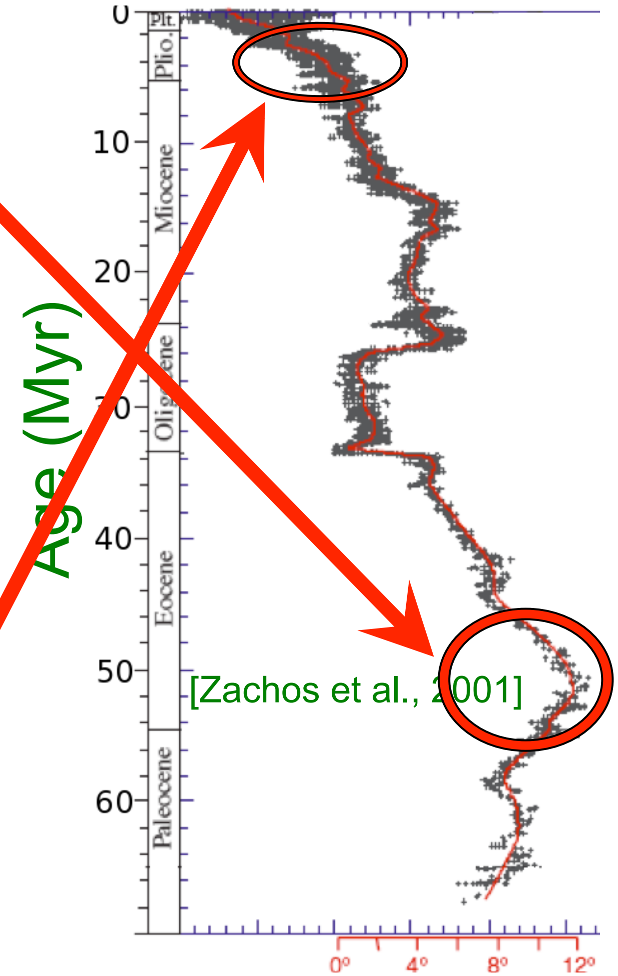
Two lessons from past warm climates

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?* Work of **Nathan Arnold,** with Brian Farrell; Rossby wave resonance and SPCAM results

Gradual cooling over past 55Myr



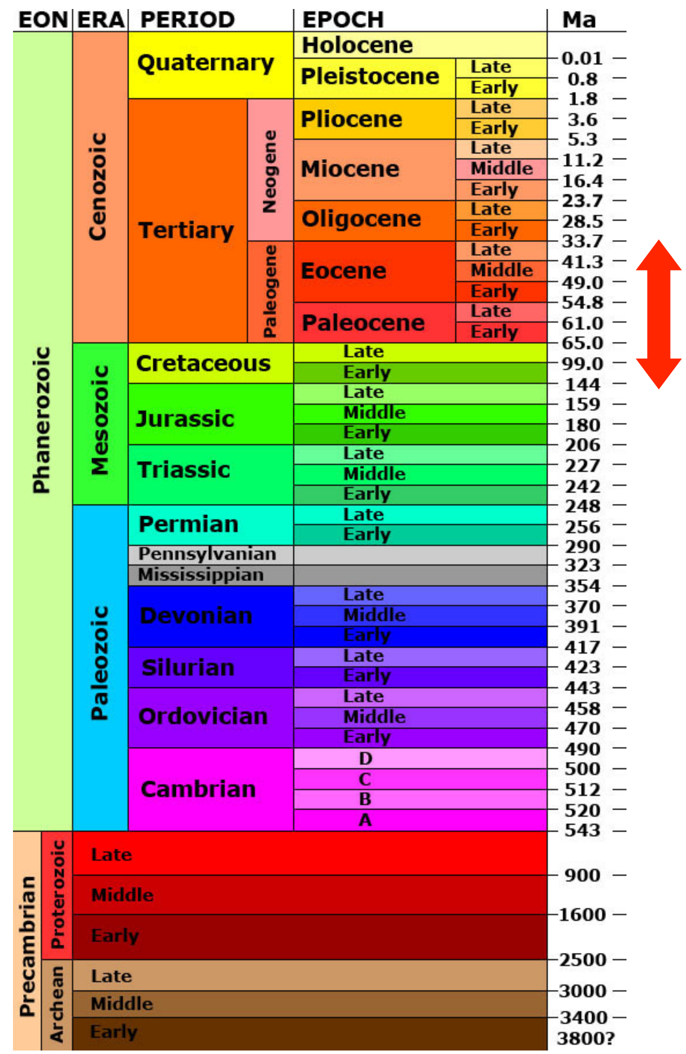
Deep ocean Temperature

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…**

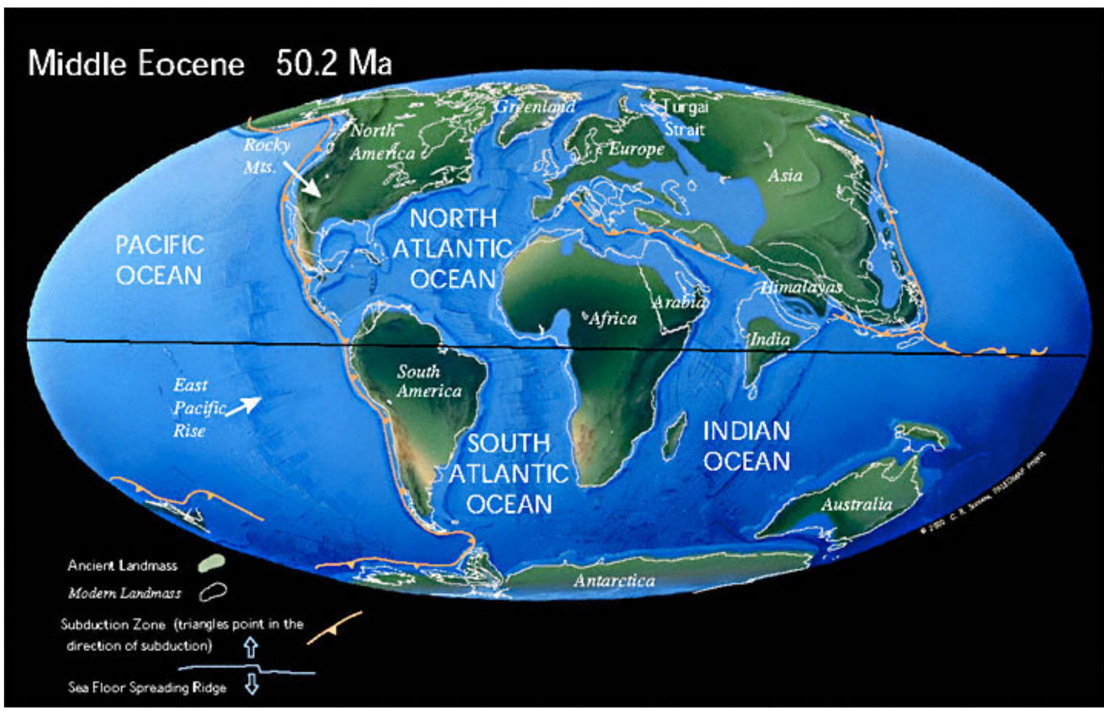
3) **Our mechanism**: a qualitatively different state of the atmosphere, with tropical-like deep atmospheric convection and high tropospheric clouds at mid- to high-latitudes providing a strong greenhouse effect.

4) **Why should you care**

Observations ($1^{st}/3$): 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

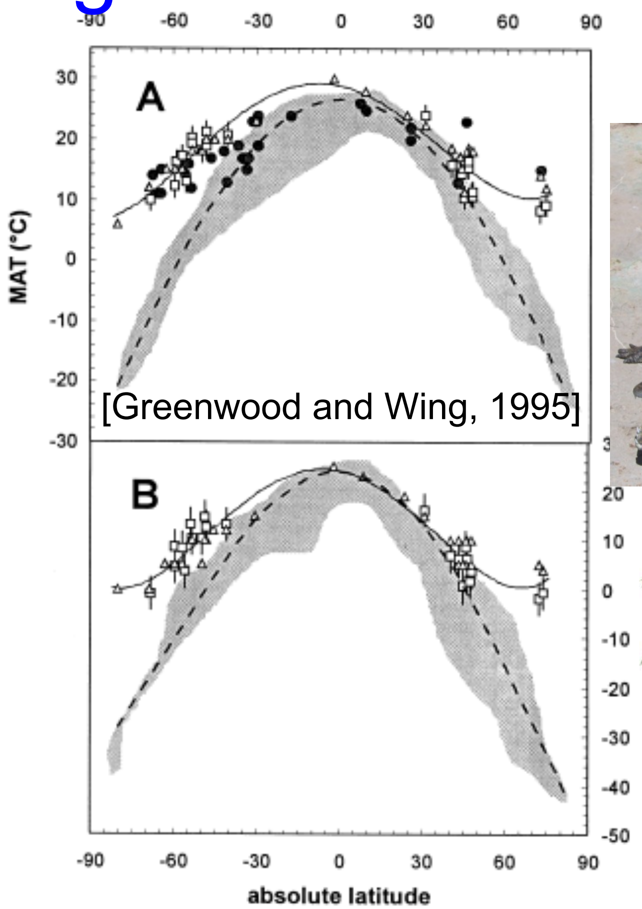


[146-34 Ma ago: Cretaceous - Paleocene - Eocene]

Eocene: modern-like continental configuration.

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

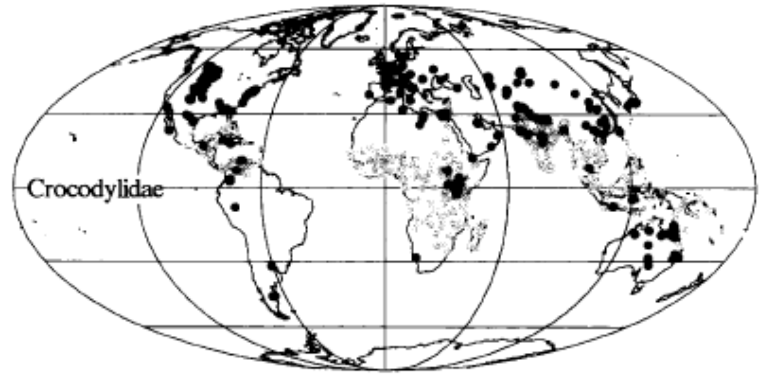
Cool tropics, warm high-latitudes

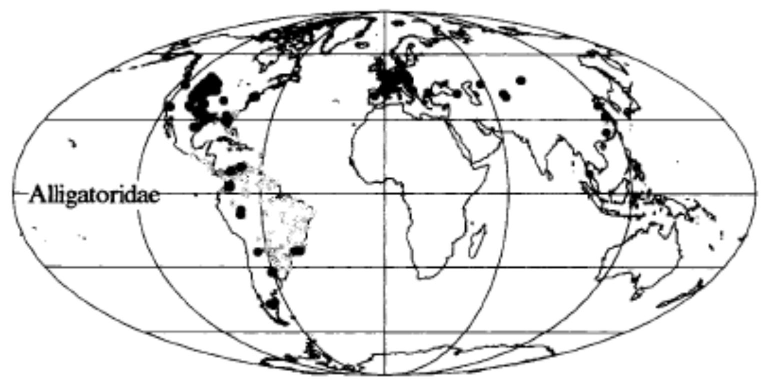


■ - Modern land temp.

● △ □ - 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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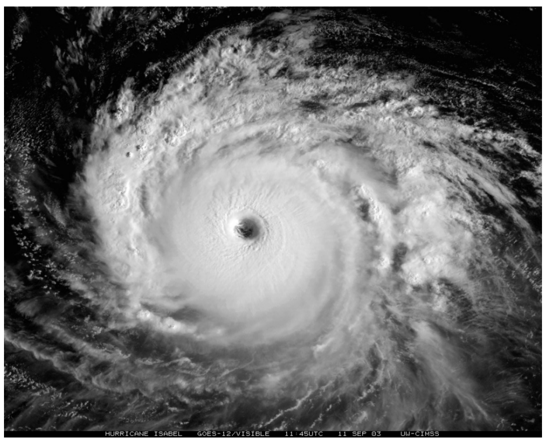
Previously proposed mechanisms

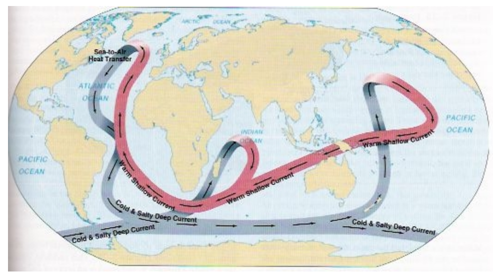
Ocean Atmosphere Stratos. clouds

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

Stronger hurricanes

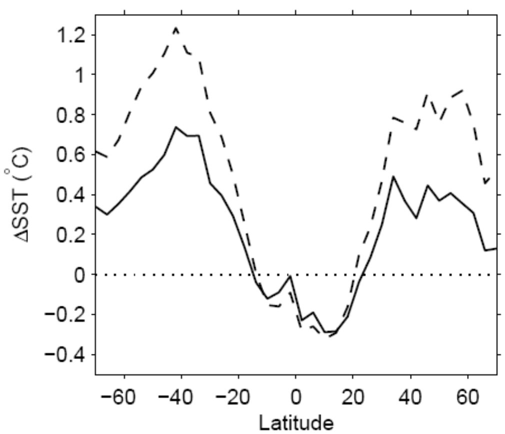


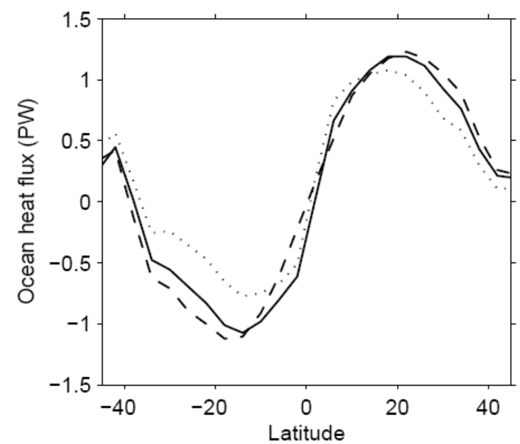
Thermohaline circulation



Warmer high latitudes

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

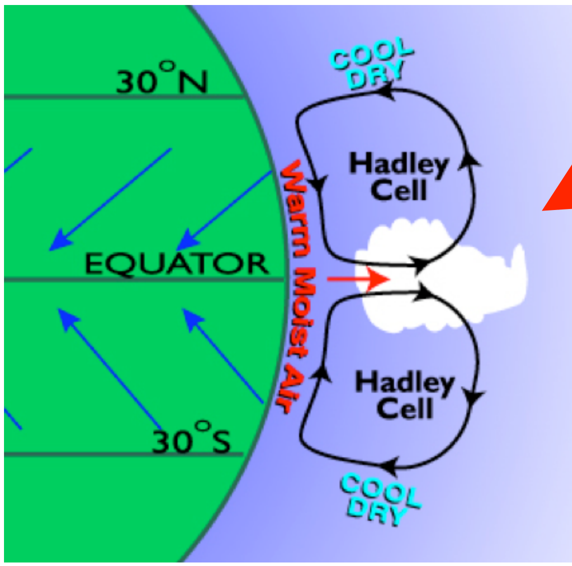




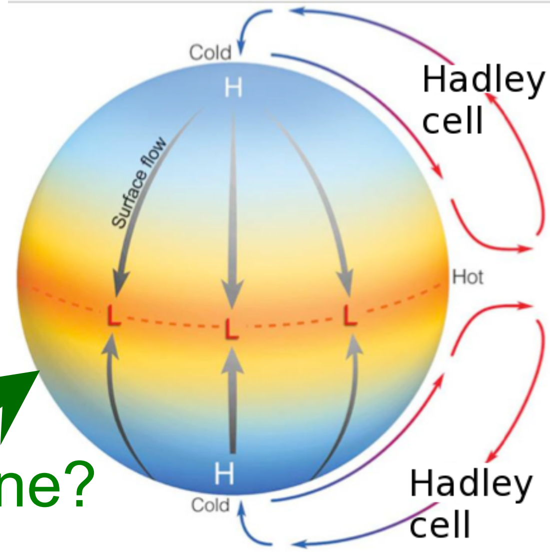
Previously proposed mechanisms

Ocean **Atmosphere** Stratos. clouds

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



Today



Eocene?

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

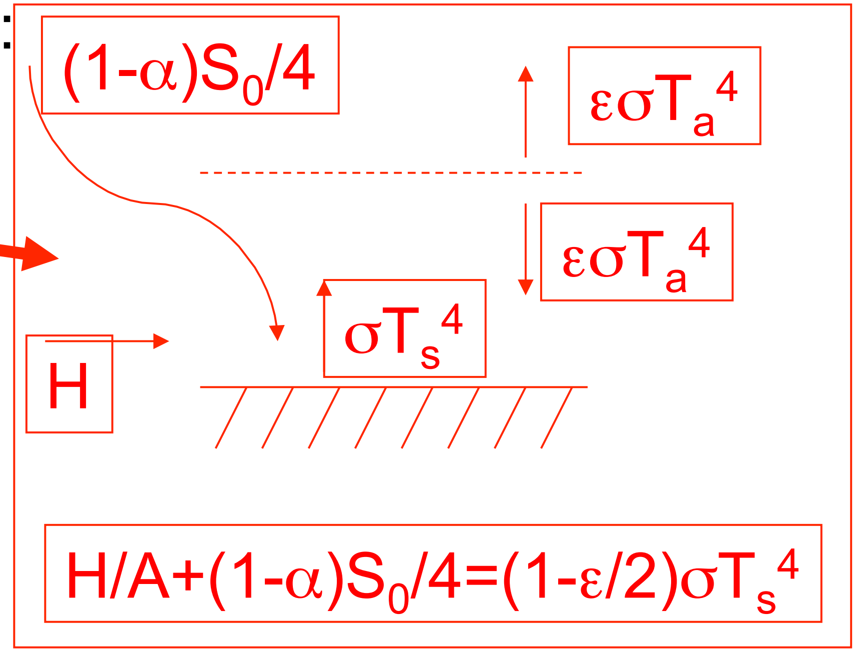
Like Venus: large Hadley cell due to slow rotation; Poles warm as Equator

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

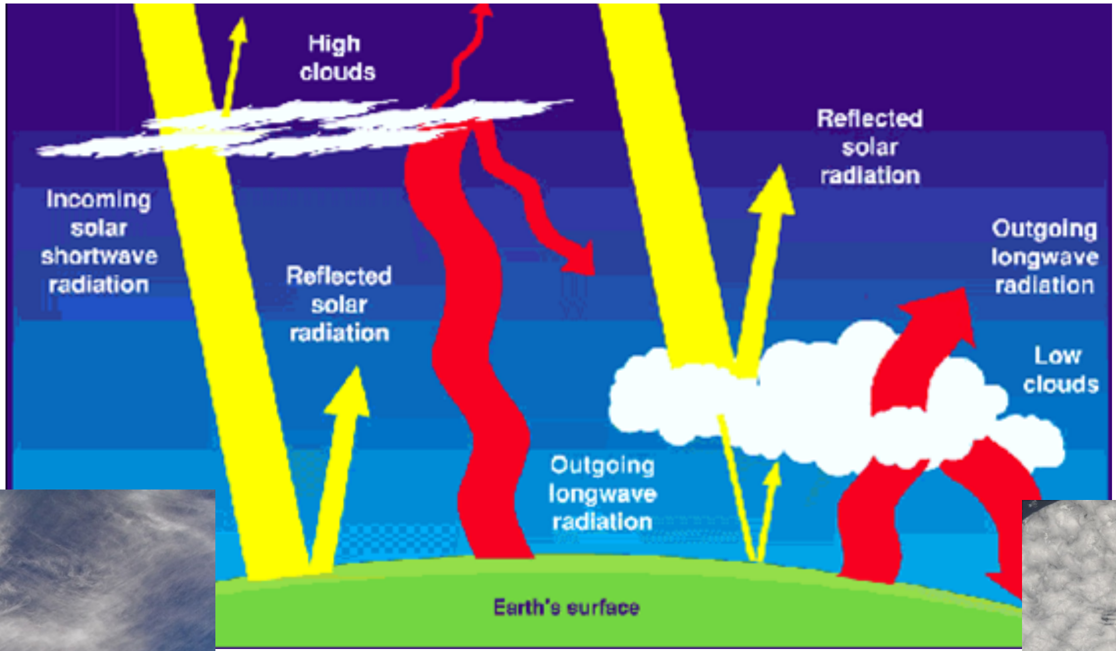
Increasing high latitude temperature:

ΔT [°C]	ΔH [PW]	$\Delta\varepsilon$ [ ]	$[CO_2]_{dry}$ [ppm]	$[CO_2]_{wet}$ [ppm]	$\Delta\alpha$ [ ]
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

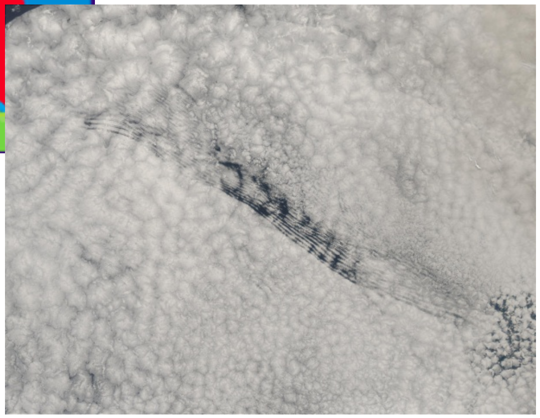
A reminder: Cloud feedbacks

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…

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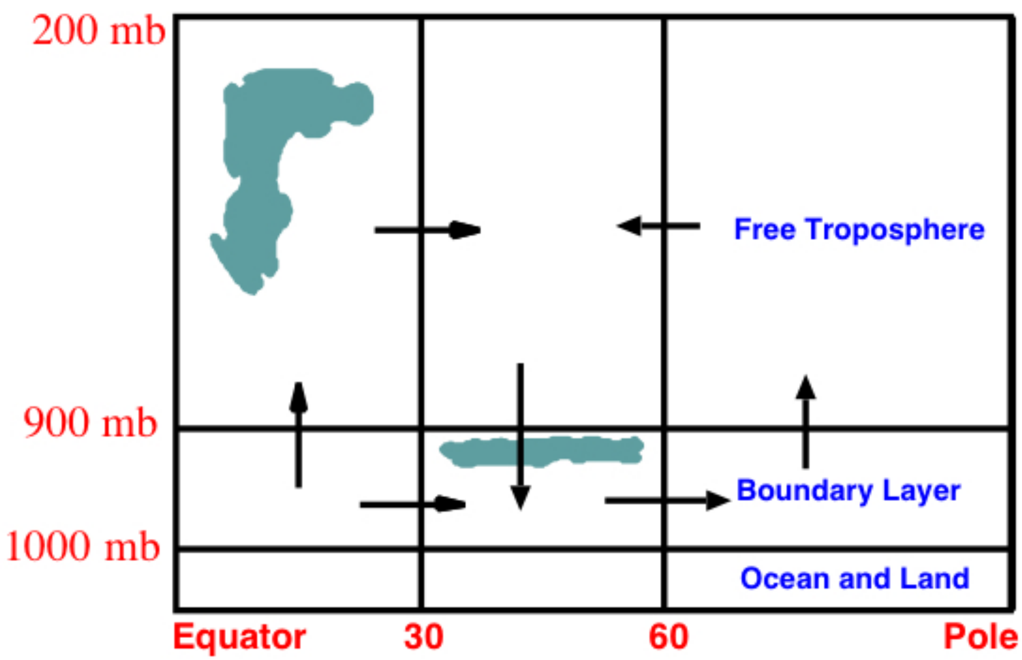
First step: a “toy” model (1st / 2)

- 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, CO2, water vapor, clouds…
- Surface fluxes

The toy model (2nd / 2): equations

Dry Static Energy and Moisture Equations

$$
\begin{aligned}
\frac{\partial DSE}{\partial t} &= \frac{\omega}{\Delta P} DSE + \frac{v}{\Delta y} DSE + D(\theta)\frac{\partial DSE}{\partial \theta} + L_v \frac{q-\tilde{q}}{\tau} + k_{con}(DSE_1 - DSE_2) \\
&\quad -\delta_{k2}\varepsilon_{re} L_v \frac{q_1 - \tilde{q}}{\tau} + \varepsilon A(F_{in} - 2\sigma T^4) + \delta_{k2}\rho_2 C_{SH}(T_S - \theta_2) \\
\frac{\partial q}{\partial t} &= \frac{\omega}{\Delta P} q + \frac{v}{\Delta y} q + D(\theta)\frac{\partial q}{\partial \theta} - \frac{q-\tilde{q}}{\tau} + k_{con}(q_1 - q_2) \\
&\quad +\delta_{k2}\varepsilon_{re}\frac{q_1 - \tilde{q}}{\tau} + \delta_{k2}\rho_2 C_{LH}(q^*(T_S) - q_2)
\end{aligned}
$$

Equations of Motion: angular momentum conservation included

$$
\begin{aligned}
u_t + \frac{1}{a\cos(\theta)}\frac{\partial}{\partial\theta}(uv\cos(\theta)) - uv\tan(\theta)/a + \frac{\partial}{\partial p}(\omega u) - 2\Omega\sin(\theta)v &= \nu\frac{\partial^2 u}{\partial\theta^2} - \delta_{k2} r u \\
v_t + 2\Omega\sin(\theta)u &= -\frac{1}{a}\frac{\partial\phi}{\partial\theta} + \nu\frac{\partial^2 v}{\partial\theta^2} - \delta_{k2} r v \\
\phi_p &= -\alpha \\
\frac{1}{a\cos(\theta)}\frac{\partial}{\partial\theta}(v\cos(\theta)) + \omega_p &= 0 \\
p\alpha &= R^* T
\end{aligned}
$$

Model experiments & results: summary

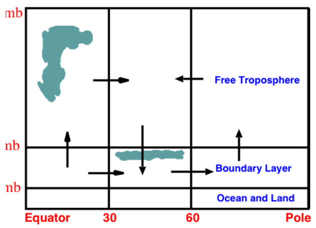
Model experiments:

Slowly increase CO2 to extreme values & then decrease it

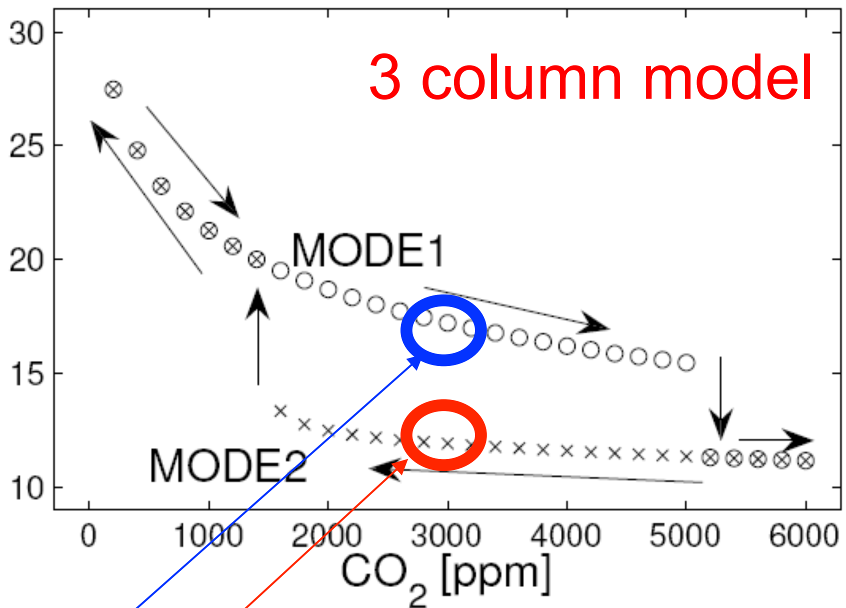
Results:

A ***qualitatively*** different climate regime at sufficiently high CO2, 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).

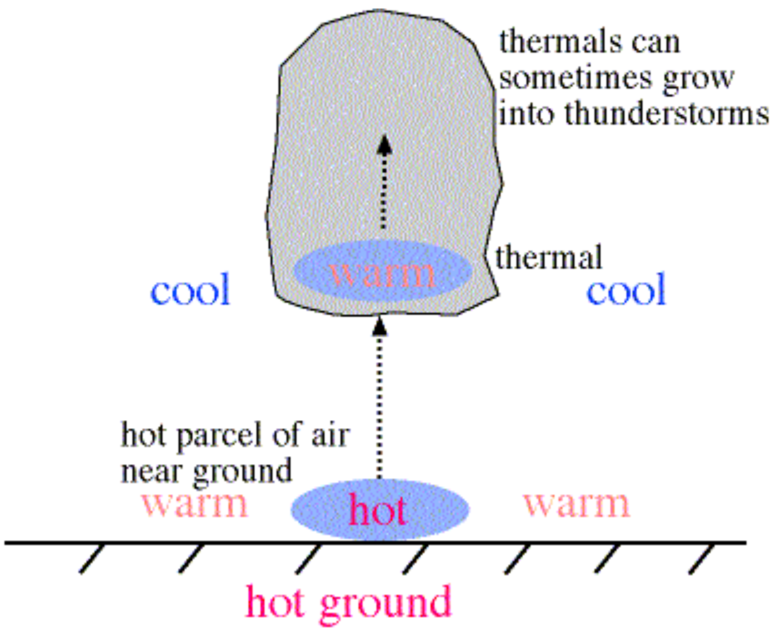


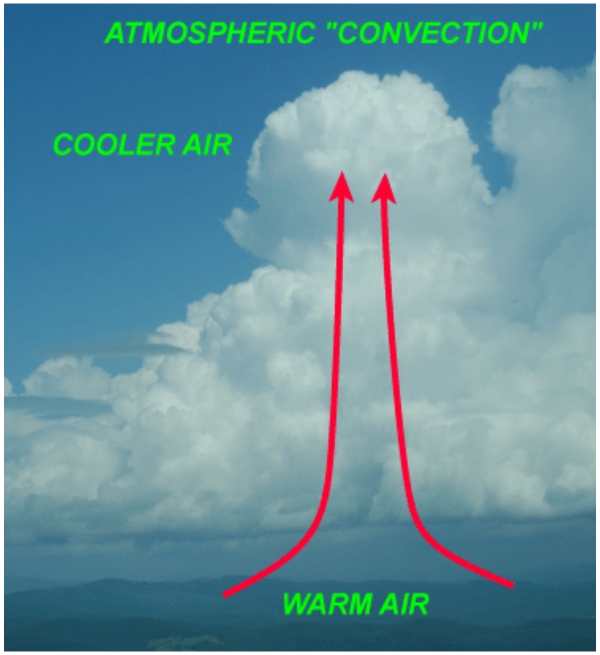
"Present-day" solution: high EPTD, colder; non convecting
"Equable" solution: low EPTD, warm; convecting, high clouds

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

A reminder: Atmospheric convection

1. Air parcel in lower atmosphere rises up
2. It expands, cools, and water vapor condenses
3. Condensation leads to latent heat release, air parcel heats
4. Parcel becomes warmer, lighter, more buoyant, and rises even more ➔ positive feedback, instability
5. Condensation creates clouds, rain



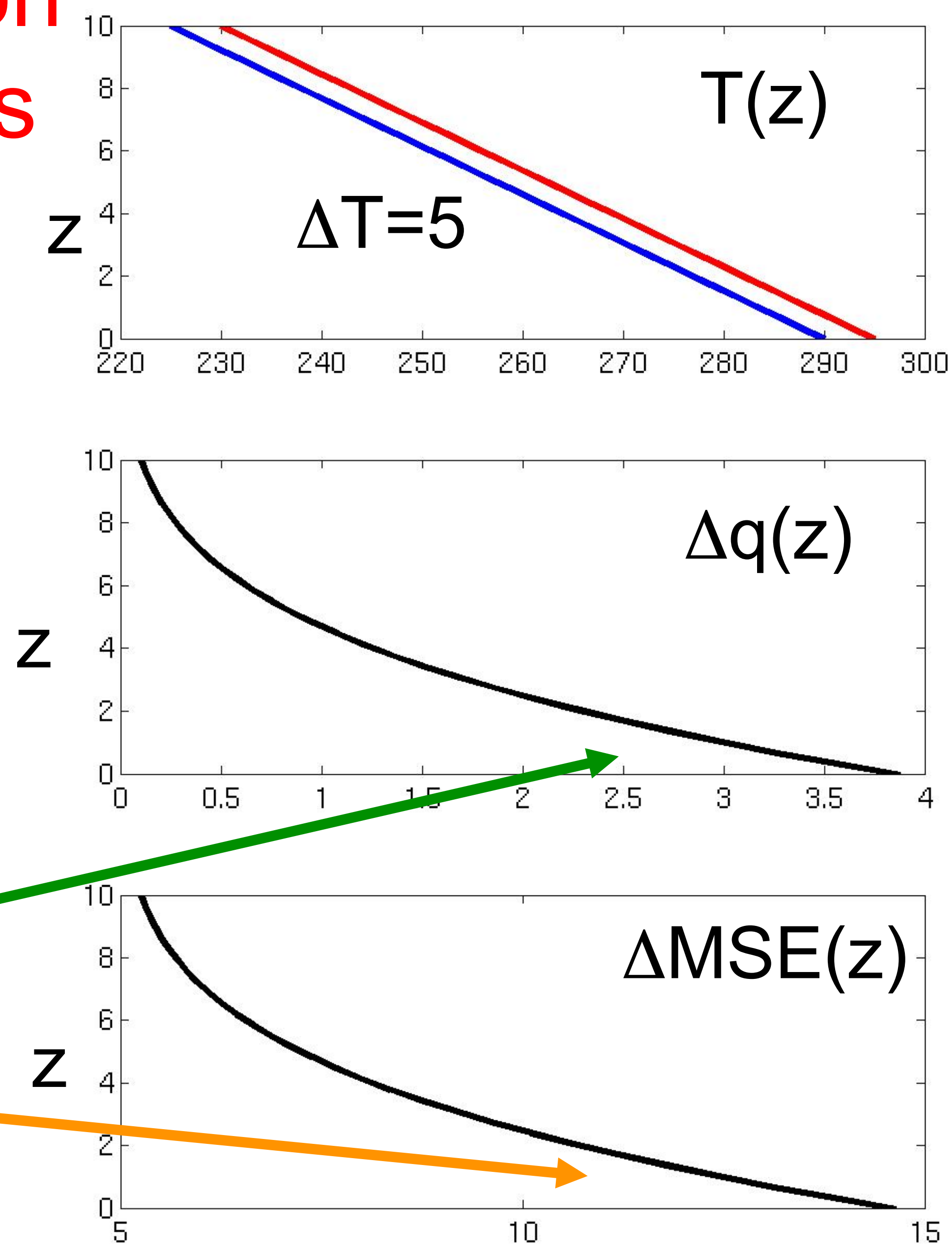


http://apollo.lsc.vsc.edu/classes/met130/

Why does convection start at high latitudes @ high CO_2?

➔ as co2 increases, moist stability decreases & eventually leads to convection.

why: Clausius-Clapeyron
➔ increasing CO_2 leads to larger moisture & Moist Static Energy increases in lower atmos,
➔ convection



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

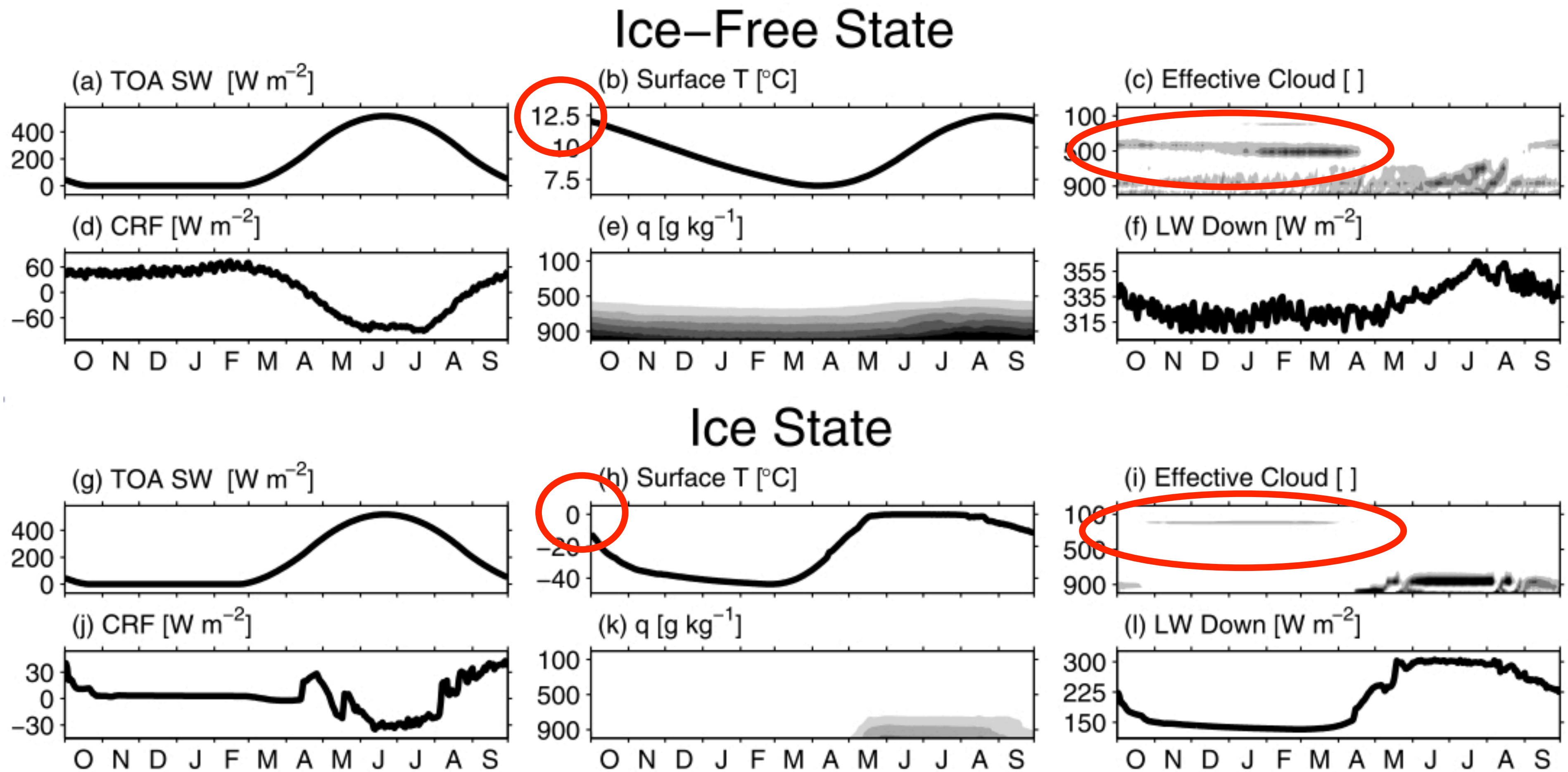
→ Positive feedback!

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)

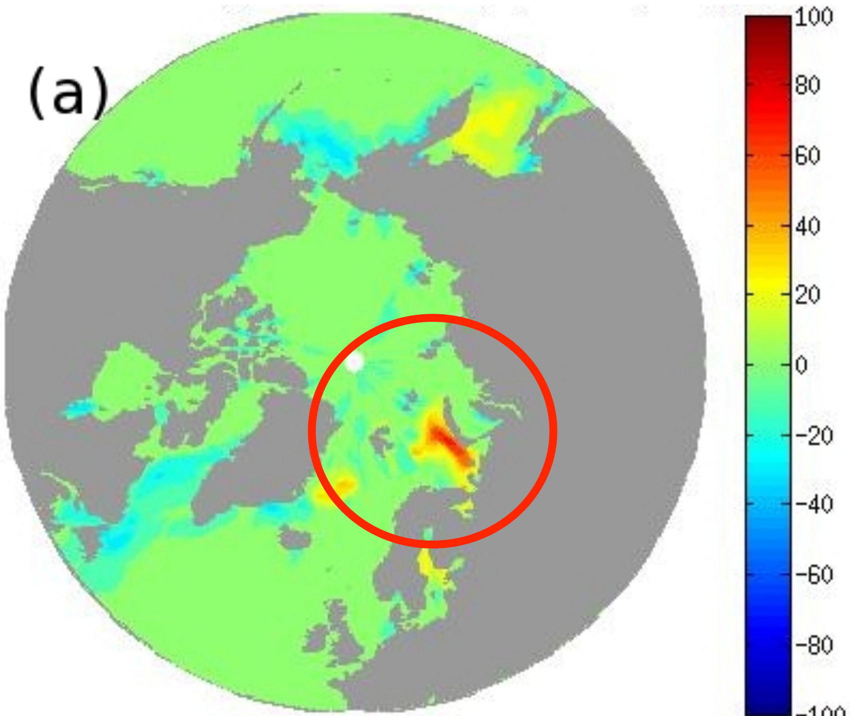
SCAM supports TOY MODEL'S mechanism for high-latitude warmth during equable climates



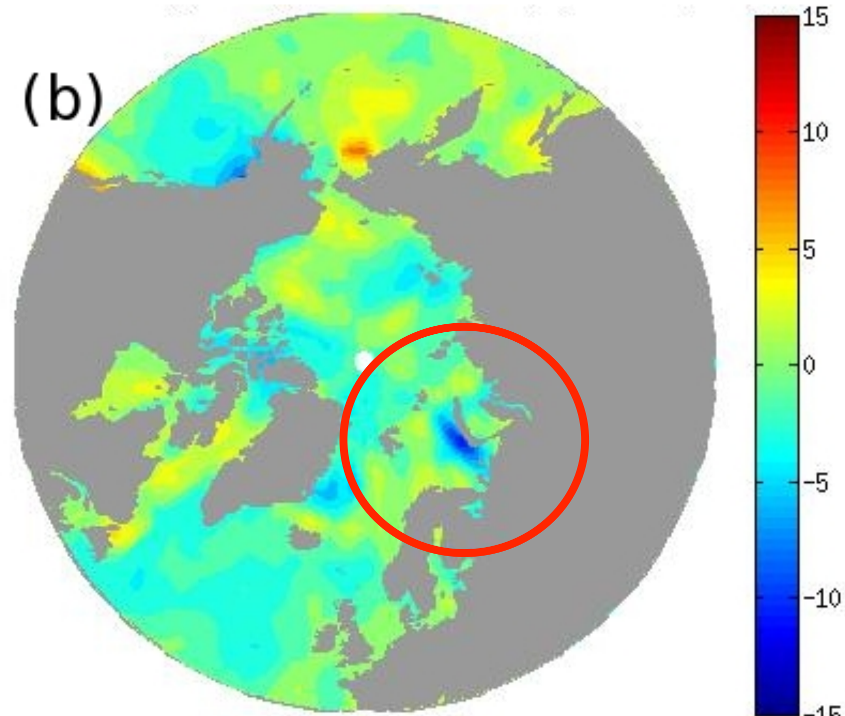
SCAM, CO2=1000ppms, different I.C. ➔ 2 different *seasonal* states, with & w/o sea ice. Also: multiple equilibria, hysteresis

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



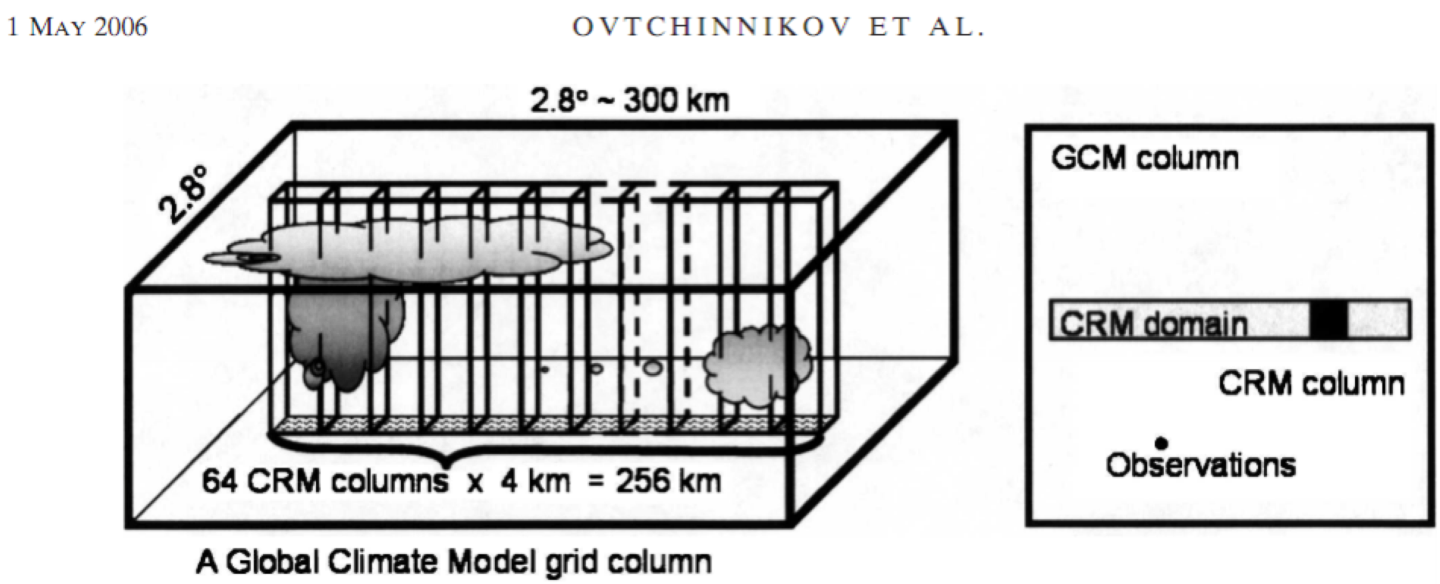
High sea ice cover anomaly during winter



➔ Negative CRF anomaly during same years

Moving (far) beyond simple models

"Super parameterized" community atmospheric general circulation model (=**SPCAM**, Grabowski, Randall & colleagues)



99% of computation time is spent on cloud resolving model which serves as the convection parameterization. ➔ Cost is GCMx100

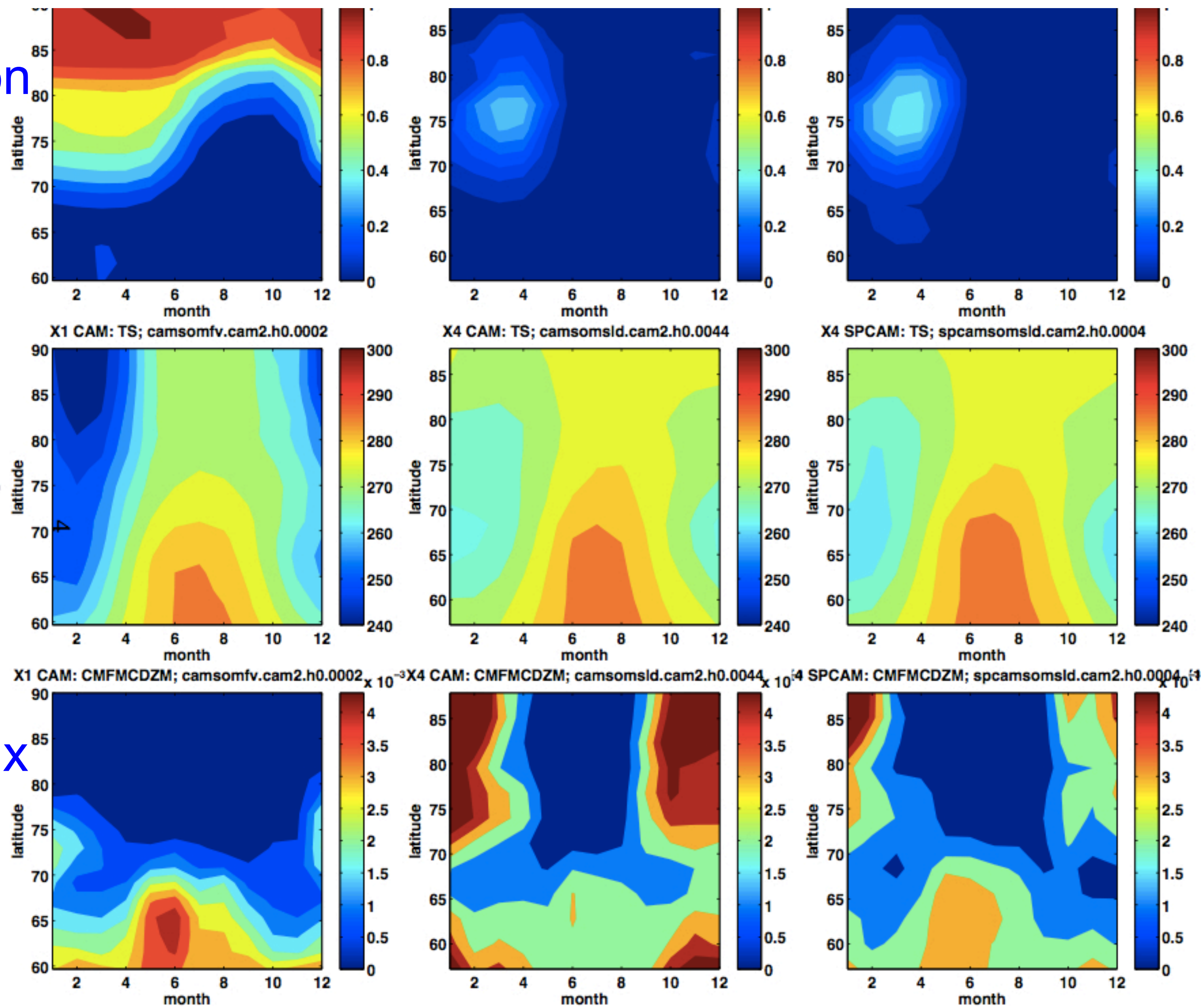
Preliminary SPCAM results: latitude (60N-90N) vs month

X1CO2,CAM; X4CO2,CAM; X4CO2, SPCAM

Sea ice fraction

TS

Conv Mass flux



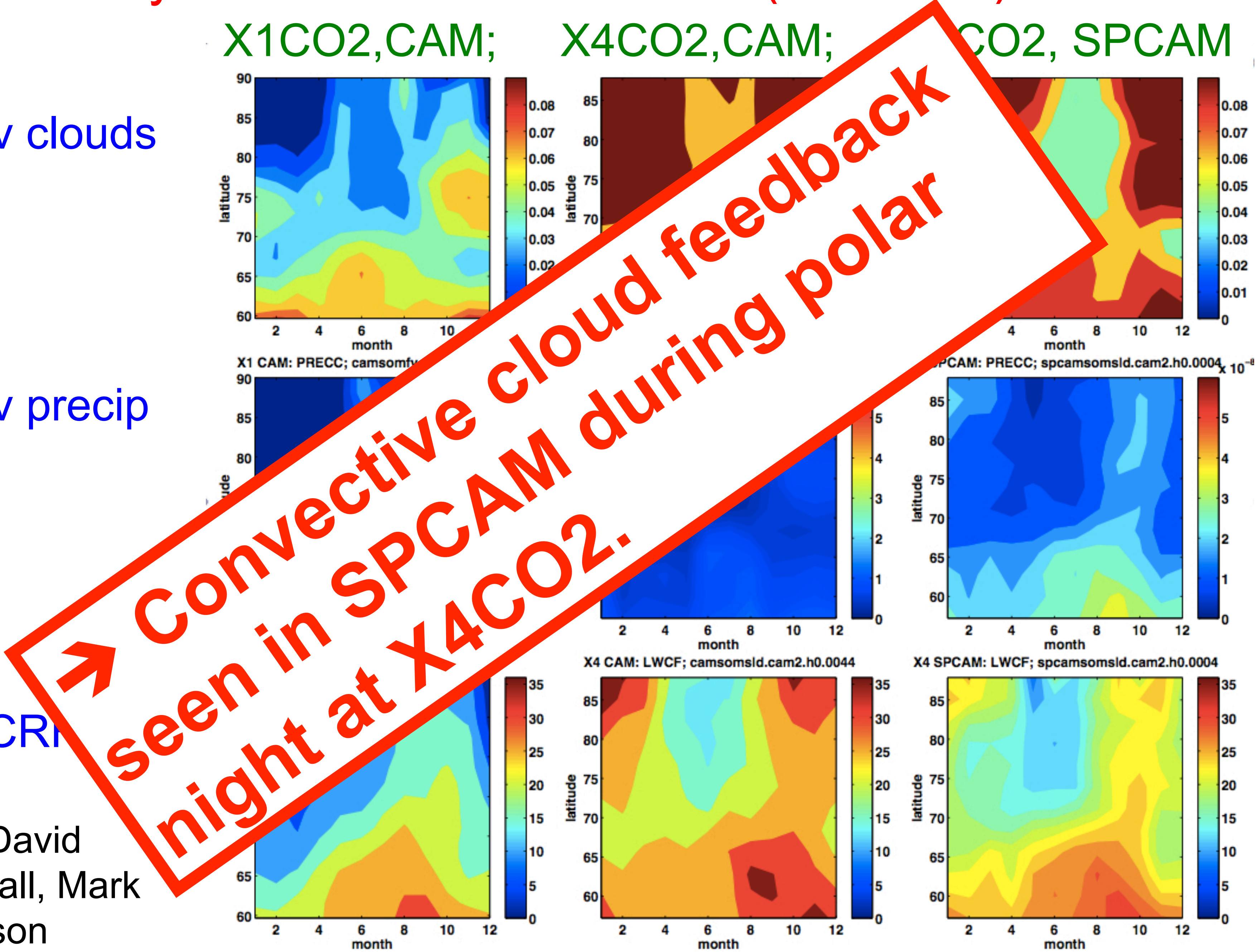
with David Randall, Mark Branson

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

Conv clouds

Conv precip

LW CRF



with David Randall, Mark Branson

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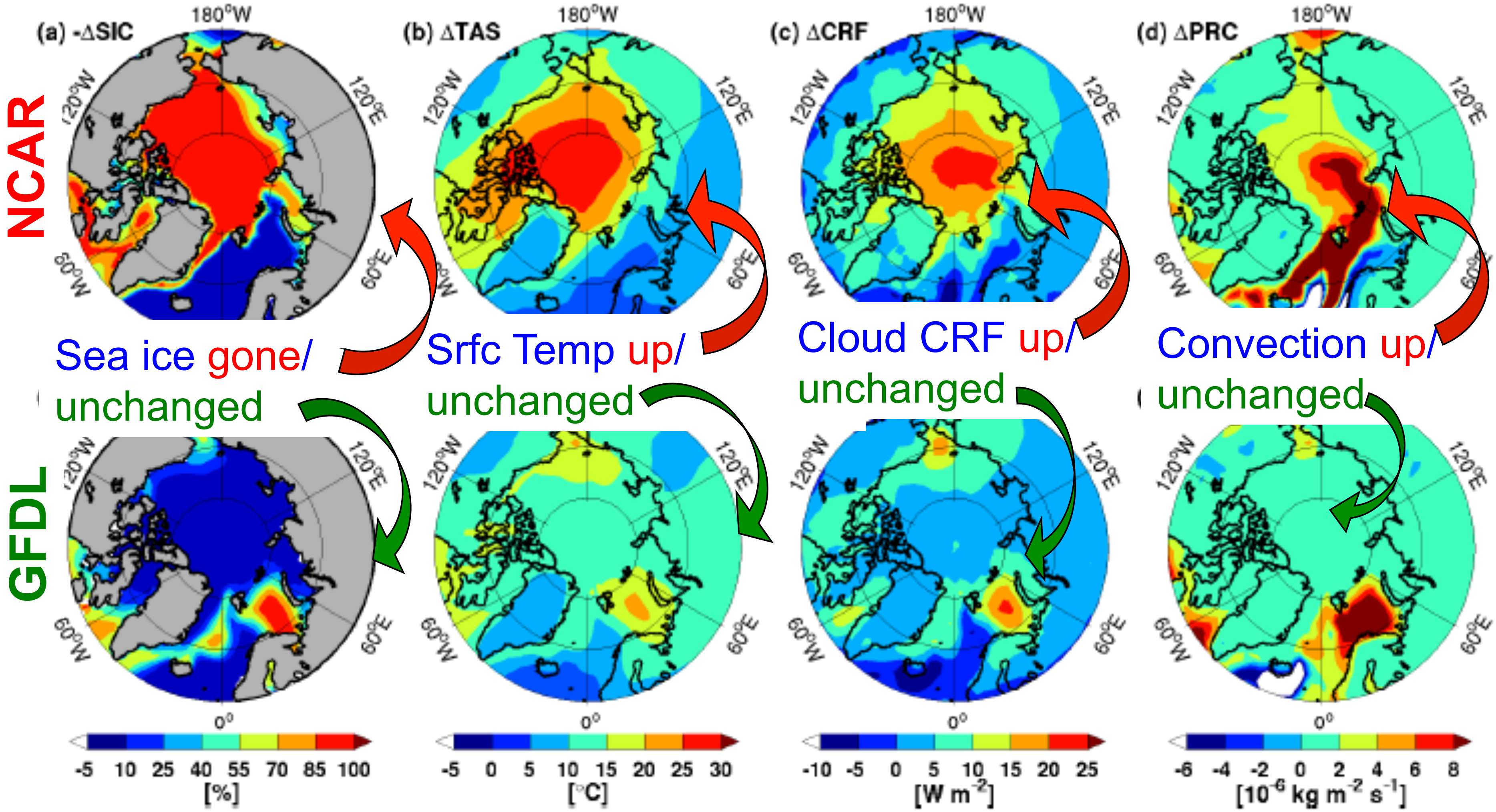
Enticing 3D IPCC Model Simulations

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!!

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

Challenge: CO_2 insufficient to explaining Eocene warmth

Good news: Found a simple, interesting & unexpected climate state at high CO_2: 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

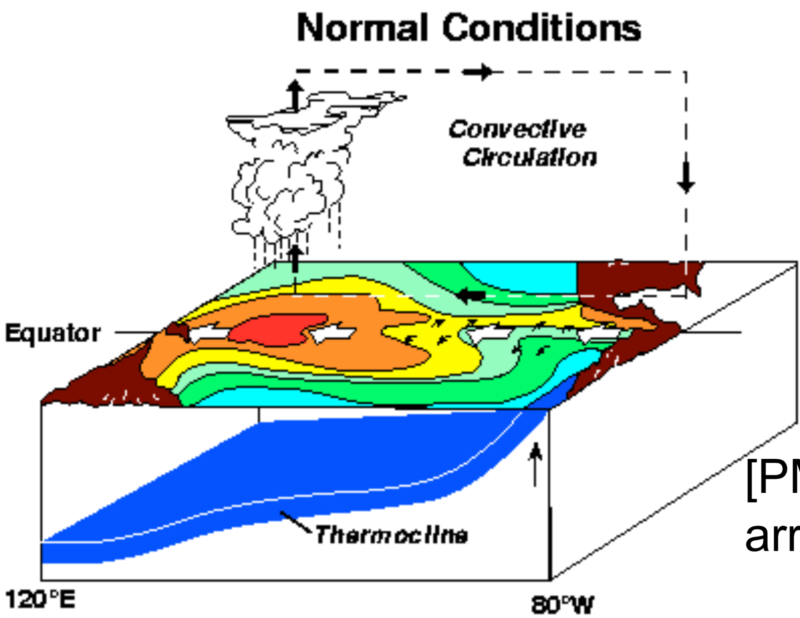
LESSON 2

Outline

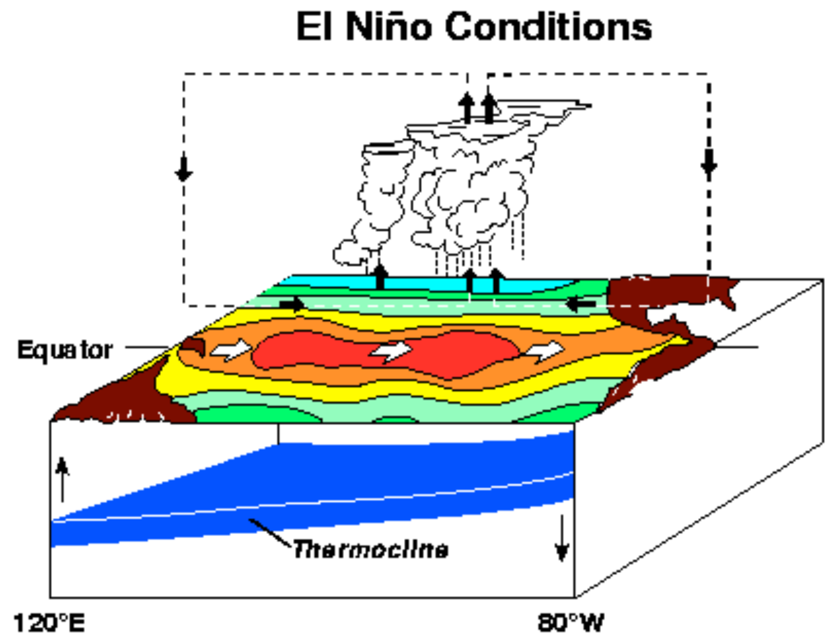
- Pliocene, "permanent El Nino"
- Some previous attempts
- Superrotation! weakening those easterlies
  - Rossby wave resonance mechanism
  - Increased convective activity with SST in SPCAM

[Tziperman & Farrell 2009; Arnold, Tziperman & Farrell 2011; Arnold, Kuang, Tziperman, 2012]

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

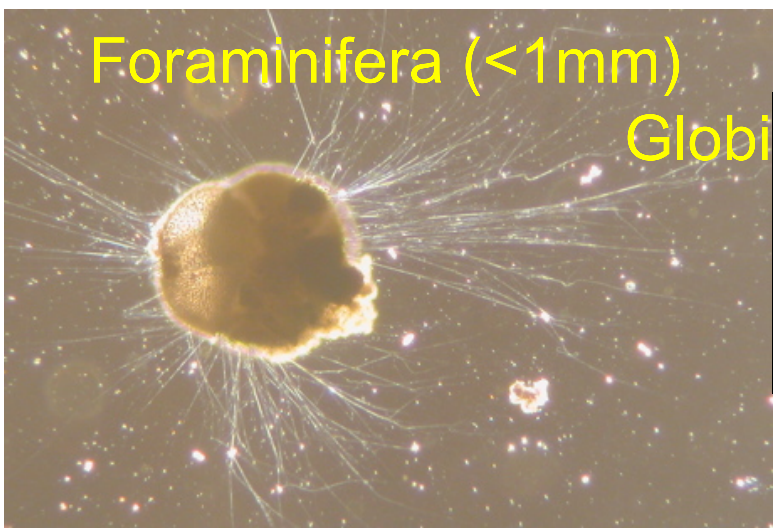
➔ Two possible ways of `making' a permanent El Nino: (1) weaken easterlies or (2) deepen thermocline.

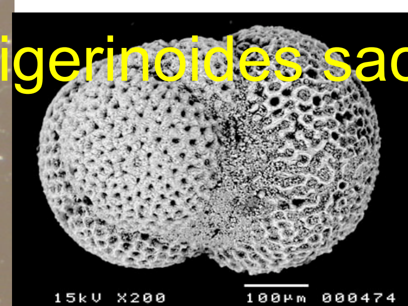
The Pliocene (2-5 Myrs)

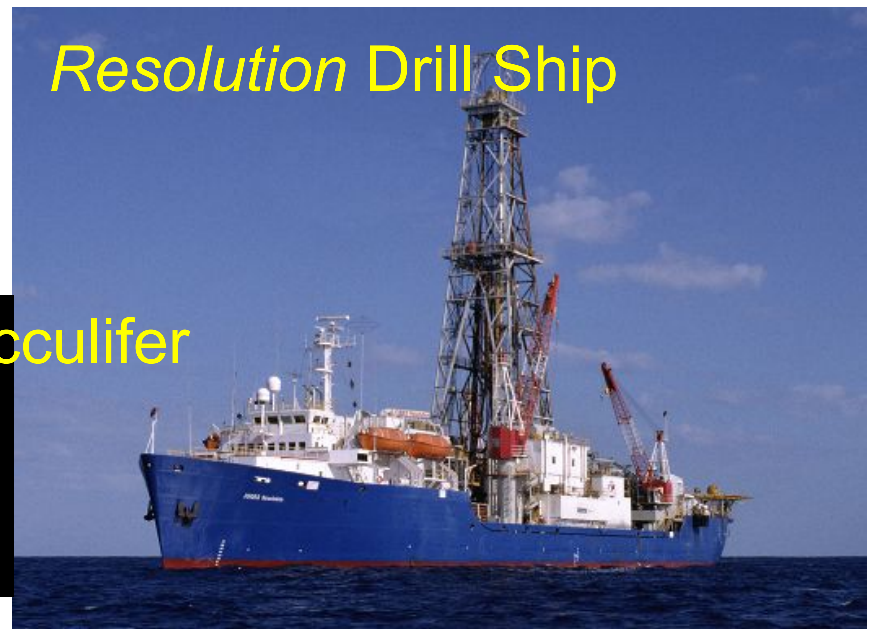
- CO_2 350-500ppm? (Today: 380; preindustrial: 280; in 50 yrs …)
- Global average surface temperature: ≈3° warmer than today
- Ice: covers Antarctica, but not much in northern hemisphere (ice ages started ≈2.7 Myrs ago)

How do we know:

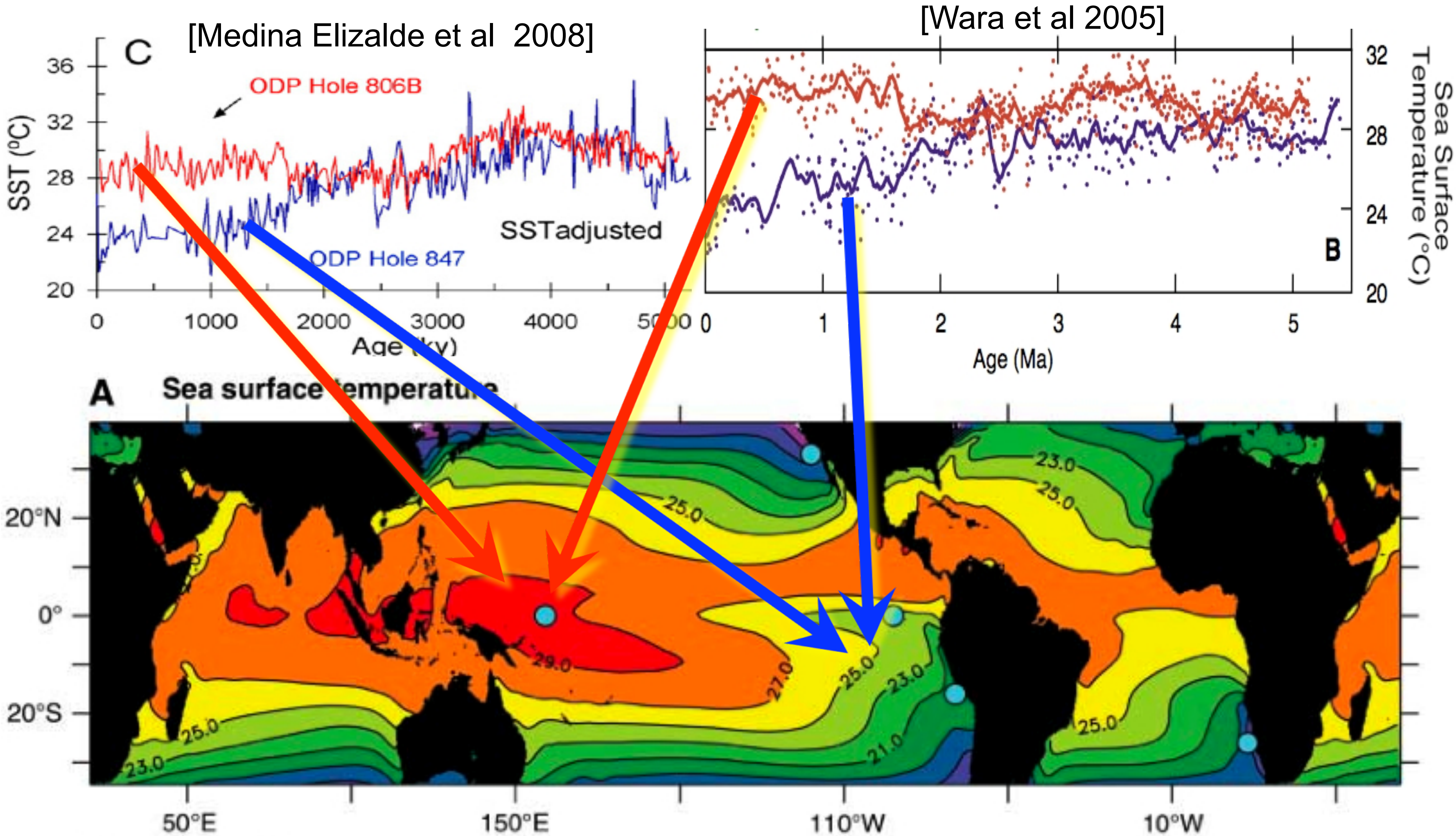
- Isotopic/ other proxy records from deep sea drilling.







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 global thermocline? 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?]

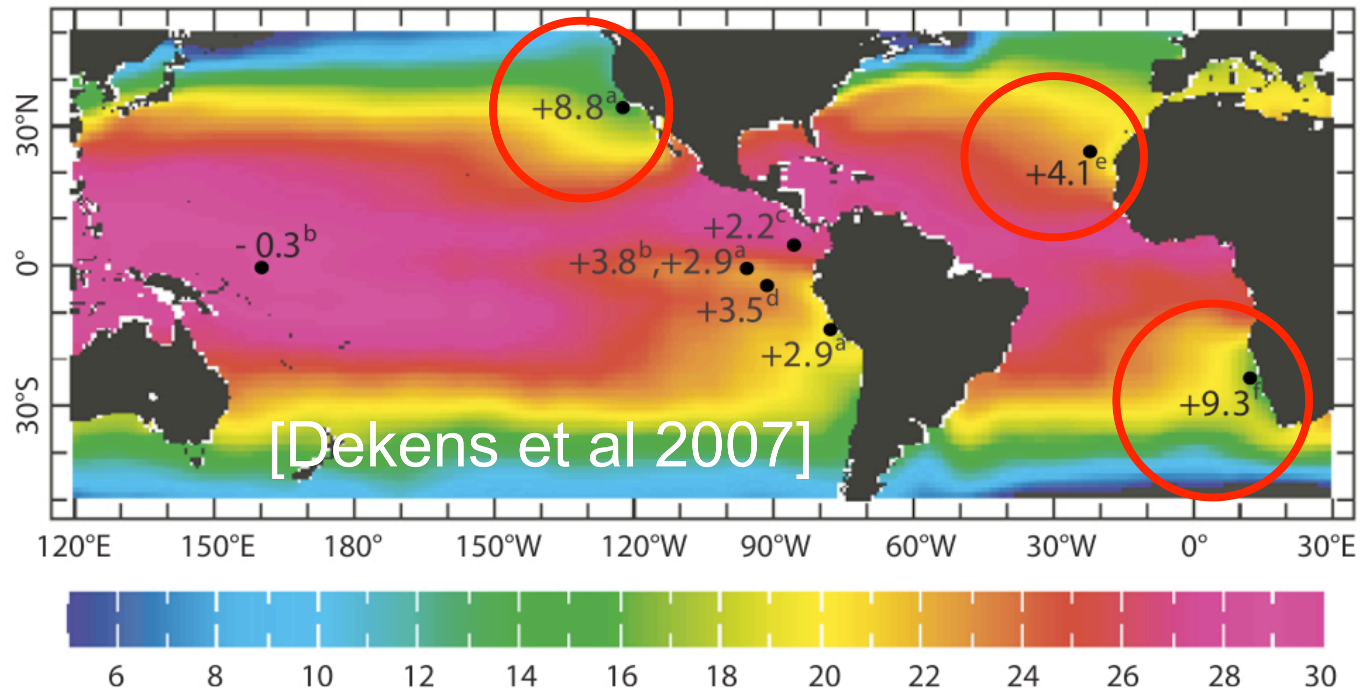
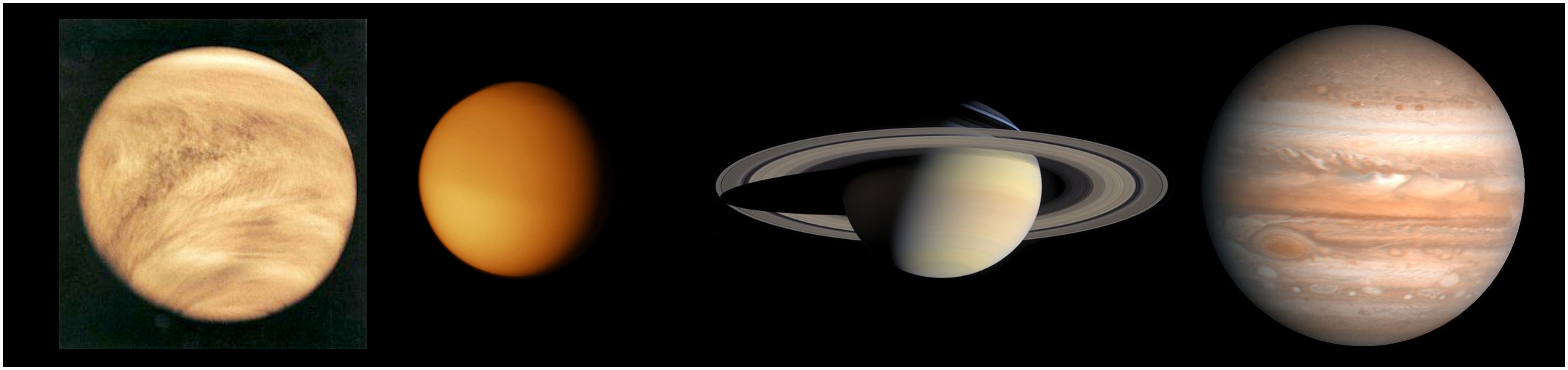


Figure 1. Difference in sea surface temperature (SST) between Pliocene and modern SST. The colored map shows modern mean annual SST [*Levitus and Boyer*, 1994]. Superimposed is the difference between

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 $$\sigma = \frac{-\beta k}{k^2 + l^2 + L_R^{-2}}$$

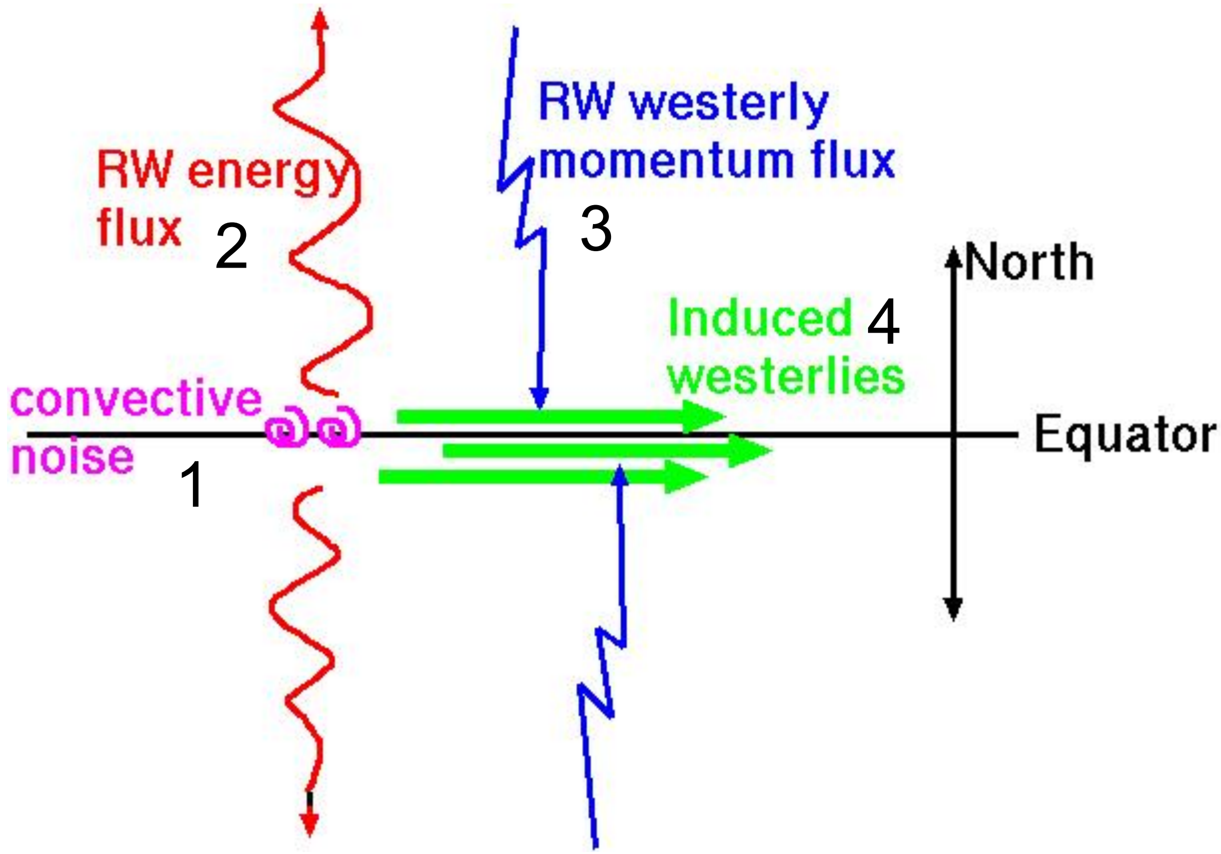
Meridional group velocity $$c_g^{(y)} = \frac{2\beta k l}{(k^2 + l^2 + L_R^{-2})^2}$$

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]

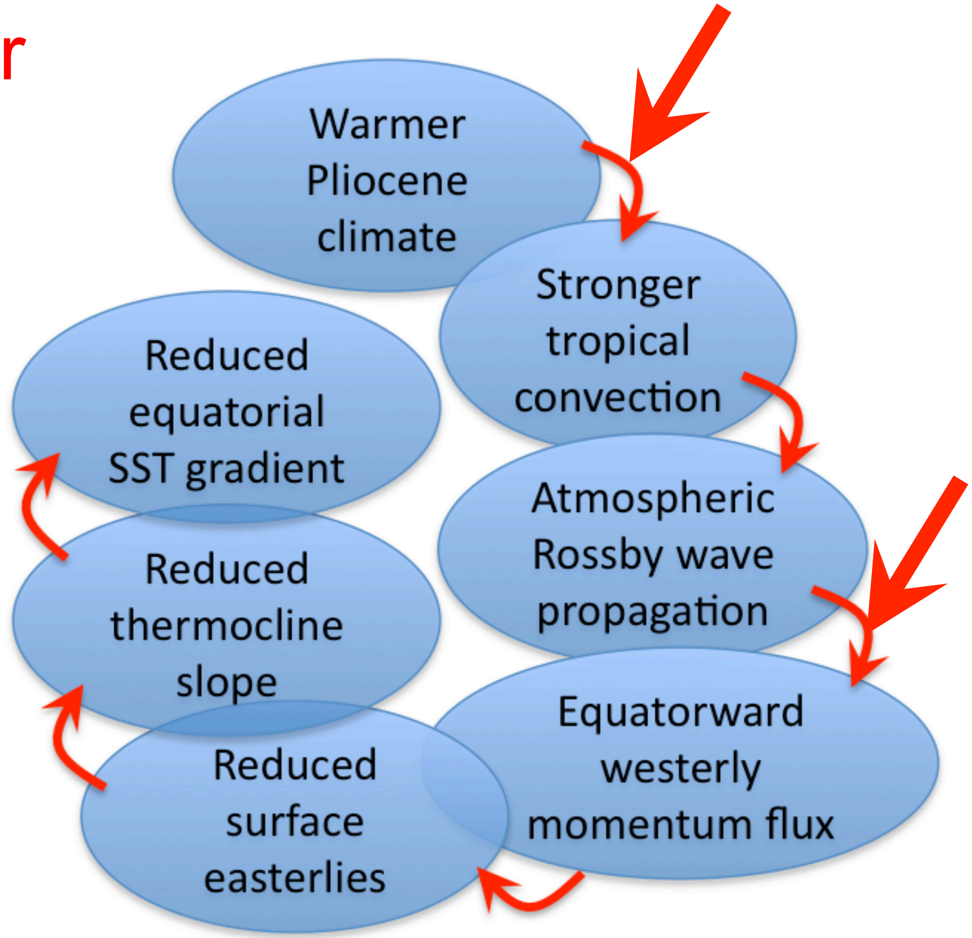
- Pierrehumbert [2002] writes:

  "*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…

Proposed mechanism for permanent El Nino

1. Warmer Pliocene ➔ stronger MJO-like tropical convection =stochastic forcing at equator.



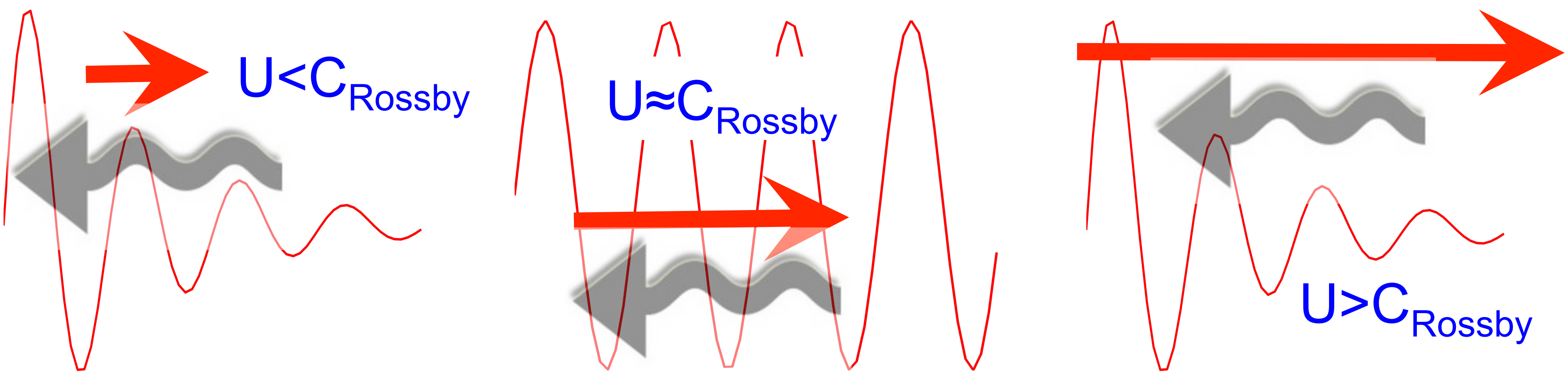
2. Rossby wave energy flux away from equator ➔ equatorward westerly momentum flux ➔ weaken equatorial easterlies.

3. Weaker easterlies ➔ decreased E-W thermocline slope ➔ eliminate East Pacific cold tongue & E-W SST gradient ➔ Permanent El Nino!

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 ➔ stronger convective activity

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.

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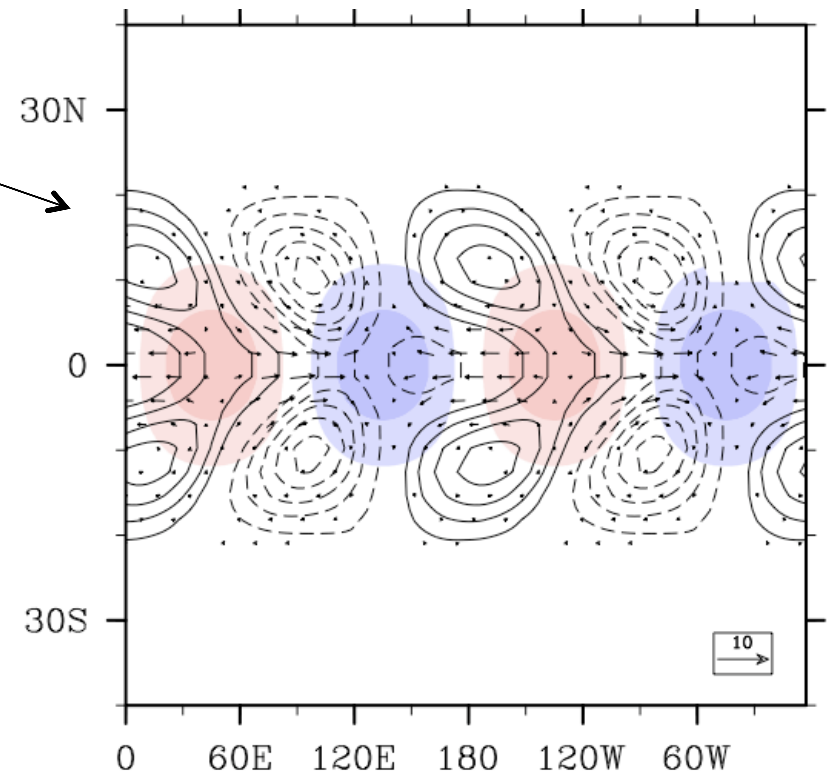
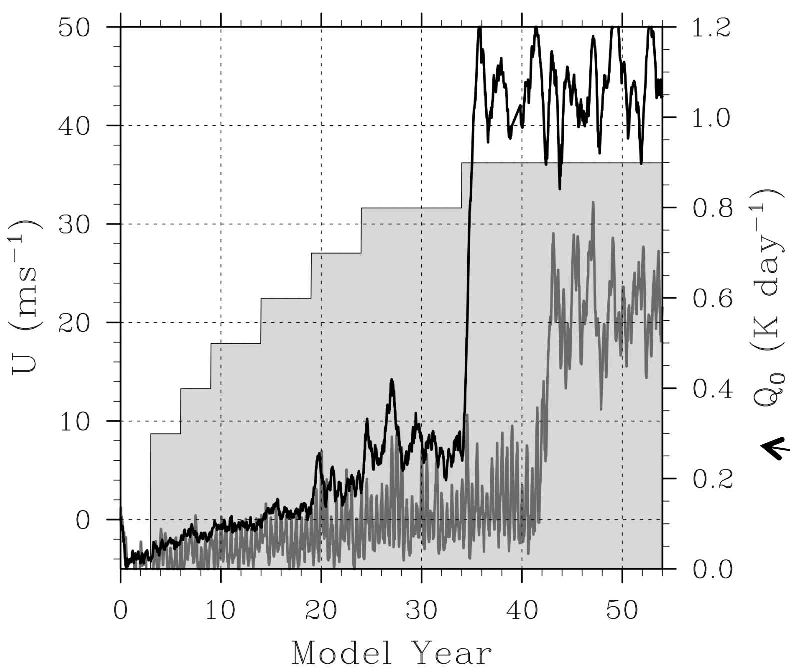
CAM experiment: (1) Impose eddy heating at equator (colors); (2) gradually increase heating rate…





Results: abrupt transition to superrotation

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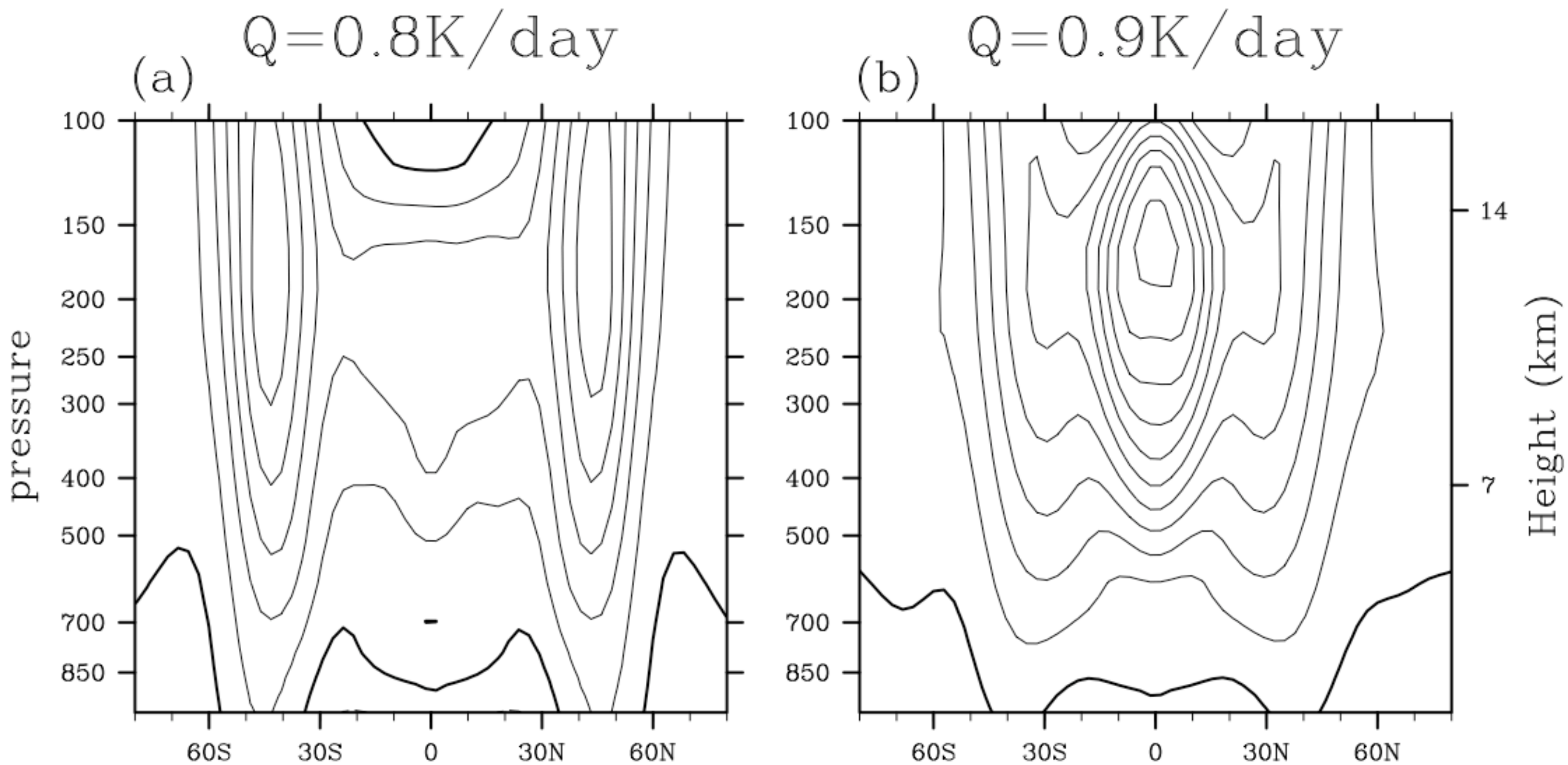

Zonal Wind before and after bifurcation, showing transition to a strong superrotation

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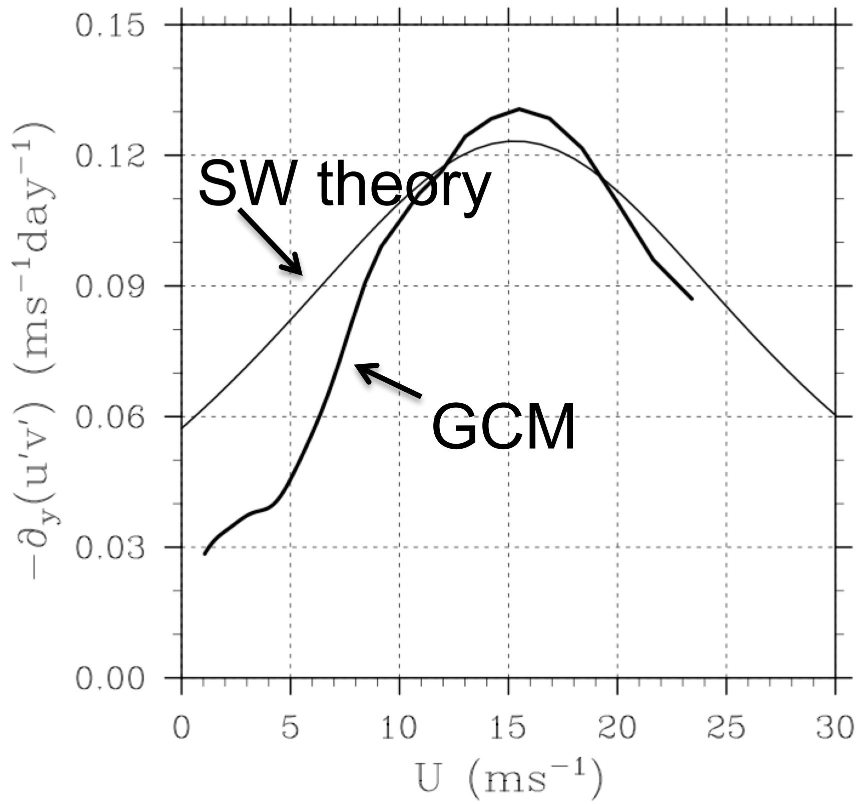

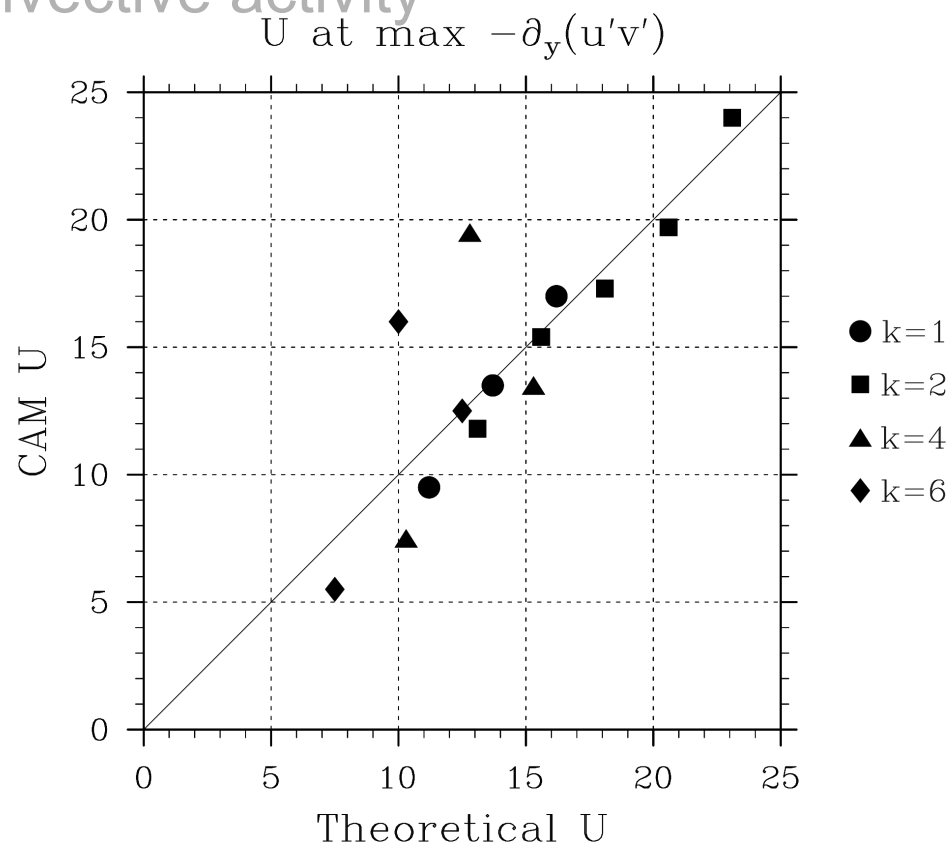

Comparison with shallow water analytical solution confirms resonance; experiments specify k & propagation speed of heating.

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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

SPCAM results:

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

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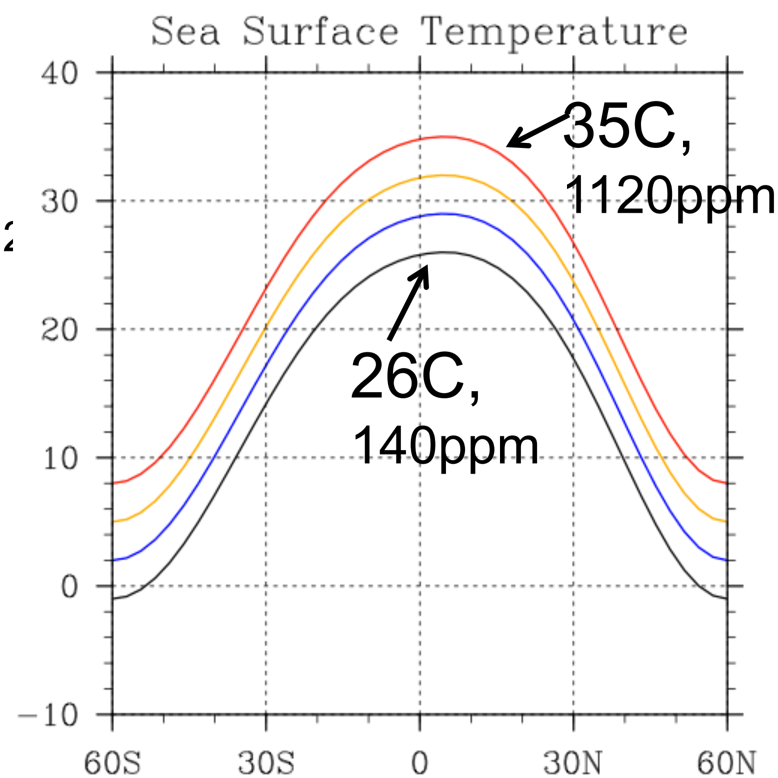
Effect of high SST in aquaplanet SPCAM3.5

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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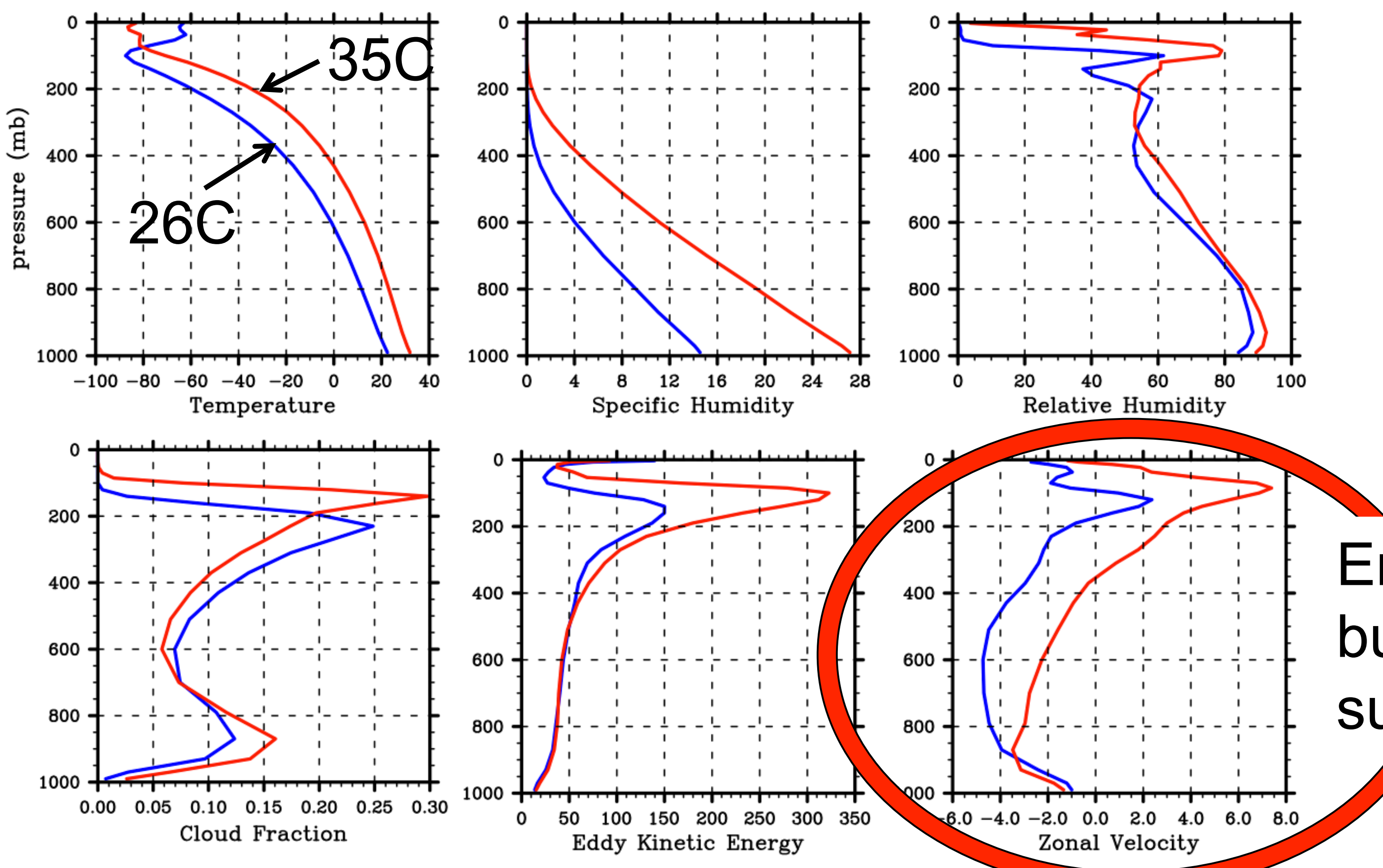

Encouraging, but no *surface* superrotation

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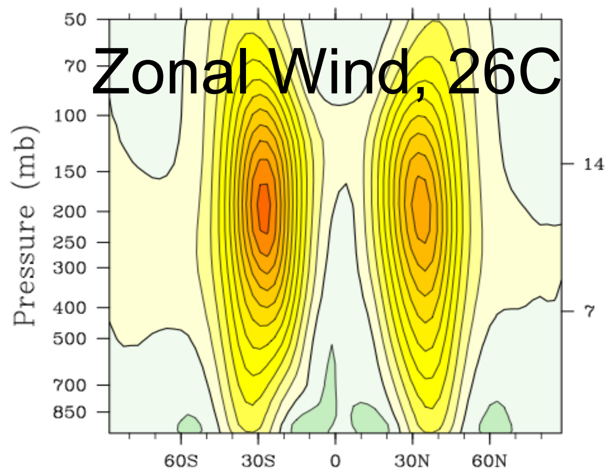
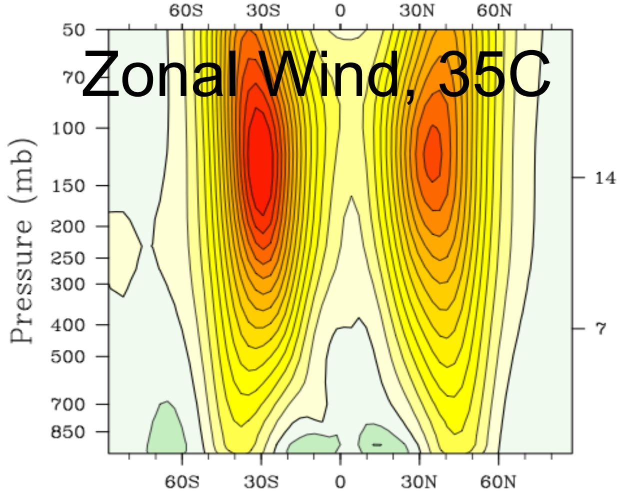
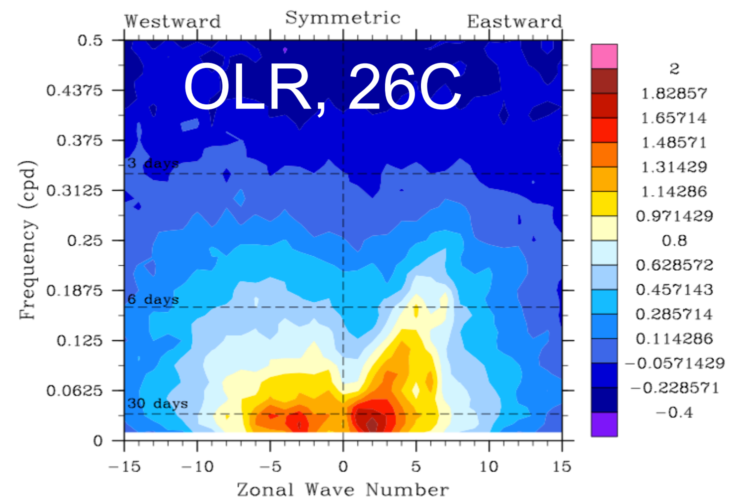
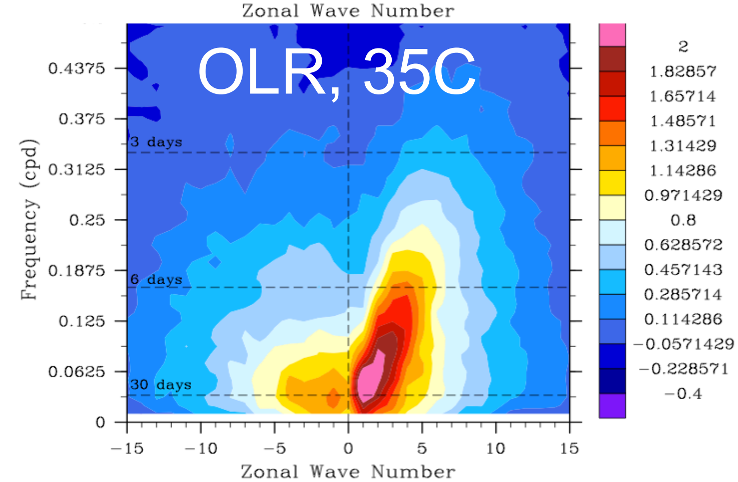




Increased MJO-like activity with SST!

Mechanism: positive feedback due to steepening of mean MSE profile in warmer climate [Arnold, Kuang, Tziperman, in press]





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; Arnold, Kuang, Tziperman, 2012]