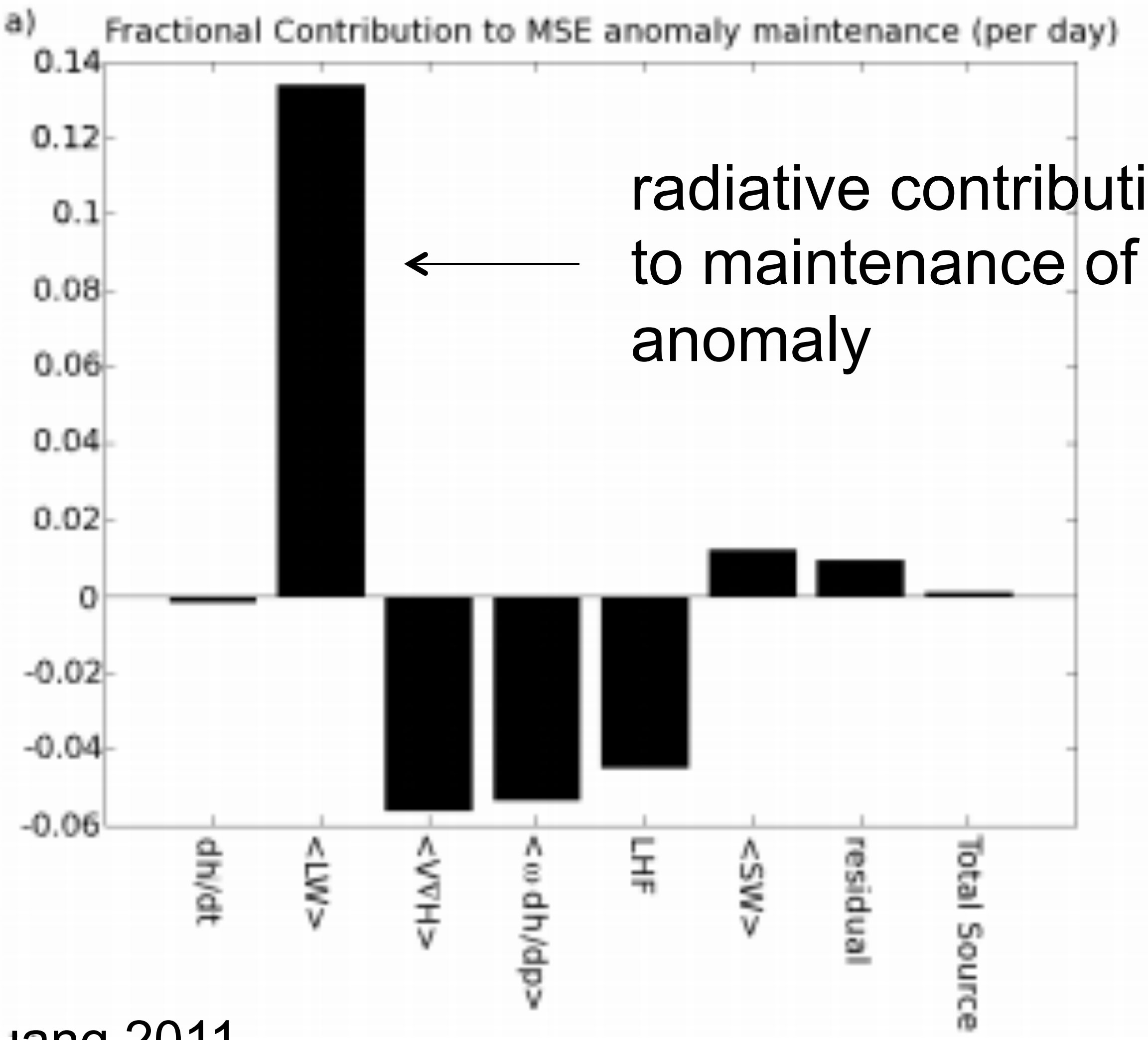


No-WISHE
(const sfc
wind speed)



Sobel et al. 2010 – calculations by Dargan Frierson

In other models, radiative feedbacks are important while surface turbulent flux feedbacks are not – but both are MSE sources



radiative contribution to maintenance of MSE anomaly

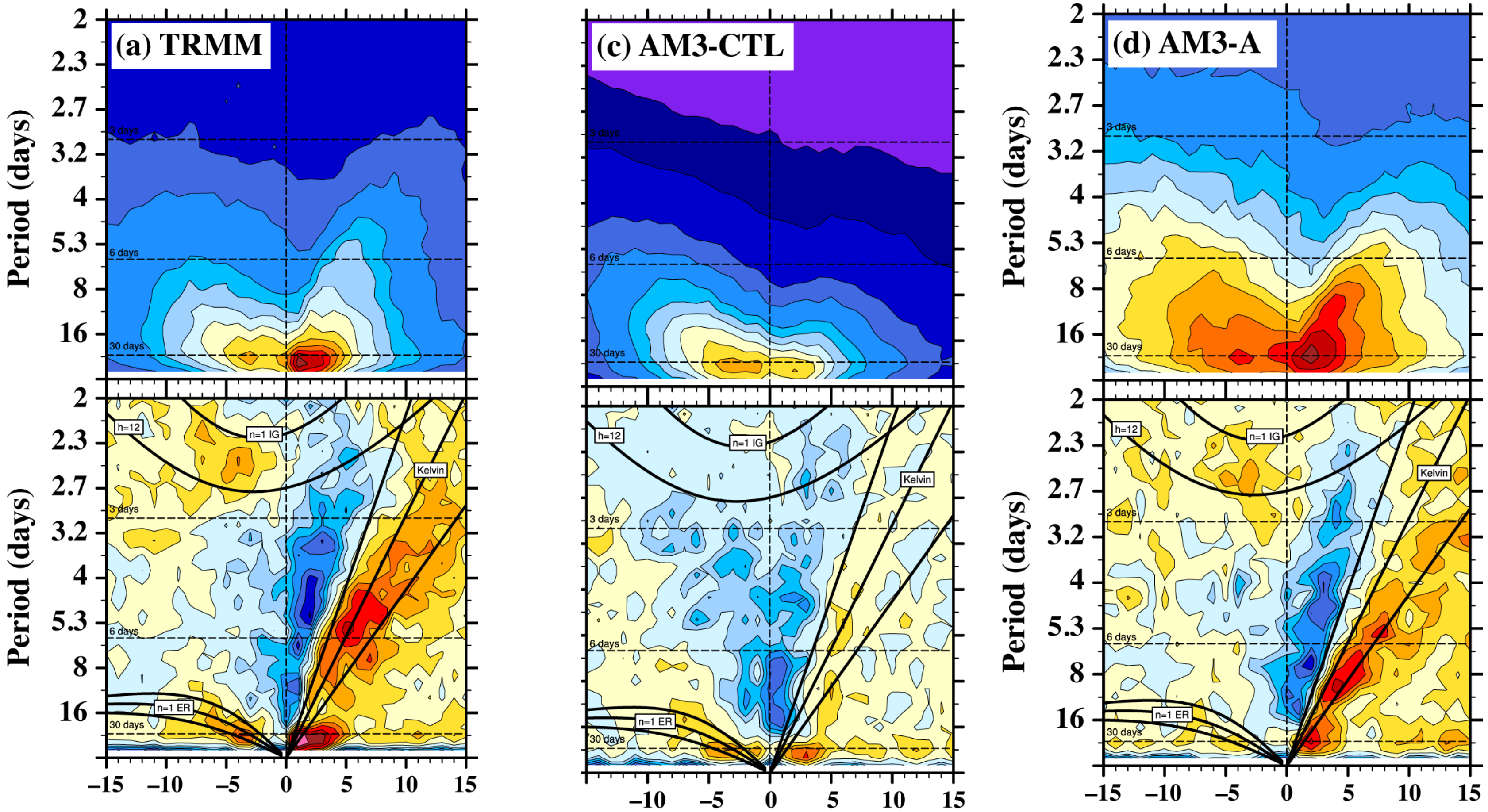
Andersen and Kuang 2011

Moisture/convection feedback

In many models (maybe all that have been tried), a weak MJO can be strengthened by making deep convection more sensitive to free-tropospheric humidity – that is, inhibited by dry air above the PBL.

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

Observations Control Modified



The improvement in intraseasonal variability comes at the cost of biases, similar to other models (Kim et al. 2011)

So, the MJO is…

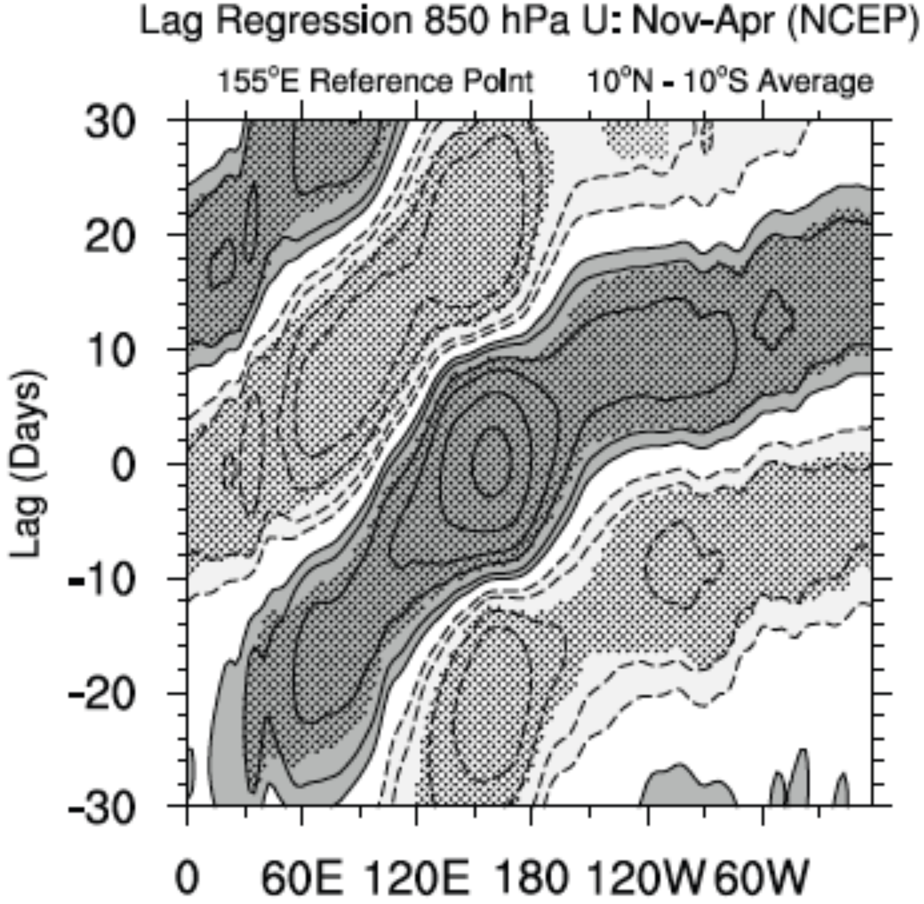
- Not a Kelvin wave
- Has convection controlled by surface fluxes and radiation
- Sensitive to moisture

So, the MJO is…

- Not a Kelvin wave
- Has convection controlled by surface fluxes and radiation
- Sensitive to moisture

Sounds like what we call a “moisture mode”
(Neelin and Yu 1994; Sobel et al. 2001; Fuchs & Raymond, Majda & Stechmann, Kuang, Sobel & Maloney 2012, 2013)

Aside: the MJO accelerates once it reaches the Pacific, and becomes more Kelvin-like. If there is a pure moisture mode, it's in the Indian ocean, & maybe western-most Pacific.



By “moisture mode” we mean (at a minimum) a dynamical mode which depends on prognostic moisture:

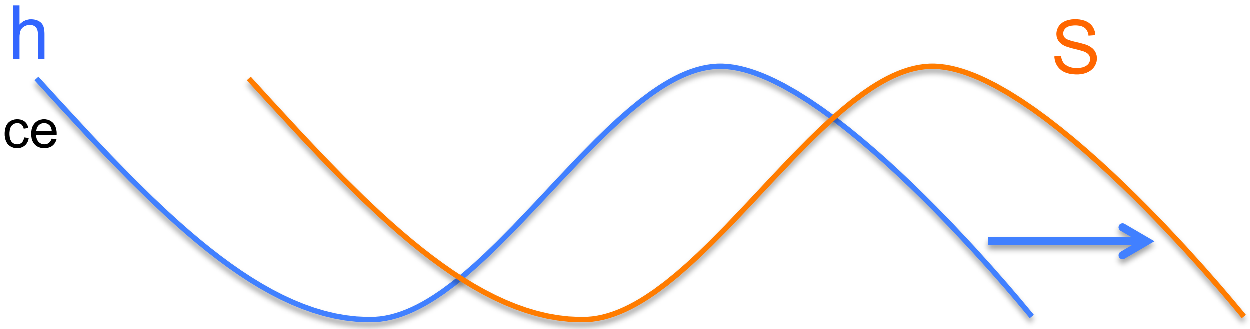
$\partial T/\partial t = \dots$
$\partial \mathbf{u}/\partial t = \dots$
$\partial q/\partial t = \dots$

not, e.g.,

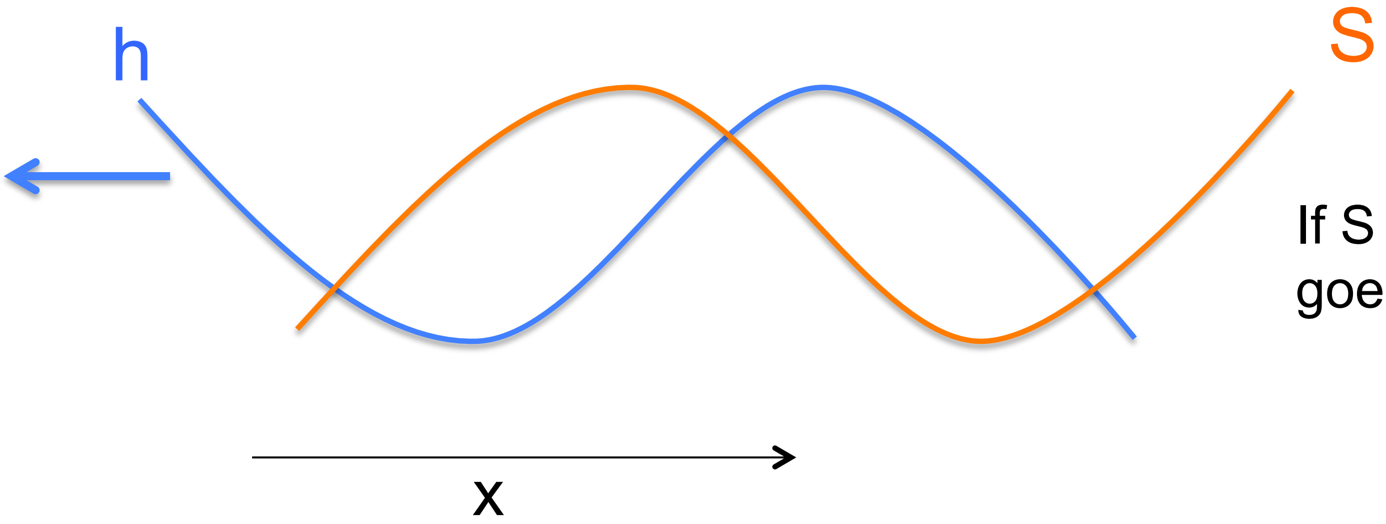
$\partial T/\partial t = \dots$
$\partial \mathbf{u}/\partial t = \dots$
$q = q(T)$

The majority of idealized tropical dynamics models are of the latter form, truncating out the moisture mode.

Consider a moist static energy equation of the form $dh/dt=S$, where S is sum of advection, surface fluxes, radiation… and h is function of (x,t)



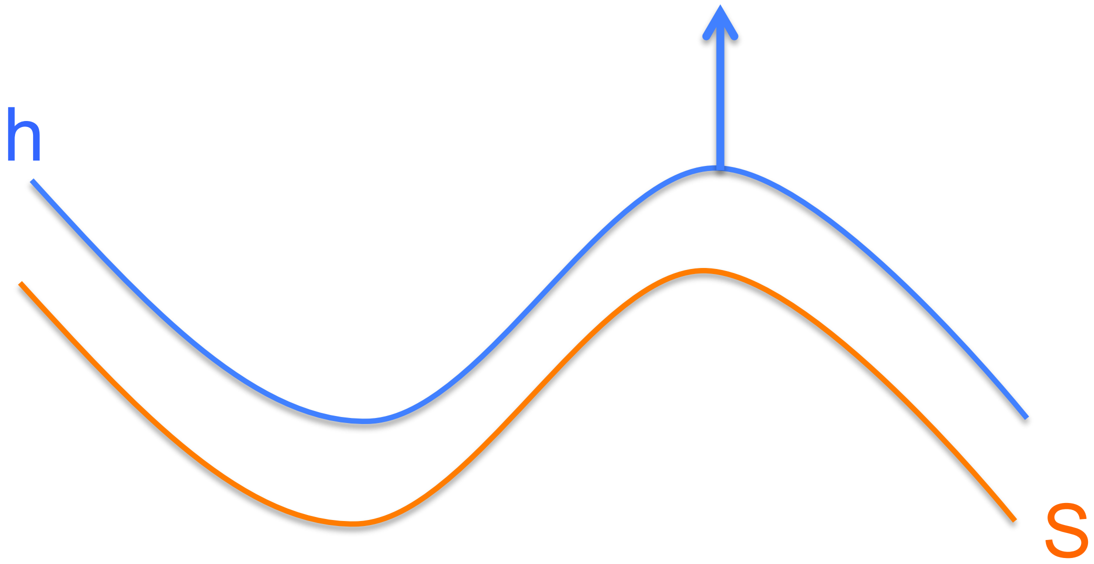
If S leads h, disturbance goes eastward

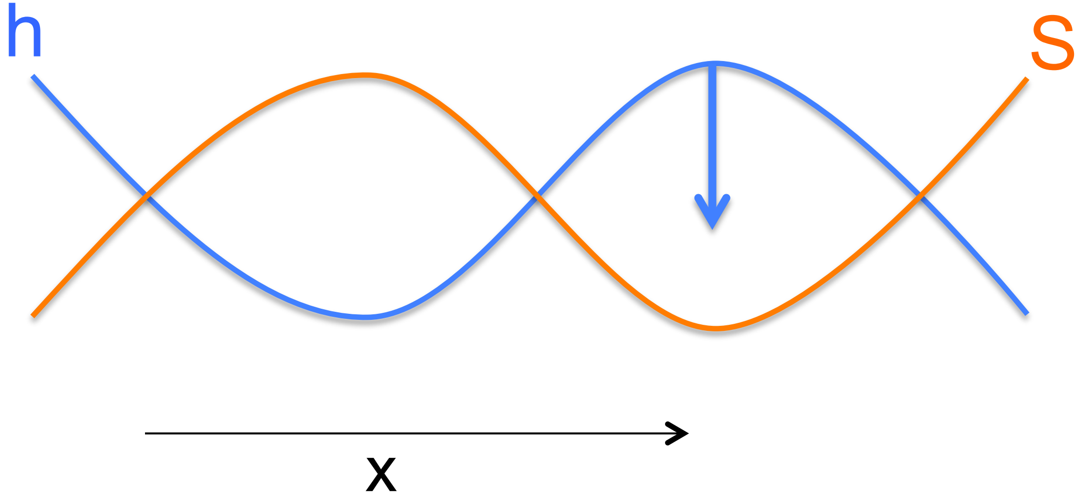


If S leads h, disturbance goes westward

Consider a moist static energy equation of the form dh/dt=S, where S is sum of advection, surface fluxes, radiation… and h is function of (x,t)

If S is in phase with h, disturbance grows





If S is out of phase with h, disturbance decays

A semi-empirical moisture mode theory

Sobel and Maloney 2012, 2013 (JAS)

The linear model in a nutshell

$$\frac{\partial W'}{\partial t} + U\frac{\partial W'}{\partial x} = -\tilde{M}P' + E' - (1-\tilde{M})R'$$

W' is perturbation column moist static energy;
U is constant background wind;
P' = P' (W') – in linear case W' /τ_c;
E' = cu '; zonal wind anomaly is computed diagnostically from P' using projection (Green's) function;

$$u(x,t) = \int G(x|x')P(x',t)dx'.$$ (I'll explain more in a moment)

R' = rP' ;
Normalized gross moist stability $\tilde{M}$ is constant, <1.

A note on the dynamical role of radiation,
via the single-column limit. Our MSE equation is:

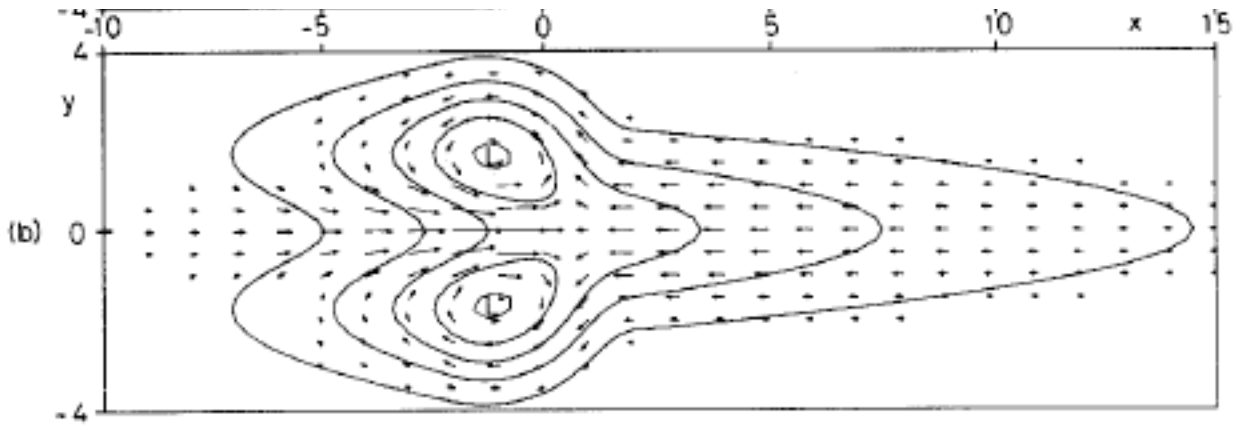
$$\frac{\partial W'}{\partial t} + U\frac{\partial W'}{\partial x} = -\tilde{M}P' + E' - (1-\tilde{M})R'$$

Now assume steady state and neglect advection, we can solve for precipitation:

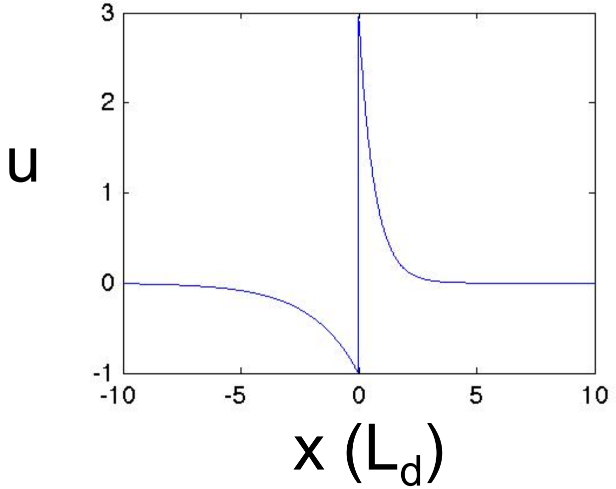
$$P' = \tilde{M}^{-1}[E' - (1-\tilde{M})R']$$

Now we know $\tilde{M} < 1$, maybe << 1
Remember R is radiative cooling (= minus radiative heating);
So a *decrease* in radiative cooling leads to an *increase* in precipitation. This is the *opposite* of what happens in radiative-convective equilibrium! Dynamics changes everything, RCE is a *bad* model locally.

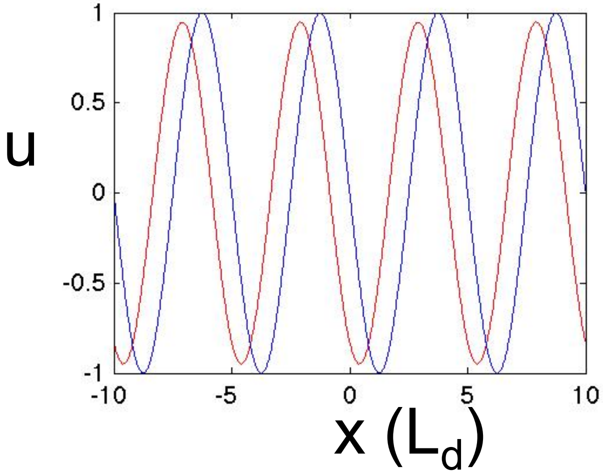
Gill (1980) wind and geopotential for localized heating (at 0,0) linear, damped, steady dynamics on equatorial beta plane



Equatorial zonal wind response to equatorial delta function (in x) heating



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



Compute zonal wind *u* from precipitation *P* via a projection operator:

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

Using Gill dynamics:

$$G(x|x') = -Ae^{-(x-x')/L}, \quad x > x',$$

$$G(x|x') = 3Ae^{3(x-x')/L}, \quad x < x'.$$

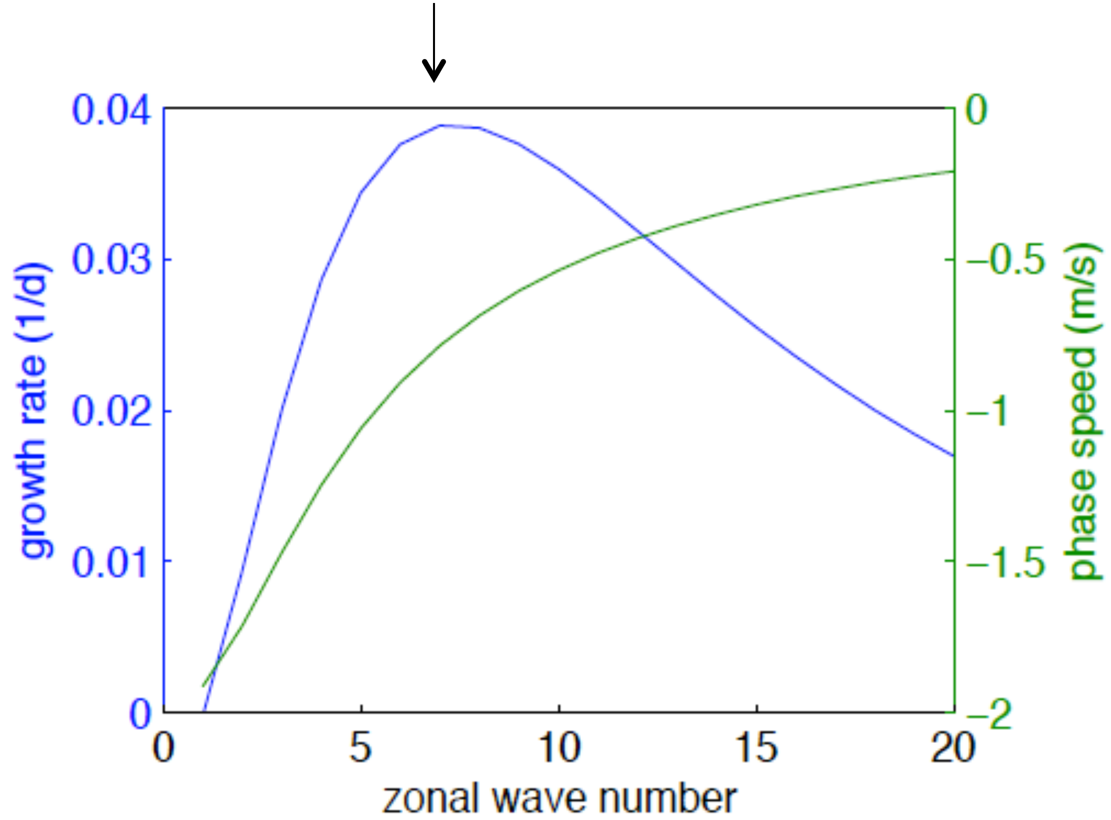
Length scale *L* = group velocity of free Kelvin wave * damping time scale.

Now put that all together, linearize (assuming background low-level westerly winds), and compute the growth rates and phase speeds of the normal modes as function of zonal wave number.

If this is a good model for the MJO, we would like to see an unstable mode (positive growth rate), maximizing at low wave number (long wavelength), with a slow eastward phase speed.

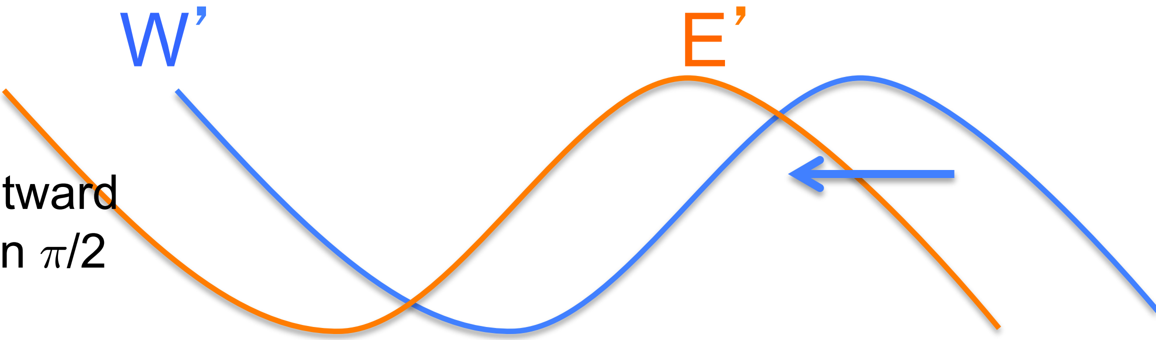
Linear model: all modes are unstable due to WISHE, but westward-propagating (in mean westerlies)

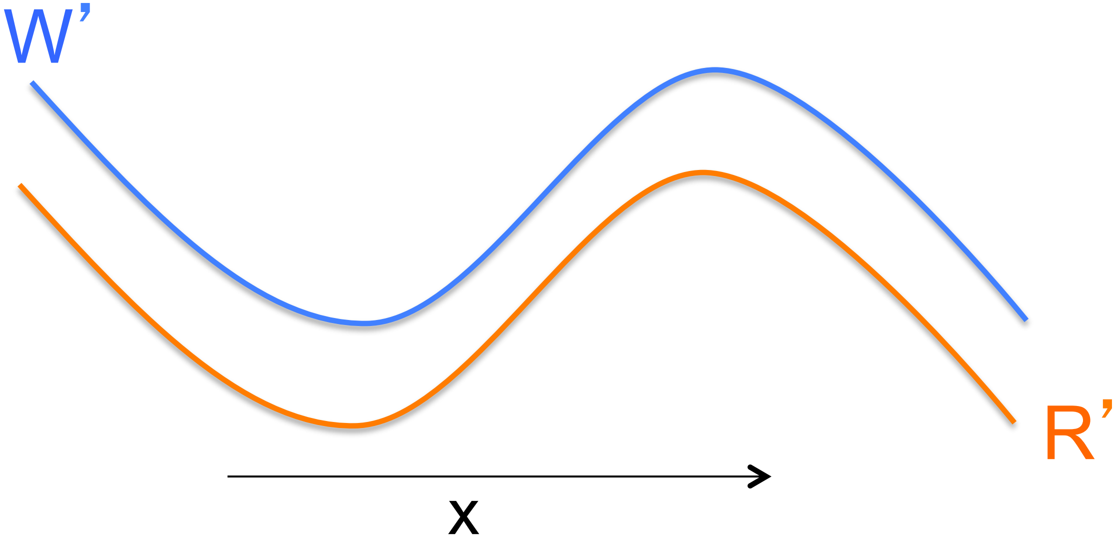
Most unstable wavelength is ~decay length scale
for stationary response to heating L (here 1500 km);
at this wavelength LH flux and humidity most in phase



Wind-evaporation feedback induces growth and westward propagation; cloud-radiative feedback induces growth and no propagation

Surface flux lags convection,
thus lags moisture, so drives westward
progagation; but lags by less than $\pi/2$
so also causes growth





Since radiative heating
~ precipitation ~ moisture,
cloud-radiative feedback
is destabilizing. No phase lead
or lag, so doesn’t
cause propagation

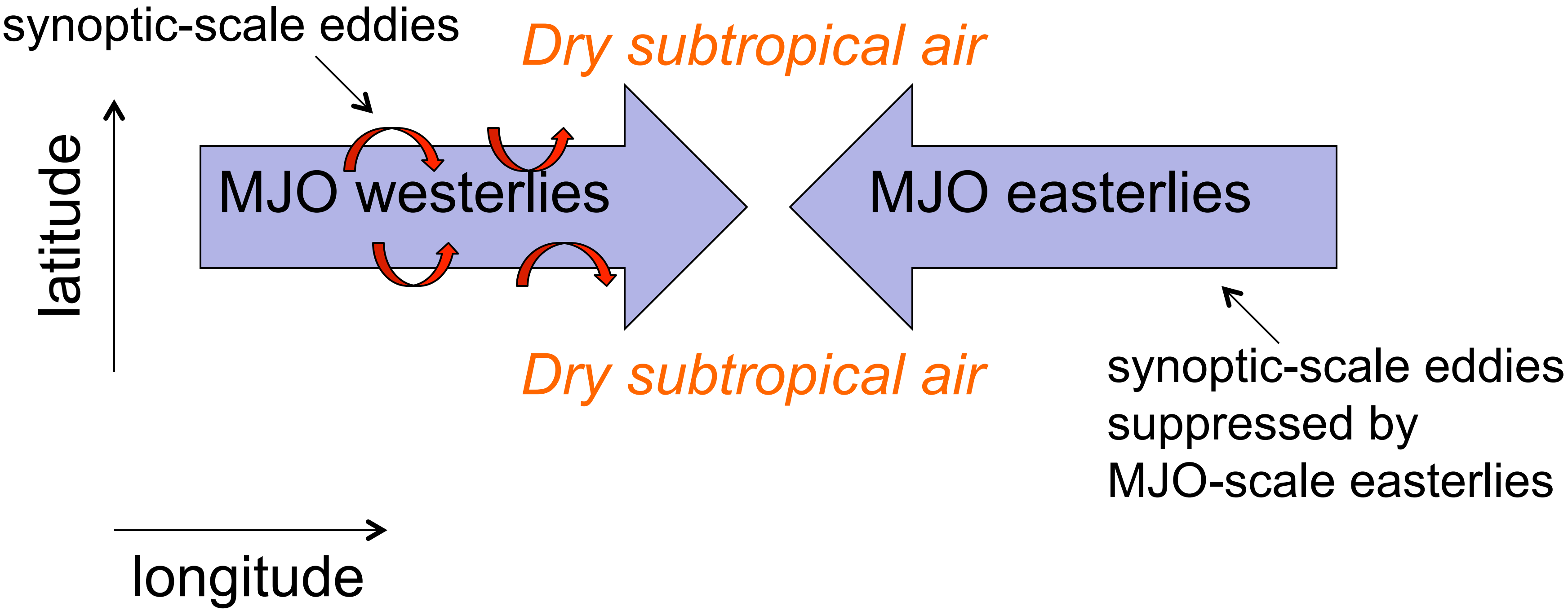
We need an MSE source that *leads* convection to the east, to produce eastward propagation.

Frictional convergence in easterlies (Wang 1988) is one possibility. We expect this to induce shallow ascent, which is a net source of MSE, i.e. $\tilde{M}$ <0.

Zonal advection will also work, if we have a +ve mean background zonal gradient (q increases to east). Then, easterlies are moistening. We saw this in DYNAMO.

Or…

In simulations, MJO modulation of dry air advection by synoptic-scale transients has been found to act as anomalous MSE source that leads convection (Maloney 2009, Andersen and Kuang 2012)



synoptic-scale eddies

Dry subtropical air

latitude

MJO westerlies

MJO easterlies

Dry subtropical air

synoptic-scale eddies
suppressed by
MJO-scale easterlies

longitude

We can add any of these processes to our idealized model very crudely as an MSE source proportional to minus MJO (‘) zonal wind. E.g. if ‘’ is a synoptic-scale perturbation

$-\partial_y(v'' q'') = -ku'$ (k>0 gives relative moistening in easterlies)

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But also surface flux is proportional to zonal wind.

$E' = cu'$, so net $E - \partial_y(v'q') = (c-k)u'$

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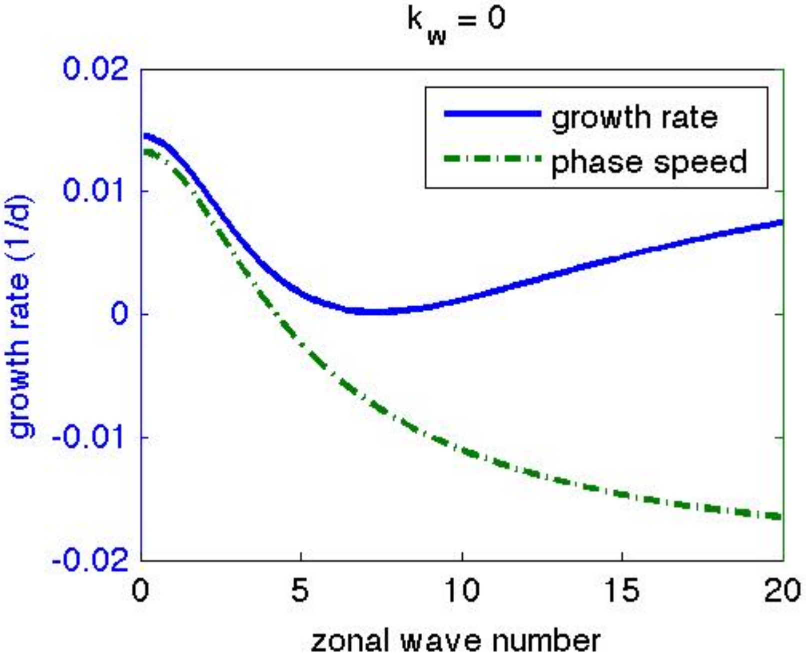
To cause eastward propagation, the advection has to be stronger than the surface fluxes, $(c-k)<0$.
In that case it also causes damping, since u' and P' are positively correlated.

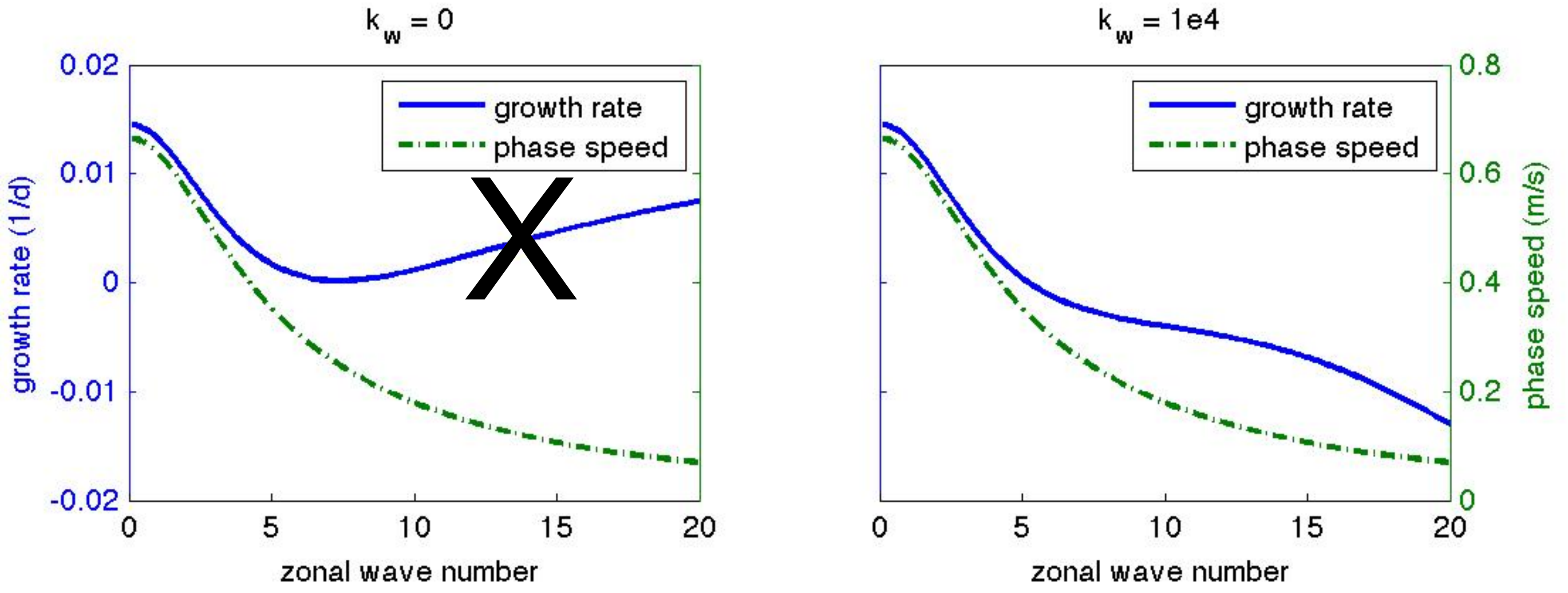
Thus we have to make the radiative feedback strong enough to overcome this if the mode is to be unstable – sufficiently large feedback parameter *r.*

If we do all this, we get eastward propagation, and largest growth rates at shortest and longest wavelengths

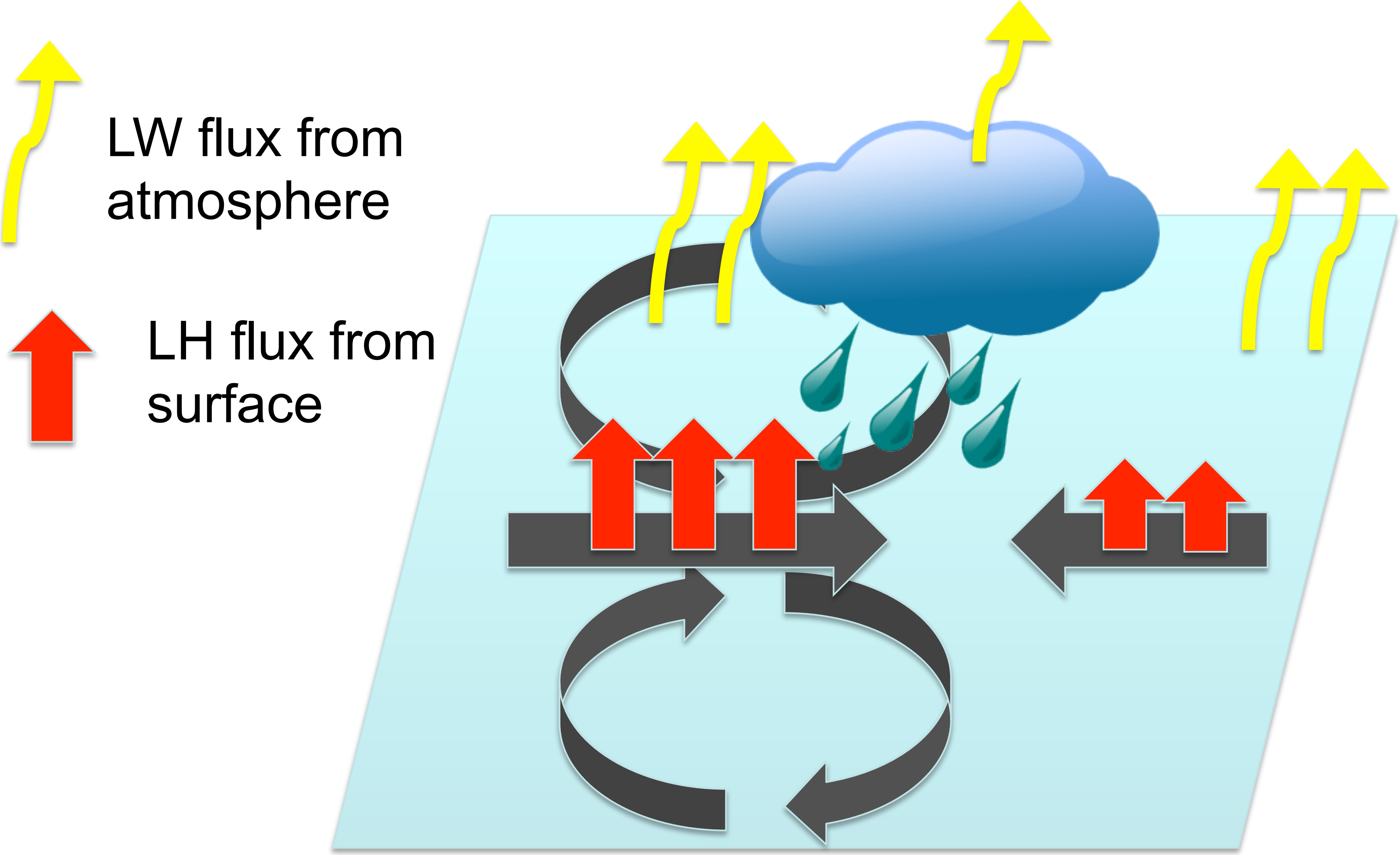


If we do all this, we get eastward propagation, and largest growth rates at shortest and longest wavelengths

Small amount of horizontal diffusion is enough to kill small-scale instability. Then only largest scales are selected.



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



What do MSE budgets look like for the real MJO?

Results from the tropical Indian ocean during the CINDY/DYNAMO field program, by Shuguang Wang and Daehyun Kim

DYNAMO
2011-2012
dynamics of the madden-julian oscillation

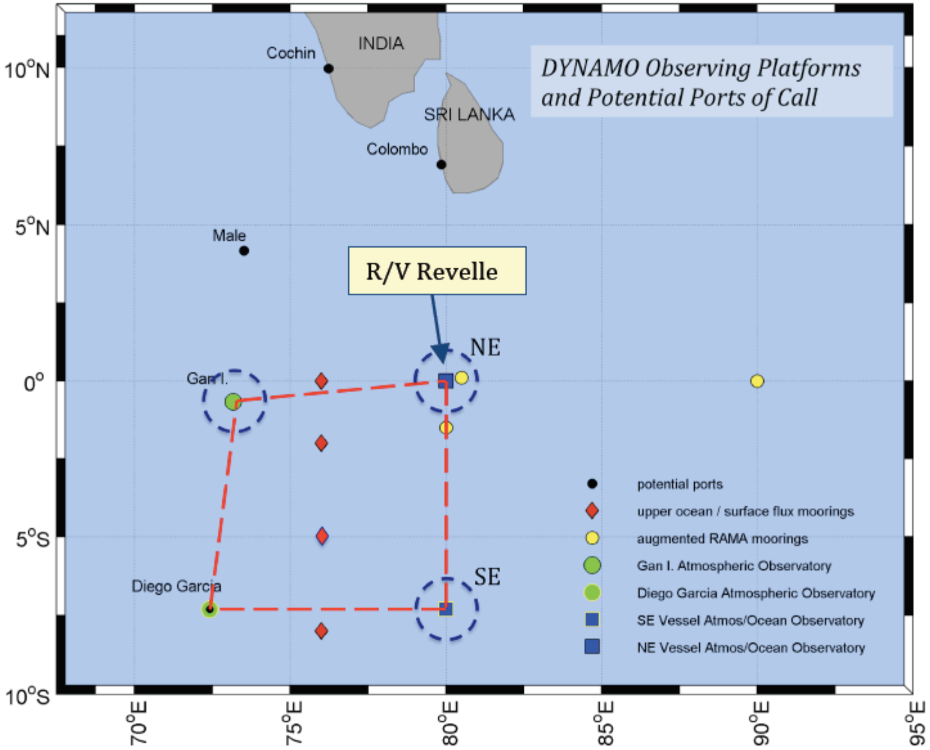


Figure 2.1 Map of DYNAMO field campaign platforms and potential ports of call. Red dashed lines mark the sounding array. Blue dashed circles indicate the radar sites.

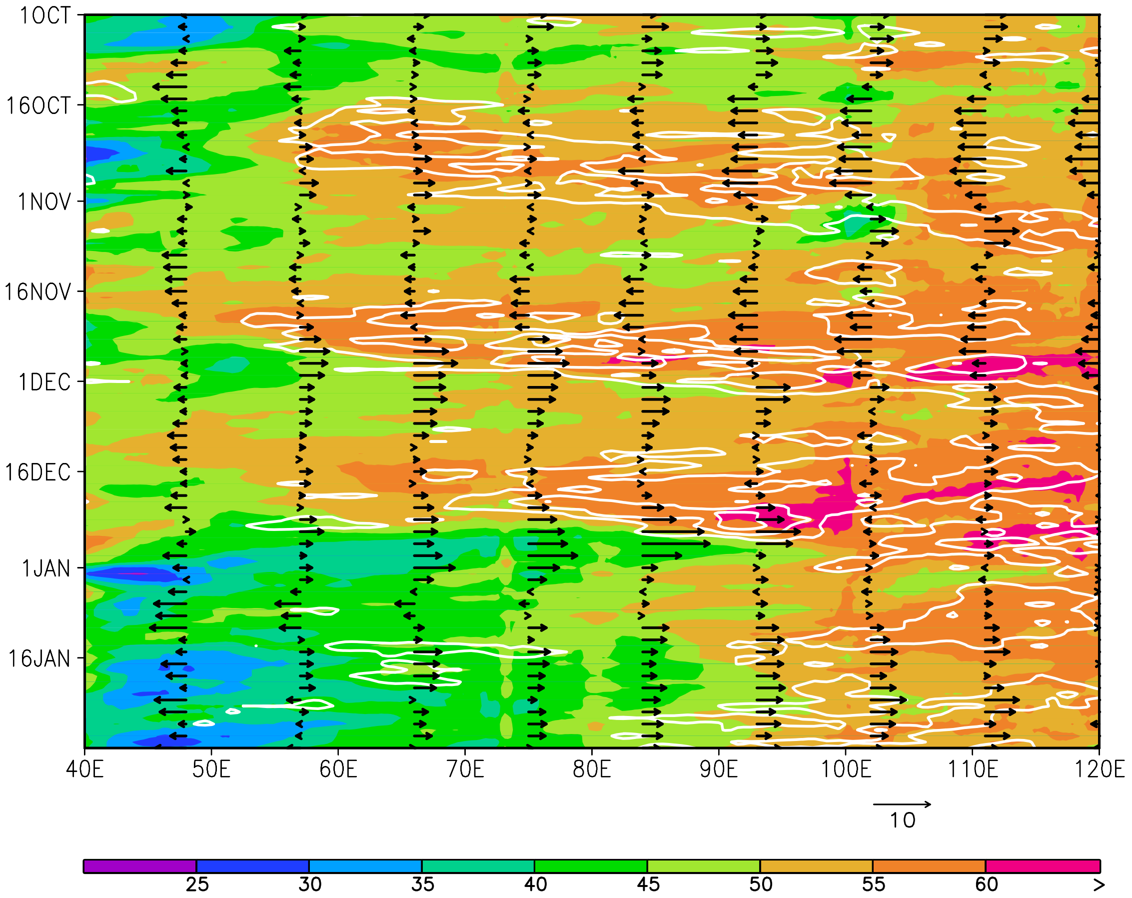


Figure 1. Hovmoeller diagram of 10°S-10°N averaged precipitable water (mm, shaded), precipitation (mm day^{-1}, contour 10), and 850hPa zonal wind (m s^{-1}, arrows) during the CINDY/DYNAMO period. By Daehyun Kim

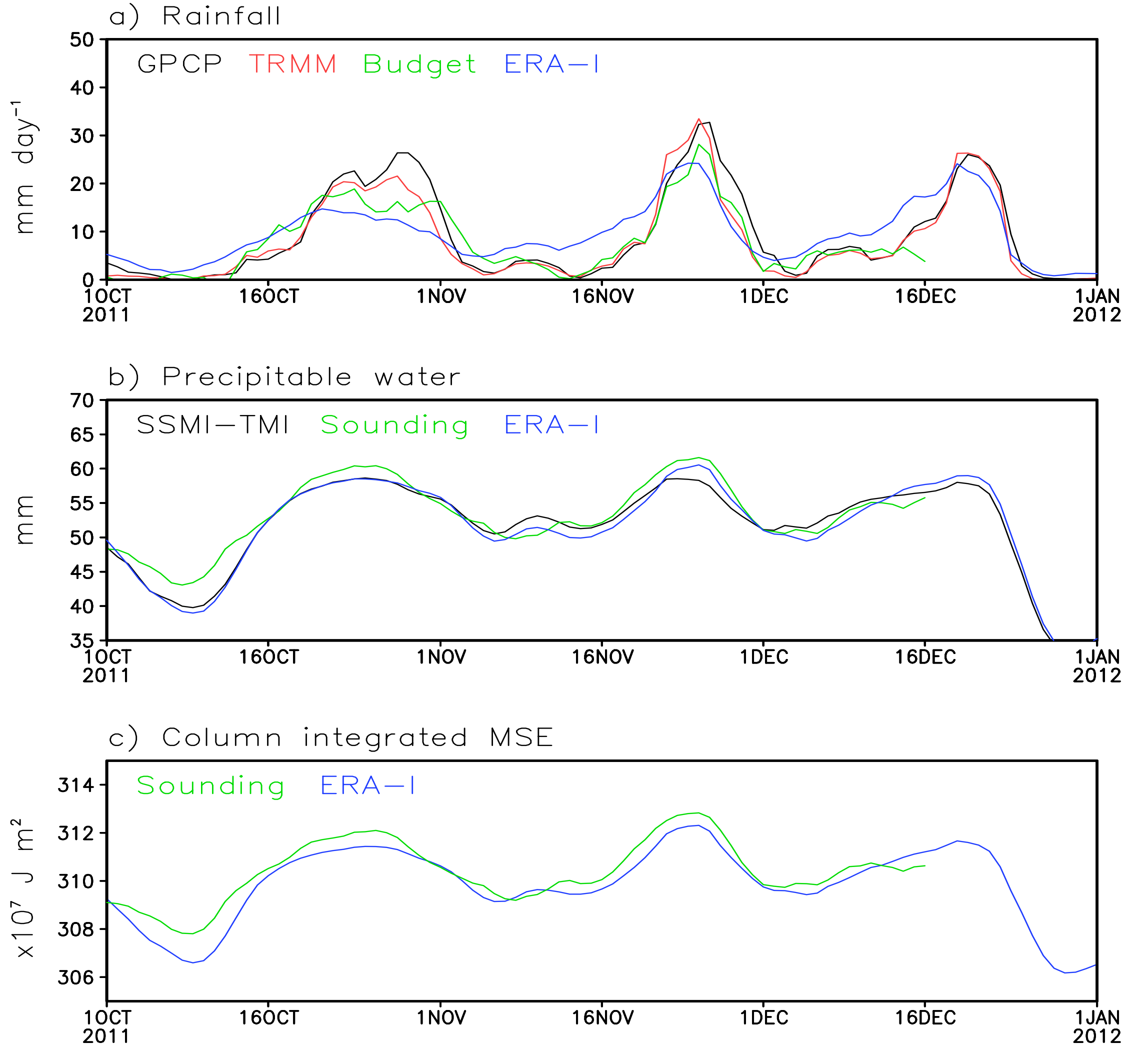
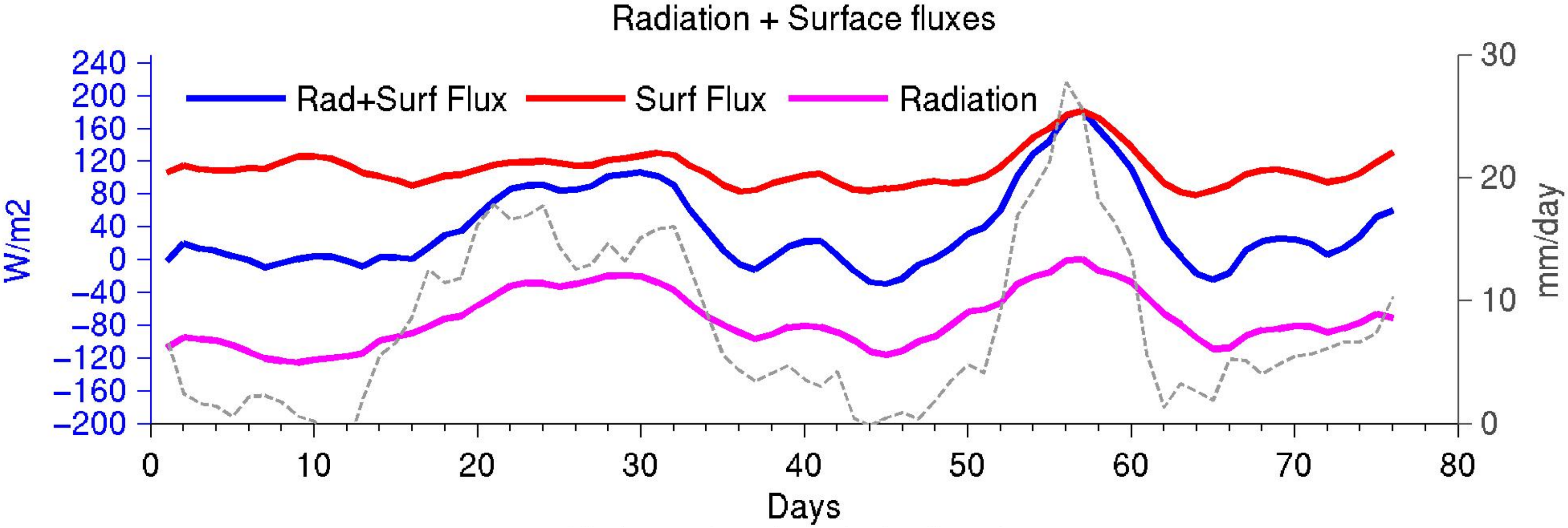


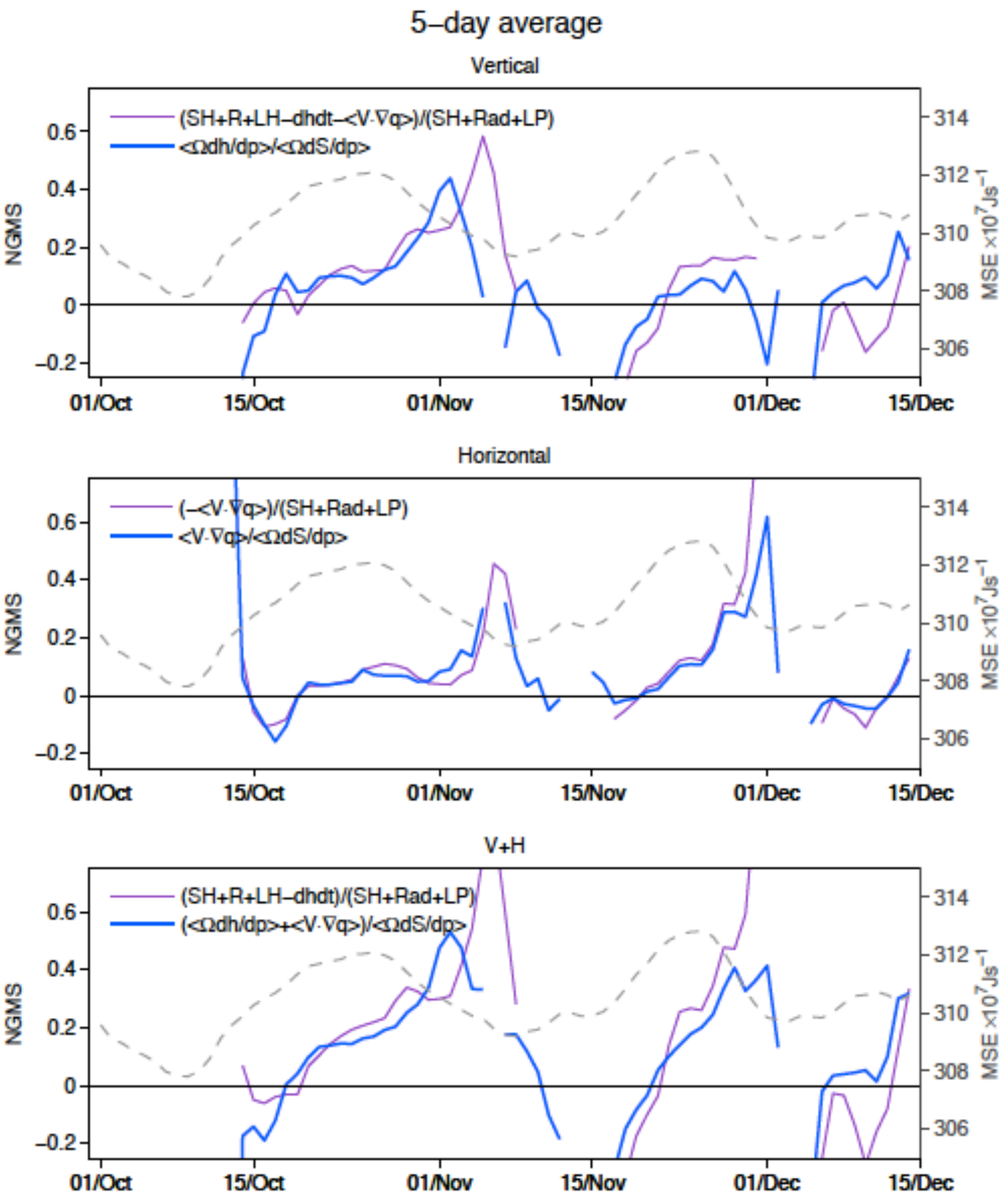
Figure 2. Area-averaged (73-80^{o}E, Eq.-5^{o}N) time-series of a) rainfall (mm day^{-1}), b) precipitable water (mm), and c) column integrated MSE (x10^7 J m^{-2}) (Daehyun Kim & Shuguang Wang)

MSE budget from DYNAMO: radiation ≥ surface flux



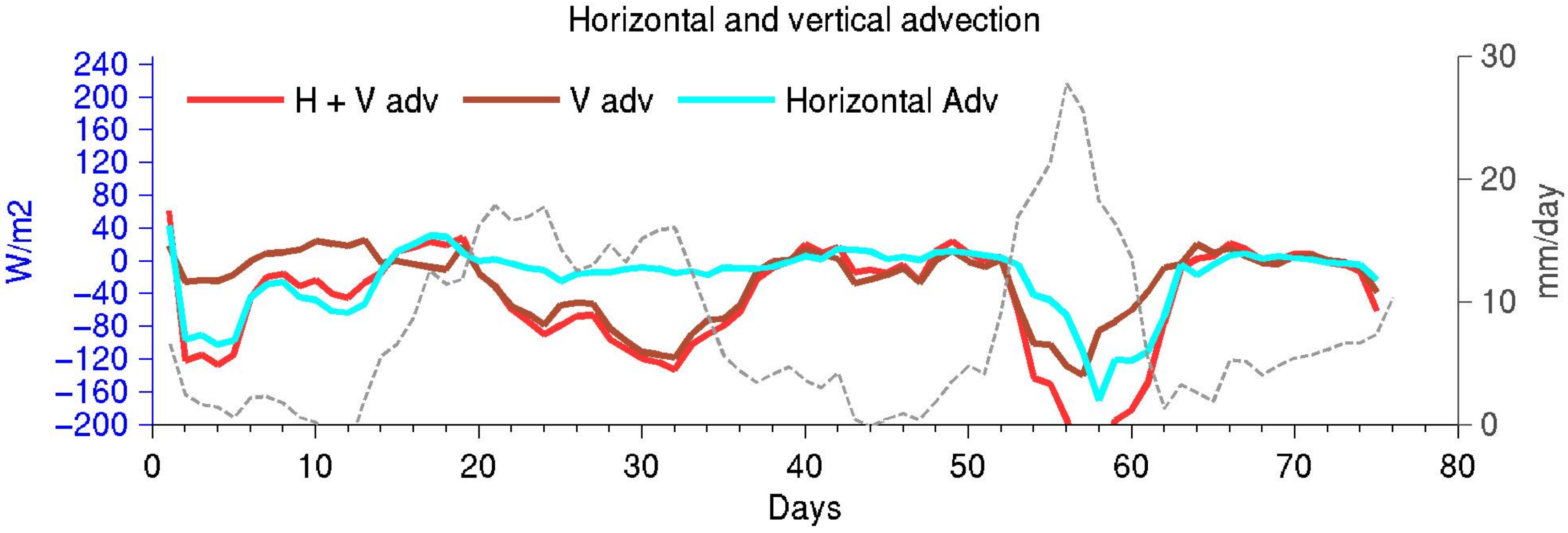
Data: sounding array (R. Johnson, P. Ciesielski), OAflux, CERES

analysis by Shuguang Wang



Plots by Shuguang Wang

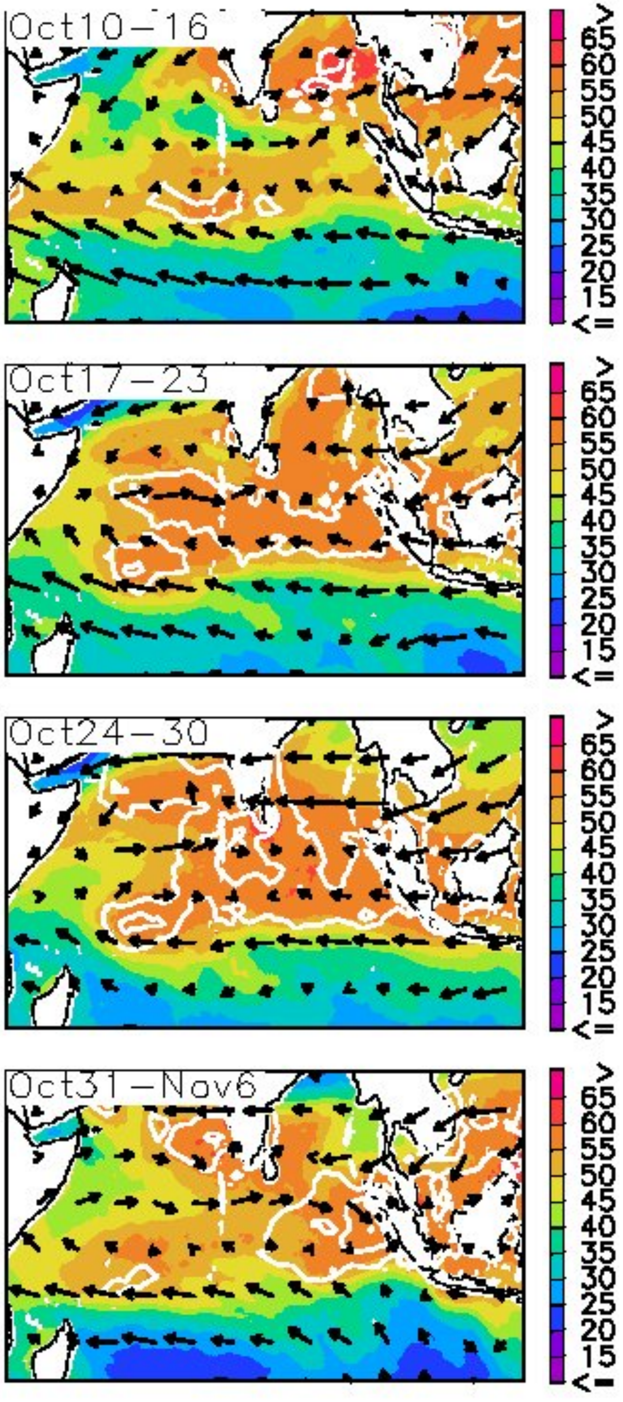
MSE budget from DYNAMO: +ve advection (esp horizontal) leads convection in 1 case; -ve shuts it down in the other.



Data: sounding array (R. Johnson, P. Ciesielski), OAflux, CERES

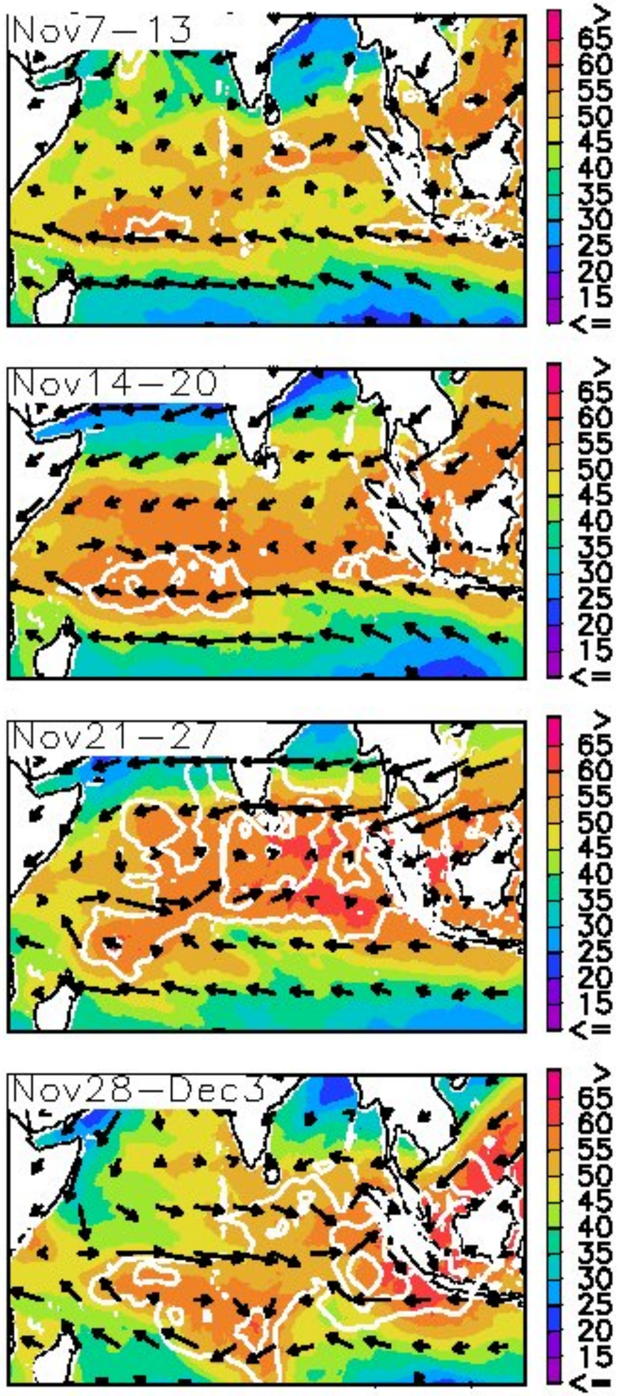
analysis by Shuguang Wang

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



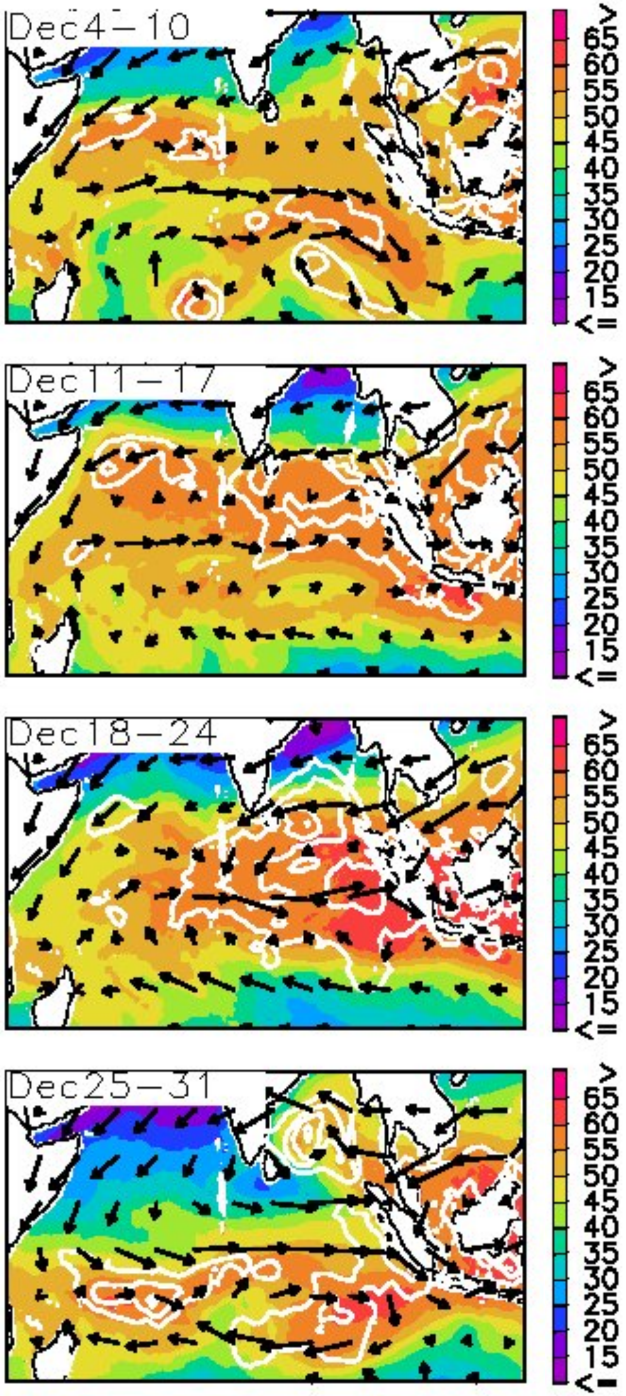
Plots by Daehyun Kim

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



Plots by Daehyun Kim

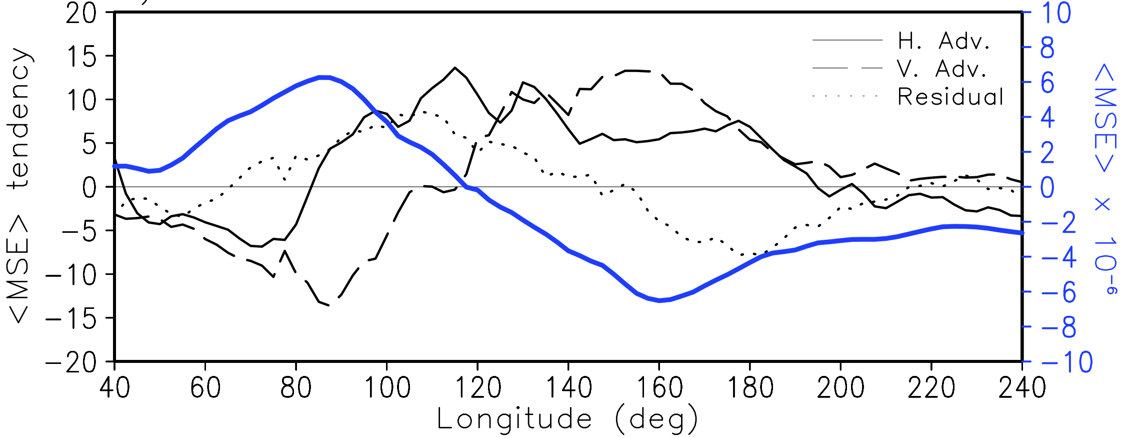
Weekly means from
CINDY/DYNAMO period:
Column water vapor (color, mm)
850 hPa wind vector,
Precipitation (mm/d, interval 10)



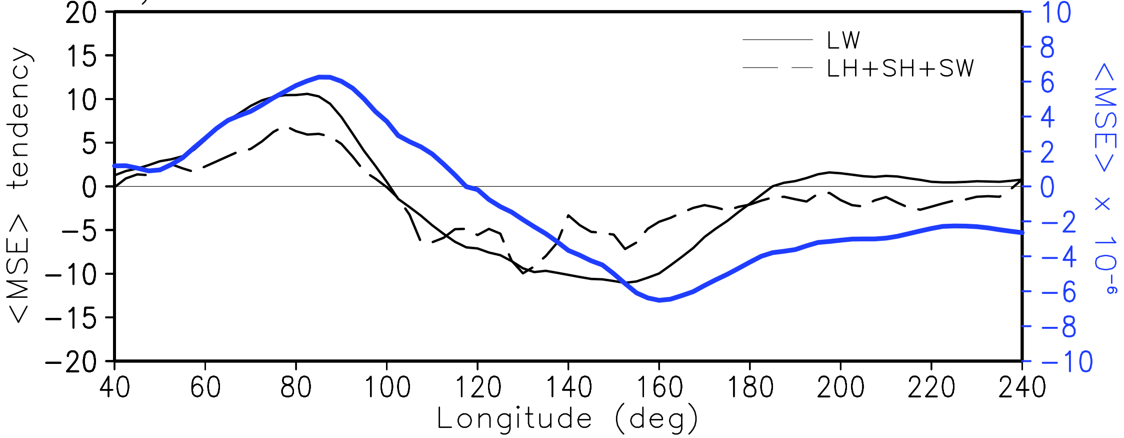
Plots by Daehyun Kim

Reanalysis MJO composite (not DYNAMO) moist static energy budget: horizontal advection seems to control propagation; radiation dominant for growth

a) Advection and residual terms



b) Turbulent and radiative flux terms



blue=composite MSE anomaly

black=MSE tendency terms

Data: ERA Interim

Kim, Kug and Sobel, *J. Climate*, in press

Conclusions

- We argue the MJO is a moisture mode.
- This means that sources and sinks of moist static energy control both the growth and propagation of the mode.
- Need moistening in easterlies for eastward propagation – has to be advection of some kind, but several possibilities,
- Cloud-radiative feedback is necessary to destabilize the mode. That is, the MJO wouldn’t exist without it.
- “self-aggregation of convection on the equatorial beta plane”

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