Pliocene “permanent El Nino” & atmospheric superrotation

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also: David Randall, Mark Branson, Melissa Burt

- Pliocene; “permanent El Nino”
- Other attempts
- Superrotation! weakening those easterlies
  - Increased convective activity in warmer climate in SPCAM
  - Rossby wave resonance Superrotation mechanism
  - Warming of mid-latitude upwelling sites due to wind shifts

Tziperman & Farrell 2009; Arnold, Tziperman & Farrell 2012; Arnold, Kuang, Tziperman, 2013; Arnold et al 2014;

Pliocene proxy obs

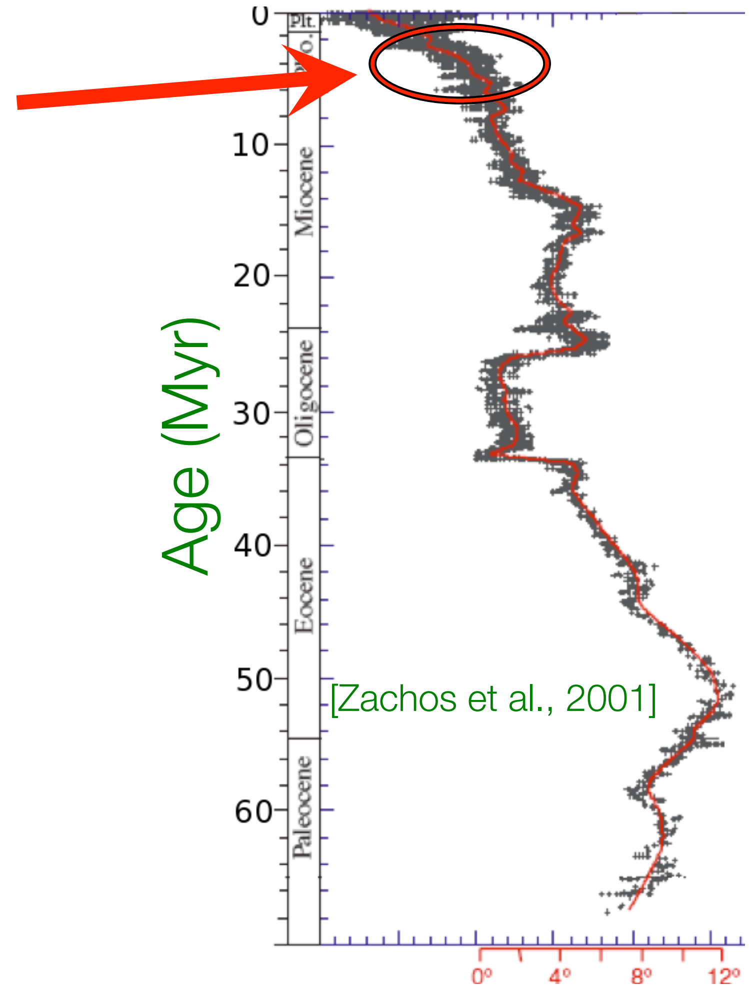
The Pliocene within the bigger picture

2-5 Myr ago: mostly just before ice ages which began 2.7Myr ago;

~3° warmer than present; not as warm as earlier (equable) periods;

Analogue of near-future climate? (represents equilibrium rather than transient climate sensitivity)

Gradual cooling over past 55Myr



Deep ocean Temperature

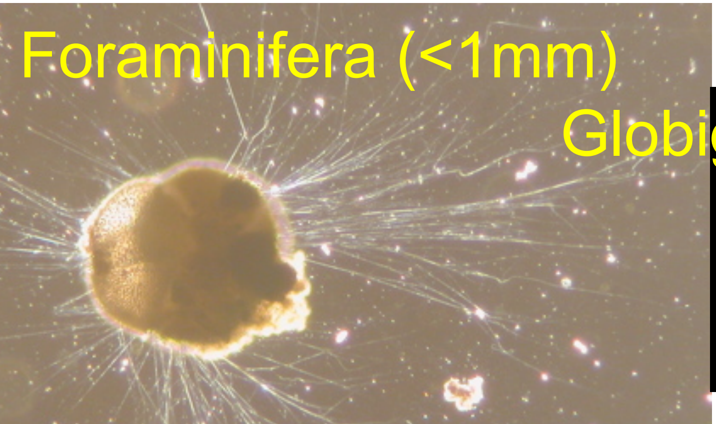
The Pliocene (2-5 Myrs)

- CO_2 350-500ppm? (Today ~400; preindustrial 280; in 50 yrs …)
- Global average surface temperature: ≈3° warmer than today
- Ice: covers Antarctica, but not much in northern hemisphere (ice ages started ≈2.7 Myrs ago)

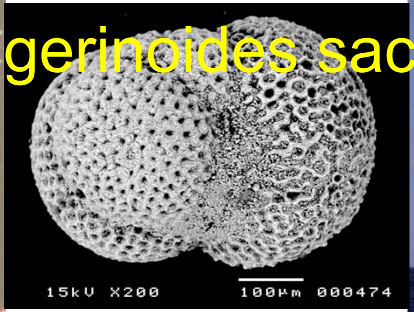
How do we know:

- Isotopic/ other proxy records

  from deep sea drilling.



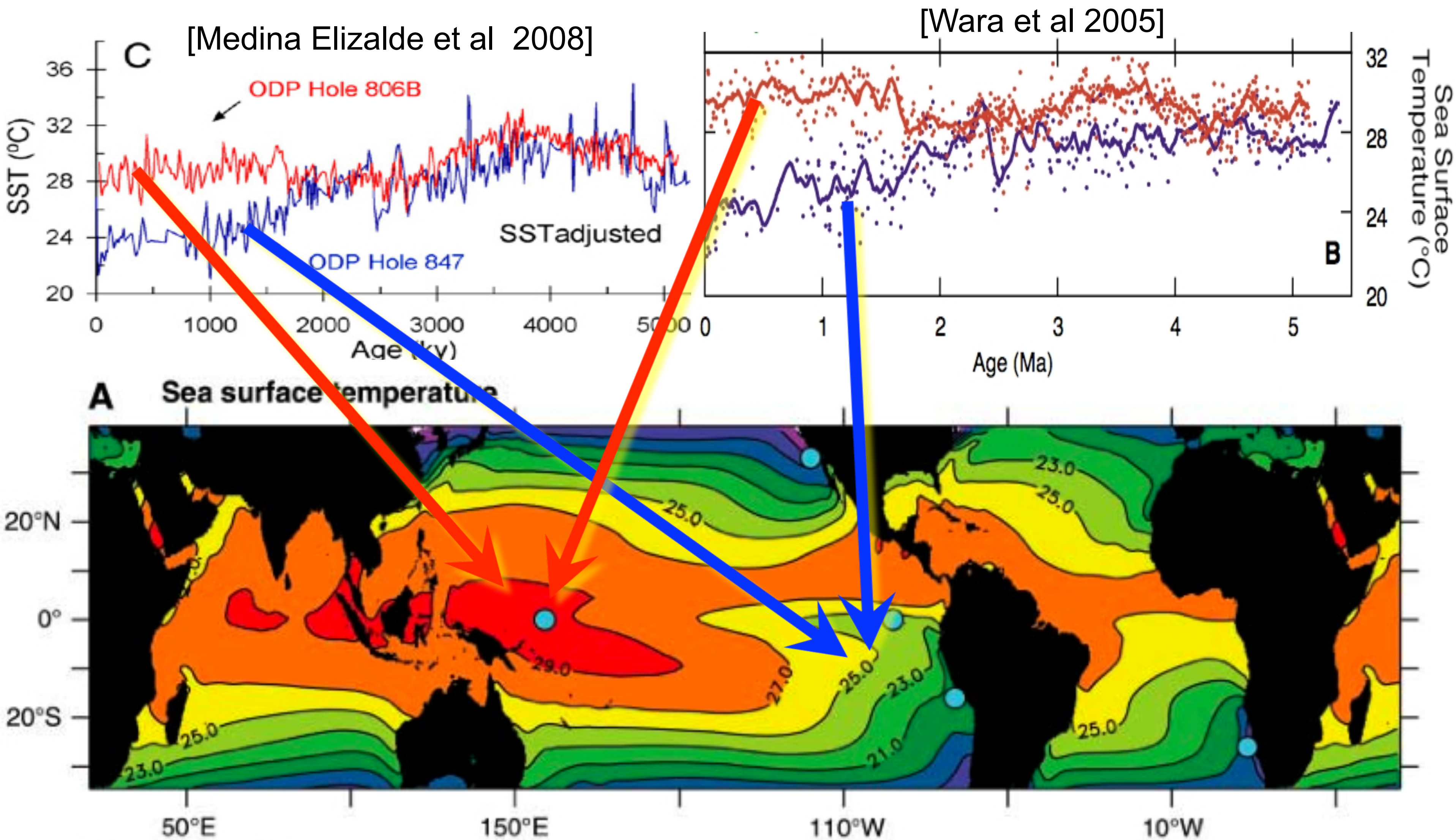
Foraminifera (<1mm)



Globigerinoides sacculifer

Resolution Drill Ship

The equatorial Pacific during the Pliocene



➔ Strong east-west temperature gradient in the equatorial Pacific did not exist during the Pliocene (~2-5 Myr ago)

Pliocene proxy obs: warm upwelling sites

Another part of the puzzle:
Strong warming in upwelling sites off Africa, California, South America

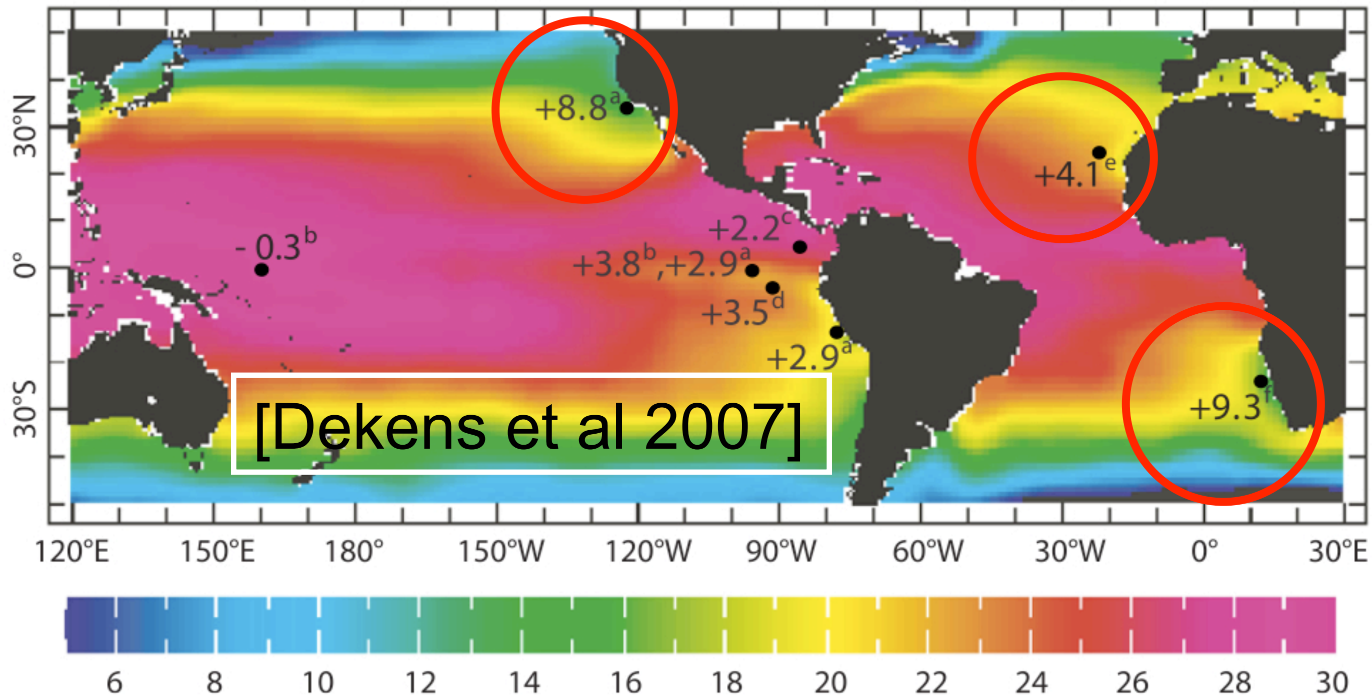
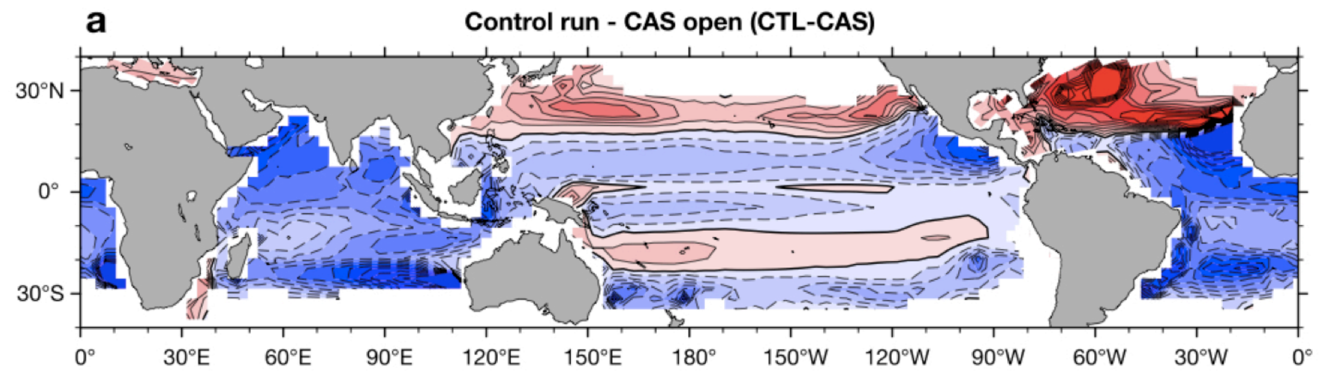


Figure 1. Difference in sea surface temperature (SST) between Pliocene and modern SST. The colored map shows modern mean annual SST [*Levitus and Boyer*, 1994]. Superimposed is the difference between

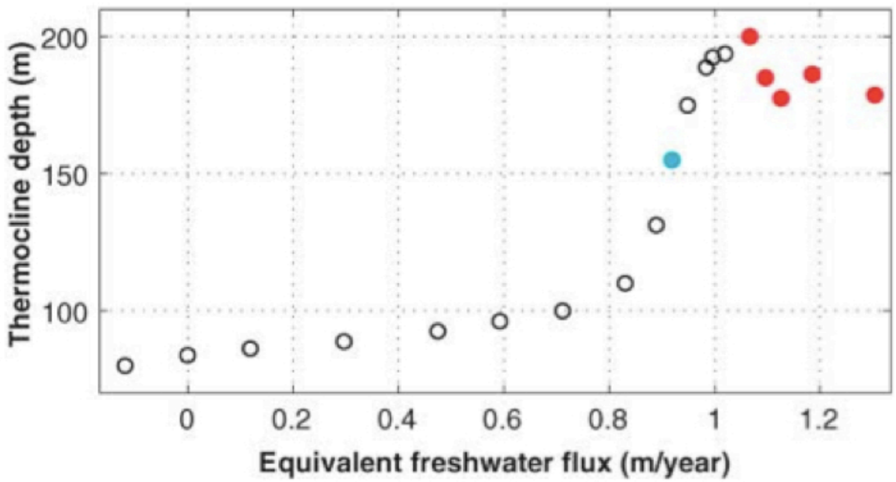
Other/ previously proposed mechanisms for Pliocene permanent El Nino/ warm upwelling sites

Other ideas

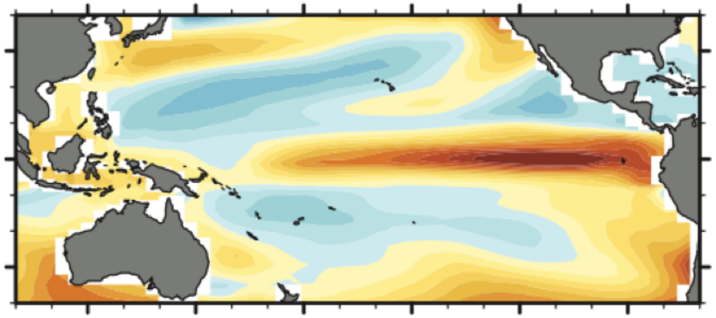
Move Papua/
New Guinea;
[Cane&Molnar 2001;
Fedorov et al 2013]



Open central American seaway [Steph et al 2010]



collapse equatorial thermocline
w/ N. Pacific fresh water flux
[Fedorov et al 2004/2006]

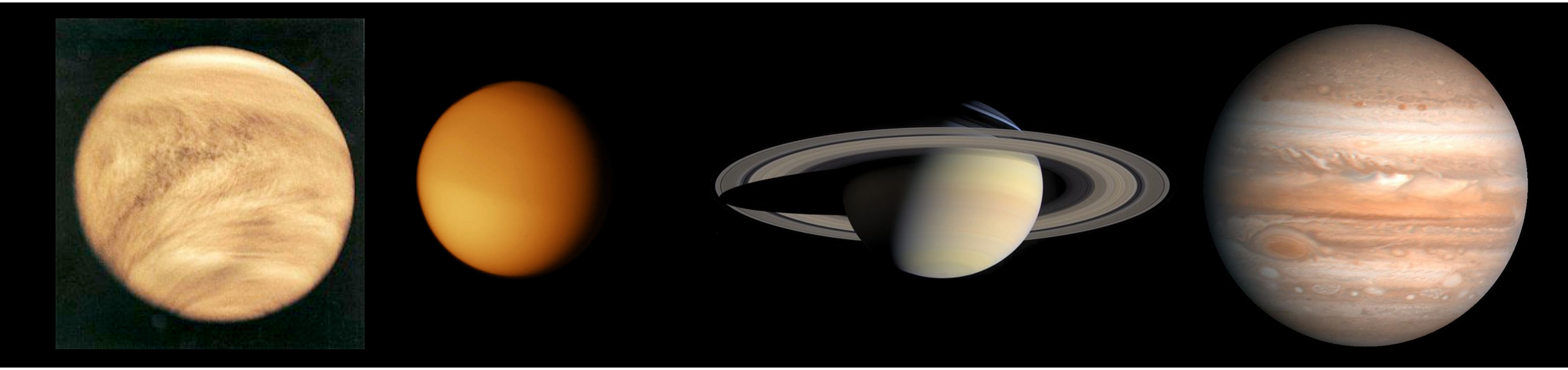


Hurricanes/ ocean mixing
[Emanuel 2002… Fedorov et al 2010/2013]

Atmospheric superrotation and Pliocene permanent El Nino

Superrotation

- Superrotation = Zonally-averaged westerly wind at the equator, basically the atmosphere rotating faster than Earth itself
- Seen in the atmospheres of Venus, Titan, Saturn, and Jupiter:



- Also seen in the upper atmosphere during MJO
- “Forbidden” by angular momentum conservation in the absence of up-gradient angular momentum fluxes (Hide’s theorem) ➔ must involve some non-trivial eddy dynamics.

A partial superrotation literature review

- 2-level PE models: multiple equilibria due to eddy fluxes from mid-latitudes: [Suarez and Duffy, 1992; Saravanan, 1993].
- & later also 3d GCMs: [Williams , 2006, 2003]
- Theoretical considerations of wave propagation [Panetta et al., 1987]
- multi-equilibria via mean circulation feedback [Shell & Held , 2004]
- 18 level AGCM: SR due to fluxes stationary planetary waves forced by steady diabatic [Kraucunas & Hartmann 05]
- Moving flame effect (Lindzen's book, Venus)
- Recently: Mitchel & Vallis (2010); Scott & Polvani (2008); Schneider & Lio 2009…
- Possible superrotation & the collapse of the walker circulation in a future global warming scenario [Held, 1999; Pierrehumbert 2002]

- Pierrehumbert [2002]:

  "There is no evidence that a westerly superrotating state has ever occurred in any climate of the Earth's past…"

Superrotation dynamics: Rossby Wave reminder…

Consider a wave solution $$\psi = A cos(kx + ly - \sigma t)$$

Rossby wave dispersion relation $$\sigma = \frac{-\beta k}{k^2 + l^2 + L_R^{-2}}$$

Meridional velocity of energy propagation: $$c_g^{(y)} = \frac{2\beta kl}{(k^2 + l^2 + L_R^{-2})^2}$$

Meridional flux of zonal momentum

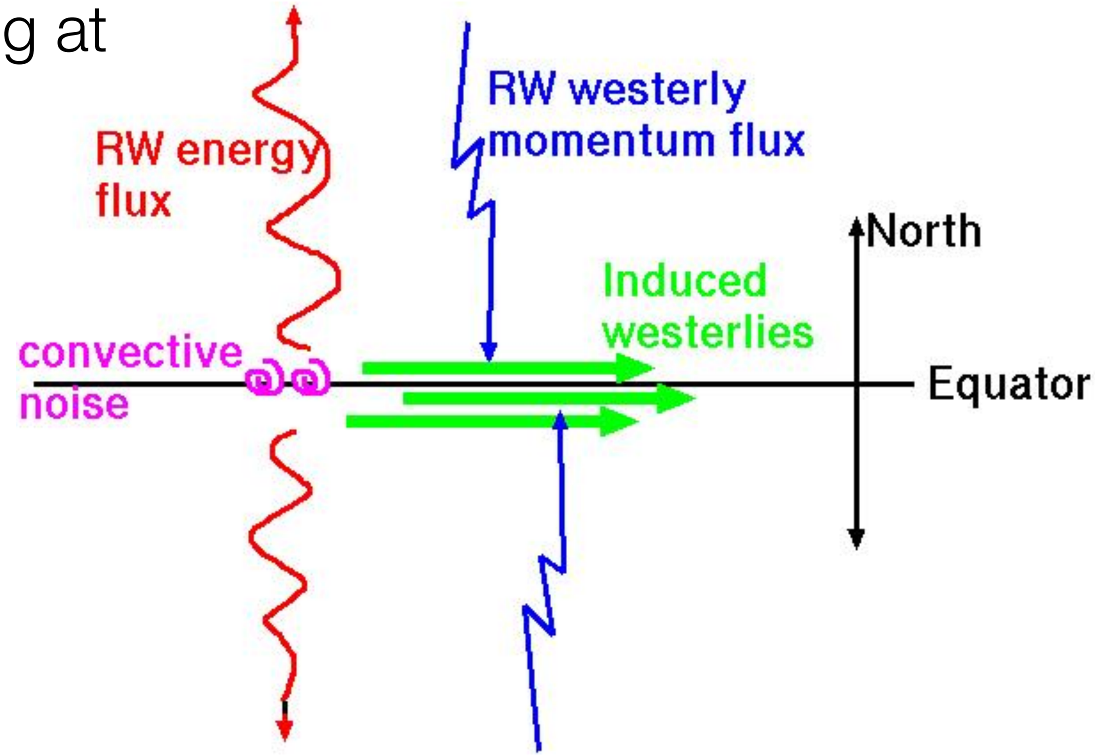
$$\overline{u'v'} = \overline{(-\psi_y)(\psi_x)} = -kl A^2 \overline{\sin^2(kx + ly - \sigma t)}.$$

➔Meridional momentum flux is in opposite direction to group velocity. Specifically, energy flux away from equator implies momentum flux toward equator westerly momentum induced at equator.

Proposed mechanism for permanent El Nino

1. Warmer Pliocene ➔ stronger convective stochastic forcing at equator.

2. ➔ Excited Rossby waves ➔ equatorward westerly momentum flux ➔ weaken equatorial easterlies.

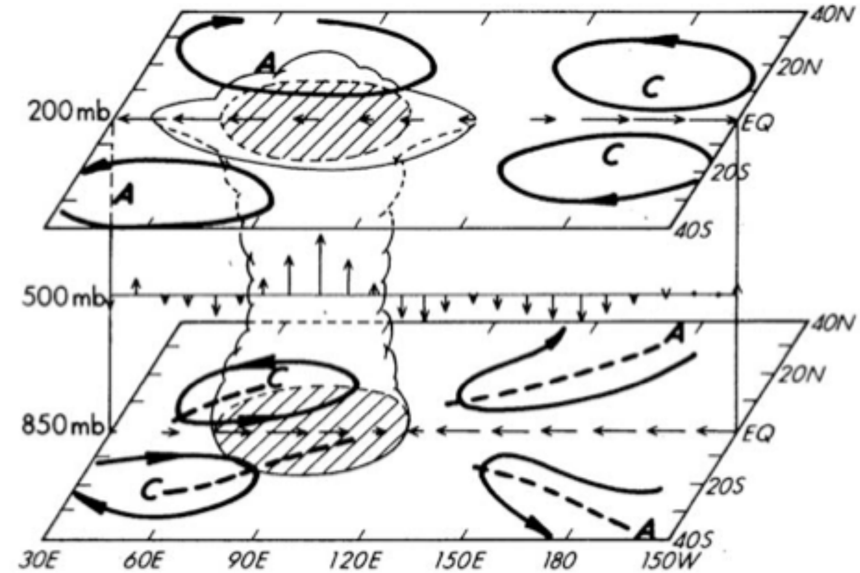


3. ➔ decreased E-W thermocline slope ➔ eliminate East Pacific cold tongue ➔ Permanent El Nino!

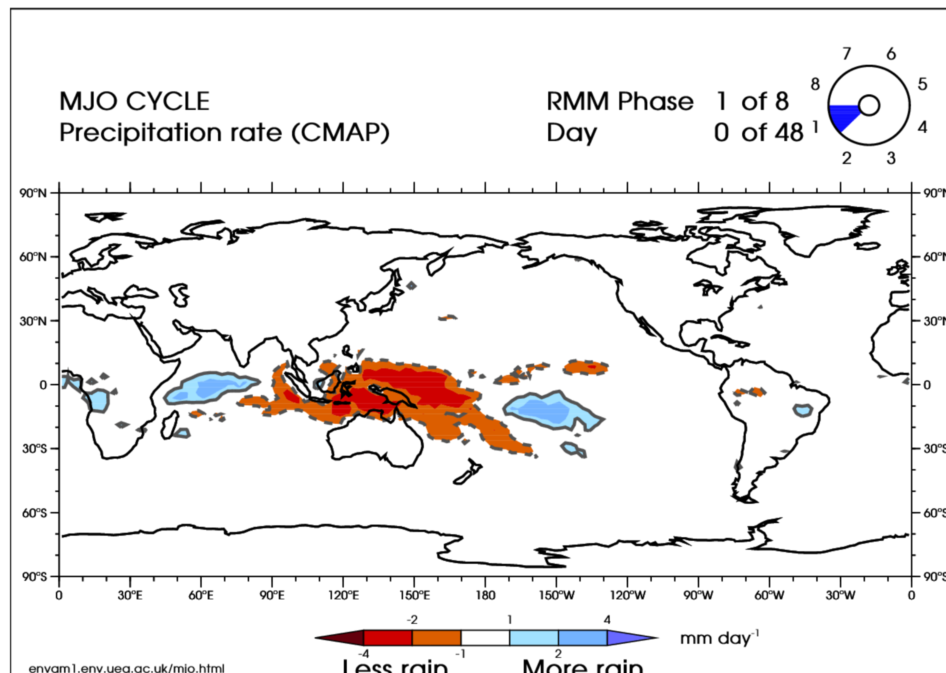
The Madden-Julian Oscillation (MJO)

- Large region of enhanced convection coupled to suppressed regions through large-scale circulation.
- Forms quasi-periodically over Indian ocean, 30-70 day timescale, propagates eastward at 4-6m/s.
- Influences Indian monsoon, ENSO, global teleconnections.

How will the MJO respond to warming?



Rui and Wang (1990)



Matthews (2013)

Stronger (MJO-like) convective noise in warmer climate?

Previous evidence of MJO response to warming:

Observations: [Slingo et al. 1999; Hendon et al 1999]: weak covariance with tropical SST. [Jones & Carvalho 2006; Oliver & Thompson 2012]: weak linear trend over 20th century.

Idealized AGCM: [Lee, 1999] eddy flux convergence due to "MJO" twice as strong due to a uniform 3 degree warming;

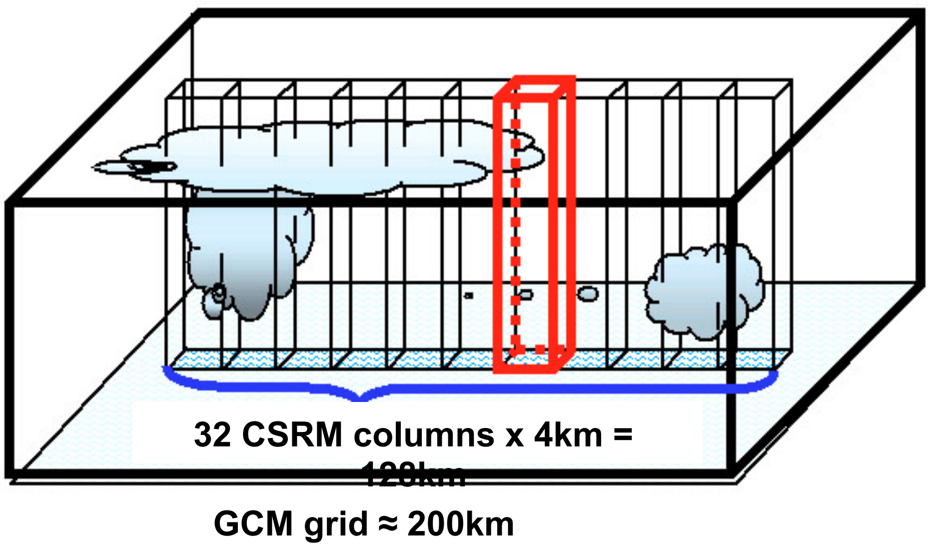
Community atmospheric model @very high co_2 [caballero & Huber 2010]

Theory: [increased variance w/SST, e.g. Sobel et al 2001; Raymond&Fuchs 2009]

Our experiments:

Response to increased SST & CO_2 in aquaplanet & realistic configurations of super parameterized community atmospheric and coupled ocean-atm models (SP-CAM, SP-CESM)

Super-Parameterized (SP) Community Atmospheric Model



Convection parameterization is replaced by a 2D cloud system resolving model in each GCM grid cell

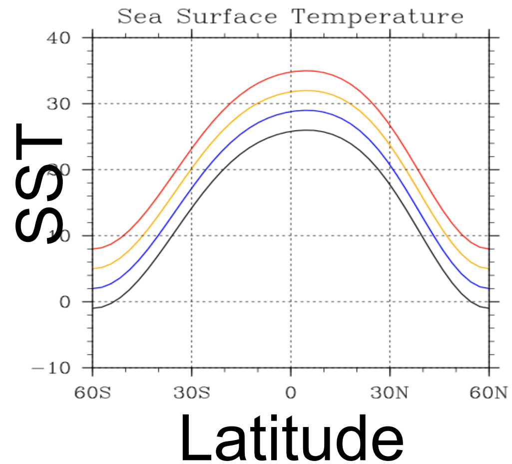
(Grabowski 2001; Khairoutdinov & Randall 2001)

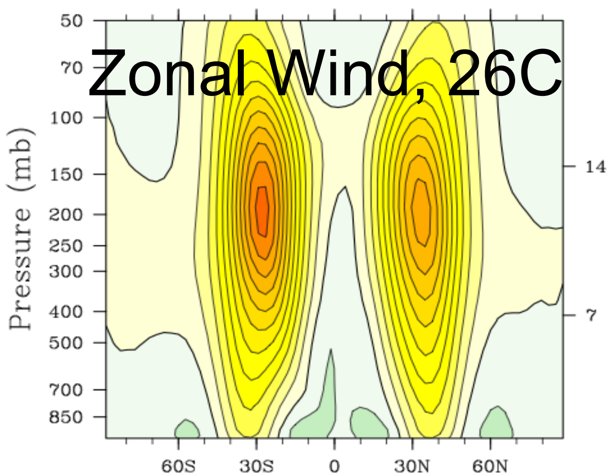
Computational cost is about 100 times higher than standard atmospheric general circulation model.

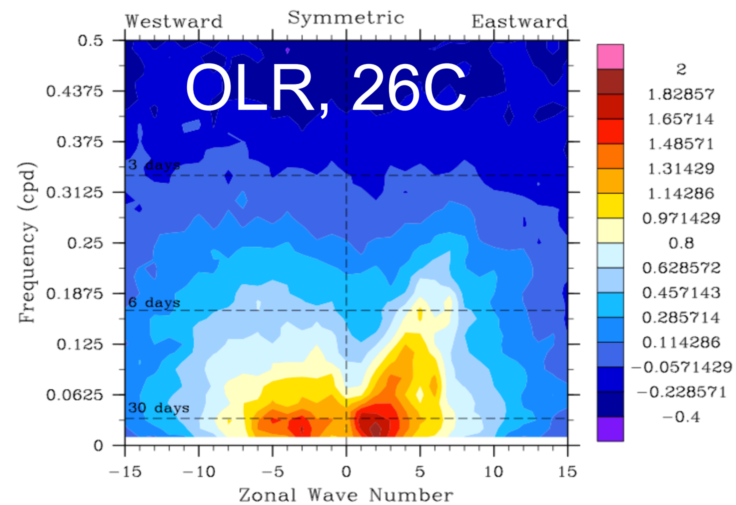
Shown to improve simulation results of tropical variability

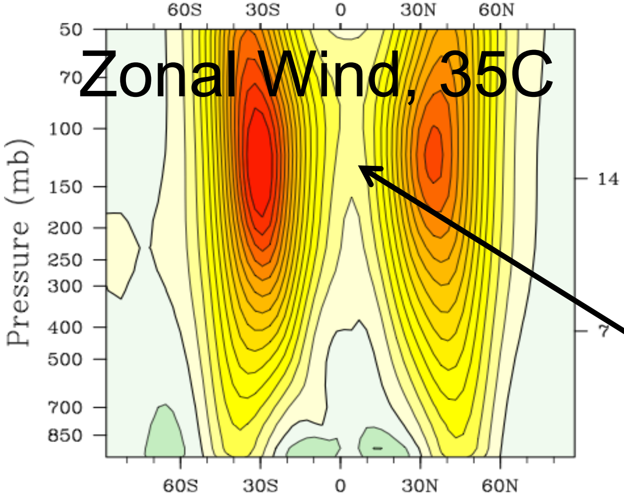
1 Warm climate→stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Enhanced MJO-like convective noise due to increased SST, aqua-planet SPCAM3.5



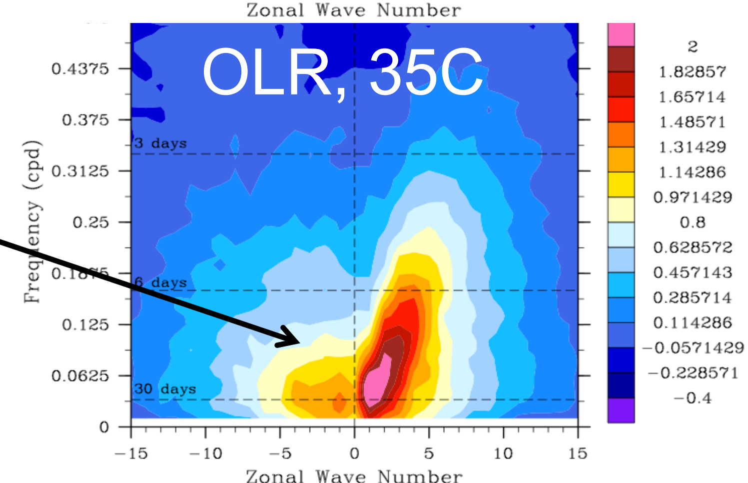






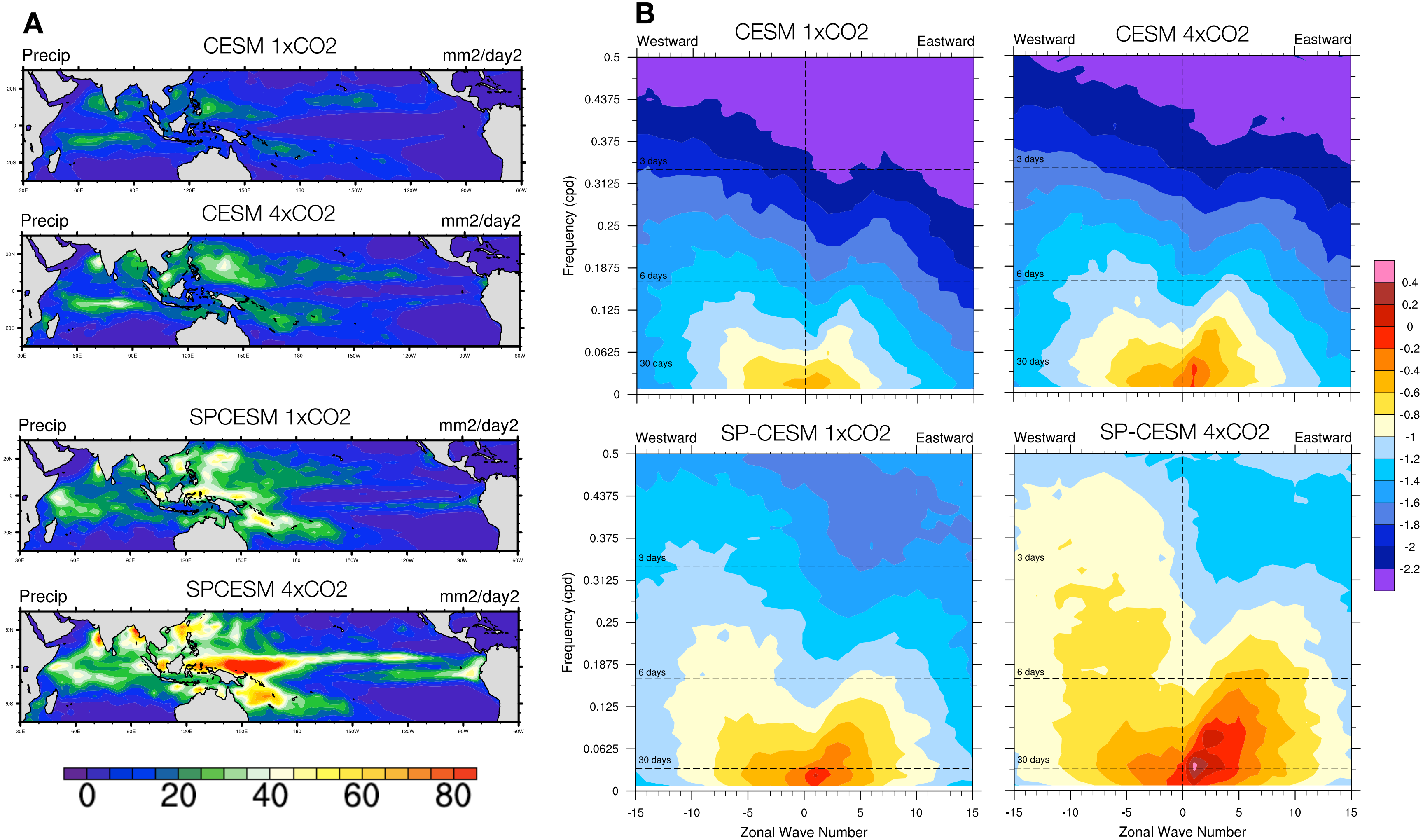
Increased MJO-like activity with SST!

Superrotation at high altitudes



1 Warm climate→stronger noise; 2 Rossby wave resonance; 3 upwelling sites

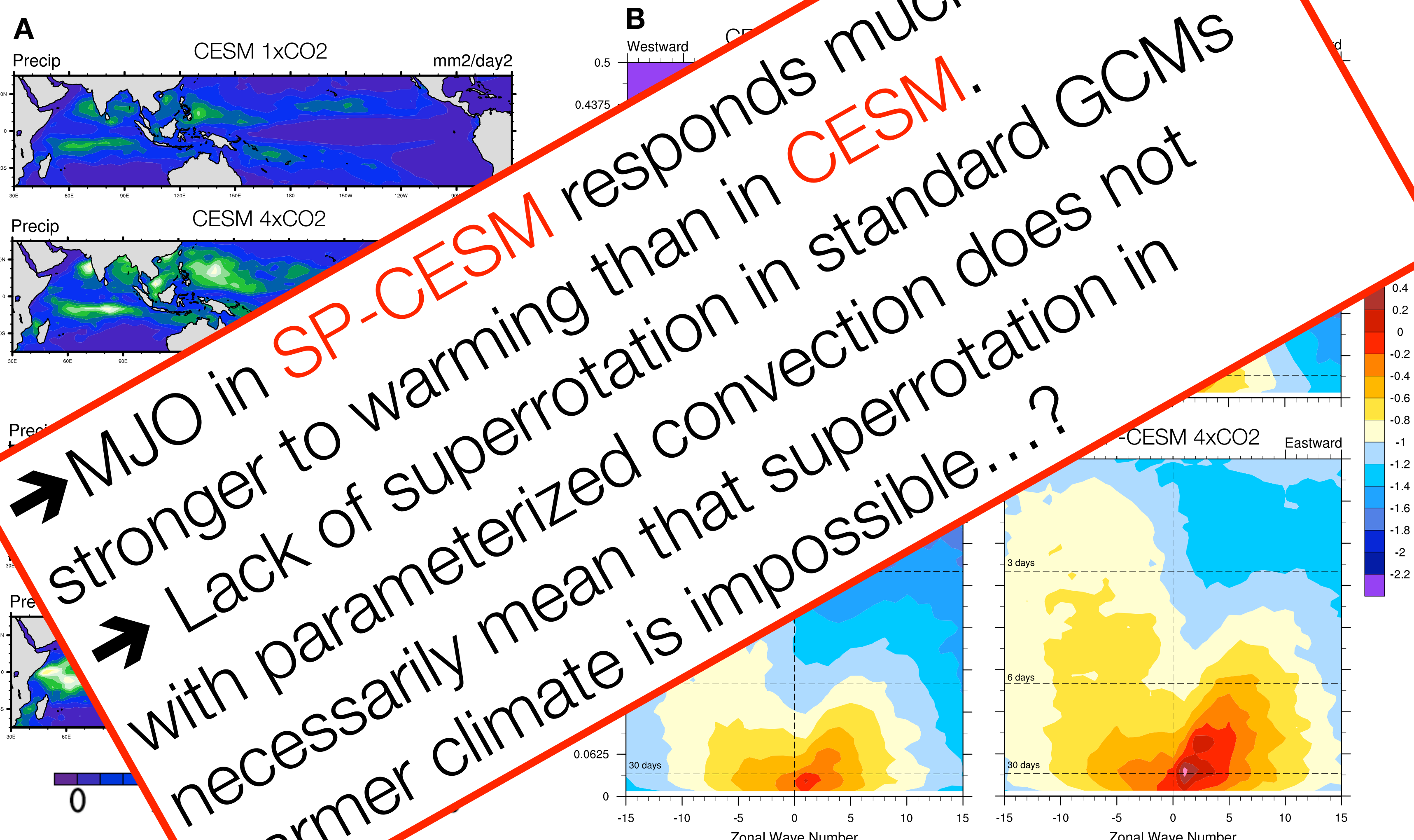
Enhanced MJO-like convective noise in a X4 CO_2 greenhouse scenario, SP-CESM, 'realistic' configuration



Stronger MJO in fully coupled ocean-atm SPCESM at x4

1 Warm climate→stronger noise; 2 Rossby wave resonance; 3 upw…ling sites

Enhanced MJO-like convective noise in a X… greenhouse scenario, using SP-CESM…



➔MJO in SP-CESM responds much stronger to warming than in CESM.

➔ Lack of superrotation in standard GCMs with parameterized convection does not necessarily mean that superrotation in warmer climate is impossible…?

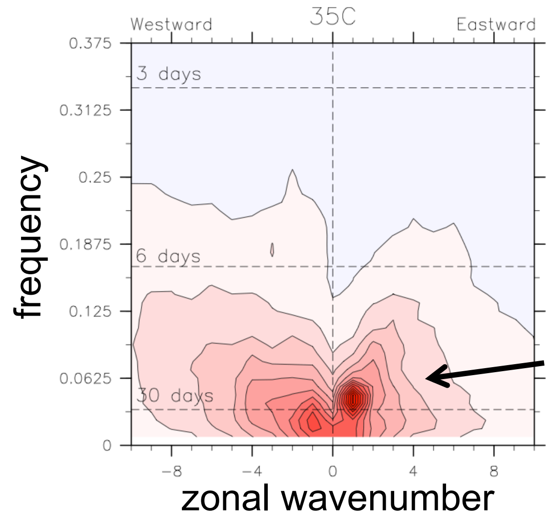
Stronger M…O in fully coupled ocean-atm SPCESM at x4

1 Warm climate➔stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Using composite moist static energy (MSE) budgets to understand MJO intensification

Calculate budget of frozen MSE:

$$h = c_p T + gz + L_v q - L_f q_i$$



MSE variance dominated by MJO

$$\left\langle \frac{\partial h}{\partial t} \right\rangle = -\left\langle \omega \frac{\partial h}{\partial p} \right\rangle - \langle \vec{v} \cdot \nabla h \rangle + LH + SH + \langle LW \rangle + \langle SW \rangle$$

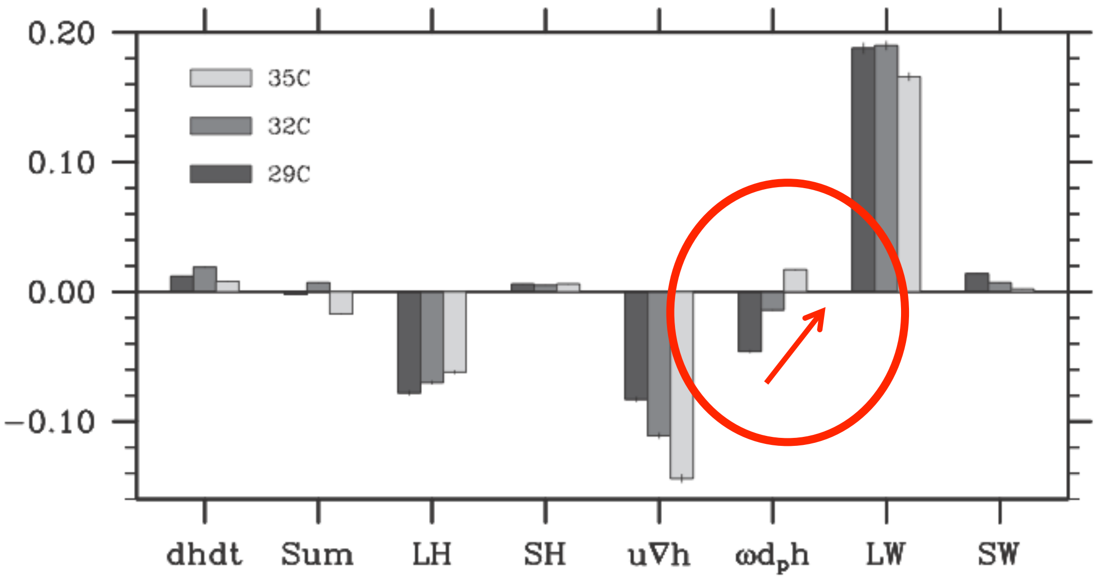
tendency; vertical advection; horizontal advection; surface latent heat; surface sensible heat; longwave heating; shortwave heating

Which term(s) responsible for intensification with SST?

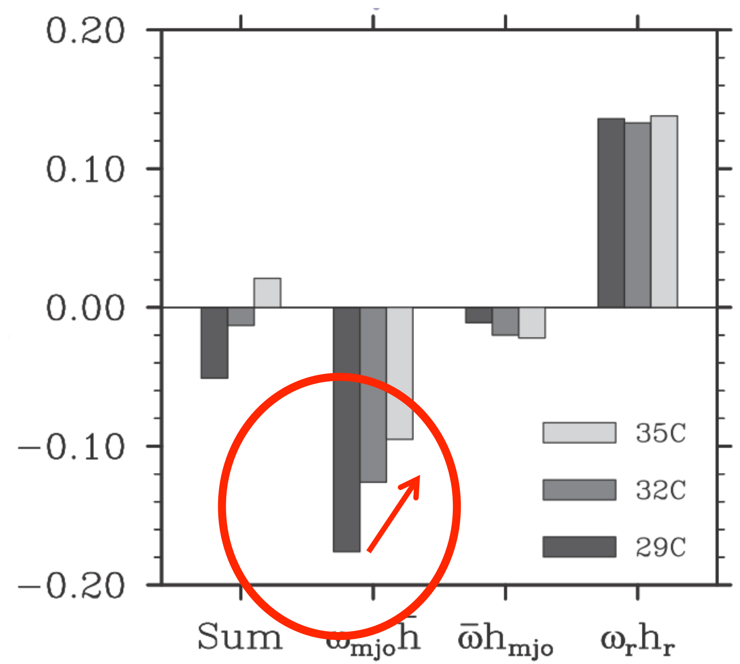
Andersen and Kuang (2012); Maloney (2009)

1 Warm climate→stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Using composite moist static energy (MSE) budgets to understand MJO intensification



stronger vertical advection
Amplifies MJO



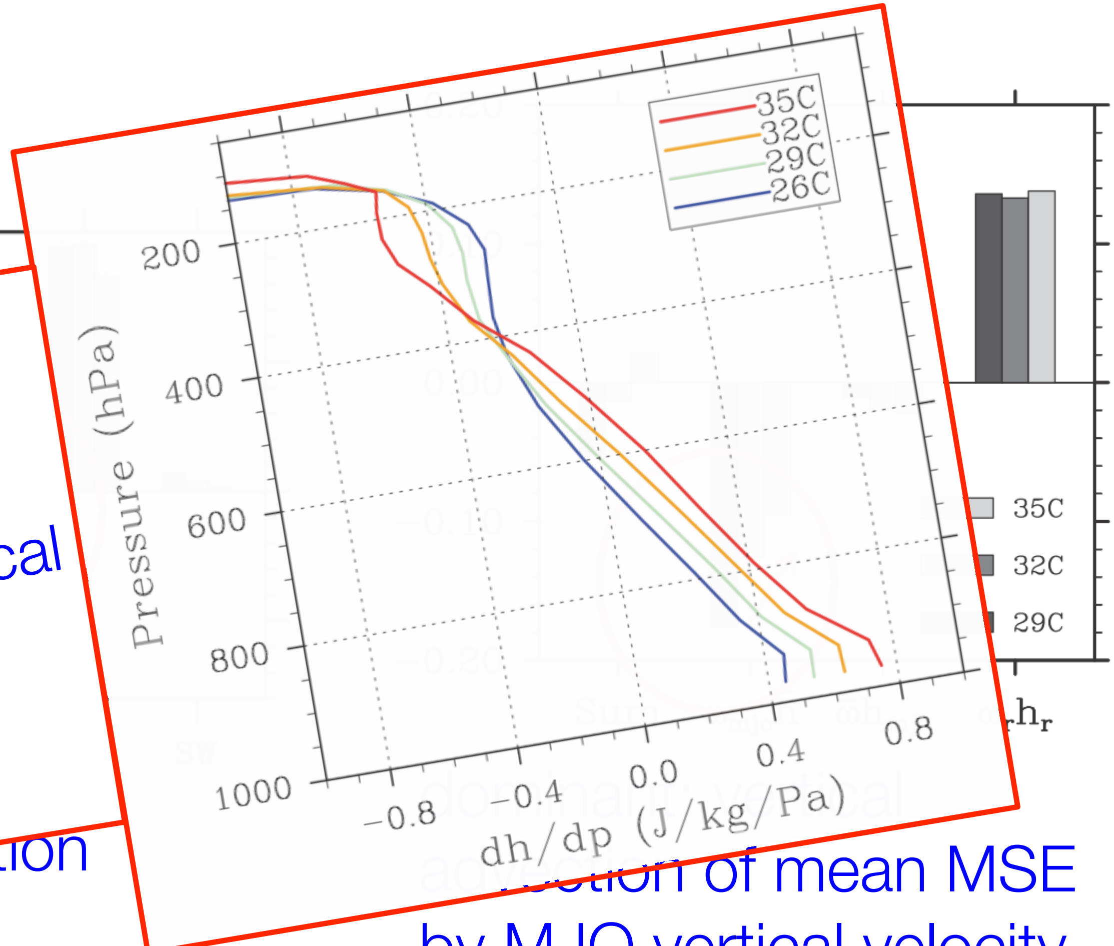
dominant: vertical advection of mean MSE by MJO vertical velocity

➔ Stronger MJO at high CO_2/SST due to enhanced vertical advection of mean MSE by MJO velocity (Arnold, Kuang, Tziperman 2013)

1 Warm climate→stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Using composite moist static energy (MSE) budgets to understand MJO intensification

MSE vertical profile steepens with increasing SST/CO_2, reinforcing vertical advection and therefore MJO amplitude



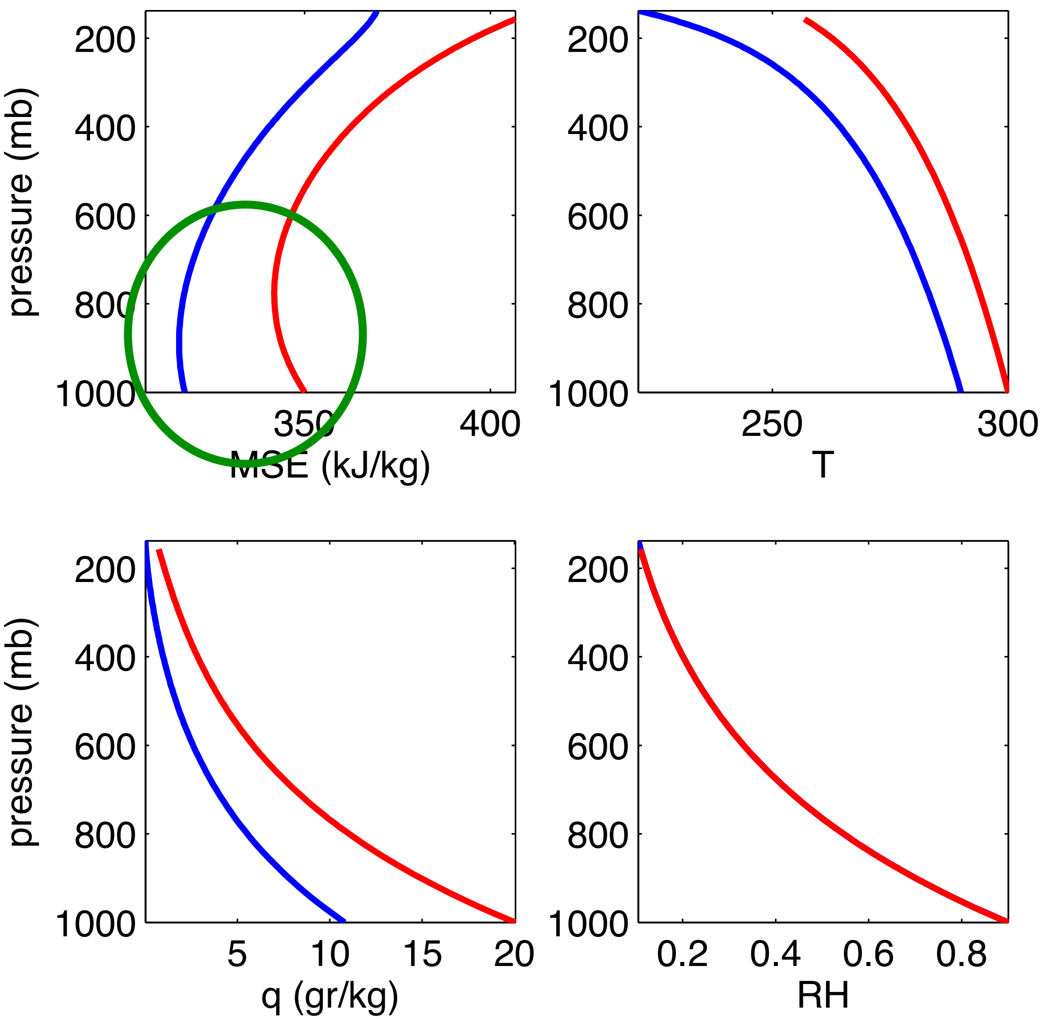
...advection

...mplifies MJO

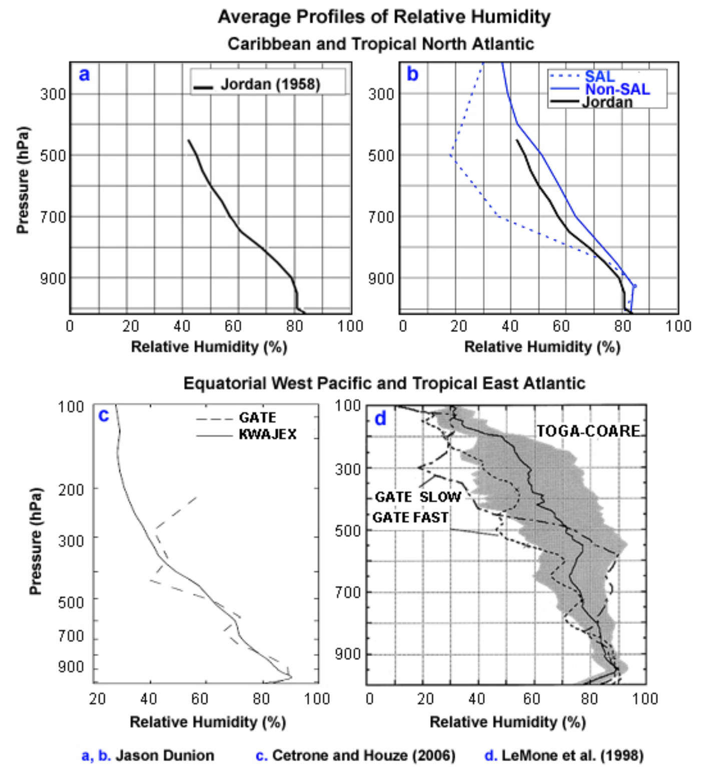
...ction of mean MSE by MJO vertical velocity

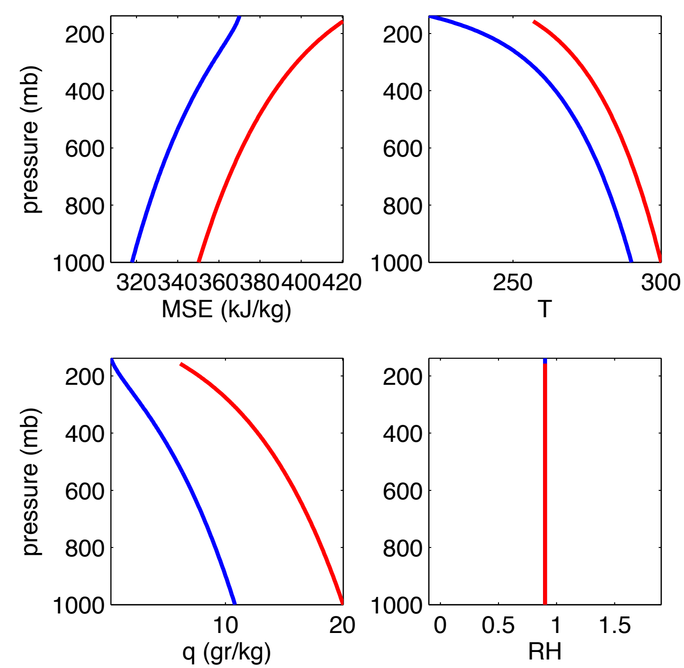
➔ Stronger MJO at high CO_2/SST due to enhanced vertical advection of mean MSE by MJO velocity (Arnold, Kuang, Tziperman 2013)

MSE profile & SST



MSE gradient in lower atmosphere steepens with increasing SST



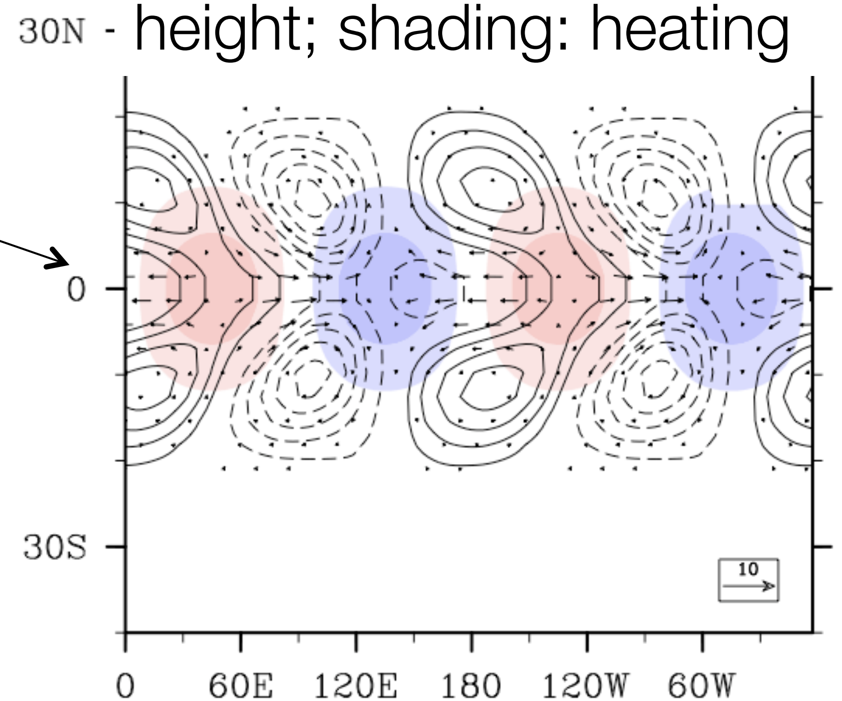


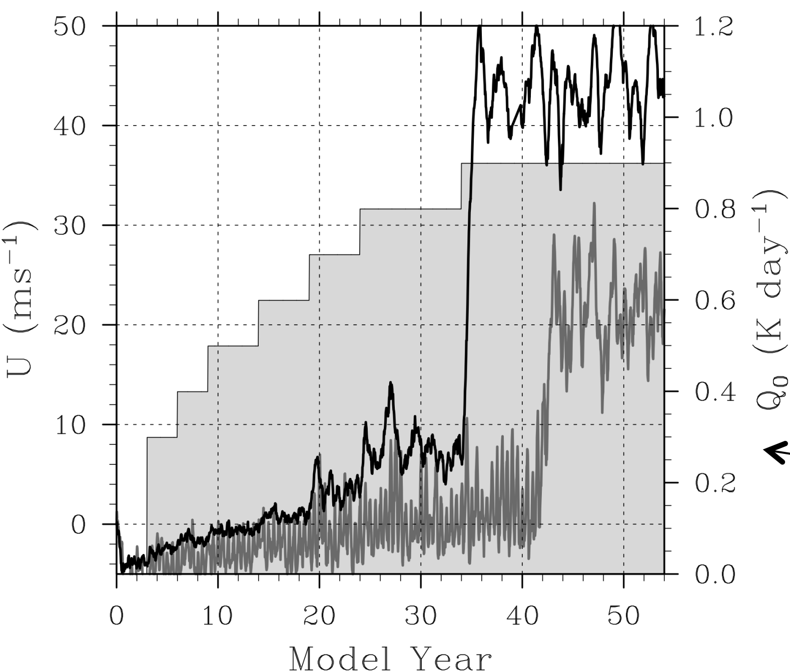
1 Warm climate➔stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Rossby-wave --- mean flow resonant interaction

CAM experiment: (1) Impose eddy heating at equator (colors); (2) gradually increase heating rate…

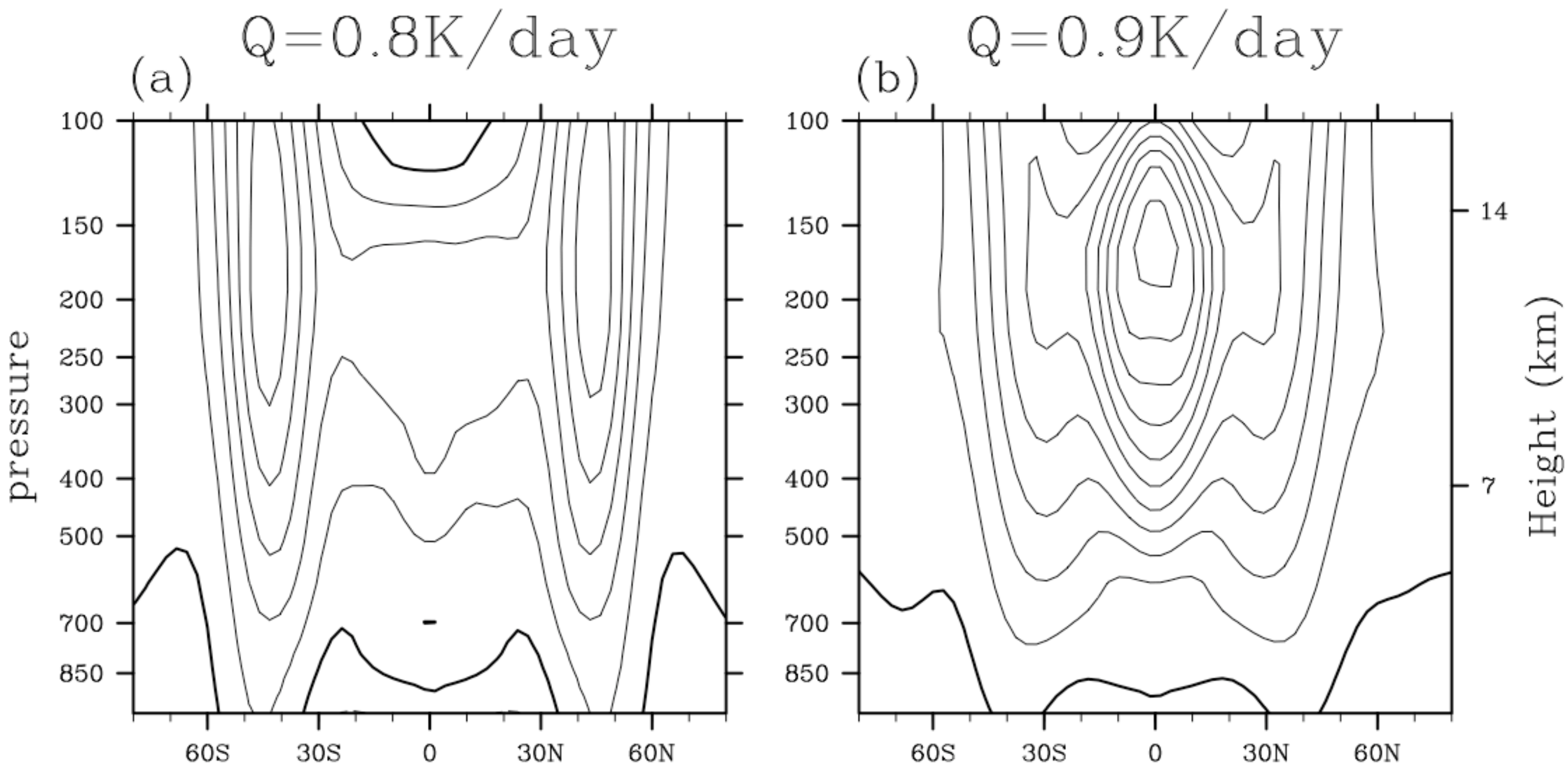
contours: geopotential height; shading: heating





Results: abrupt transition to superrotation

Rossby-wave --- mean flow resonant interaction

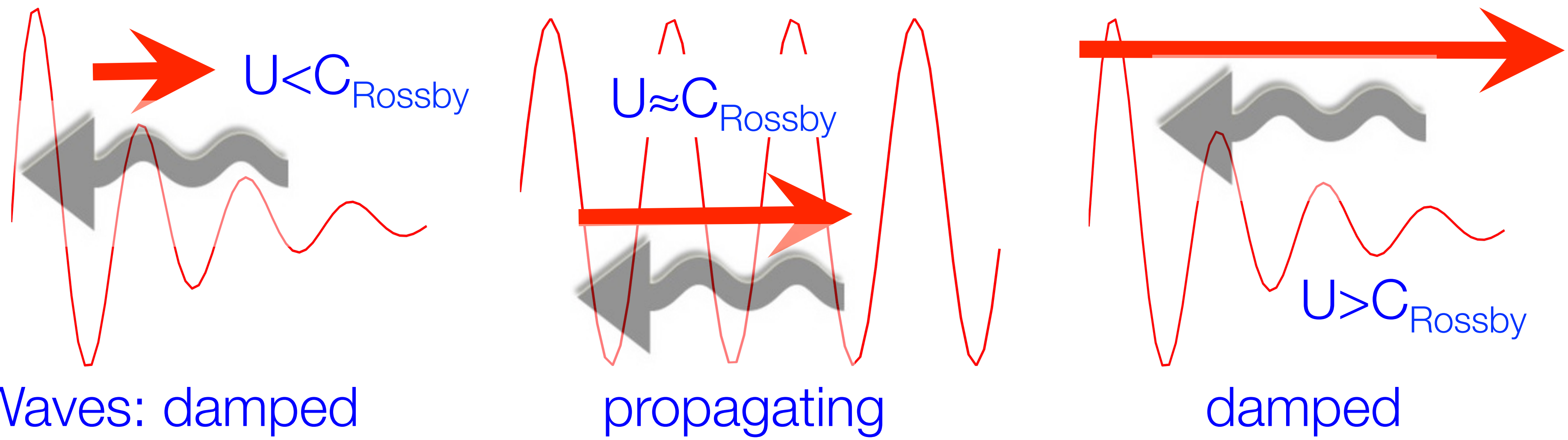


Zonal Wind before and after bifurcation,
showing transition to a strong superrotation

1 Warm climate➔stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Rossby-wave --- mean flow resonant interaction

Mechanism: Forced Rossby waves are evanescent unless mean flow speed is equal and opposite to free Rossby wave phase speed.

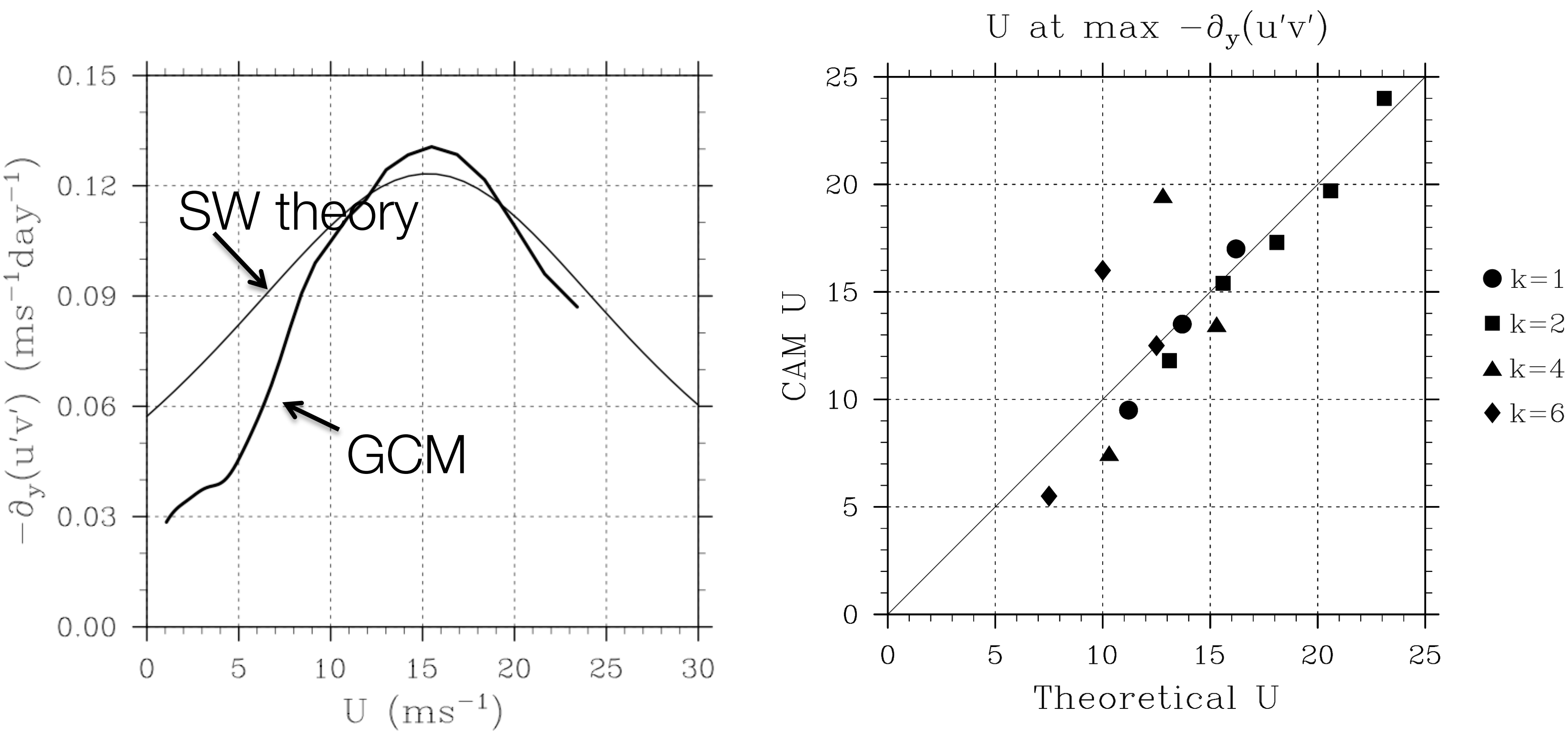


positive feedback: westerly wind strengthens ➔ approaches phase speed of free Rossby wave ➔ waves amplify ➔ stronger equatorward momentum flux ➔ enhanced westerlies

➔ A resonance! maximum wave amplification & westerly acceleration occur when westerly speed = Rossby wave speed.

1 Warm climate➔stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Rossby-wave --- mean flow resonant interaction



Comparison with shallow water analytical solution confirms resonance; experiments specify k & propagation speed of heating.

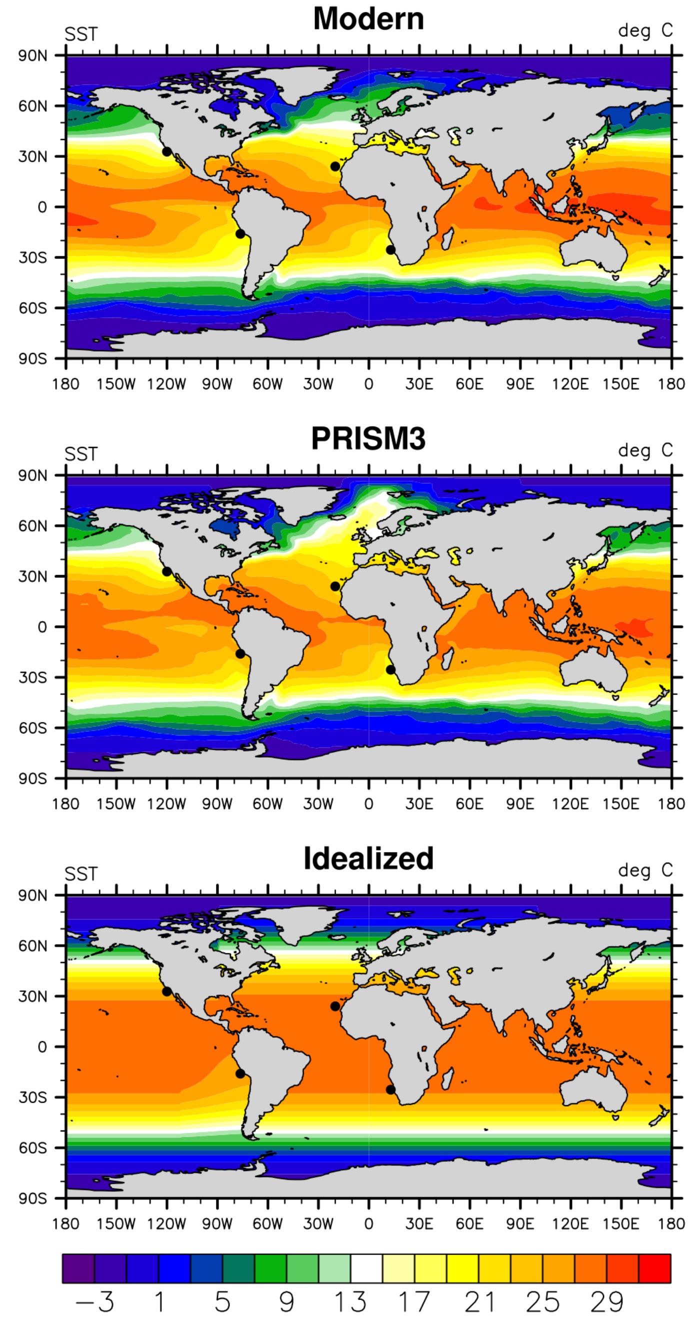
1 Warm climate→stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Warming of upwelling sites

Upwelling-favorable coastal wind in mid-lats is due to:
- (1) subtropical high at around 30N;
- (2) land-sea contrast

Warm SST effects on Hadley cell, & propagating Rossby waves, can shift location of subtropical high meridionally,
→change location of upwelling site.
→ warming of present-day sites.

Testing this: specify warm Pliocene SST in an atmospheric GCM (CAM)
SST: Modern, PRISM3, Brierly et al.

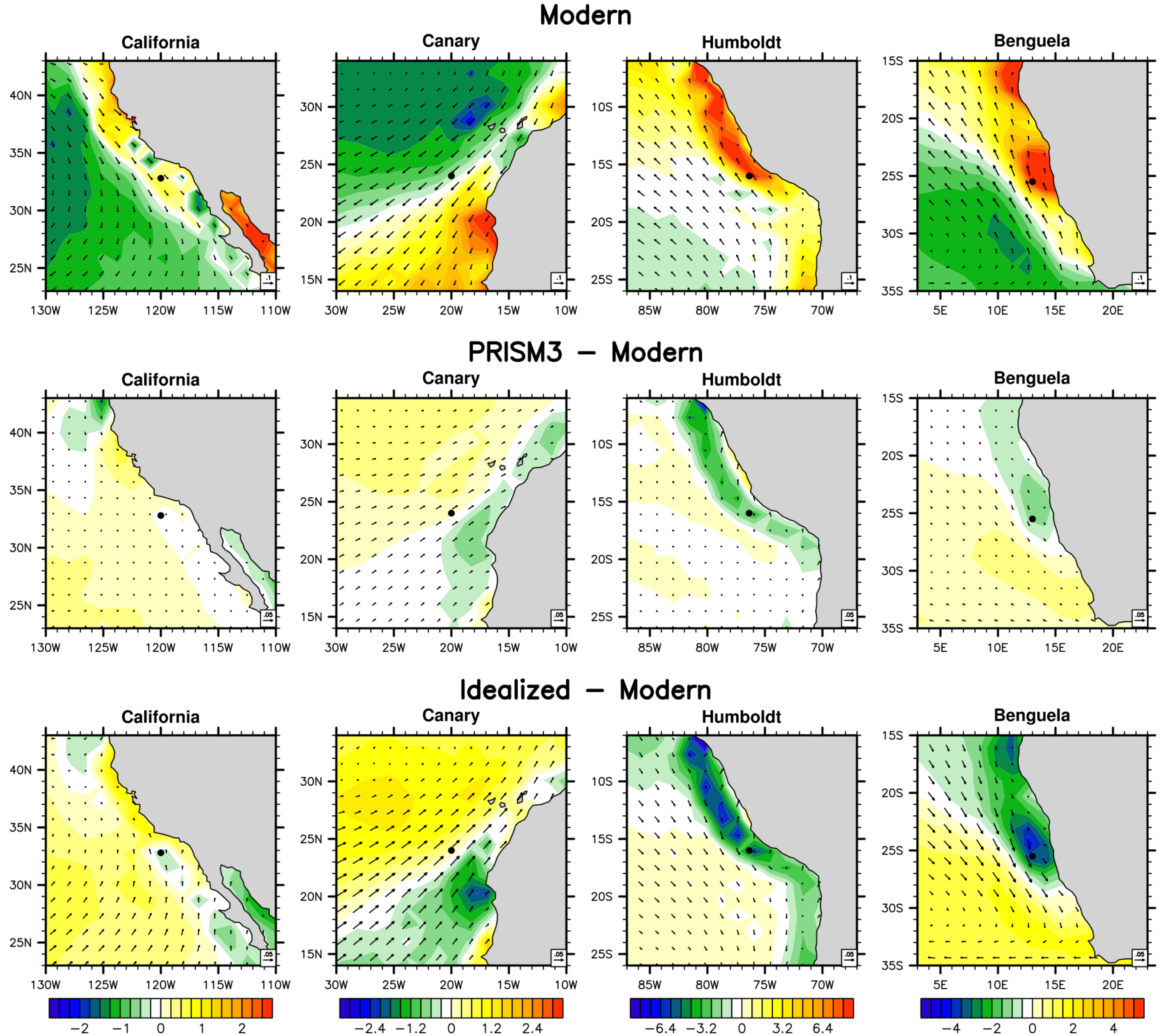


1 Warm climate➔stronger noise; 2 Rossby wave resonance; 3 upwelling sites

Warming of upwelling sites

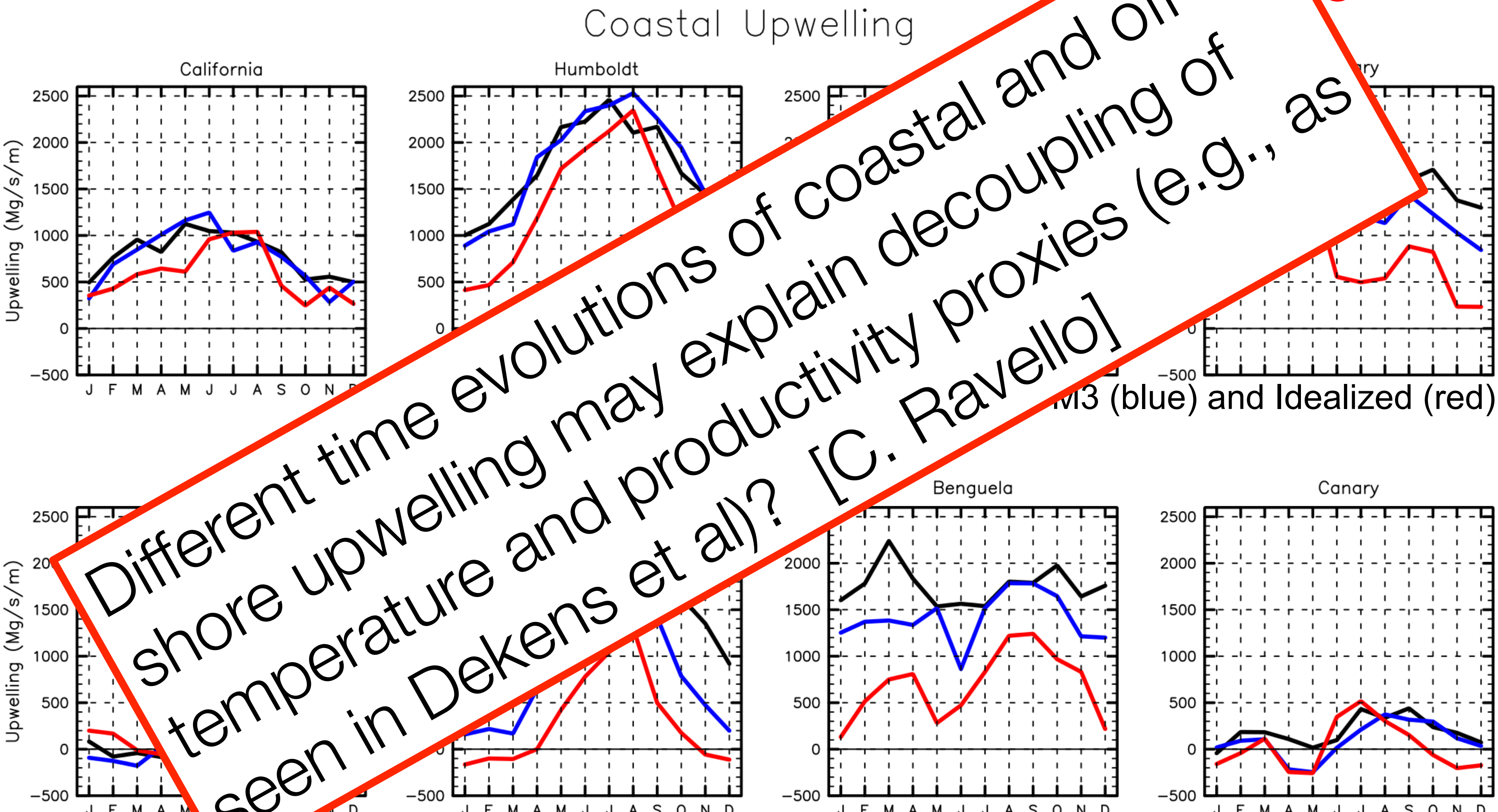
Specify warm Pliocene SST in an atmospheric GCM, using:
(1) Modern,
(2) PRISM3,
(3) Brierly et al.

➔ Along-shore wind and curl of wind at upwelling sites both change in response to Pliocene forcing



1 Warm climate➔stronger noise; 2 Rossby wave resonance; 3 upwelling sites

warming of upwelling sites: driven by wind changes? Also: coastal vs off-shore curl-driven upwelling



Different time evolutions of coastal and off-shore upwelling may explain decoupling of temperature and productivity proxies (e.g., as seen in Dekens et al)? [C. Ravello]

Wind changes lead to shift in upwelling-favorable coastal winds.
➔ upwelling sites simply moved & therefore the warming?

Conclusions: Pliocene permanent El Nino & superrotation

- We tried to make the case for superrotation as a mechanism for the vanishing equatorial Pacific SST gradient 3-5 Myr ago:
  - (1) SP-CESM: steepening of MSE profile ➔ enhanced convective variability at equator➔Rossby waves ➔ westerlies
  - (2) CAM+shallow water: Rossby wave resonance mechanism, tends to lead to abrupt transition (bifurcation) to superrotation
  - (3) Warming of mid-lat upwelling sites due to wind changes.
- Major challenge: getting superrotation effects to surface… CMT?
- Could this mechanism lead to a permanent El Nino in the future? [as suggested by Held 1999 & Pierrehumbert 2002]

Tziperman & Farrell 2009; Arnold, Tziperman & Farrell 2012; Arnold, Kuang, Tziperman, 2013; Arnold et al 2014;