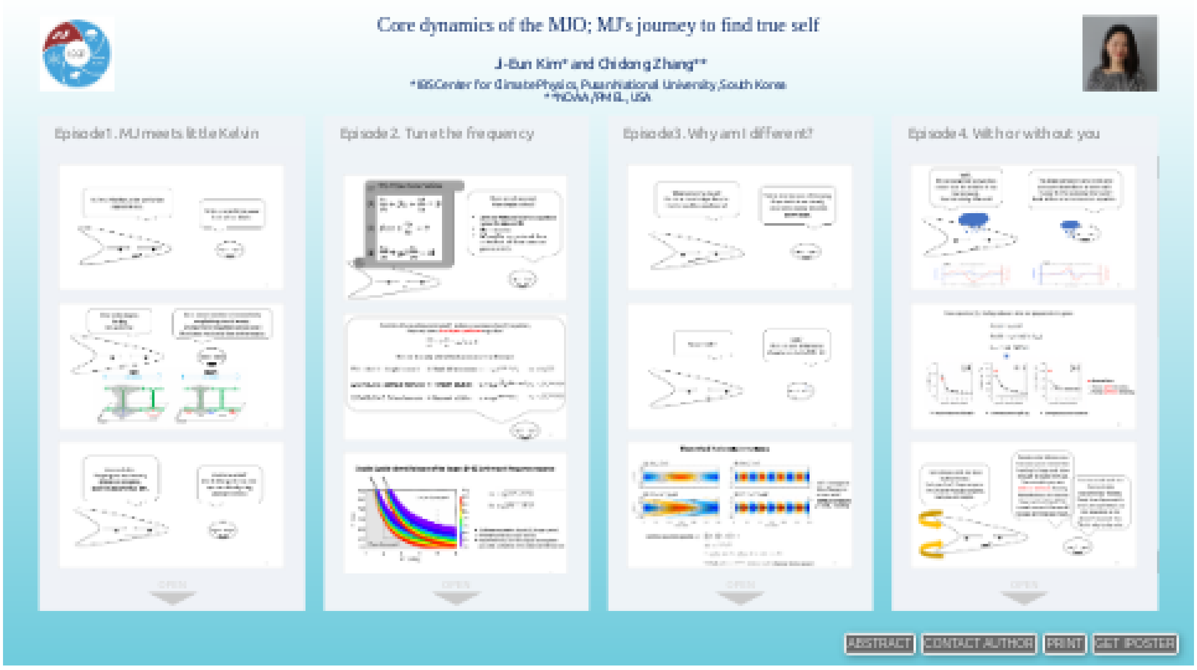
Core dynamics of the MJO; MJ's journey to find true self



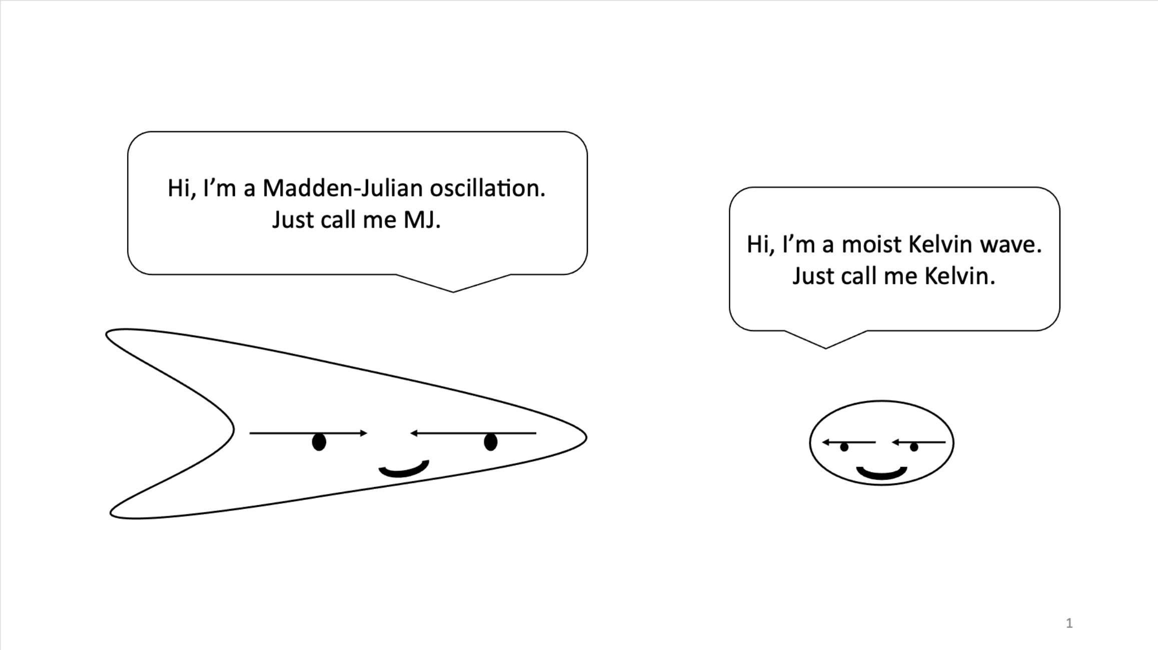
Ji-Eun Kim* and Chidong Zhang**

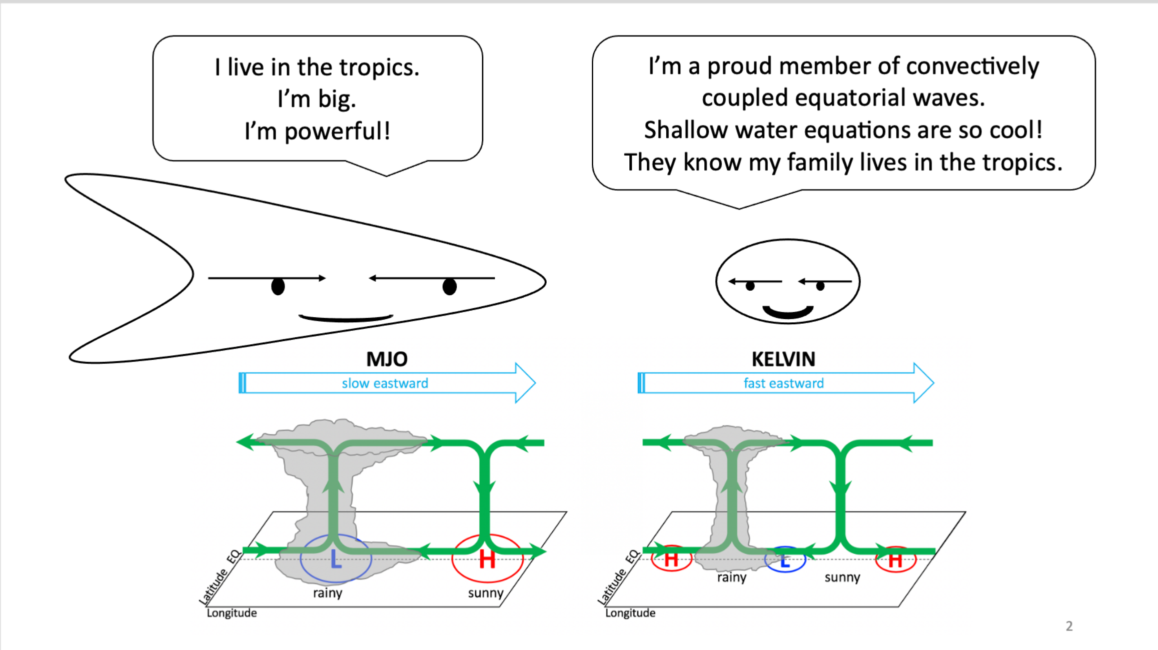
*IBS Center for Climate Physics, Pusan National University, South Korea
**NOAA/PMEL, USA

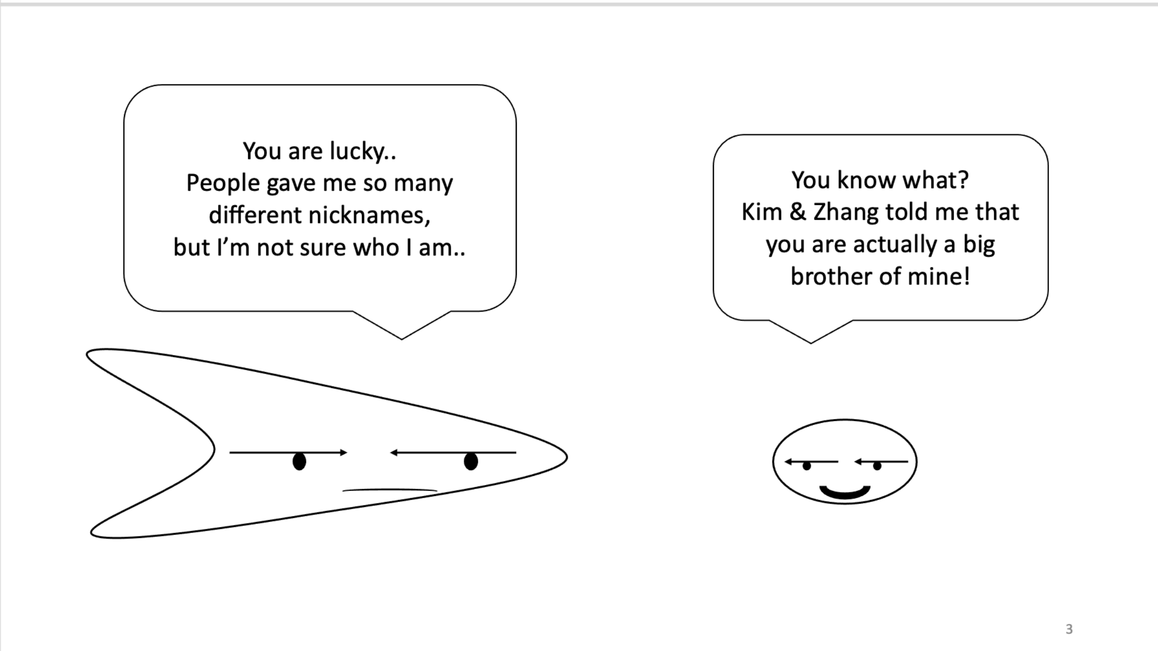
PRESENTED AT:

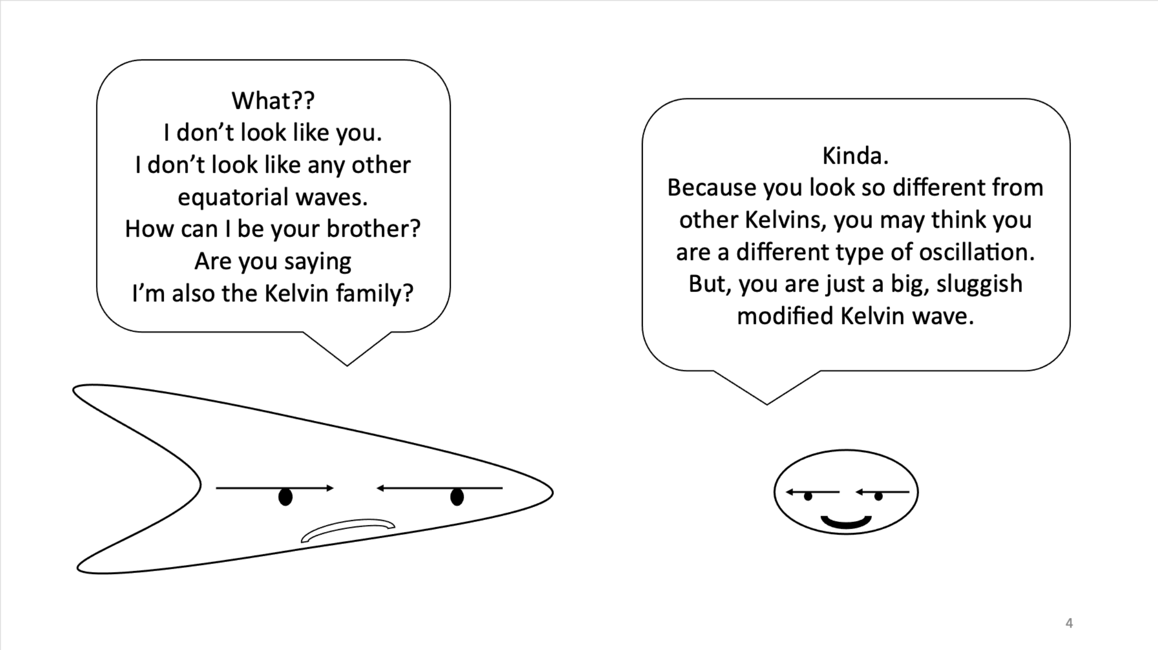
AGU FALL MEETING
Online Everywhere | 1–17 December 2020

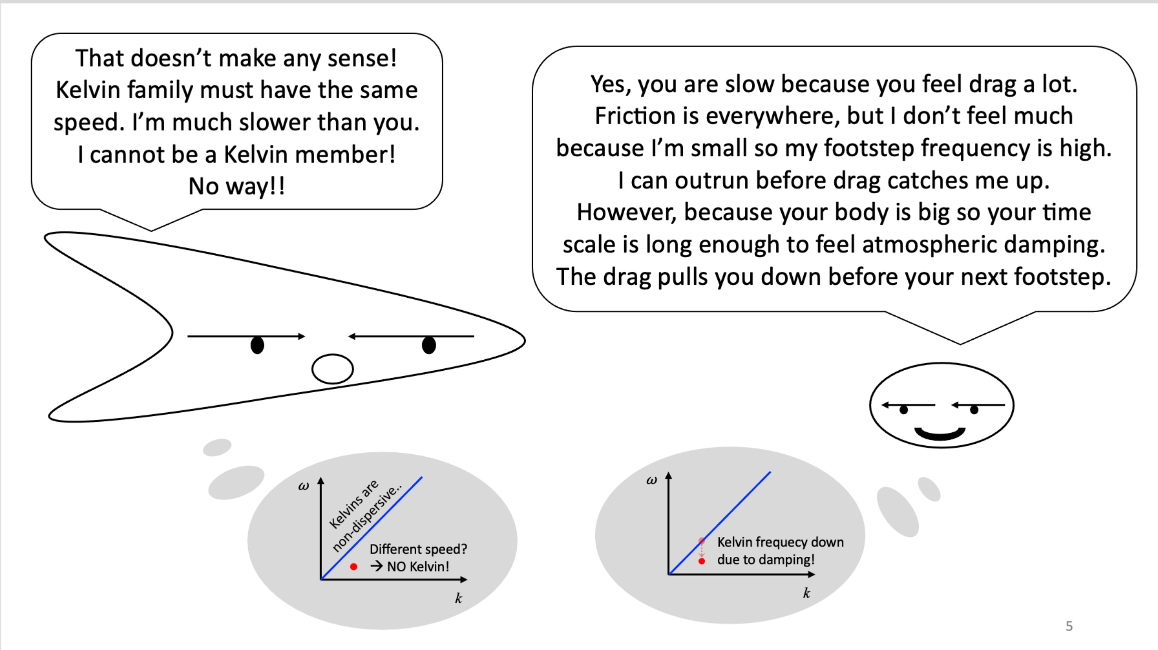
EPISODE1. MJ MEETS LITTLE KELVIN

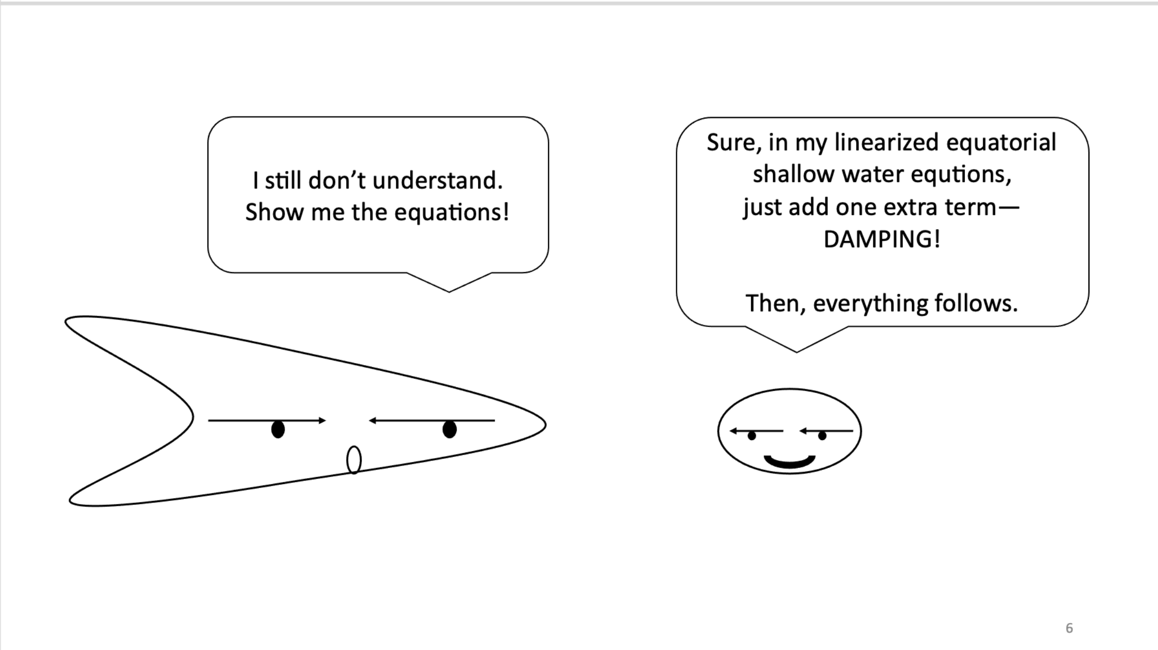

Hi, I'm a Madden-Julian oscillation. Just call me MJ.
Hi, I'm a moist Kelvin wave. Just call me Kelvin.
1


I live in the tropics. I'm big. I'm powerful!
I'm a proud member of convectively coupled equatorial waves. Shallow water equations are so cool! They know my family lives in the tropics.
MJO
slow eastward
L
H
rainy
sunny
Latitude
EQ
Longitude
KELVIN
fast eastward
H
L
H
rainy
sunny
Latitude
EQ
Longitude
2


You are lucky.. People gave me so many different nicknames, but I'm not sure who I am..
You know what? Kim & Zhang told me that you are actually a big brother of mine!
3


What??
I don’t look like you.
I don’t look like any other equatorial waves.
How can I be your brother?
Are you saying
I’m also the Kelvin family?
Kinda.
Because you look so different from other Kelvins, you may think you are a different type of oscillation.
But, you are just a big, sluggish modified Kelvin wave.
4


That doesn’t make any sense!
Kelvin family must have the same speed. I’m much slower than you.
I cannot be a Kelvin member!
No way!!
Yes, you are slow because you feel drag a lot.
Friction is everywhere, but I don’t feel much because I’m small so my footstep frequency is high.
I can outrun before drag catches me up.
However, because your body is big so your time scale is long enough to feel atmospheric damping.
The drag pulls you down before your next footstep.
ω
Kelvins are non-dispersive..
Different speed?
→ NO Kelvin!
k
ω
Kelvin frequecy down due to damping!
k
5


I still don’t understand.
Show me the equations!
Sure, in my linearized equatorial shallow water equtions,
just add one extra term—
DAMPING!
Then, everything follows.
6

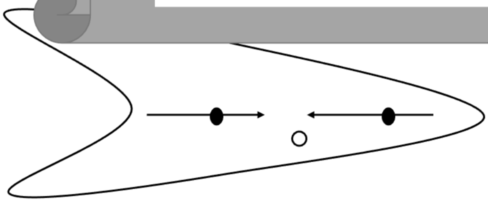
EPISODE2. TUNE THE FREQUENCY

The Three Conservations

(1) $$\frac{\partial u}{\partial t} + Du + \frac{\partial \phi}{\partial x} = 0$$

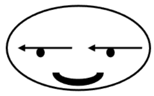
(2) $$\beta y u + \frac{\partial \phi}{\partial y} = 0$$

(3) $$\frac{\partial \phi}{\partial t} + gH\frac{\partial u}{\partial x} = M$$



There are all we need.
How simple is that!!

- ✓ Same as Matsuno's Kelvin equations except for ***Du*** and ***M***.
- ✓ ***Du*** is damping.
- ✓ ***M*** could be zero, external force, or feedback. All three cases can generate MJOs.



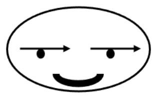
7

Combine the zonal momentum (1) and mass conservation (3) equation, then we have a **harmonic oscillator** equation!

$$\frac{\partial^2 u}{\partial t^2} + D\frac{\partial u}{\partial t} + {\omega_0}^2 u = X$$

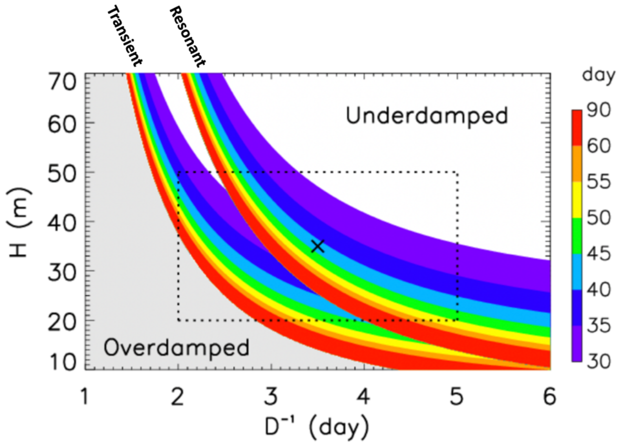
This can be easily solved (and solutions are well known):

- ❑ D=0 & X=0 : Simple harmonic → Classical Kelvin waves: $u = u_0 e^{i(kx-\omega_0 t)}$, $\omega_0 = k\sqrt{gH}$
- ❑ D≠0 & X=0 : Damped harmonic → Transient solution: $u = u_0 e^{-\frac{D}{2}t} e^{i(kx-\omega_D t)}$, $\omega_D = \sqrt{{\omega_o}^2 - D^2/4}$
- ❑ D≠0 & X ≠ 0 : Driven harmonic → Resonant solution: $u = u_0 e^{i(kx-\omega_R t)}$, $\omega_R = \sqrt{{\omega_o}^2 - D^2/2}$



8

Double (upside-down) Rainbow of the longest (k=1) Earth wave's frequency response



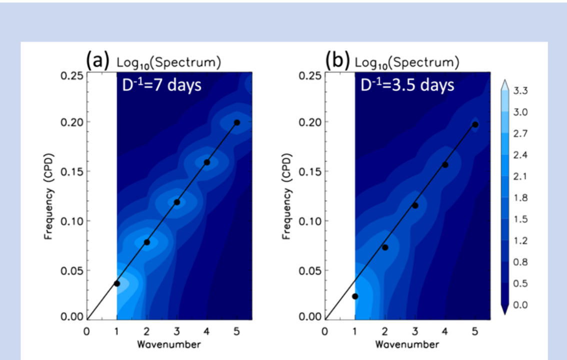
$$\omega_D = \sqrt{gHk^2 - D^2/4}$$

$$\omega_R = \sqrt{gHk^2 - D^2/2}$$

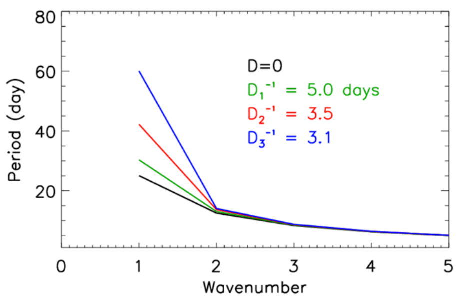
- Shallower equivalent depth (H), longer period.
- Stronger damping, longer period.
- Observed H and D in the tropical atmosphere generate oscillations at the observed MJO period.

9

Spectral response under different damping magnitudes for H=35m



- Spectrum is like Kelvin under weak damping
- Spectrum maxima shifts to lower freqeuncies
- Biggest shift occurs at k=1 (like MJO!)

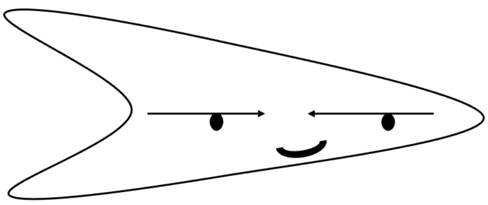


$$\omega_R = \sqrt{gHk^2 - D^2/2}$$

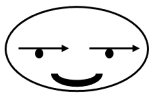
Strong response at k=1, negligible at k≥2
→ Scale selection!

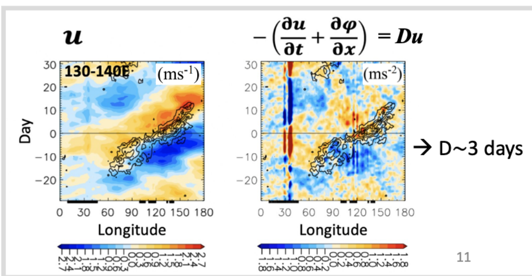
10

The used damping seems too strong. Can the atmosphere have the damping time scale of ~3 days?

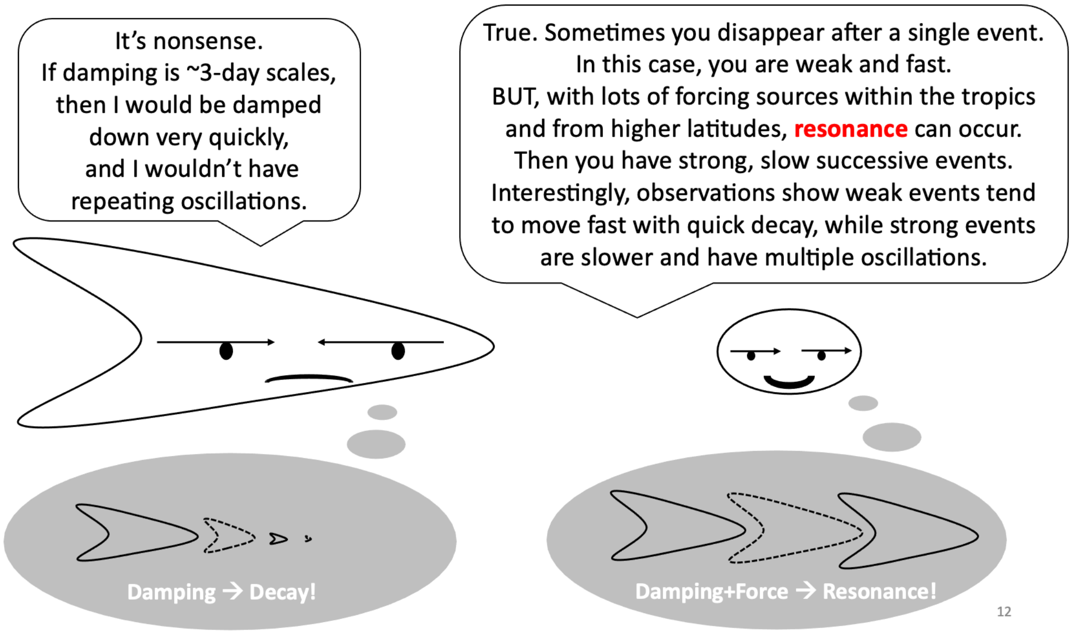


Such strong damping is needed to explain other large-scale convection-circulation coupled phenomena such as monsoon and Walker circulation. Many studies have already used similar scales, and I can prove it with observational data!



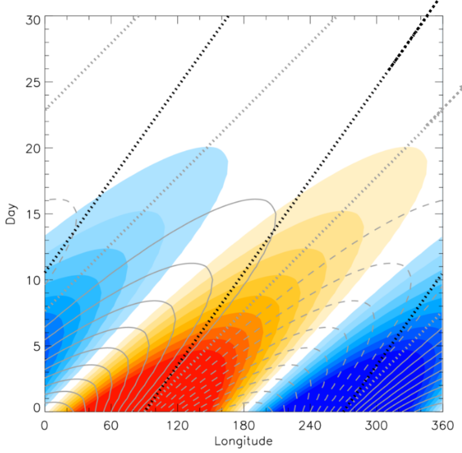


11



12

Hovmoller in Theory



*for resonance with forcing (slower)

$$\omega_R = \sqrt{{\omega_o}^2 - D^2/2}$$

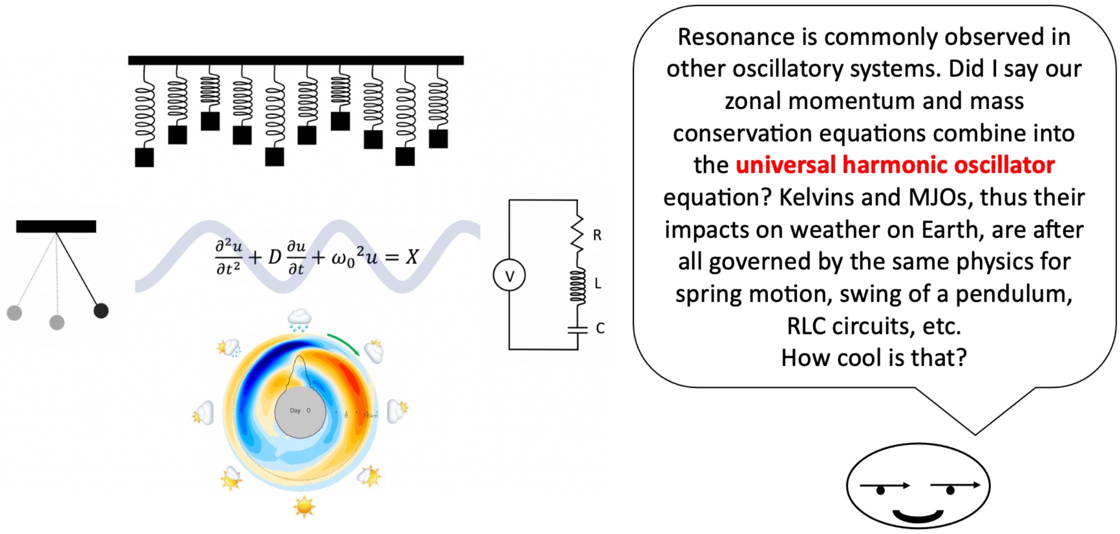
*for transient damped (faster)

$$\omega_D = \sqrt{{\omega_o}^2 - D^2/4}$$

- **Color and contour: transient solution of a damped harmonic oscillator for k=1, H=35, D^{-1}=3.5days**

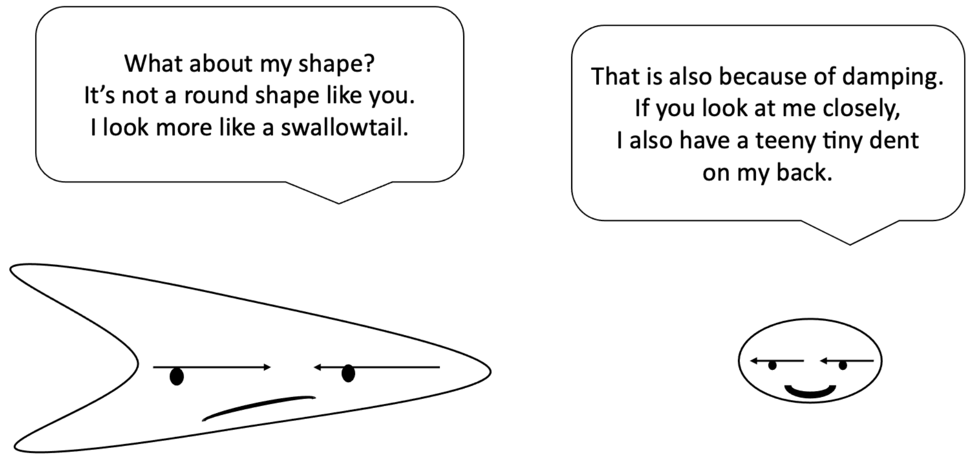
- Initial perturbation is imposed
- Convergence (red) and divergence (blue)
- Zonal wind (contours: solid for positive, dashed for negative, gray dotted for zero,)

13

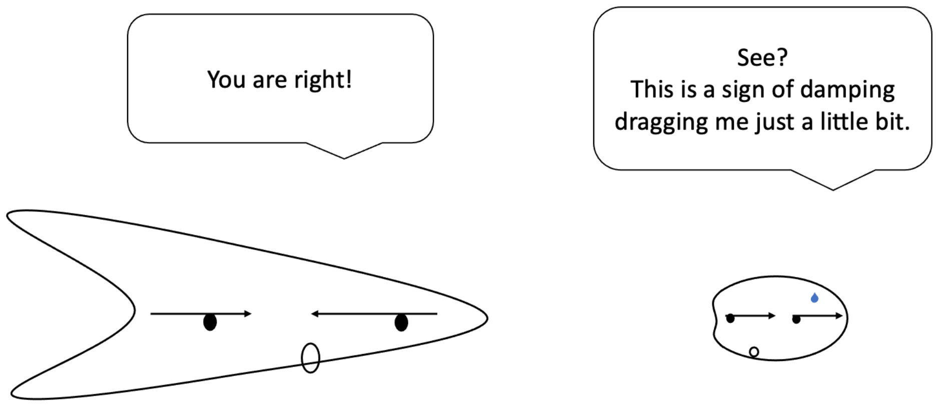


14

EPISODE3. WHY AM I DIFFERENT?

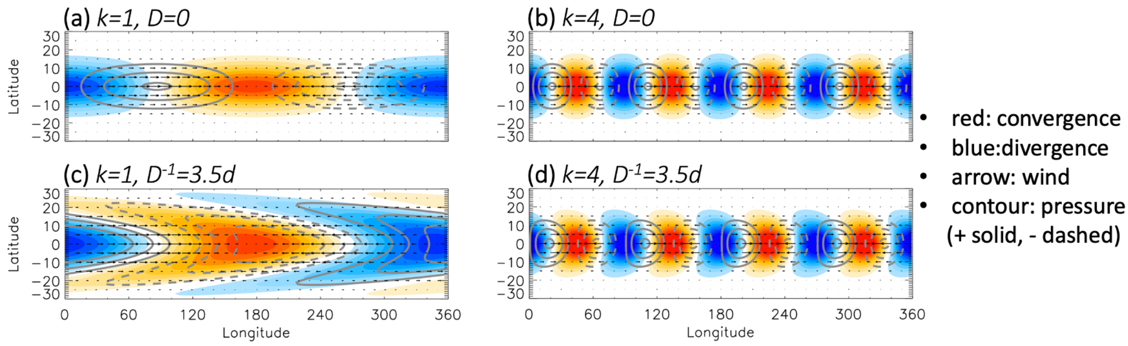


15



16

Theoretical horizontal structures



Combine equations (1) and (2): $\frac{\partial^2 u}{\partial y \partial t} + D\frac{\partial u}{\partial y} - \beta y \frac{\partial u}{\partial x} = 0$

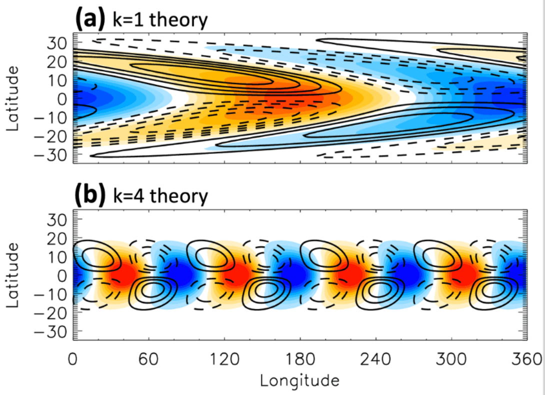
$$u(y) = e^{-l^2 y^2} e^{i m^2 y^2}$$

$$l^2 = \frac{\beta c_r}{2(c_r^2+c_i^2)} \text{ and } m^2 = \frac{\beta c_i}{2(c_r^2+c_i^2)} \text{ with } c_r = \omega/k, \quad c_i = D/k$$

* If D=0; $u(y) = e^{-\beta y^2/2c_0}$ where $c_0 = \omega_0/k$ (classical Kelvin waves!)

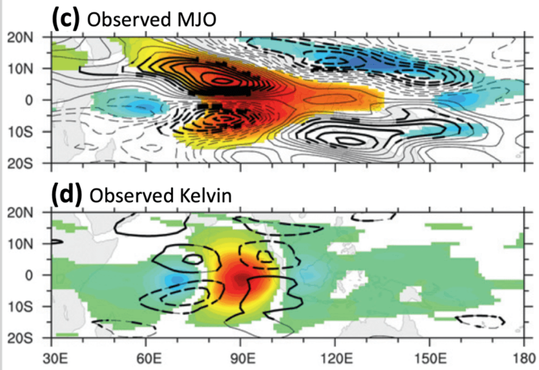
17

Theory



- red/blue: convergence/divergence
- contour (vorticity)

Observations

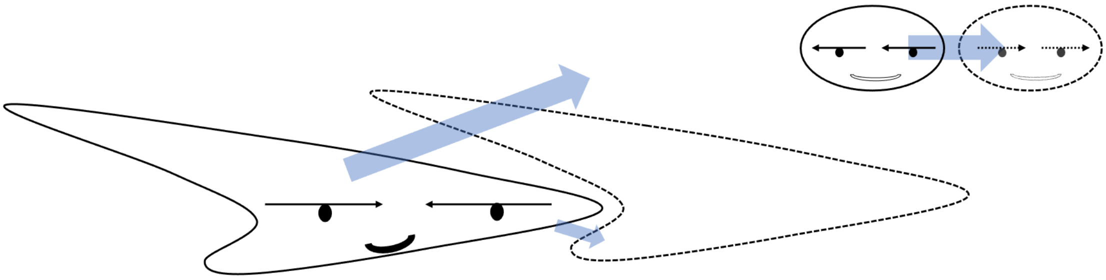


- red/blue: precipitation anomalies
- contour (vorticity)

18

Still…
I sometimes move poleward into the summer hemisphere. You don't do.

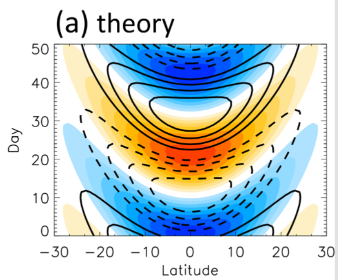
Damping sometimes steers you into the subtropics when ocean is warm enough to support large-scale convection. The solution of shallow water equations with damping predicts your eastward & poleward propagation.



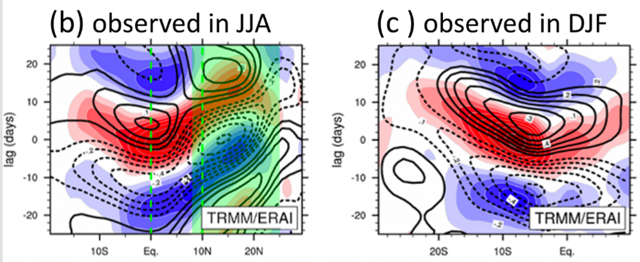
Imaginary part of the full solution: $e^{i(kx+m^2y^2-\omega t)}$

19

Poleward propagation of the MJO



- solid/dashed: westerly/easterly
- red/blue: convergence/divergence

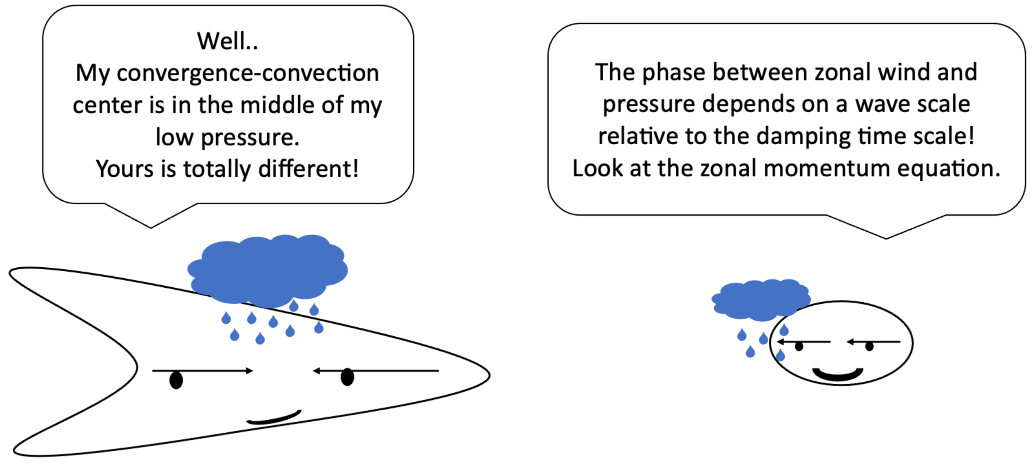


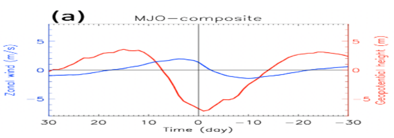
[(b) and (c) are reproduced from Meehl et al. (2020).]

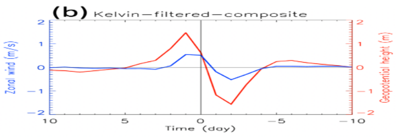
- solid/dashed: westerly/easterly
- red/blue: precipitation anomalies

20

EPISODE4. WITH OR WITHOUT YOU







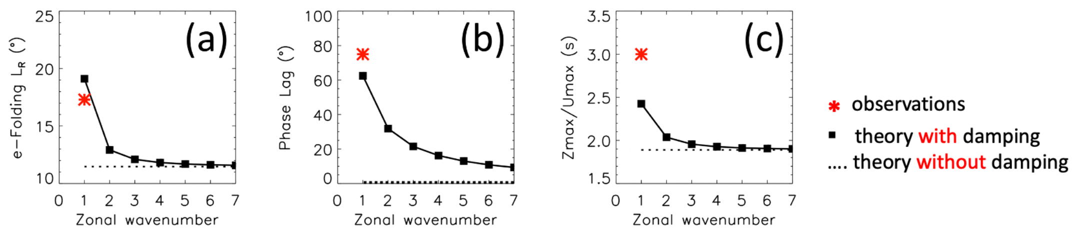
21

From equation (1), the lag between wind and geopotential is given:

$$Re(u) = u_0 cos\theta$$

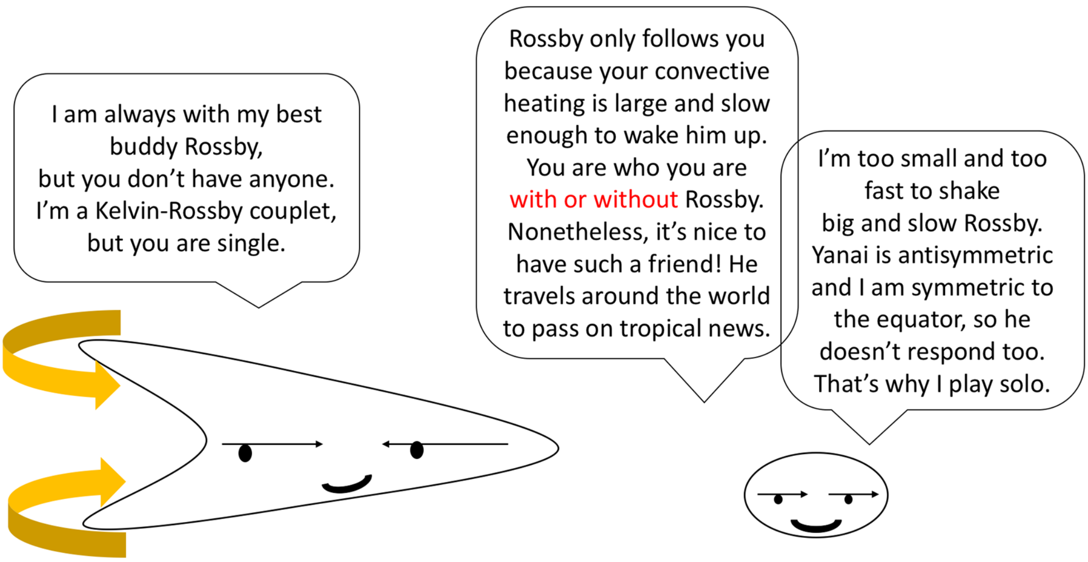
$$Re(\phi) = u_0 Acos(\theta + \theta_{lag})$$

$$\theta_{lag} = \tan^{-1}(D/\omega)$$

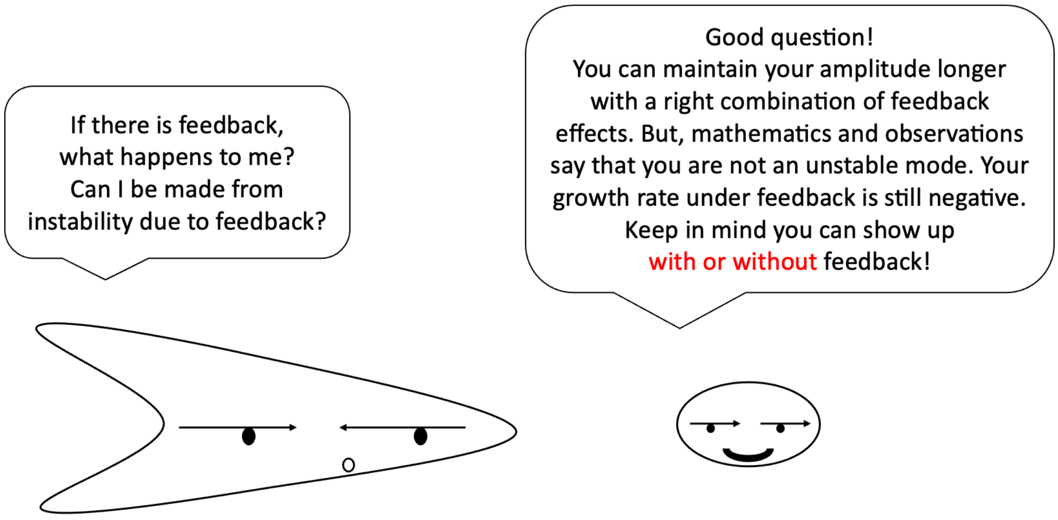


- Much wider meridionally
- Almost quarter angle lag
- Stronger pressure response

22



23



24

- For the mass equation (3), take a simplest form to represent feedback effects that are relevant to wind and pressure.

$$\frac{\partial \phi}{\partial t} + gH\frac{\partial u}{\partial x} = au + b\phi$$

- Combine with Equation (1).

$$\frac{\partial^2 u}{\partial t^2} + D\frac{\partial u}{\partial t} + \omega_0^2 u = -a\frac{\partial u}{\partial x} + b\frac{\partial u}{\partial t} + bDu$$

- Solution would be like this.

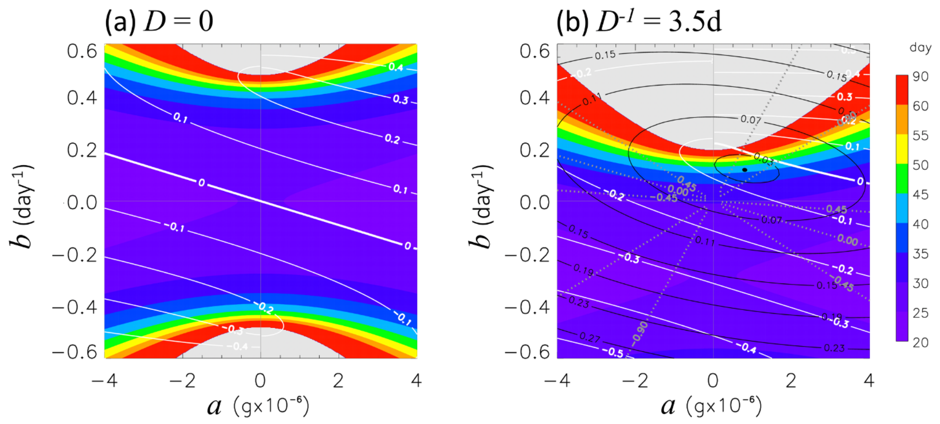
$$u(x,t) = e^{\alpha t} e^{i(kx-\omega t)}$$

- Solve!
  Then, we get the growth/decay rate and dispersion relation.

$$\alpha = \frac{1}{2}\left(a\frac{k}{\omega} + b - D\right)$$

$$\omega^2 = \frac{1}{8}\left\{4gHk^2 - (b+D)^2 + \sqrt{[4gHk^2 - (b+D)^2]^2 + 16a^2k^2}\right\}$$

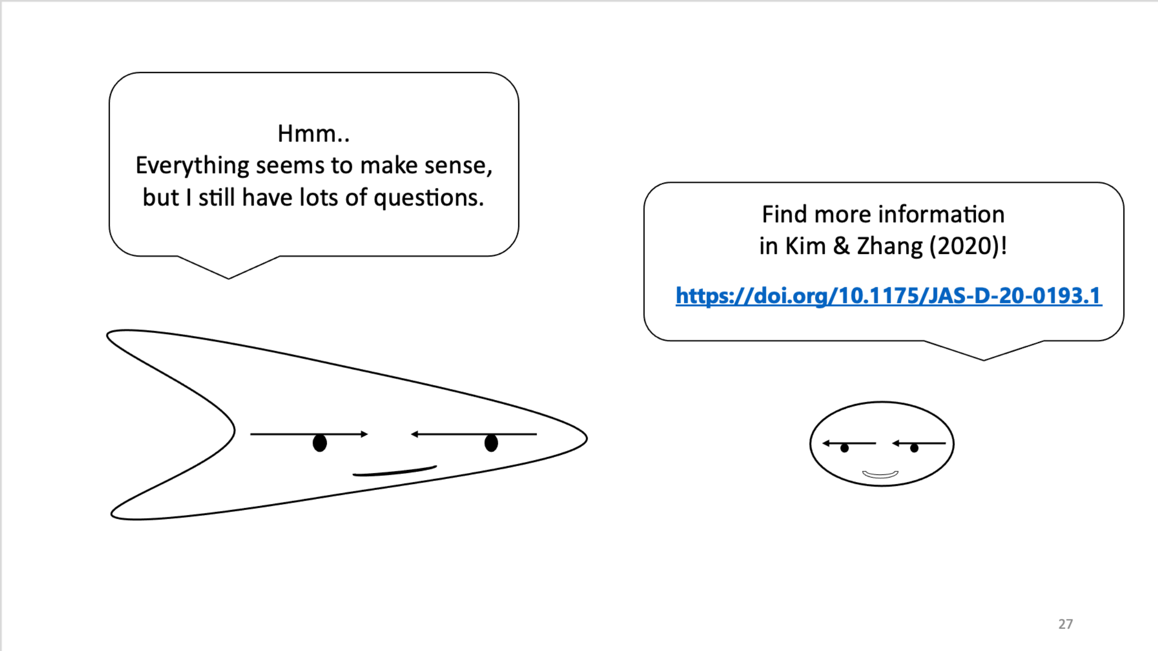
25



Periods (color) and the growth/decay rate (white curves). Negative values of white curves represent decay. (b) Black lines show RMSD between the observation-based budget and theoretical estimates, and gray dotted lines are correlation coefficients between them. The minimum RMSD and maximum correlation between observations and theory is located at the black point.

The black point in (b) suggests -- the most likely values of two feedback coefficients (a, b)
-- negative growth rate (so, no instability)
-- period matching the observed one

26


Hmm..
Everything seems to make sense,
but I still have lots of questions.
Find more information
in Kim & Zhang (2020)!
https://doi.org/10.1175/JAS-D-20-0193.1
27

ABSTRACT

Substantial progress has been made in understanding the dynamics of the MJO during the past decades. However, there is no consensus on the underlying mechanism for the MJO. Most current ideas of MJO dynamics involves atmospheric deep convection and its interaction with moisture. These theories explain the eastward propagation of the MJO through moisture enhancement to the east of large-scale convection. Here, using a simple analytical approach with equatorial shallow water equations, we revisit the view on the MJO as slowed-down Kelvin waves due to damping. We show that the dynamic core of the MJO can be described in terms of a harmonic oscillator that can be excited by stochastic forcing. The mechanism for selecting MJO scales comes from momentum damping, and the mode propagates eastward because of exactly the same reason for Kelvin waves to propagate eastward due to the Coriolis effect. Our unified theory of fast Kelvin waves at synoptic scales and the slow MJO at planetary scales supports the notion of a distinction and continuous transition between equatorial Kelvin waves and the MJO. We also discuss the role of feedback mechanisms that help sustain an MJO event longer.