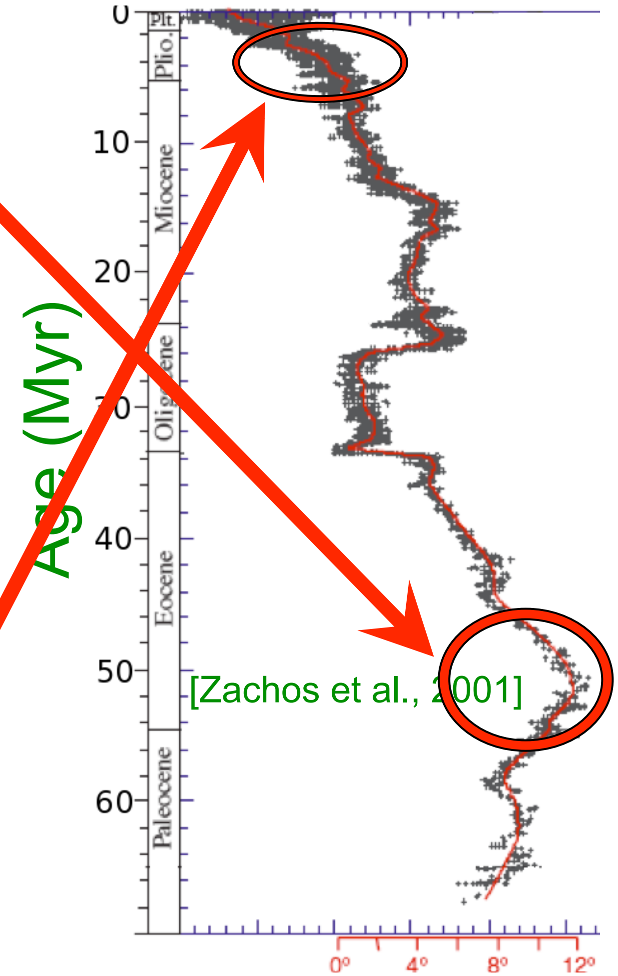
Two lessons from past warm climates

1. 34-146 Myr ago: warming of the high latitudes by a convective cloud feedback.

   Work of **Dorian Abbot;** recent updates using SPCAM: David Randall, Mark Branson.

1. 2-5 Myr ago: *Permanent El Nino: due to atmospheric superrotation?* With Brian Farrell; recent updates, including preliminary SPCAM result: **Nathan Arnold;**

Gradual cooling over past 55Myr



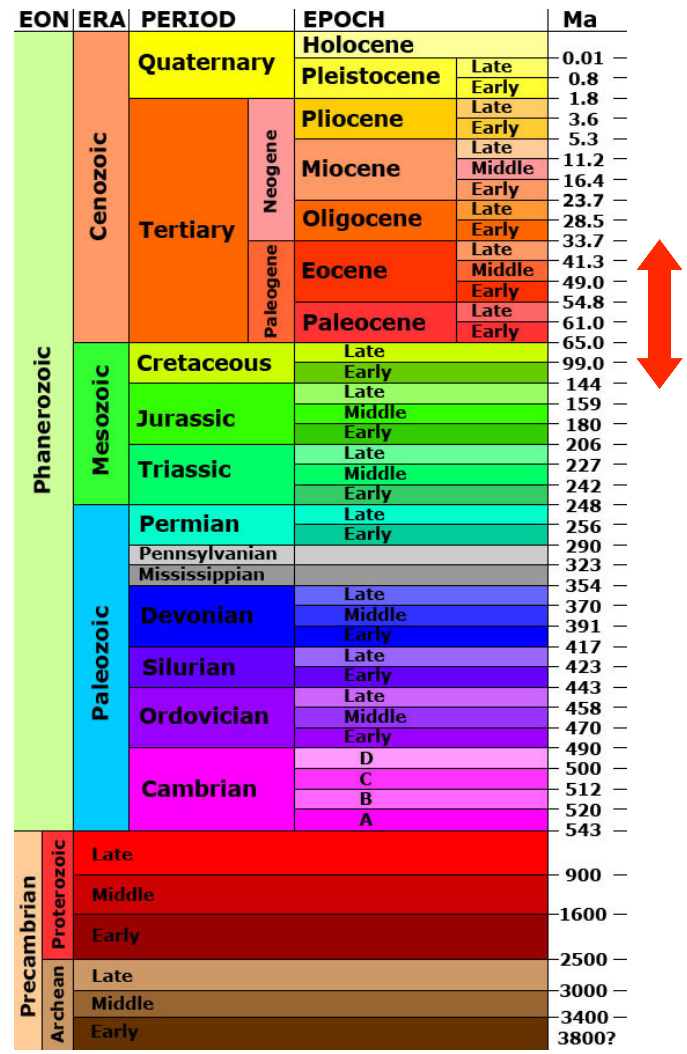
Deep ocean Temperature

A High Latitude Convective Cloud Feedback and Equable Climates

Dorian S. Abbot

Recent SPCAM updates: with David Randall, Mark Branson

Hadrosaurus – Cretaceous [Karen Carr]



[Abbot & Tziperman, 2008,9: QJRMS, GRL, JAS, J. Climate]

Outline: Eocene (50 Myr) warmth & a convective-cloud feedback

1) **Observations**: very warm climate 146-34 Myr ago; what's the mechanism..??

2) **Previous explanations…**

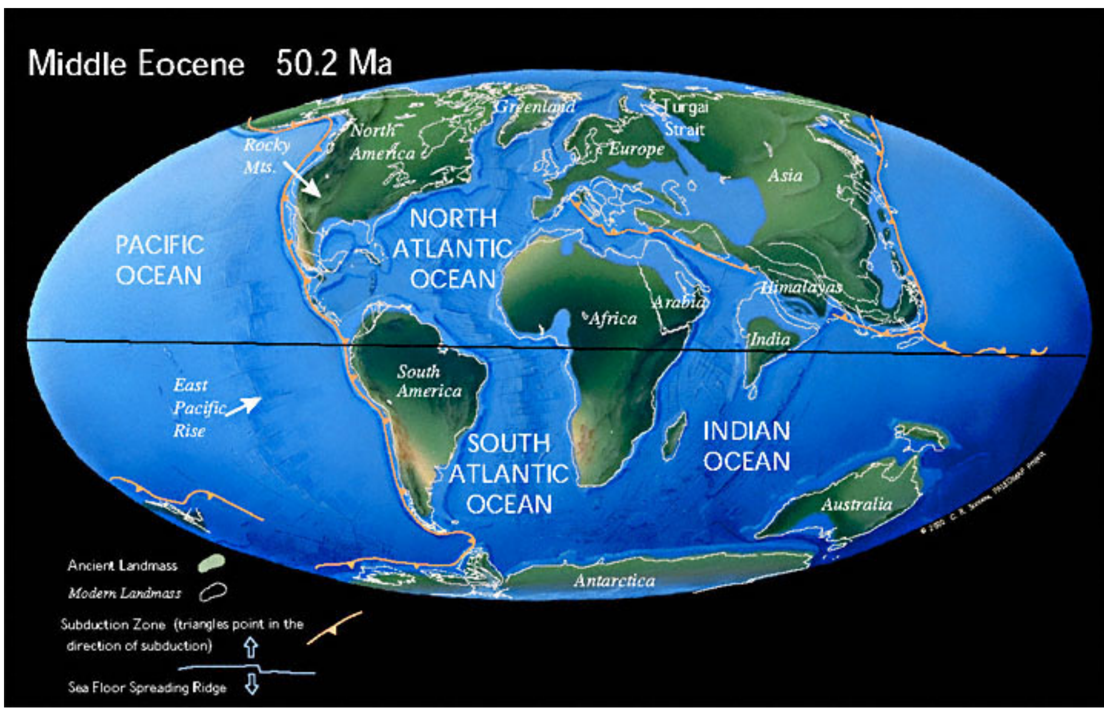
3) **Our mechanism**: a qualitatively different state of the atmosphere, with tropical-like deep atmospheric convection and high tropospheric clouds at mid- to high-latitudes providing a strong greenhouse effect.

4) **Why should you care**

Observations (1st/3): warm climate ~146-34 Ma

- High global mean temperature
- Low Equator-pole temperature difference: ~ 25°C (now ~45°C).
- above freezing winter temperatures @ 60N, interior of N. America (now -30°C);
- Weak high-lat seasonality
- No significant ice
- Tropical SSTs >≈ modern
- Warm deep ocean: 15°C
- CO_2=500-5,000 ppm(??)

“Equable” climate ≡ warm poles, mild winters

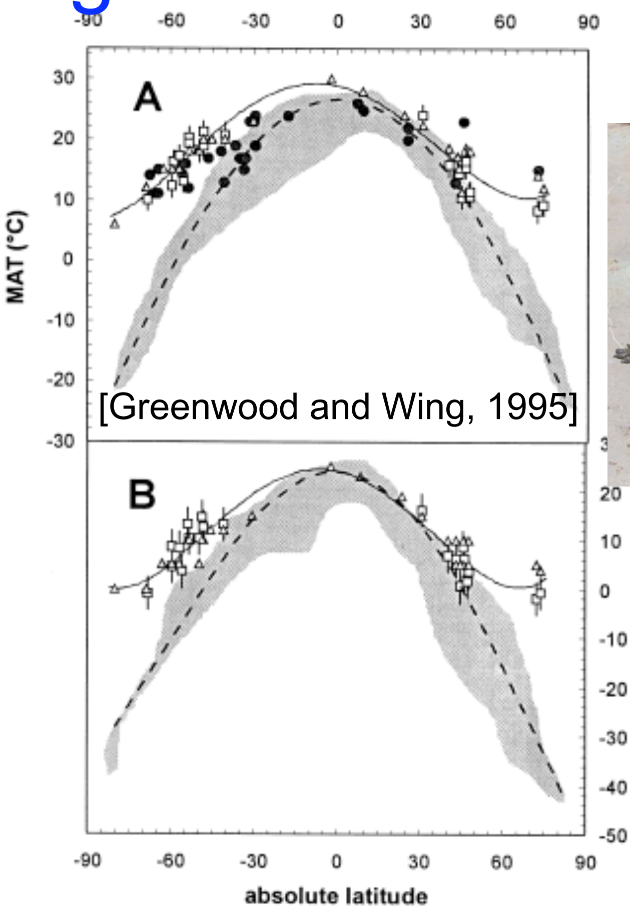


[146-34 Ma ago: Cretaceous - Paleocene - Eocene]

Eocene: modern-like continental configuration.

Observations (2nd/3): warm climate ~146-~34Ma

Cool tropics, warm high-latitudes

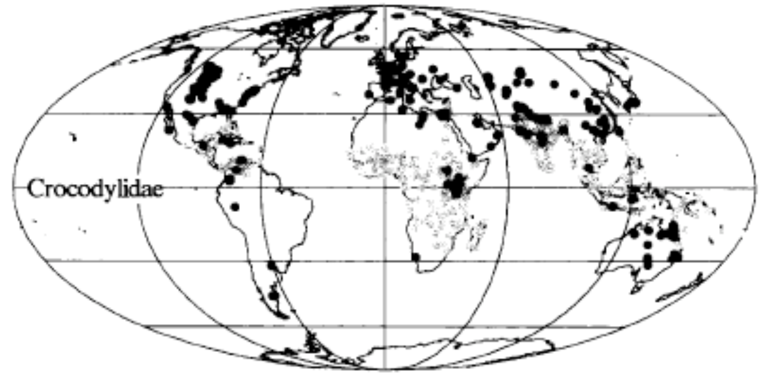


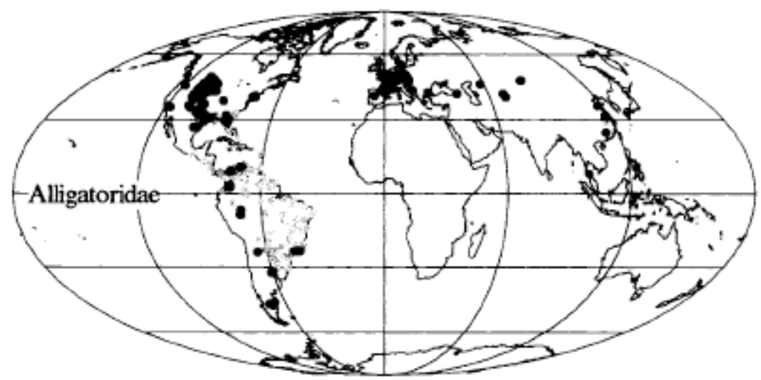
[Greenwood and Wing, 1995]

■ - Modern land temp.

● △ □ - Eocene SST; NLR&LMA, CLAMP

Crocodiles in Greenland, Palm trees in Wyoming!





Crocodiles need: Mean annual T>14.2°C & Cold month mean >5.5°C [Markwick, 1998]

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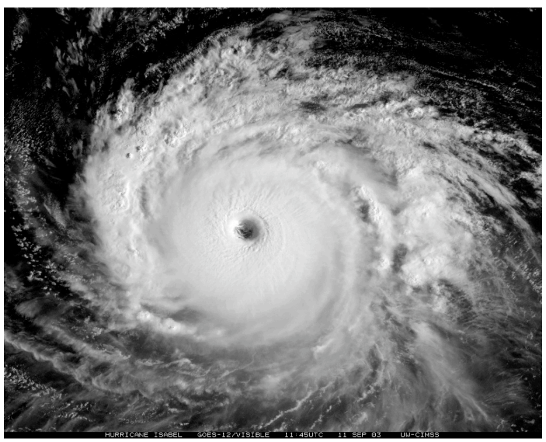
Previously proposed mechanisms

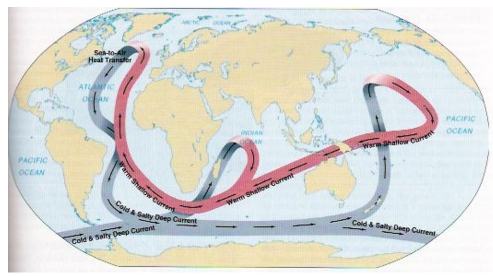
Ocean Atmosphere Stratos. clouds

Warm climate ➔ stronger Hurricanes ➔ stronger oceanic thermohaline circulation ➔ more heat transport to the pole ➔ warmer poles [Emanuel 2002]:

Stronger hurricanes

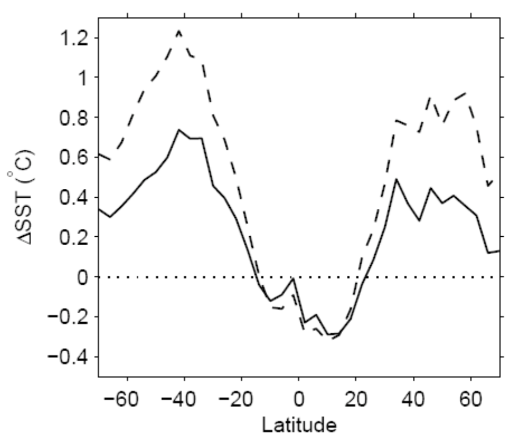


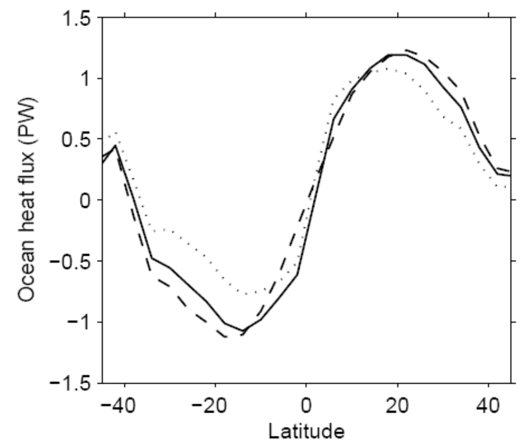
Thermohaline circulation



Warmer high latitudes

However, this feedback may cool the tropics better than warm the high latitudes [Korty & Emanuel 2007]

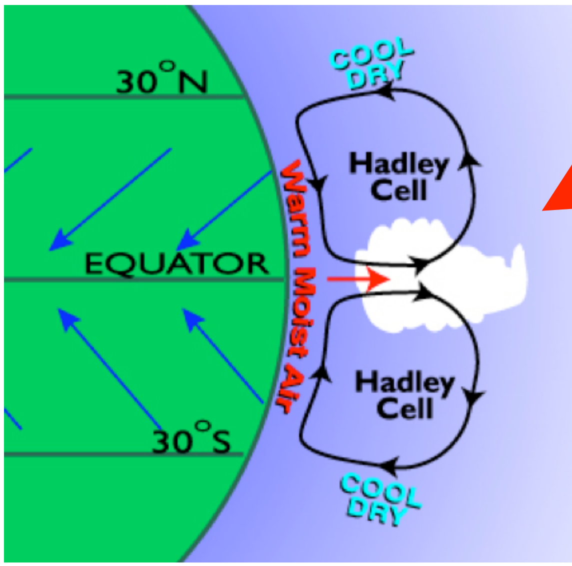




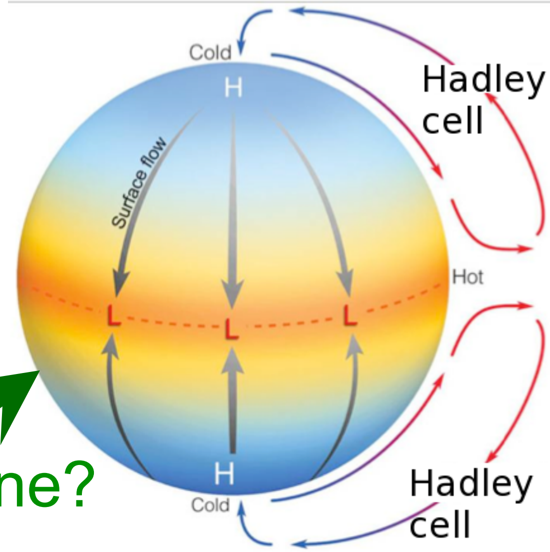
Previously proposed mechanisms

Ocean **Atmosphere** Stratos. clouds

Equator-to-pole Hadley cell: **B. Farrell, 1990**



Today



Eocene?

Giant Pterosaur: strong Easterly zone could help them fly… ☺?

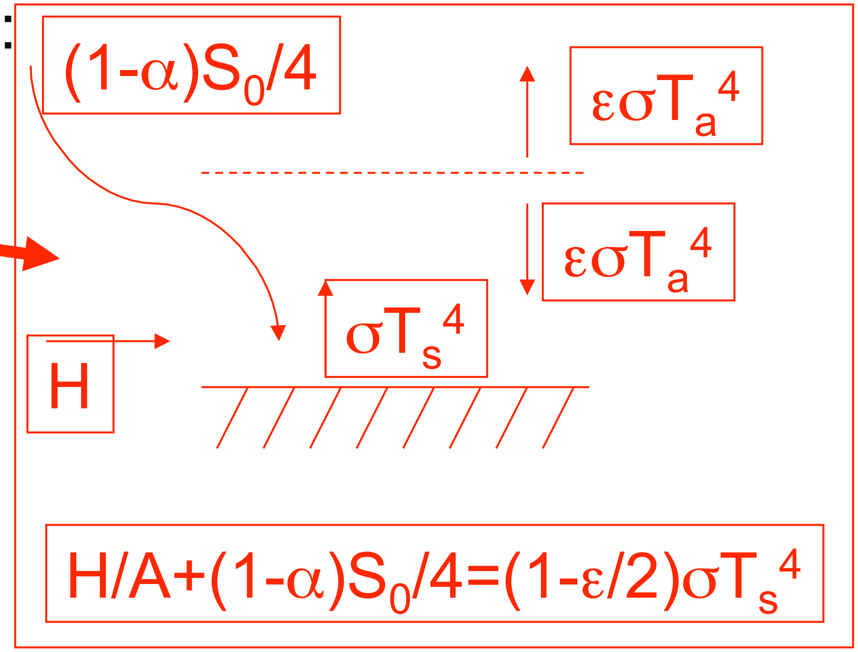
Like Venus: large Hadley cell due to slow rotation; Poles warm as Equator

But: requires X8 angular momentum dissipation; Based on now challenged theory of [Schneider 77; Held Hou 80]

Back of the envelope…

It is very difficult to reduce the equator-to-pole temperature gradient by increasing CO2 or meridional heat fluxes; far easier using long-wave emissivity (***clouds!***):

Energy-balance model



Modern climate:

T [°C]	H [PW]	ε [ ]	α [ ]
-8.0	3.5	0.60	0.55

Increasing high latitude temperature:

ΔT [°C]	ΔH [PW]	Δε [ ]	$[CO_2]_{dry}$ [ppm]	$[CO_2]_{wet}$ [ppm]	Δα [ ]
10.0	1.1	0.20	$x2^5 \approx 9x10^3$	$x2^{2.5} \approx 2x10^3$	-0.15
15.0	1.7	0.28	$x2^{7.5} \approx 5x10^4$	$x2^{3.75} \approx 4x10^3$	-0.23

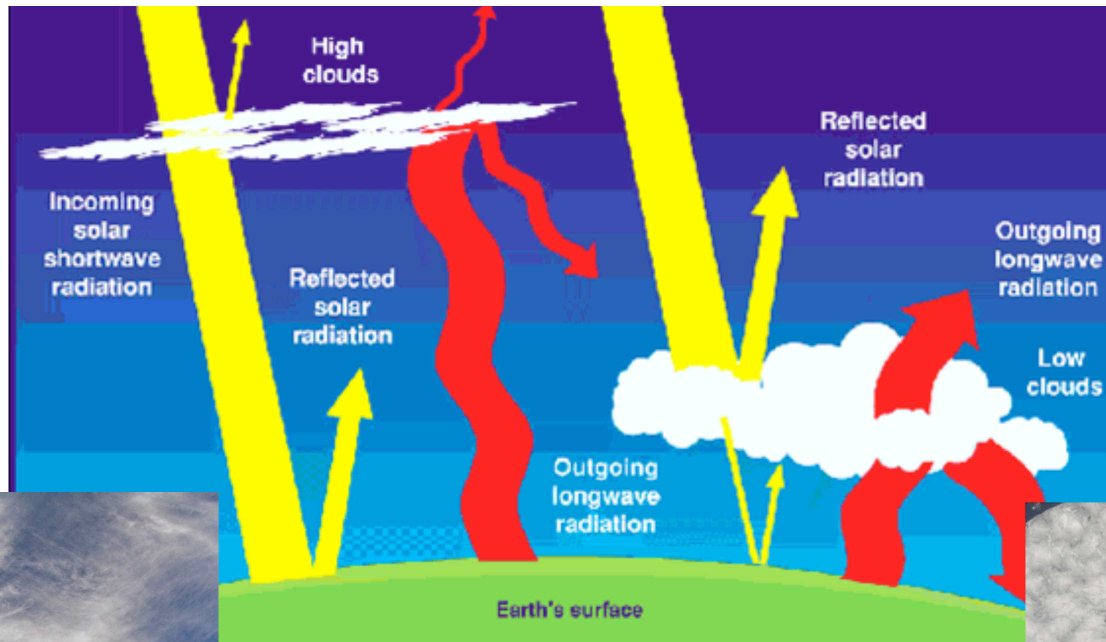
A reminder: Cloud feedbacks

High clouds (cirrus)

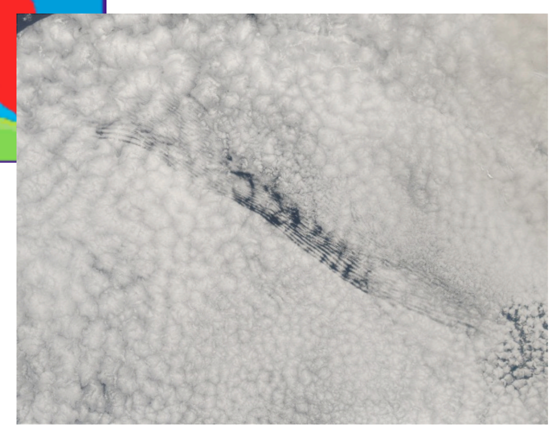
- low albedo, high emissivity
- High altitude (>8 km)
- Warming effect on climate

Low clouds (marine stratus)

- High albedo
- Low altitude (<1km)
- Cooling effect on climate



➔ high clouds may help explain equable climate



[End of] Previously proposed mechanisms

Ocean Atmosphere **Stratos. clouds**

Polar Stratospheric Clouds (PSCs), at 15-25km, have a strong greenhouse effect! Formed via methane-moistening of stratos.

•Eocene PSCs due to methane [Sloan'92];

BUT: methane source not clear

•PSCs due cooling & *weakening* of Brewer-Dobson stratospheric circulation [Kirk-Davidoff et al 2002] : BUT stratospheric circulation may ***increase*** in warm climate [Korty & Emanuel 2007]

[PSCs at dusk over the Arctic region of Sweden]

http://www.nasa.gov/images/content/65932main_sageii_psc_640x480.jpg

An interim summary…

- High CO_2, water vapor, increased poleward heat flux by ocean/ /atmosphere cannot explain equable climates (Eocene, 50Myr)

- Perhaps clouds? Polar *Stratospheric* clouds not so simple…

Outline: Eocene (50 Myr) warmth & a convective-cloud feedback

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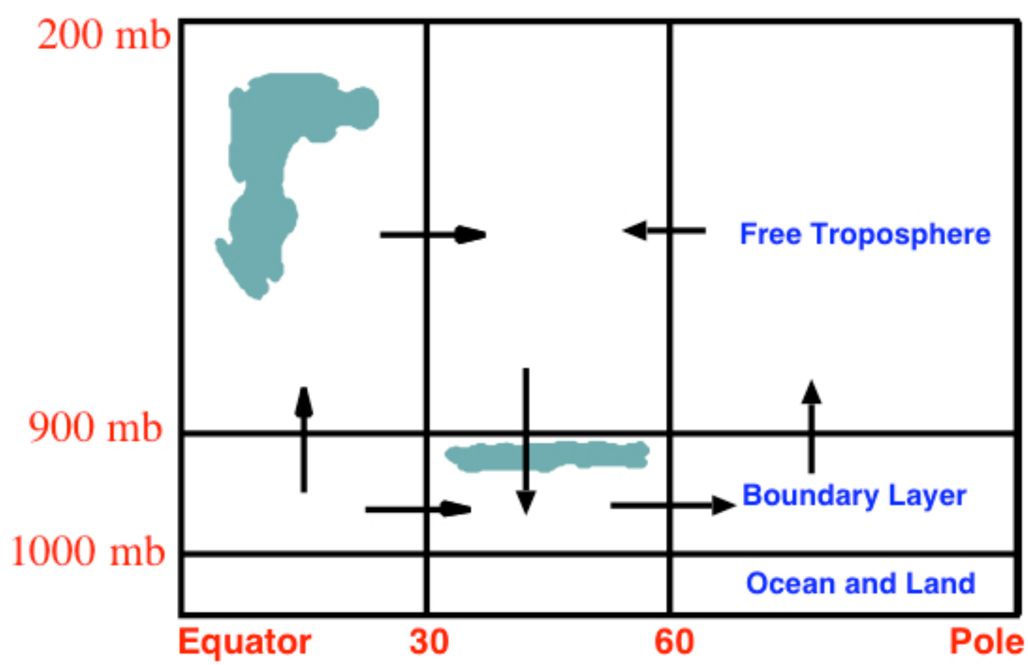
4) **Why should you care**

First step: a "toy" model (1st / 2)

- Zonally averaged
- Equator to pole
- Two levels: Boundary Layer + Free Troposphere
- Mixed layer ocean
- Non-linear momentum eqns
- Merid resolution: 3 columns



- Prognostic dry static energy & water vapor
- Simple land surface
- Advection
- Diffusive eddies
- Convection + Precipitation
- Clouds: convective and large-scale
- Radiation: SW, LW, CO_2, water vapor, clouds…
- Surface fluxes

The toy model (2nd / 2): equations

Dry Static Energy and Moisture Equations

$$\frac{\partial DSE}{\partial t} = \frac{\omega}{\Delta P} DSE + \frac{v}{\Delta y} DSE + D(\theta)\frac{\partial DSE}{\partial \theta} + L_v \frac{q - \tilde{q}}{\tau} + k_{con}(DSE_1 - DSE_2)$$
$$-\delta_{k2}\varepsilon_{re} L_v \frac{q_1 - \tilde{q}}{\tau} + \varepsilon A(F_{in} - 2\sigma T^4) + \delta_{k2}\rho_2 C_{SH}(T_S - \theta_2)$$

$$\frac{\partial q}{\partial t} = \frac{\omega}{\Delta P} q + \frac{v}{\Delta y} q + D(\theta)\frac{\partial q}{\partial \theta} - \frac{q - \tilde{q}}{\tau} + k_{con}(q_1 - q_2)$$
$$+\delta_{k2}\varepsilon_{re}\frac{q_1 - \tilde{q}}{\tau} + \delta_{k2}\rho_2 C_{LH}(q^*(T_S) - q_2)$$

Equations of Motion: angular momentum conservation included

$$u_t + \frac{1}{a\cos(\theta)}\frac{\partial}{\partial \theta}(uv\cos(\theta)) - uv\tan(\theta)/a + \frac{\partial}{\partial p}(\omega u) - 2\Omega\sin(\theta)v = \nu\frac{\partial^2 u}{\partial \theta^2} - \delta_{k2} r u$$

$$v_t + 2\Omega\sin(\theta)u = -\frac{1}{a}\frac{\partial \phi}{\partial \theta} + \nu\frac{\partial^2 v}{\partial \theta^2} - \delta_{k2} r v$$

$$\phi_p = -\alpha$$

$$\frac{1}{a\cos(\theta)}\frac{\partial}{\partial \theta}(v\cos(\theta)) + \omega_p = 0$$

$$p\alpha = R^* T$$

Model experiments & results: summary

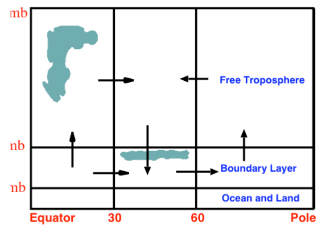
Model experiments:

Slowly increase CO_2 to extreme values & then decrease it

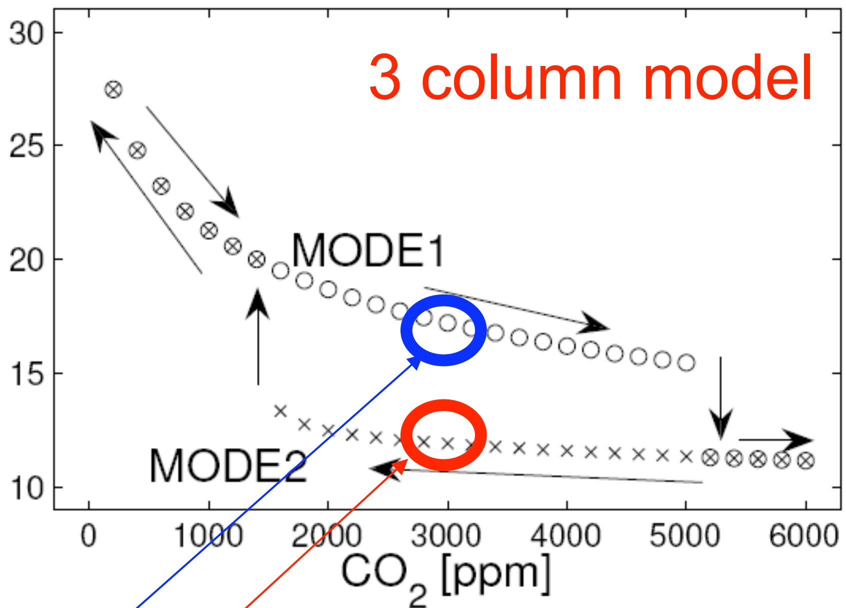
Results:

A ***qualitatively*** different climate regime at sufficiently high CO_2, warm high latitudes and low equator-to pole temperature difference.

Results: 2 modes of atmospheric dynamics; [& multiple equilibria at a given CO_2, hysteresis]



Equator to pole temperature difference (EPTD, °K).



"Present-day" solution: high EPTD, colder; non convecting

"Equable" solution: low EPTD, warm; convecting, high clouds

Arrows: path of solution if CO_2 slowly increased then decreased.

A summary of the proposed mechanism for equable-climate via high latitude convection*

warmer surface
➔ unstable air column
➔ deep convection
➔ high clouds
➔ greenhouse effect
warmer surface

This positive feedback supports 2 states:

(1) Equable (high lat deep convection, high clouds & warm)

(2) present-day-like: deep convection only at equator

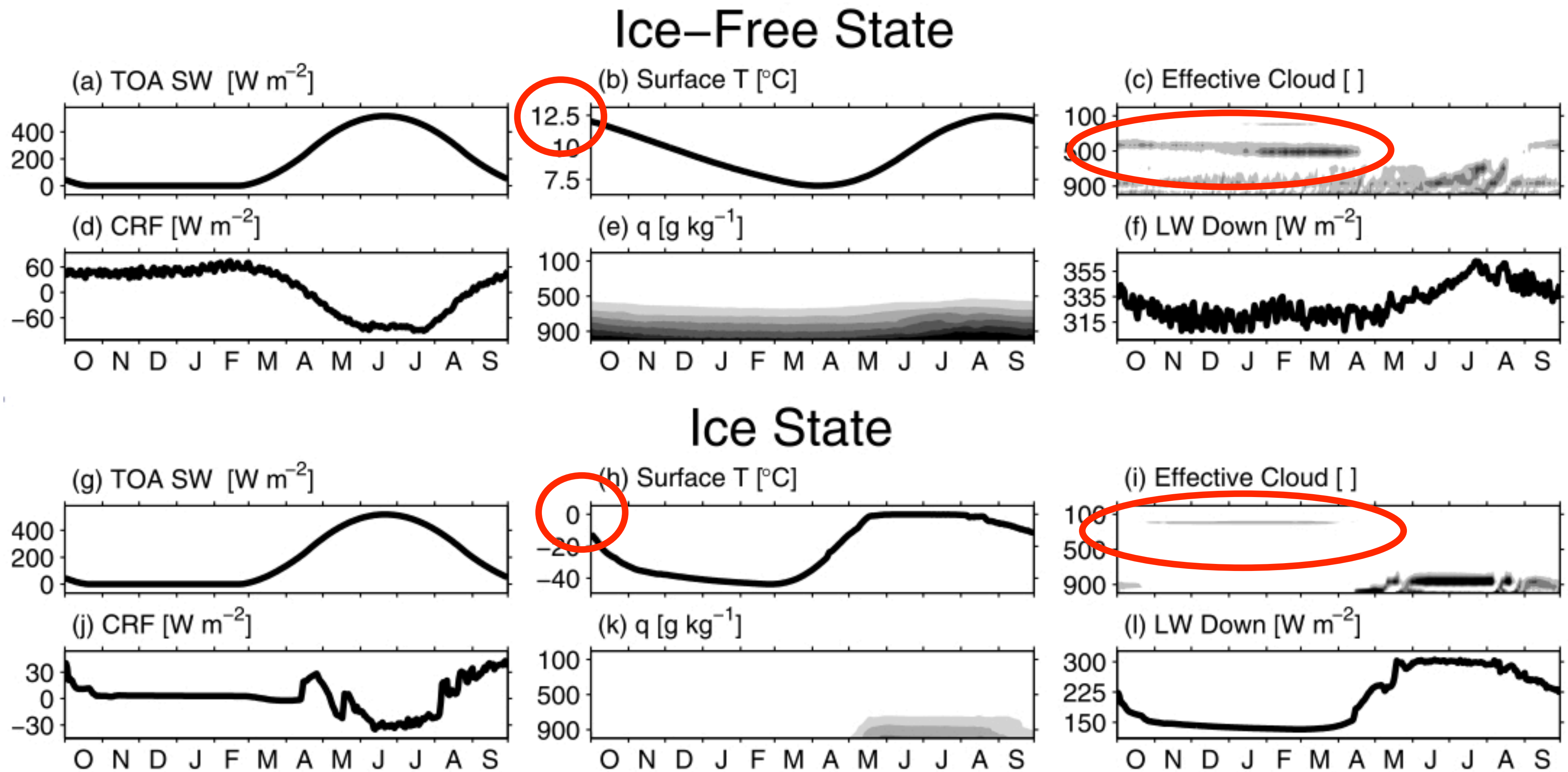
➔ Positive feedback!

Low CO_2: only present-like state; **High CO_2**: equable only

Intermediate CO_2 : both (may be sensitive to model details...)

*(a related suggestion was made by Huber et al 1999)

SCAM supports TOY MODEL'S mechanism for high-latitude warmth during equable climates



SCAM, CO2=1000ppms, different I.C. ➔ 2 different *seasonal* states, with & w/o sea ice. Also: multiple equilibria, hysteresis

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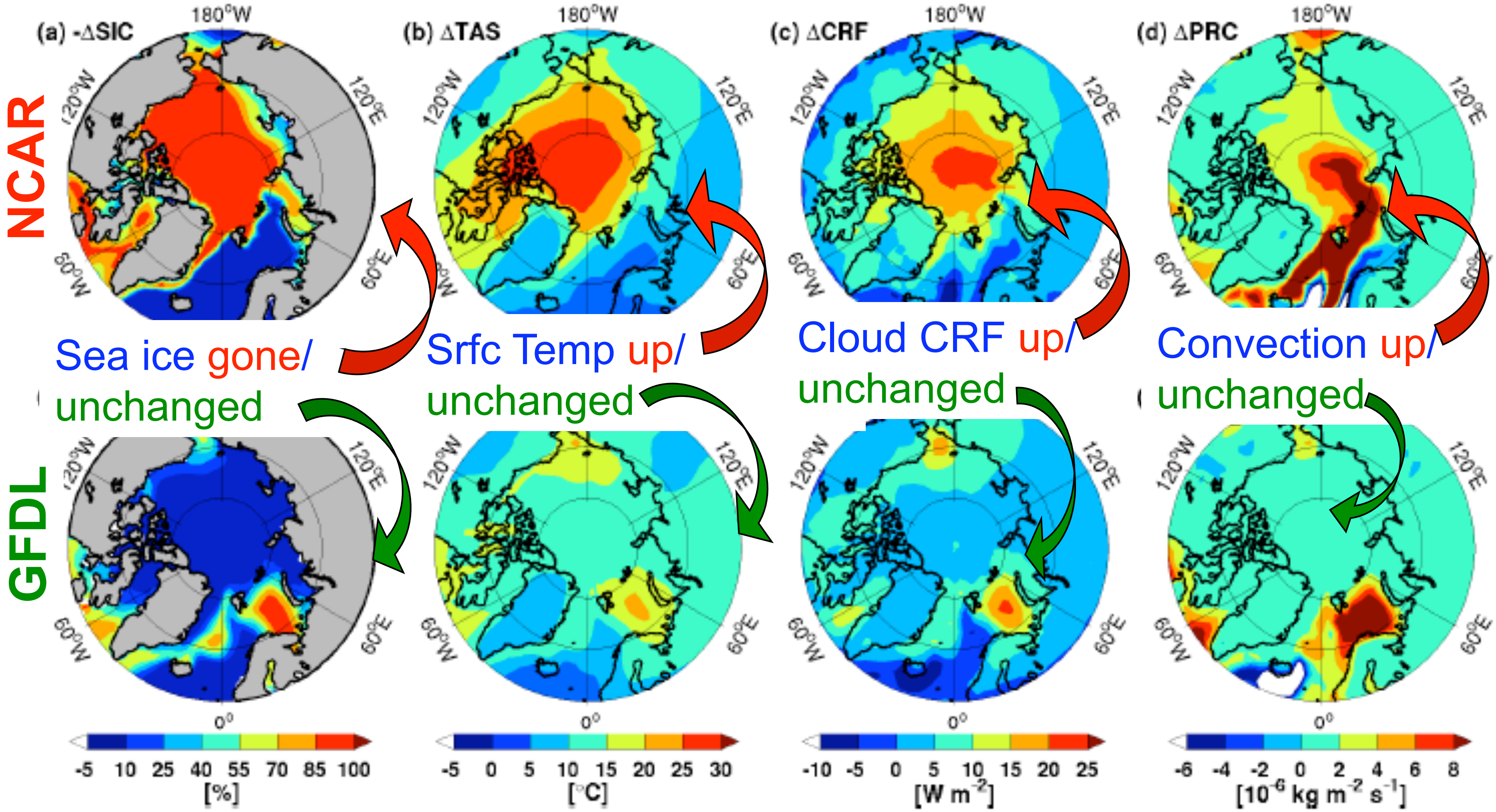
Enticing 3D IPCC Model Simulations

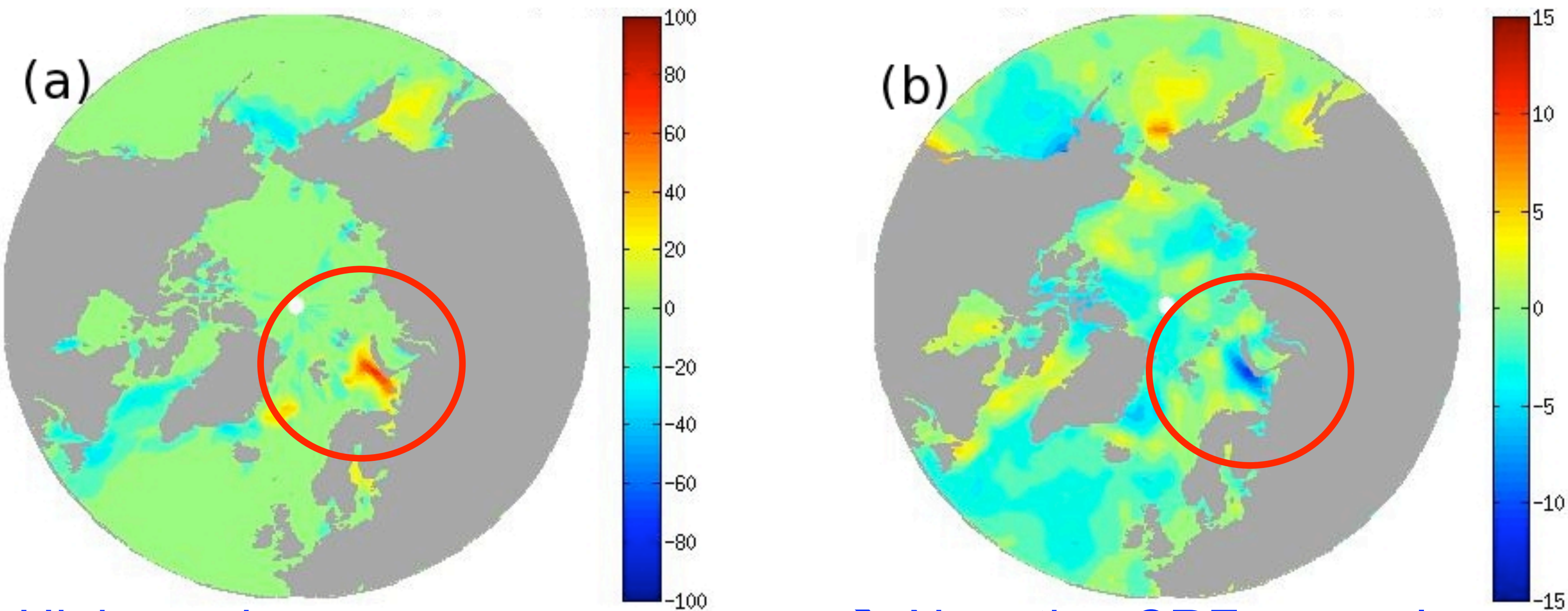
Consider the solutions of **NCAR** & **GFDL** 3d coupled ocean-atm state-of-the-art models, at x4 CO_2; anomaly from pre-industrial:



➔ IPCC NCAR 3d model behaves like toy model & 1d SCAM!!

Additional evidence using reanalysis products
with Kerry Emanuel, Ben Leibowicz

- Consider times with a high/ low sea ice cover and examine cloud radiative forcing then.
- ➔ Results indicate a clear correlation, so feedback seems active in today's atmosphere



High sea ice cover anomaly during winter

➔ Negative CRF anomaly during same years

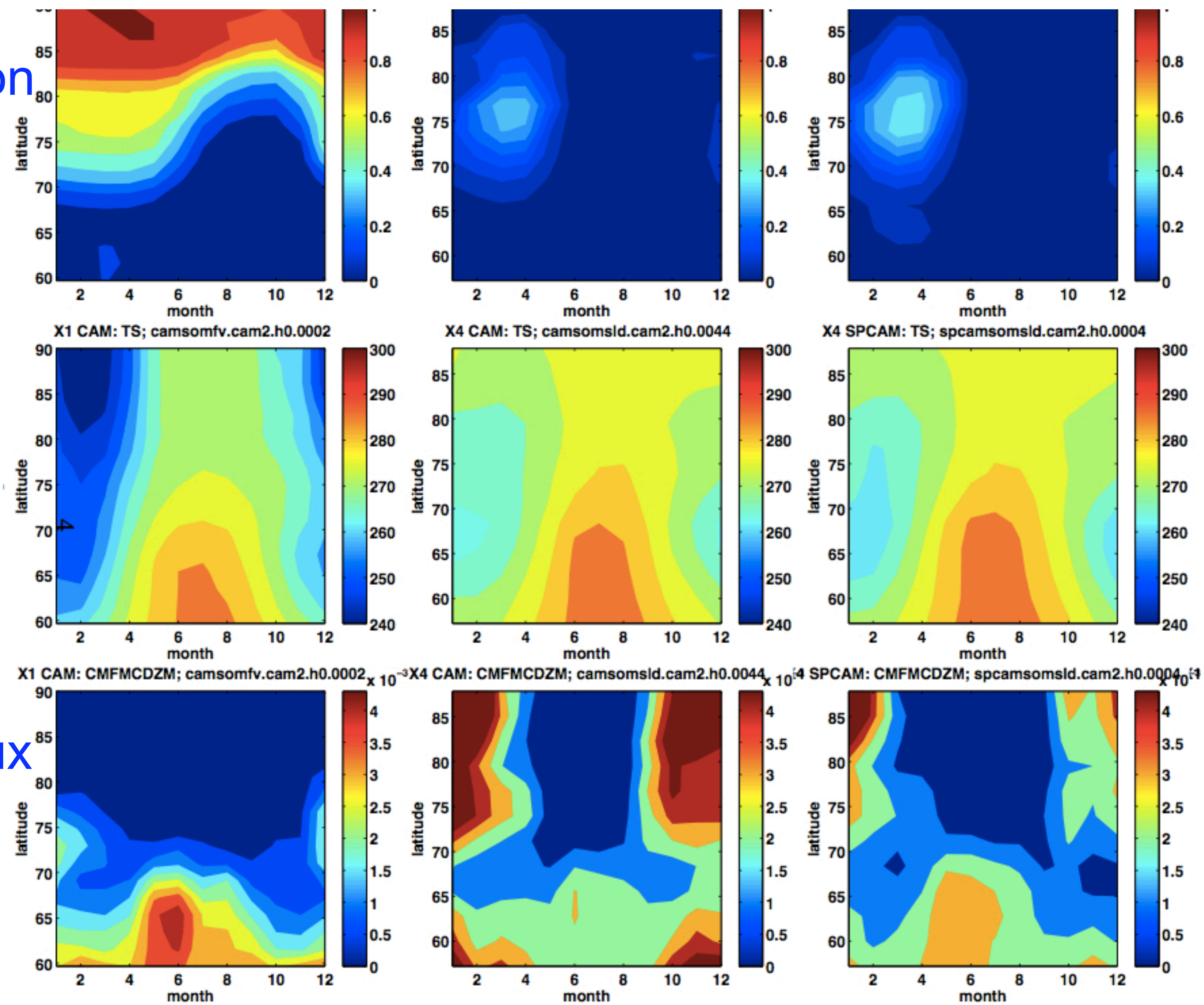
Preliminary SPCAM results: latitude (60N-90N) vs month

X1CO2,CAM; X4CO2,CAM; X4CO2, SPCAM

Sea ice fraction

TS

Conv Mass flux



with David Randall, Mark Branson

Preliminary SPCAM results: latitude (60N-90N) vs month

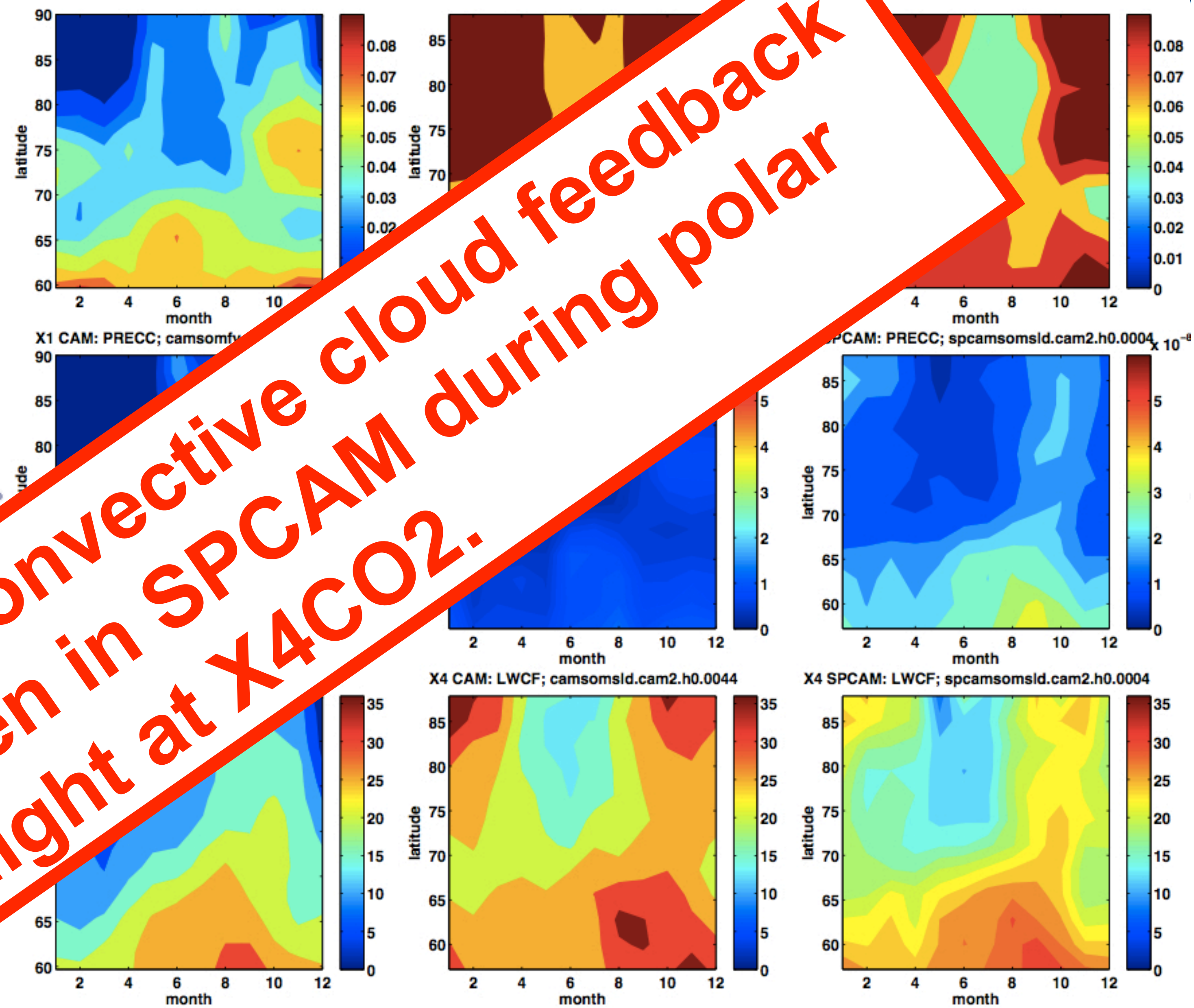
X1CO2,CAM; X4CO2,CAM; CO2, SPCAM

Conv clouds

Conv precip

LW CRF

→ Convective cloud feedback seen in SPCAM during polar night at X4CO2.



with David Randall, Mark Branson

Conclusions: Eocene (50 Myr) warmth & convective-cloud feedback

Challenge: CO2 insufficient to explaining Eocene warmth

Good news: Found a simple, interesting & unexpected climate state at high CO2: high-latitude deep atmc convection & high tropospheric clouds result in an equable-like climate

- Solution is self-consistent, clouds and convection reinforce each other and don't need to be specified arbitrarily, confirmed in full complexity state-of-the-art atmospheric and climate models.

- Future? Arctic uncertainty may mean *more* warming… 14 IPCC models: feedback strength uncorrelated w/ climate sensitivity!

[Abbot & Tziperman, 2008,9: QJRMS, GRL, JAS, J. Climate]

Pliocene (1.8-5.3 Myr) "*permanent El Nino*" & atmospheric superrotation

with: **Nathan Arnold, Brian Farrell**

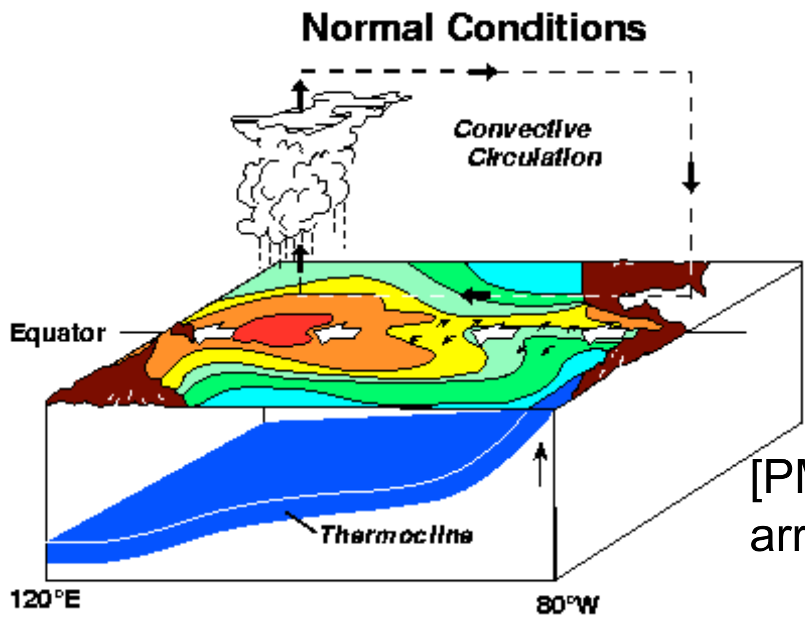
LESSON 2

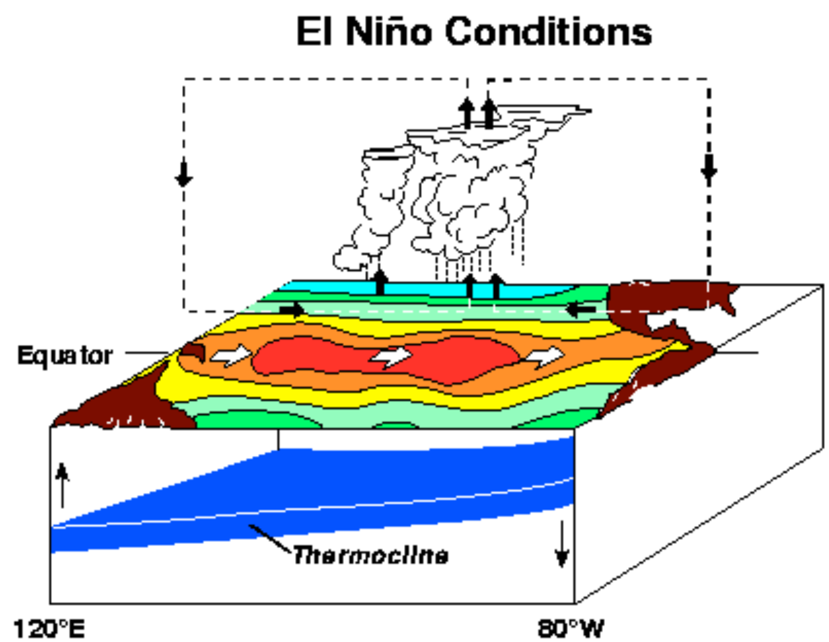
Outline

- Pliocene, "permanent El Nino"
- Some previous attempts
- Superrotation! turning off those easterlies
  - Rossby wave resonance mechanism
  - Increased convective activity with SST in SPCAM

[Tziperman & Farrell 2009; Arnold, Tziperman & Farrell 2011]

Reminder: El Nino, the equatorial Pacific easterlies & thermocline





[PMEL TAO array page]

Normal conditions: easterly winds push warm water to west, East Pacific cools bec. of shallow thermocline there.

El Nino: easterlies weaken, East Pacific thermocline deepens, EP surface ocean warms

➔ Two possible ways of `making' a permanent El Nino: (1) weaken easterlies or (2) deepen thermocline.

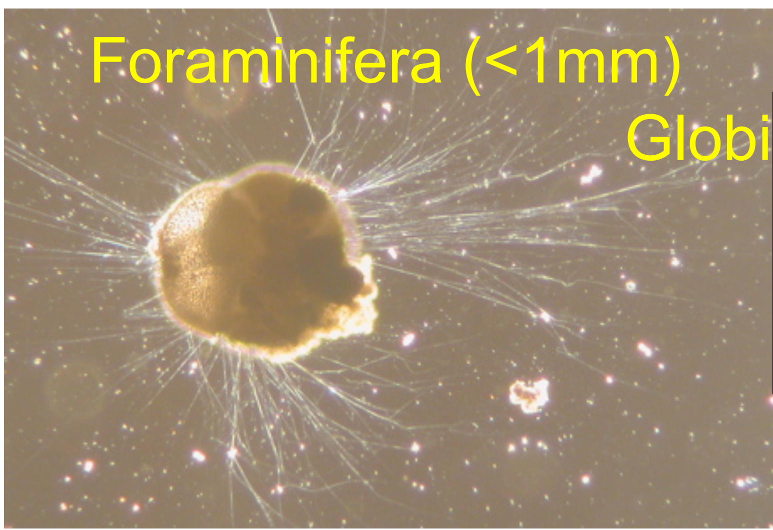
The Pliocene

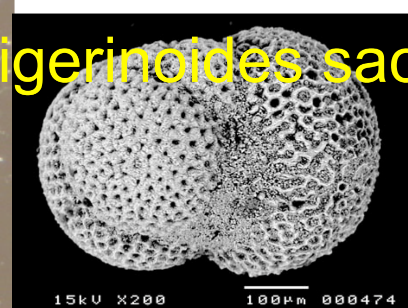
Some general mid-Pleistocene climate characteristics:

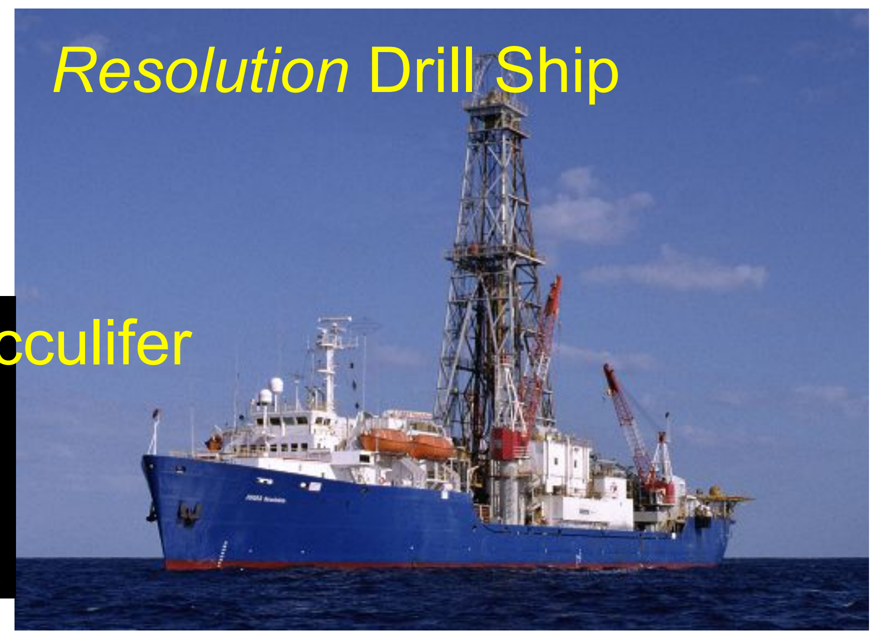
- Atmospheric CO_2 concentration: **???** Possibly 350-500ppm?? (Today: 380; preindustrial: 280; in 50 years: …)
- Global average surface temperature: ≈3° warmer than today??
- Ice: covers Antarctica, but not much in northern hemisphere (ice ages started ≈2.7 Myrs ago)

How do we know:

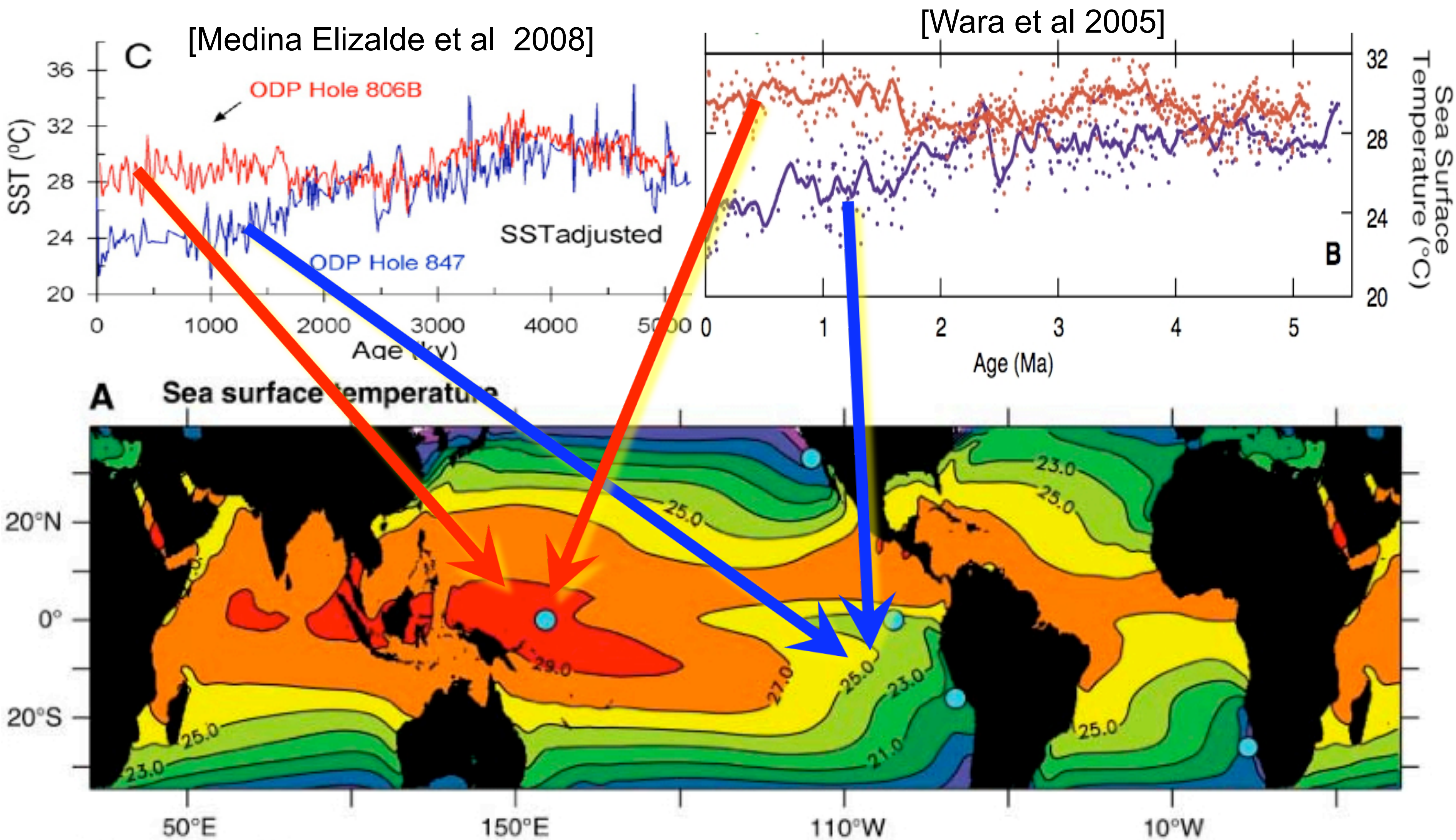
- Isotopic/ other proxy records from deep sea drilling.







The equatorial Pacific during the Pliocene



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

Previous explanations of the Pliocene "*permanent El Nino*"

- Deeper thermocline, possibly globally? Evidence: strong warming in upwelling sites off Africa, California, South America
- Mechanism [Fedorov et al]: a collapse of the thermocline by a very strong fresh water forcing [in the north Pacific?]

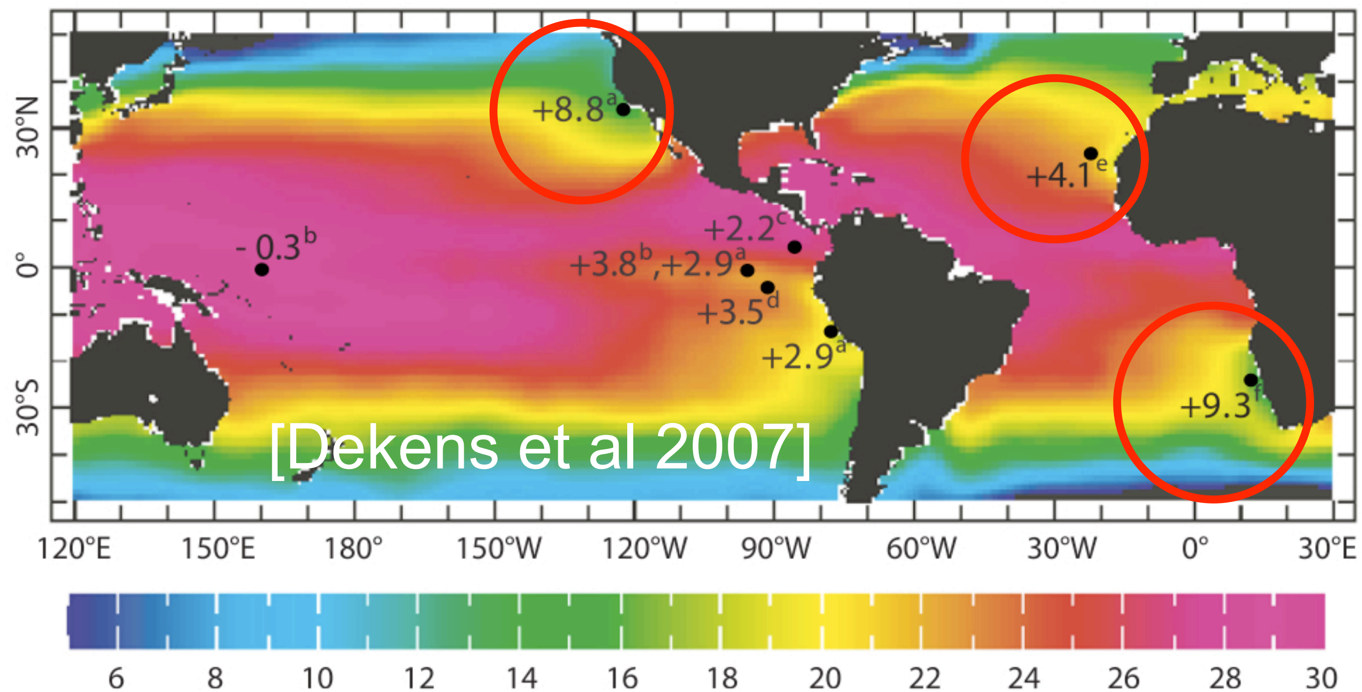
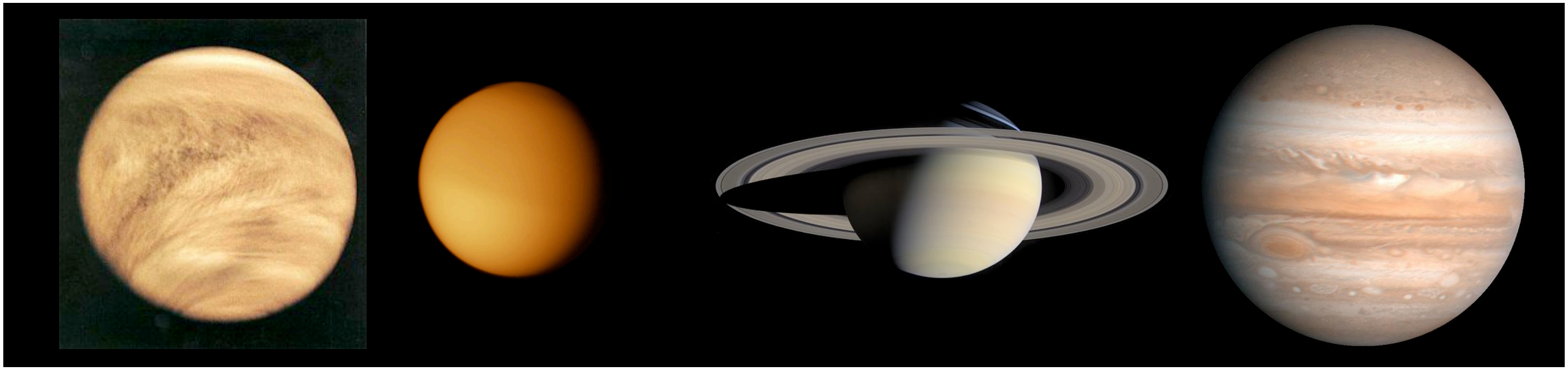


Figure 1. Difference in sea surface temperature (SST) between Pliocene and modern SST. The colored map shows modern mean annual SST [*Levitus and Boyer*, 1994]. Superimposed is the difference between

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.

Superrotation dynamics: Rossby Wave reminder…

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

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

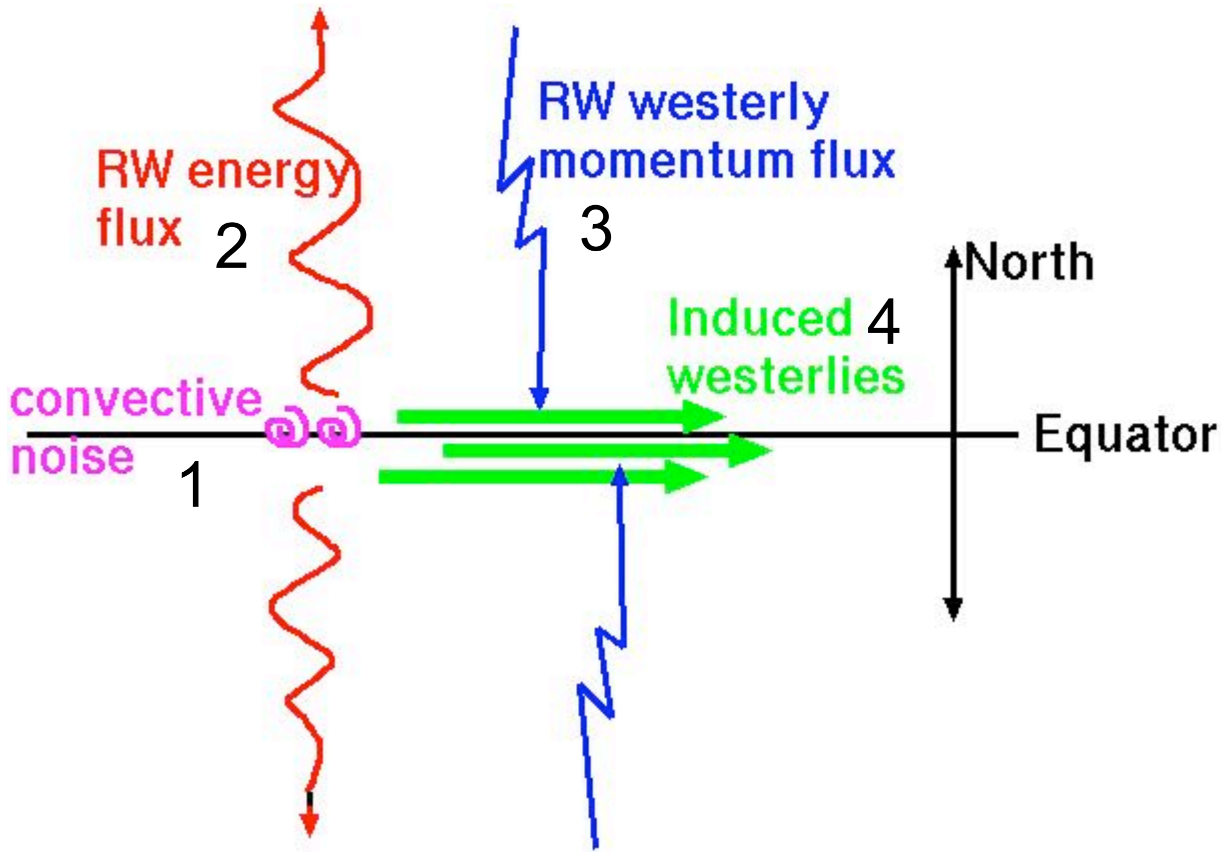
Meridional group velocity $c_g^{(y)} = \dfrac{2\beta kl}{(k^2 + l^2 + L_R^{-2})^2}$

Meridional momentum flux

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

➔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.

Superrotation dynamics: Rossby Wave reminder…



A partial superrotation literature review

- 2-level PE models search for multiple equilibria due to eddy fluxes from mid-latitudes: [Suarez and Duffy, 1992; Saravanan, 1993].
- and later also 3d GCMs: [Williams , 2006, 2003]
- Theoretical considerations of wave propagation [Panetta et al., 1987]
- Superrotation multi-equilibria due to a feedback of mean circulation not involving momentum wave flux [Shell & Held , 2004]
- 18 level AGCM: Steady longitudinal variations in diabatic heating ➔ horiz eddy momentum fluxes stationary planetary waves ➔ superrotation [Kraucunas & Hartmann 05]
- Moving flame effect (Lindzen's book, Venus)
- Possible superrotation & the collapse of the walker circulation in a future global warming scenario [Held, 1999; Pierrehumbert 2002]

- Pierrehumbert [2002] writes:

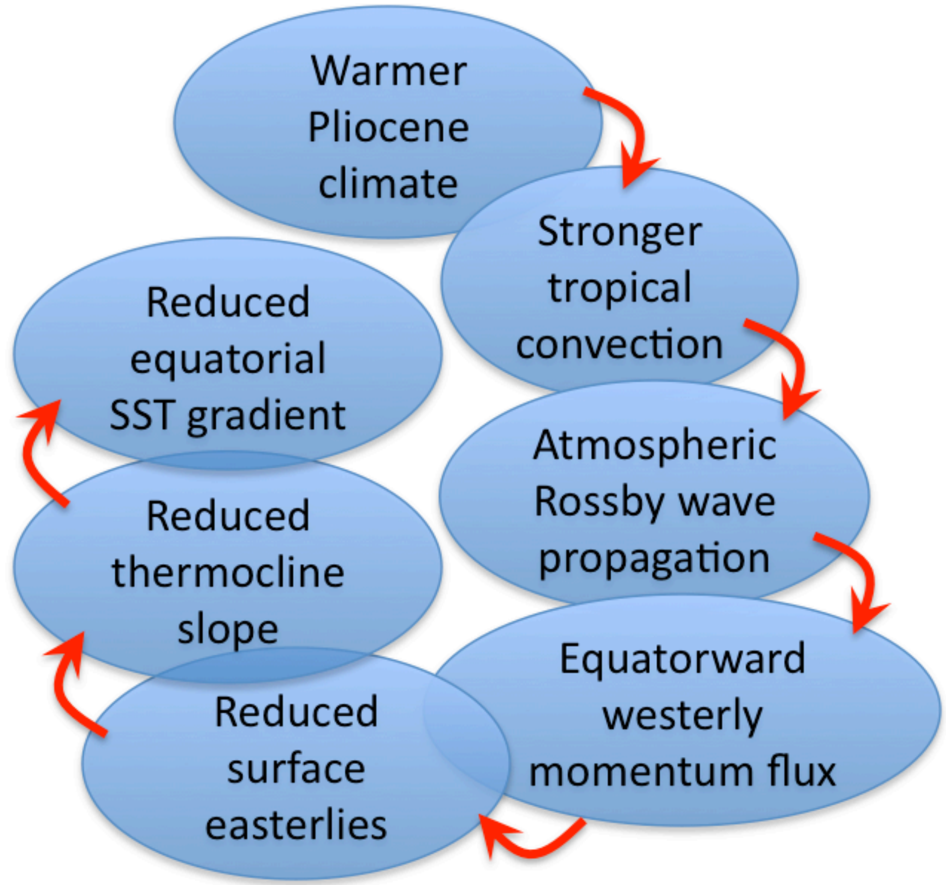
  "*There is no evidence that a westerly superrotating state has ever occurred in any climate of the Earth's past…*"

  And this is where it gets interesting…

Superrotation during Pliocene?

Summary of proposed scenario:

1. Warmer Pliocene ➔ stronger/ rearranged (MJO-like?) tropical convection activity = stochastic forcing at equator.



2. Rossby wave energy flux away from equator ➔ equatorward westerly momentum flux ➔ weaken equatorial easterlies.

3. Weaker easterlies ➔ decreased E-W thermocline slope ➔ eliminate East Pacific cold tongue & E-W SST gradient ➔ further weakened the Walker circulation, strengthened East Pacific convective activity

Exploring 2 critical elements of superrotation mechanism

1) From convective noise to Rossby wave propagation via a wave-mean flow resonance mechanism
2) Warm climate ➔ more/stronger/rearranged convective activity

A resonant Rossby wave response to equatorial heating:

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

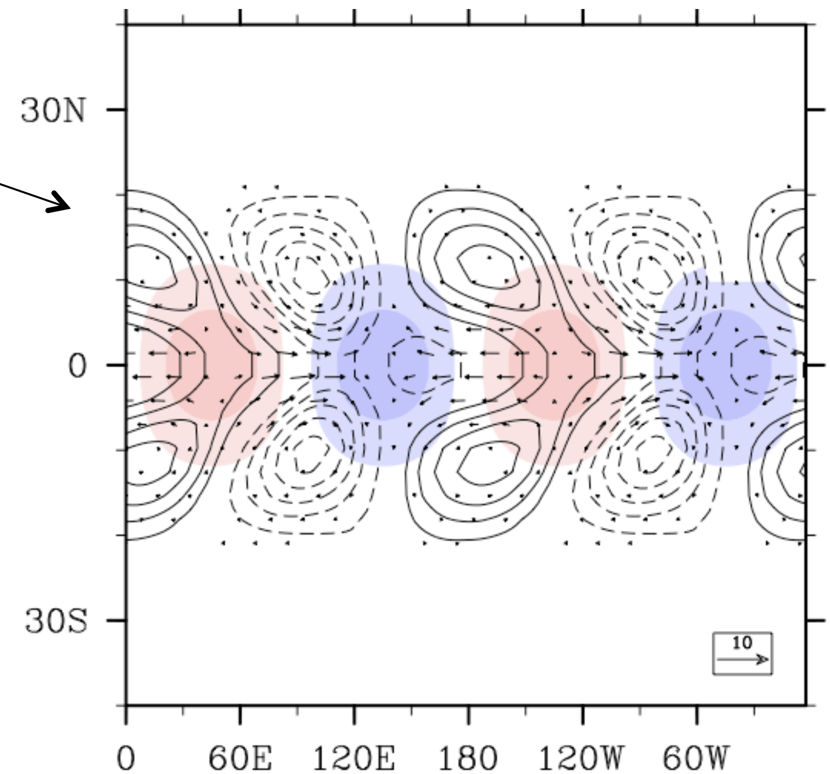
➔ positive feedback: westerly background wind strengthens ➔ approaches phase speed of free Rossby wave ➔ waves amplify ➔ stronger equatorward momentum flux ➔ enhanced westerlies

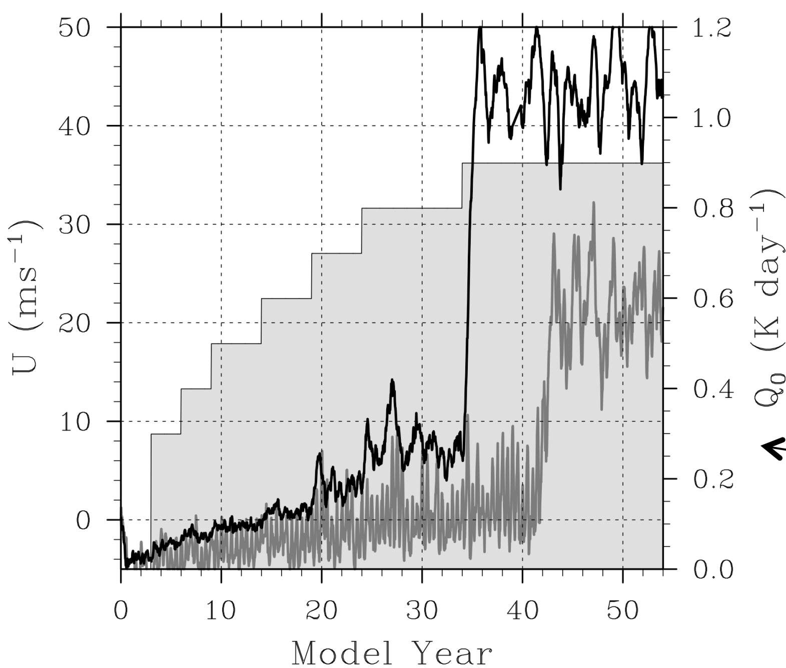
A resonance is implied: maximum wave amplification & westerly acceleration occur when westerly speed = Rossby wave speed.

Exploring 2 critical elements of superrotation mechanism

1) From convective noise to Rossby wave propagation via a wave-mean flow resonance mechanism
2) Warm climate ➔ more/stronger/rearranged convective activity

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

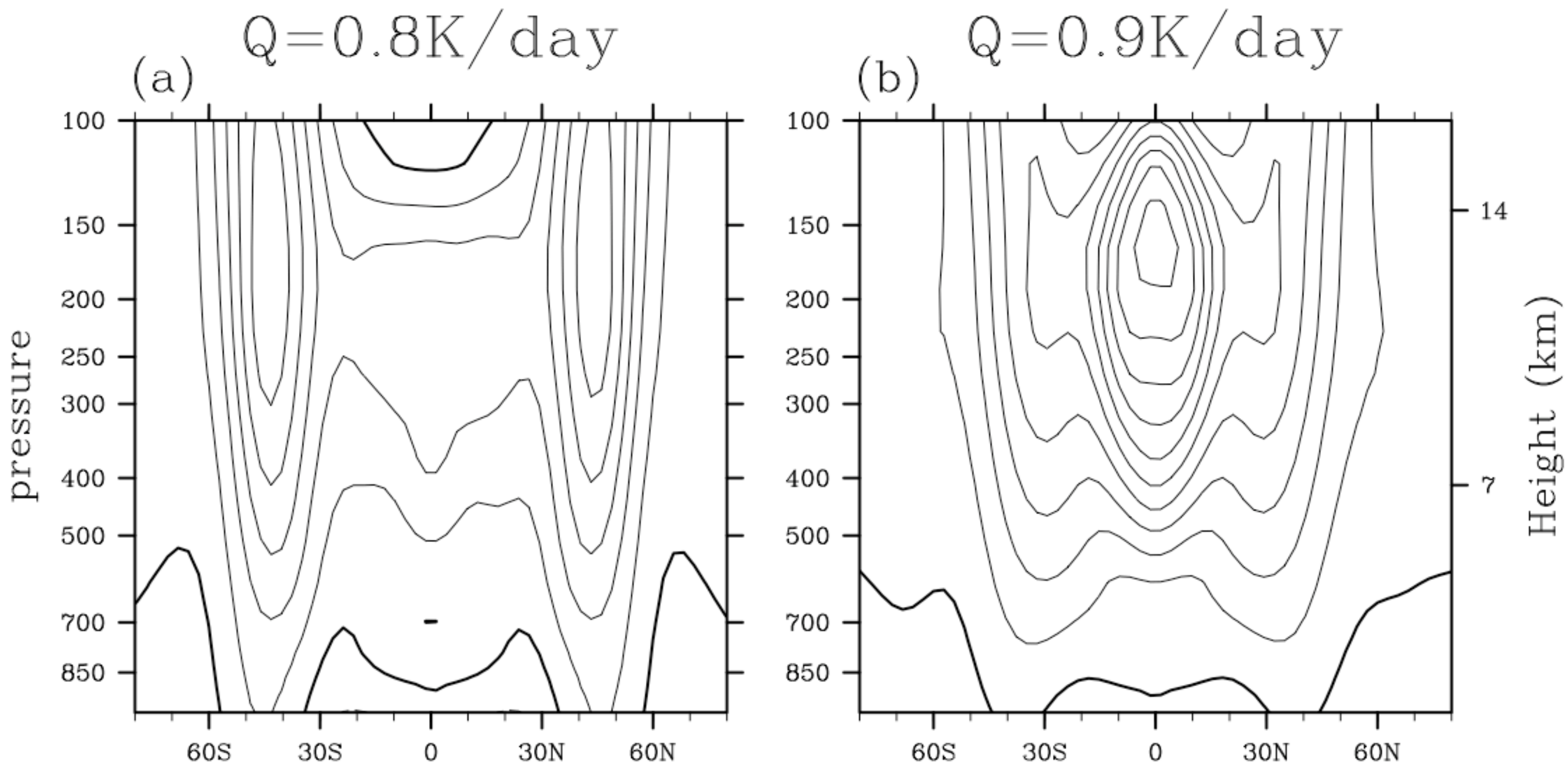




Results: abrupt transition to superrotation

Exploring 2 critical elements of superrotation mechanism

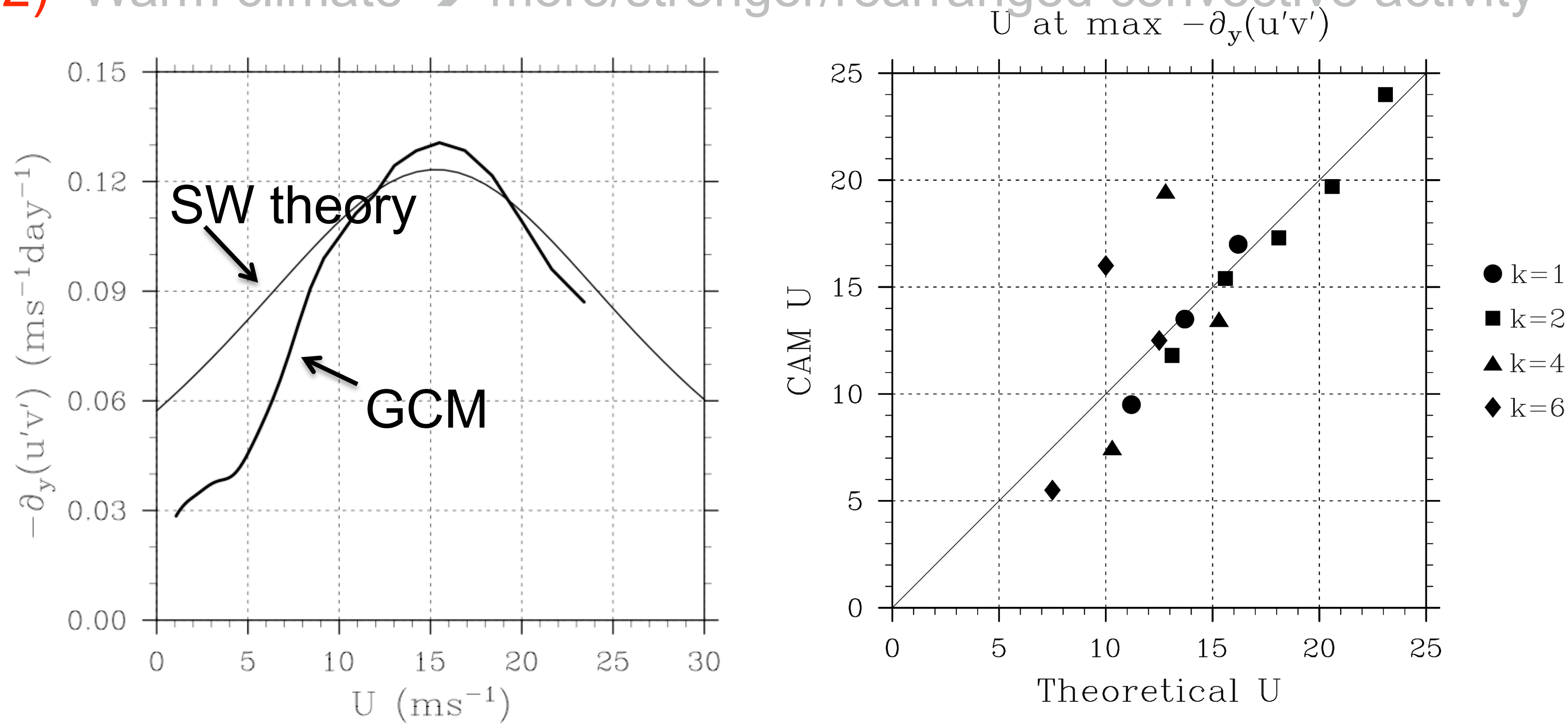
1) From convective noise to Rossby wave propagation via a wave-mean flow resonance mechanism
2) Warm climate ➔ more/stronger/rearranged convective activity



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

Exploring 2 critical elements of superrotation mechanism

1) From convective noise to Rossby wave propagation via a wave-mean flow resonance mechanism
2) Warm climate ➔ more/stronger/rearranged convective activity



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

Exploring 2 critical elements of superrotation mechanism

1) From convective noise to Rossby wave propagation via a wave-mean flow resonance mechanism
2) Warm climate ➔ more/stronger/rearranged convective activity

Some previous evidence:

Observations: [Slingo et al. 1999]: increased MJO activity since 1970s? due to decadal tropical SSTs warming?

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

[very] preliminary SPCAM results:

Compare aquaplanet with imposed zonally-averaged SST, with a uniformly increased SST run.

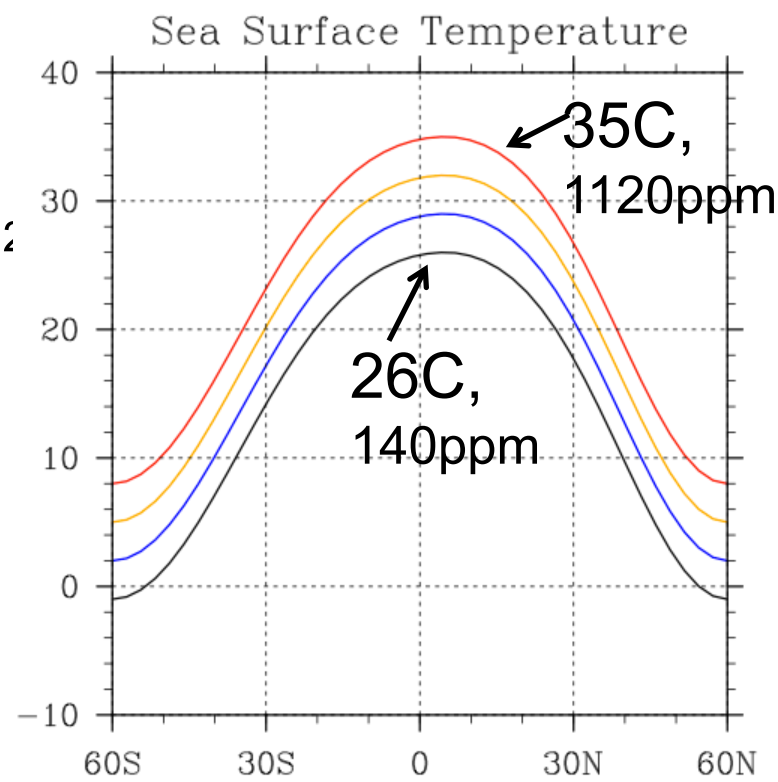
Exploring 2 critical elements of superrotation mechanism

1) From convective noise to Rossby wave propagation via a wave-mean flow resonance mechanism
2) Warm climate ➔ more/stronger/rearranged convective activity

Effect of high SST in aquaplanet SPCAM3.5

Experimental Setup:

- Prescribed zonally symmetric SST, constant in time.
- Uniformly increased by 3C with CO_2 doublings
- SST peak offset to 5N,
  - creates "ITCZ"
  - cross-equator flow opposes superrotation
- No sea ice



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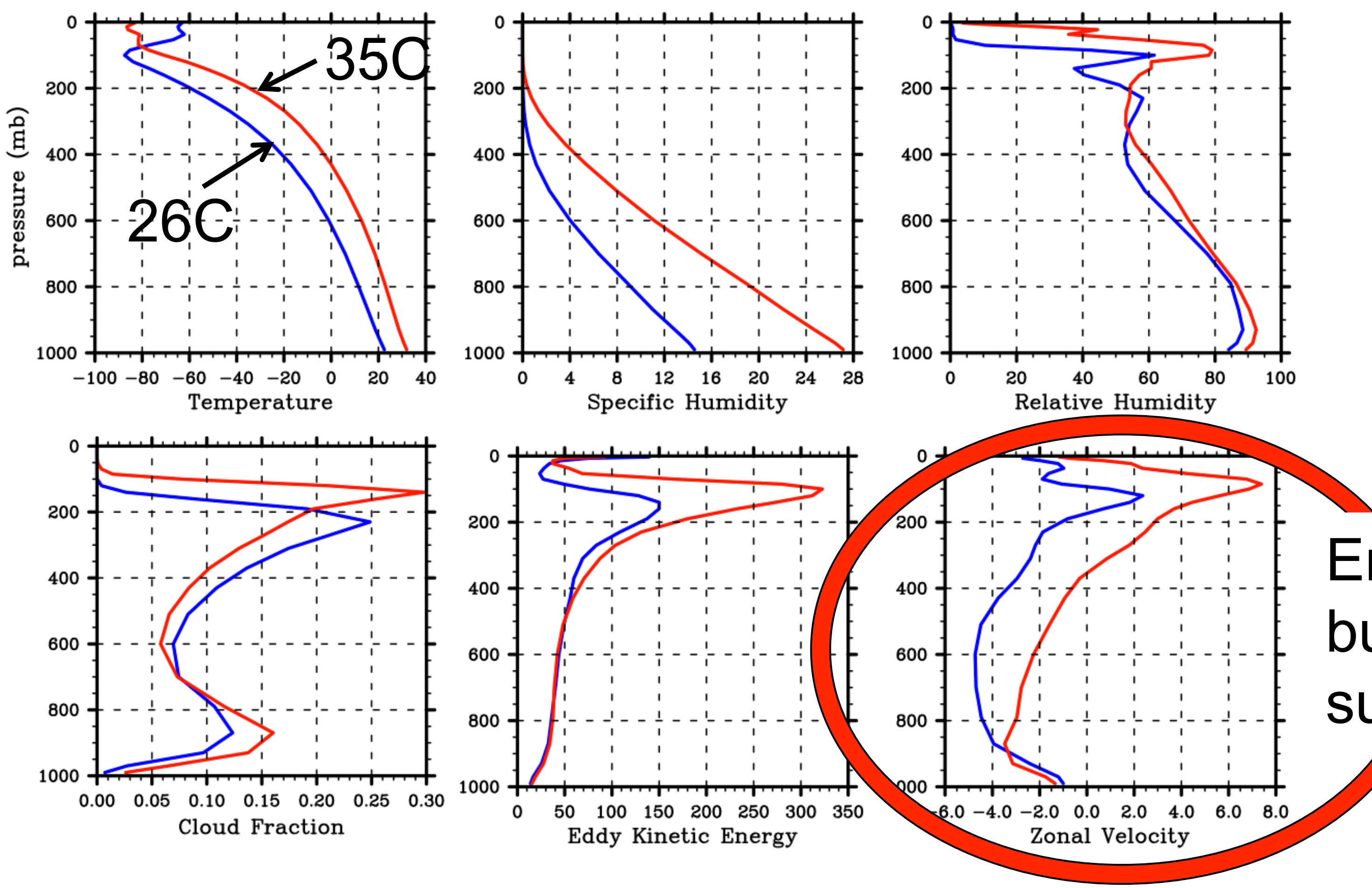


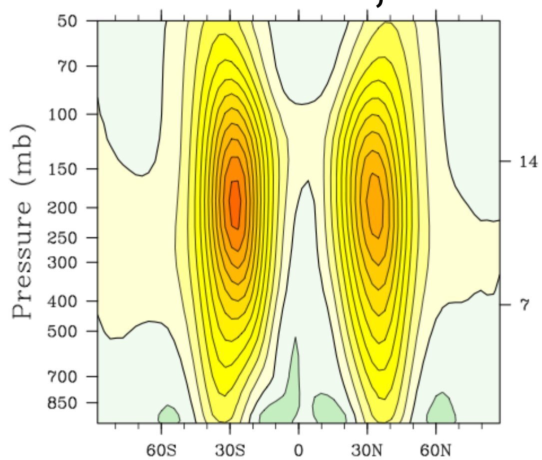
Encouraging, but no *surface* superrotation

Exploring 2 critical elements of superrotation mechanism

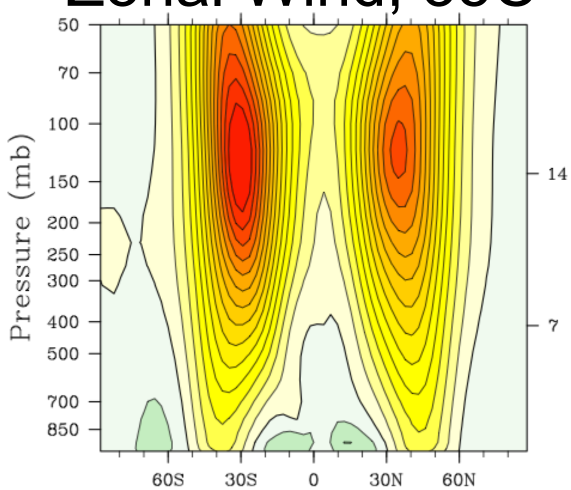
2) Warm climate ➔ more/stronger/rearranged convective activity

Effect of high SST in aquaplanet SPCAM3.5

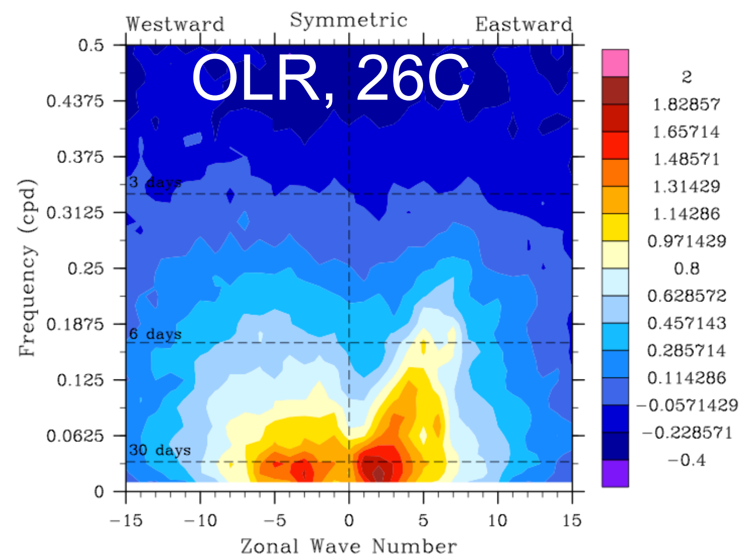
Zonal Wind, 26C

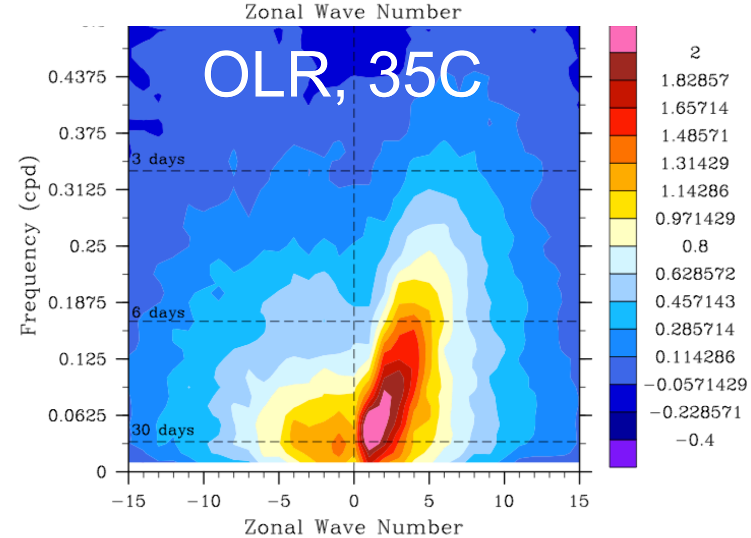


Zonal Wind, 35C



Encouraging signs of increased (MJO-like?) convective activity; Mechanism still not clear; [Nathan Arnold, with Zhiming Kuang]





conclusions: 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.

- Mechanism: enhanced convective "noise" at equator, radiating Rossby waves and inducing westerlies at equator.

- We proposed a Rossby wave resonance mechanism, which tends to lead to *abrupt transition* (bifurcation) to superrotation

- We find evidence in SPCAM, of enhanced convective activity & tendency to superrotation at high altitudes for warmer SST.

- Major challenge now: getting superrotation to surface… CMT?

- Could this mechanism lead to a permanent El Nino in the near future…? [as suggested by Held 1999 & Pierrehumbert 2002]

[Tziperman & Farrell 2009; Arnold, Tziperman & Farrell 2011]