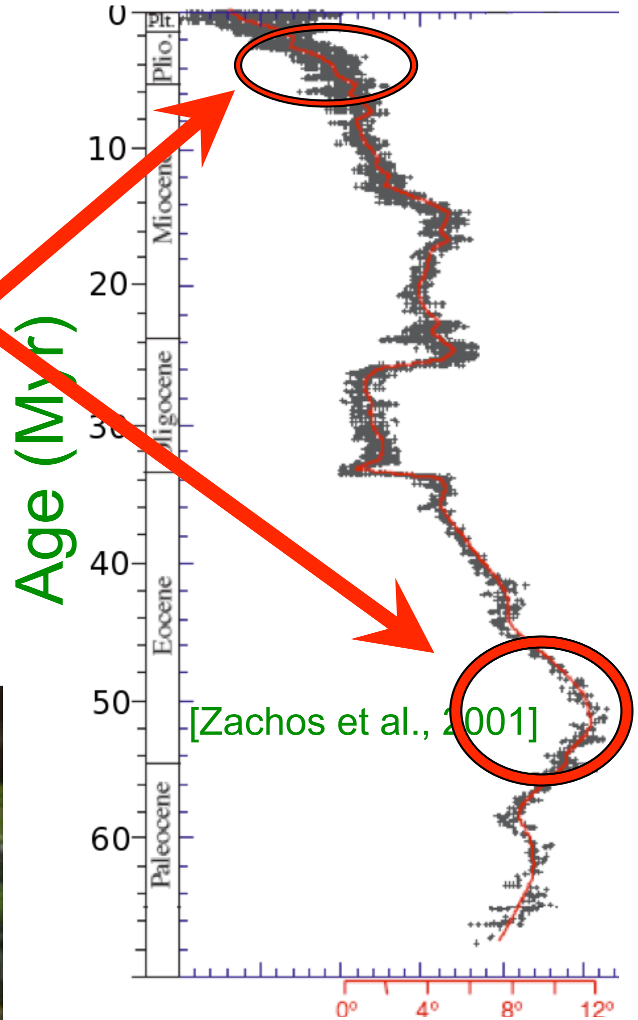
Two lessons from past warm climates

1. 34-146 Myr ago: *Dinosaur forecast: cloudy* (warming of the high latitudes by a convective cloud feedback) **Dorian Abbot**
2. 2-5 Myr ago: *Permanent El Nino: due to atmospheric superrotation?* Brian Farrell

Gradual cooling over past 55Myr



Deep ocean Temperature

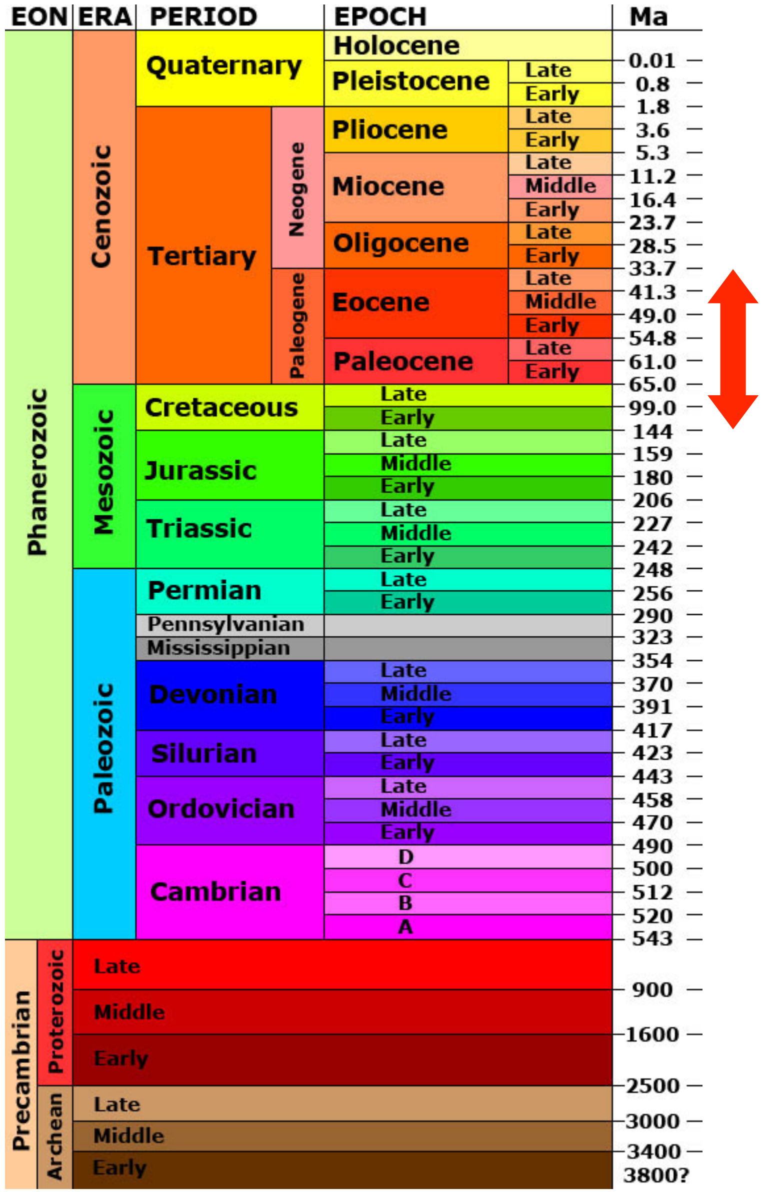
A High Latitude Convective Cloud Feedback and Equable Climates

LESSON 1

Dorian S. Abbot

Eli Tziperman

Hadrosaurus – Cretaceous [Karen Carr]



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

1) **Observations**: very warm climate 146-34 Myr ago

2) **The mystery**: Warm high-lats & warm continental winters cannot be reproduced by GCMs even at *very* high CO2 levels. Even when they do get close, it is not clear why…

3) **Previous explanations…**

4) **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.

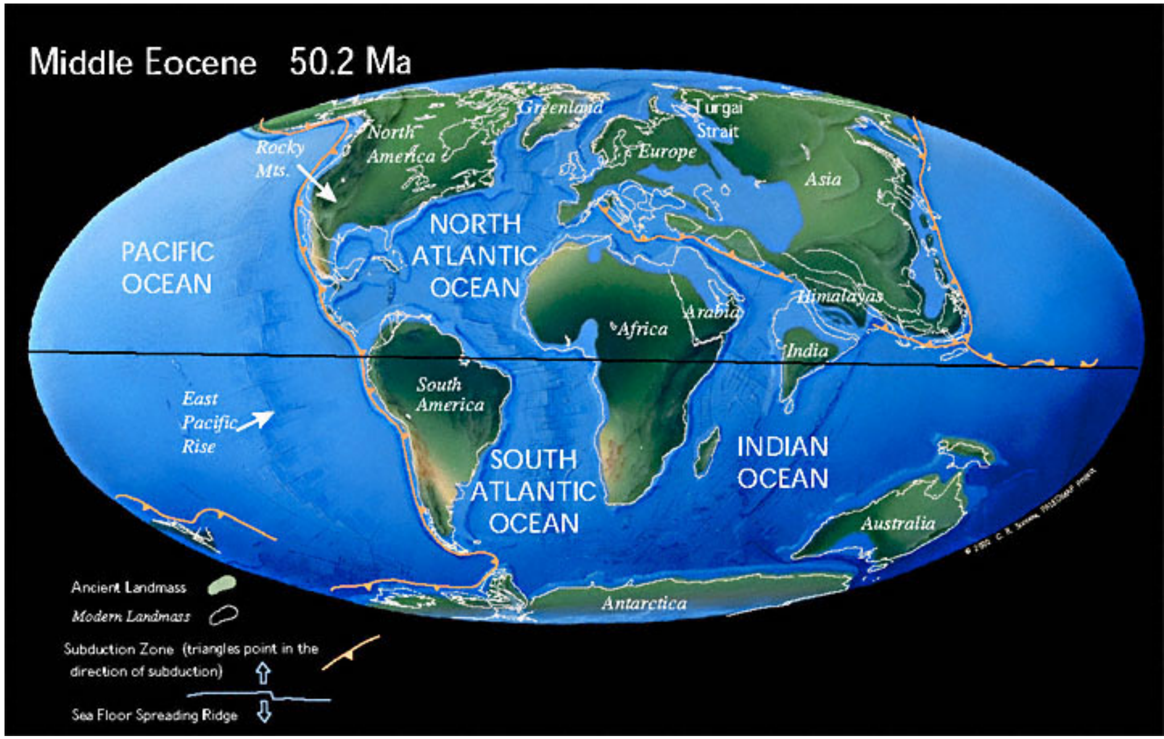
5) **Why should you care**

[Abbot & Tziperman, 2008a,b,c,d: QJRMS, GRL, JAS, submitted]

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

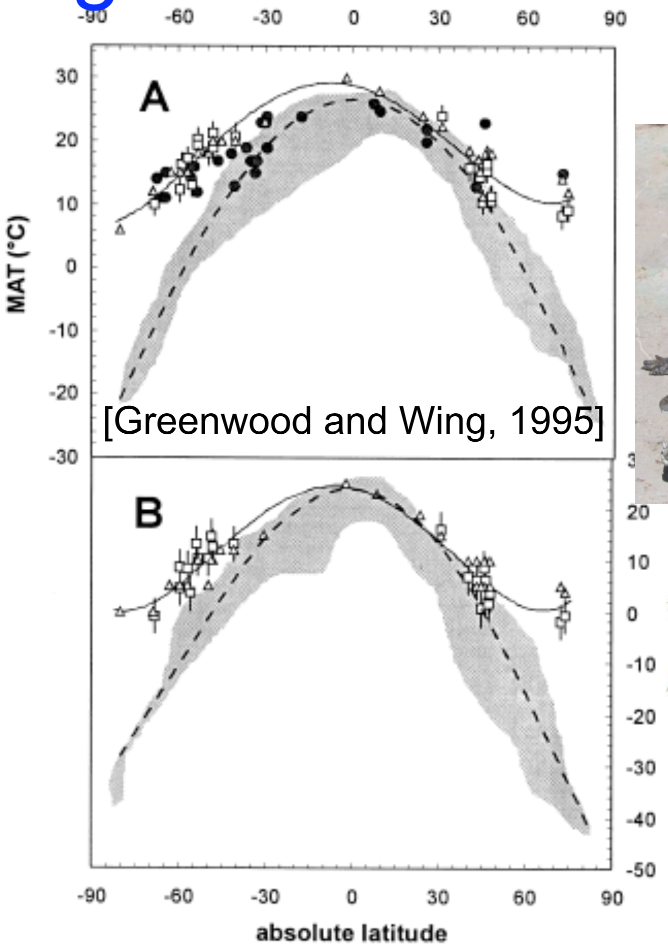


[146-34 Ma ago: Cretaceous - Paleocene - Eocene]

Eocene: modern-like continental configuration.

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

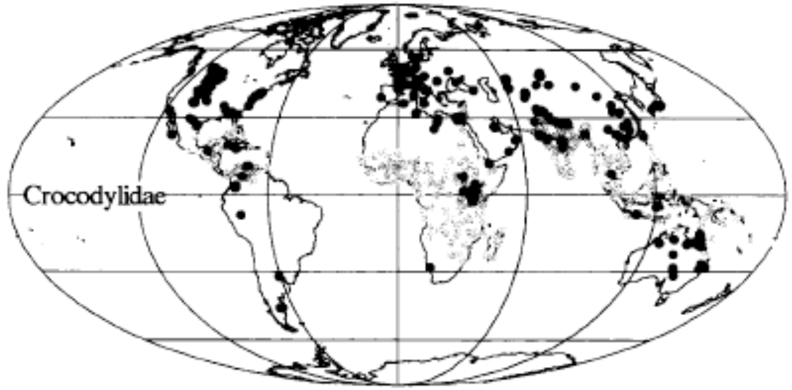
Cool tropics, warm high-latitudes

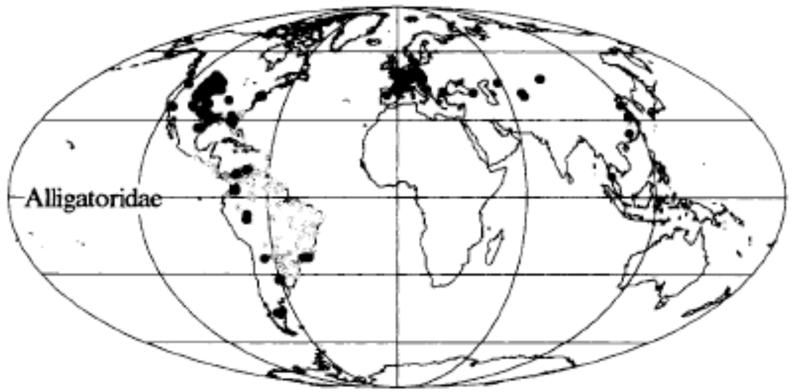


■ - Modern land temp.

● △ □ - Eocene SST; NLR&LMA, CLAMP

Crocodiles in Greenland, Palm trees in Wyoming!

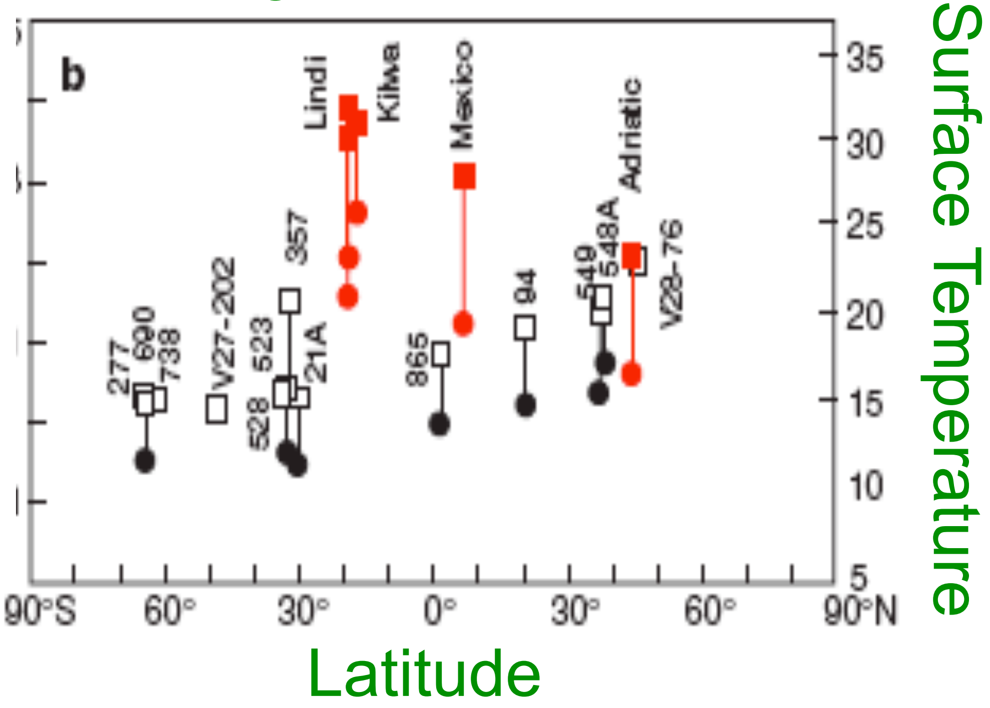




Crocodiles need: Mean annual T>14.2°C & Cold month mean >5.5°C [Markwick, 1998]

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

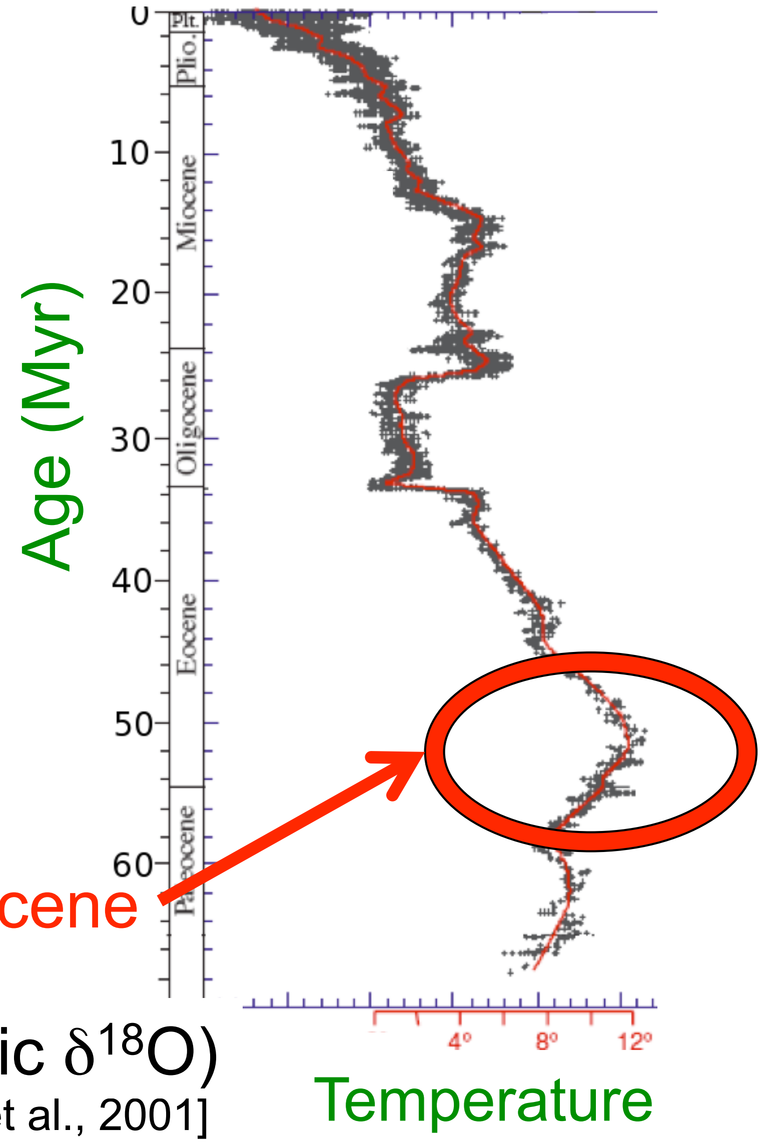
Surface ocean: Cool tropics, warm high-latitudes.



□ -Mixed Layer
○ -Intermediate
-New
-Old

(Planktonic $\delta^{18}O$, Mid-Eocene)
[Pearson et al., 2001]

Deep ocean: Warm, gradual cooling over 55Myr



(Benthic $\delta^{18}O$)
[Zachos et al., 2001]

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

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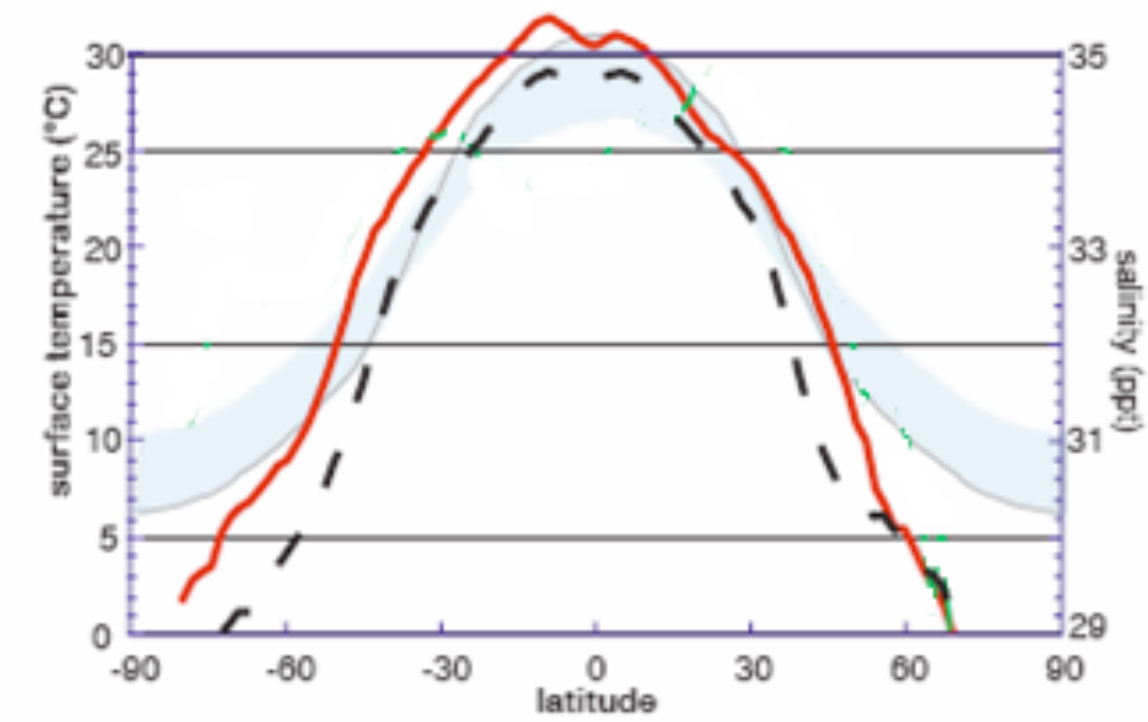
The good news: GCMs & data don't agree:

➔ State-of-the-art fully coupled GCMs cannot reproduce Eocene (~50Myr) proxy observations [e.g. Huber and Sloan, 2001]

➔ When some of them get close [Sheillito et al 2003], the mechanism is not clear



- - - - Modern Model SST

—— - Eocene Model SST

- Eocene Proxy SST

Coupled GCM study of [Huber and Sloan, 2001], for example. Uses best guess Eocene:

1. Bathymetry
2. Topography
3. Land Surface
4. Vegetation
5. CO_2 (560 ppm)

Sheillito et al 2003: AGCM at ***2000 ppm*** gets closer, but mechanism not clear

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

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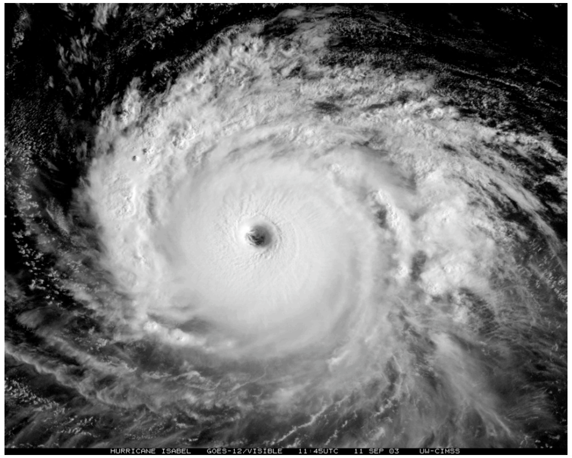
Previously proposed mechanisms

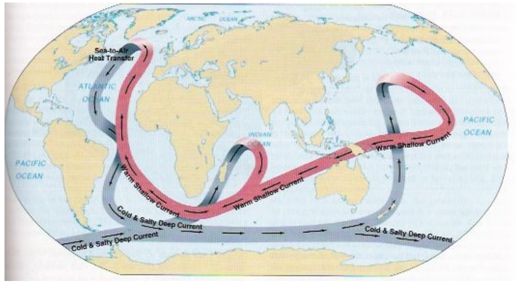
Ocean Atmosphere Stratos. clouds

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

Stronger hurricanes

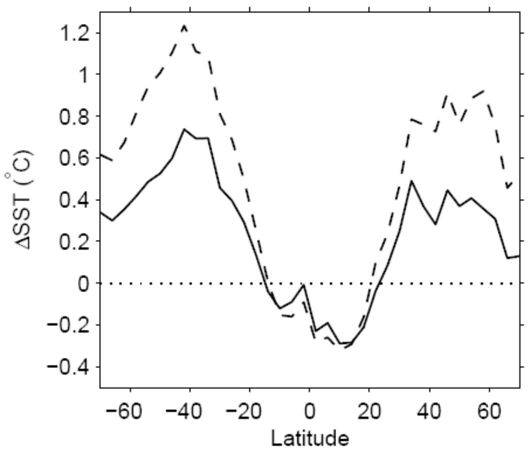


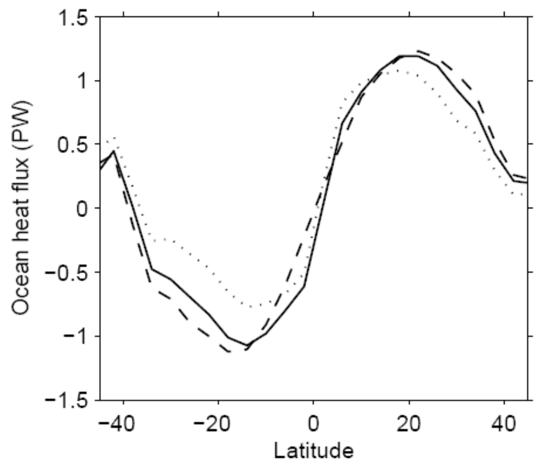
Thermohaline circulation



Warmer high latitudes

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

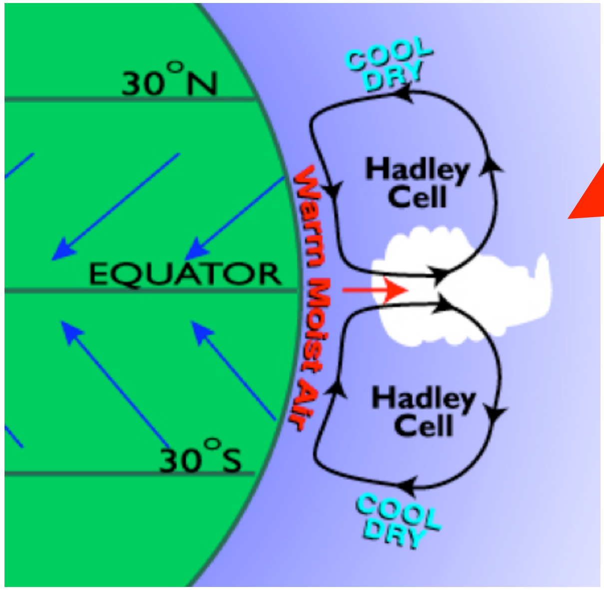




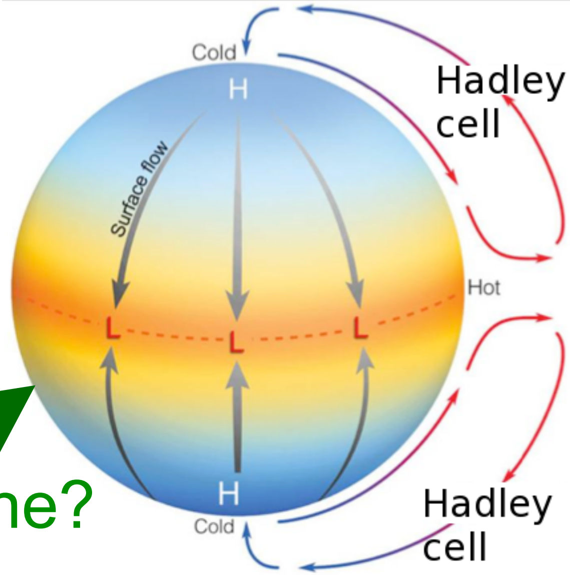
Previously proposed mechanisms

Ocean **Atmosphere** Stratos. clouds

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



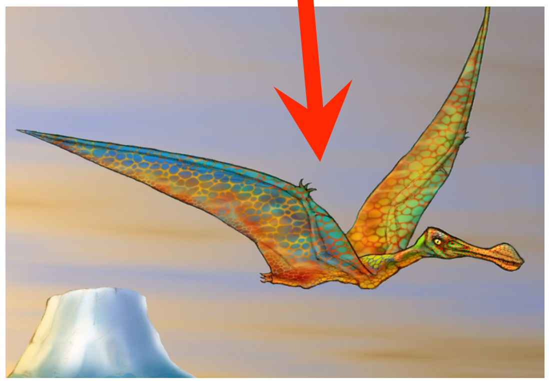
Today



Eocene?

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

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

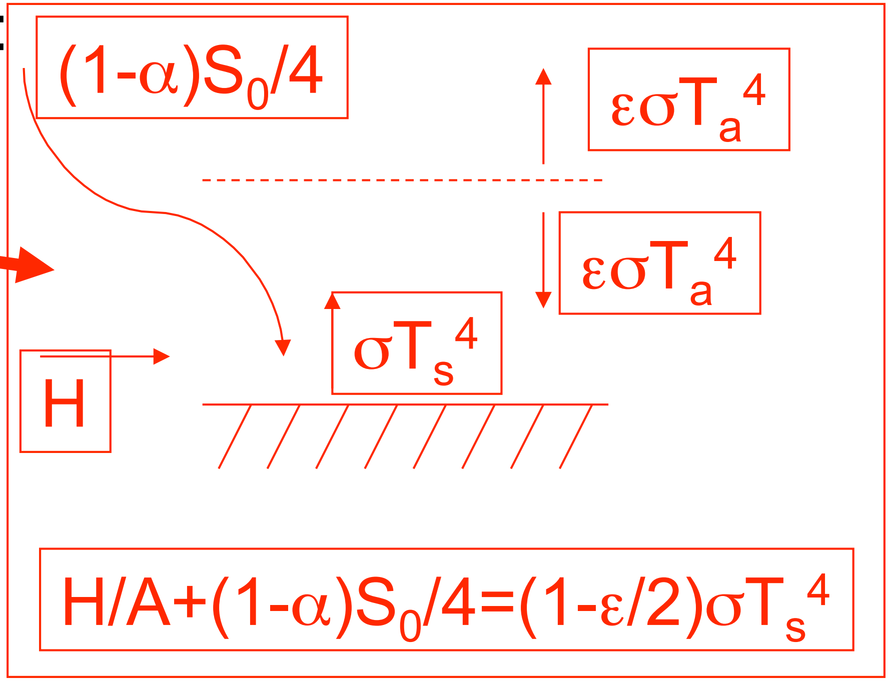


But: requires X8 angular momentum dissipation; Based on now challenged theory of [Schneider 77; Held Hou 80]

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

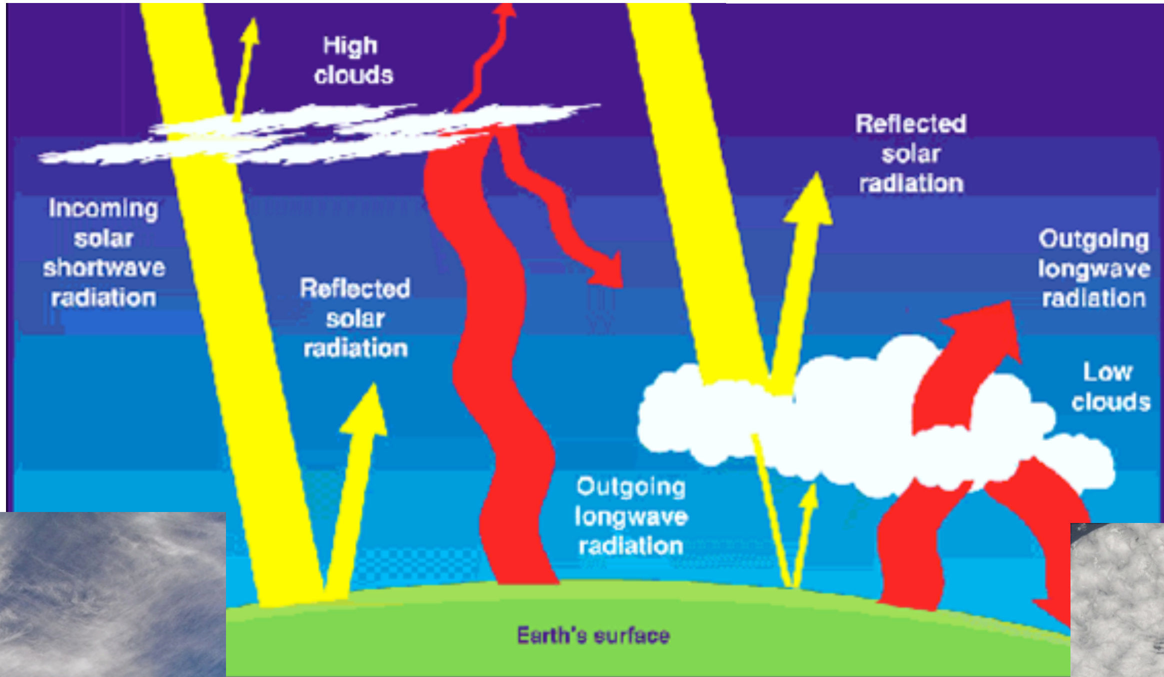
A reminder: Cloud feedbacks

High clouds (cirrus)

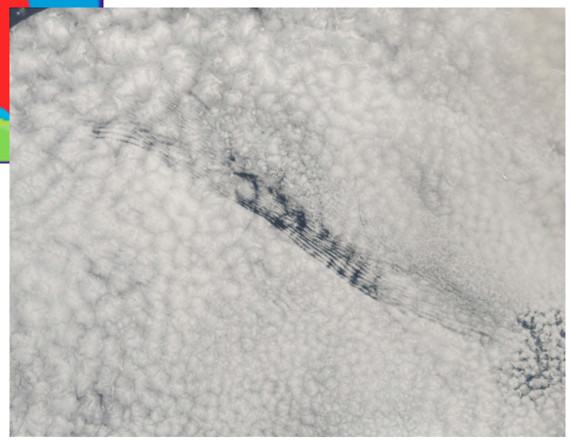
- low albedo, high emissivity
- High altitude (>8 km)
- Warming effect on climate

Low clouds (marine stratus)

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



➔ high clouds may help explain equable climate



[Back to] 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.

[PSCs at dusk over the Arctic region of Sweden]

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

[End of] Previously proposed mechanisms

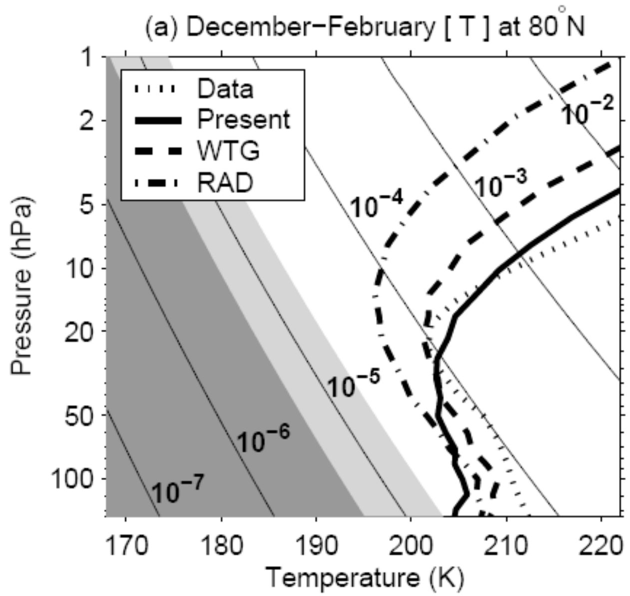
Ocean Atmosphere **Stratos. clouds**

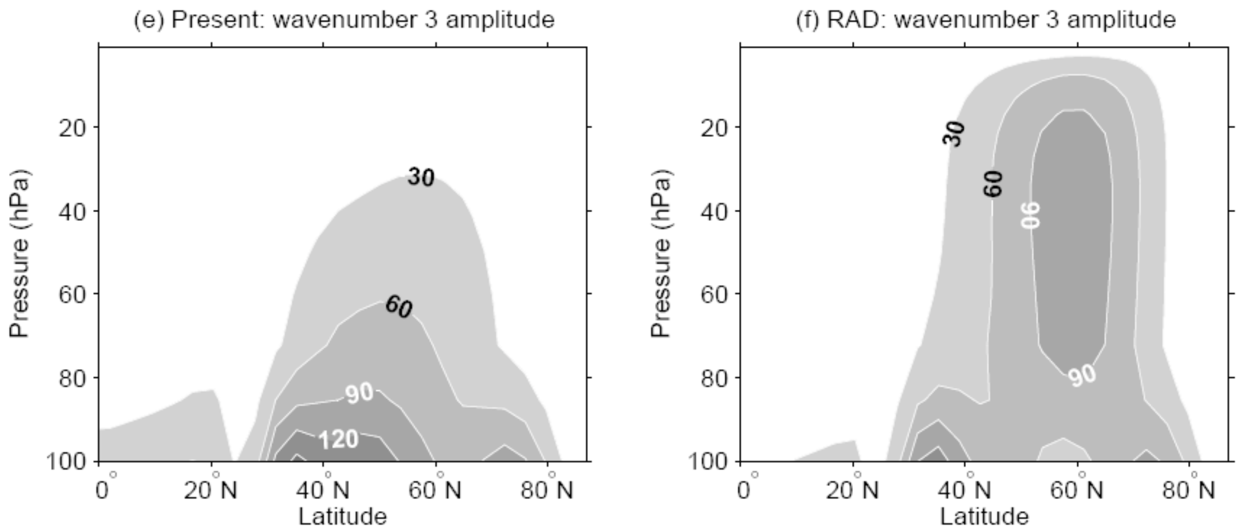
Polar Stratospheric Clouds have a strong greenhouse effect:

- 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]





Stronger waves ➔ stronger BD circ

Shaded = PSCs can form

An interim summary…

- High CO2, water vapor, increased poleward heat flux by ocean/ atmosphere cannot explain equable climates (Eocene, 50Myr)
- Perhaps clouds? Polar *Stratospheric* clouds not so simple…
- Next, our proposed mechanism…

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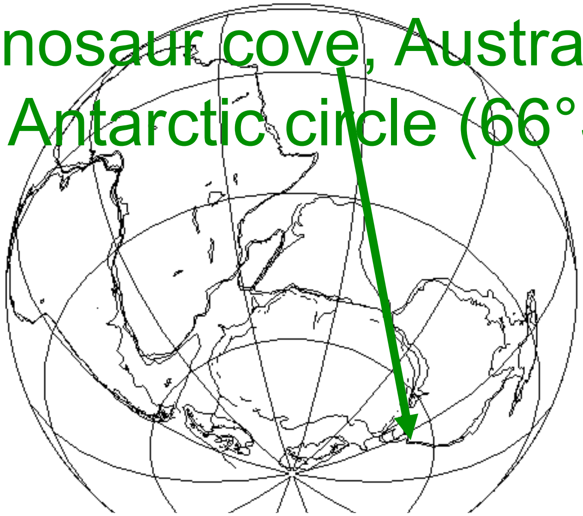
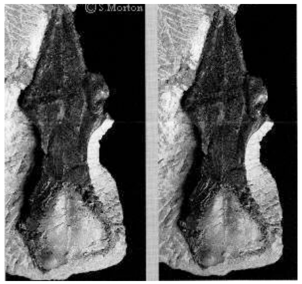
but 1st, more data: Polar dinosaurs! an evidence for warm *Antarctic* temperatures:

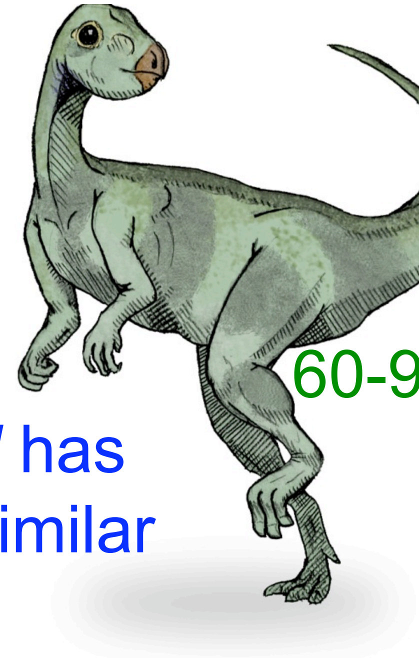
Large-eye dinosaurs roaming in the darkness of the polar night…

Dinosaur cove, Australia, south of Antarctic circle (66°S) 120Myr



Fossil optical lobes





60-90 cm

juvenile *hypsilophodontid* has immense optical lobes. Similar tropical species don't.

Thanks to **Brian Farrell** for pointing out this evidence…

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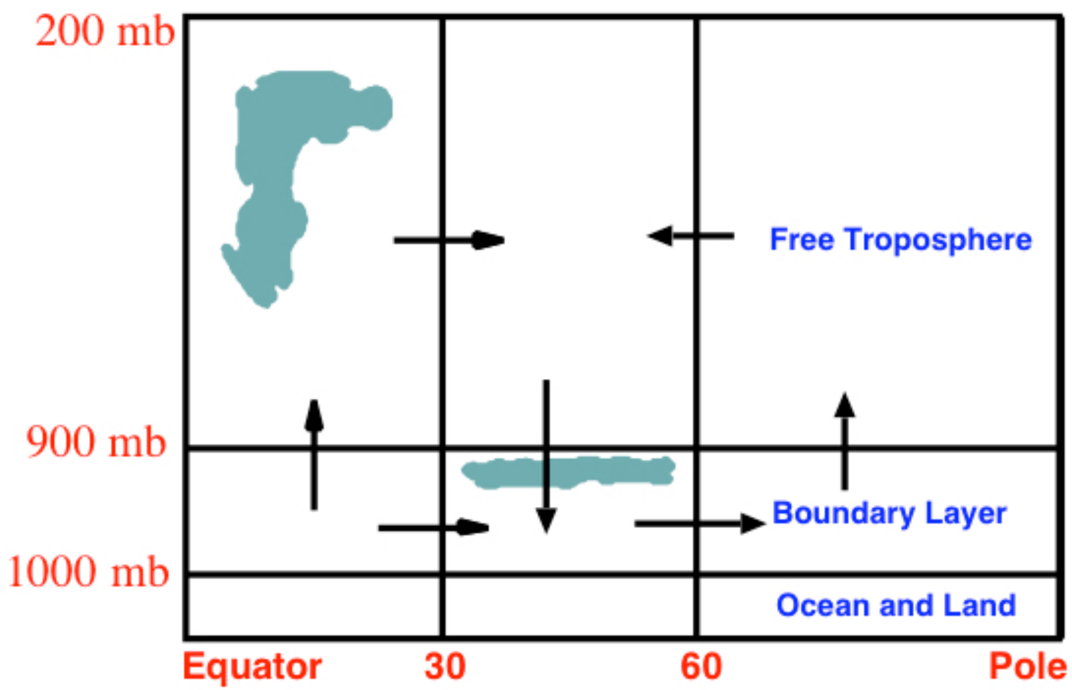
First step: a “toy” model (1^{st} / 2)

- 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 (2^{nd} / 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

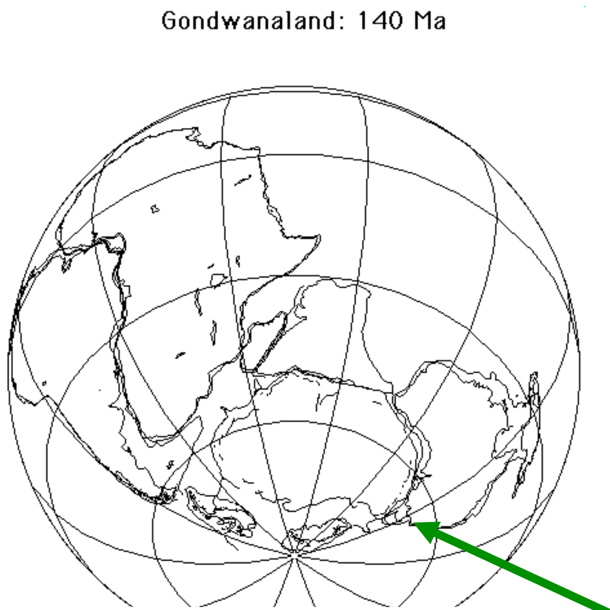
$$
\begin{aligned}
u_t + \frac{1}{a\cos(\theta)}\frac{\partial}{\partial \theta}(uv\cos(\theta)) - uv\tan(\theta)/a + \frac{\partial}{\partial p}(\omega u) - 2\Omega\sin(\theta)v &= \nu\frac{\partial^2 u}{\partial \theta^2} - \delta_{k2} r u \\
v_t + 2\Omega\sin(\theta)u &= -\frac{1}{a}\frac{\partial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

Polar dinosaurs! An evidence for warm Antarctic temperatures

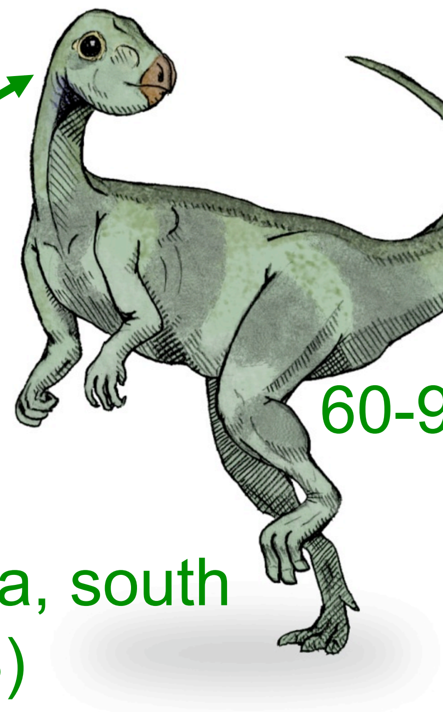
→ **A brain of a juvenile *hypsilophodontid***, a large-chicken size **dinosaur** from Australia, **has immense optical lobes** - where nerve impulses from brain are processed to form a visual image.

→ Non-polar similar dinosaurs don't show such optical lobes.

→ Such a creature would have been able to see very well while roaming in the darkness of the polar night…



Fossil
optical lobes



60-90 cm

Dinosaur cove, Australia, south of Antarctic circle (66°S)

Thanks to Brian Farrell for pointing out this evidence…

Model experiments & results: summary

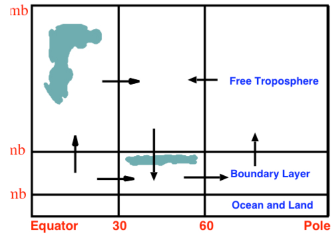
Model experiments:

Slowly increase CO_2 to extreme values & then decrease it

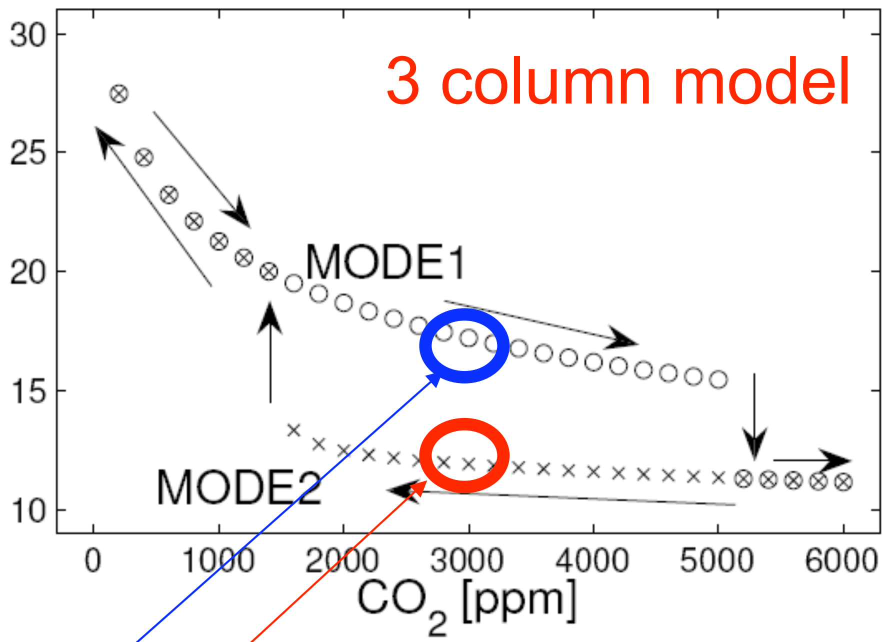
Results:

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

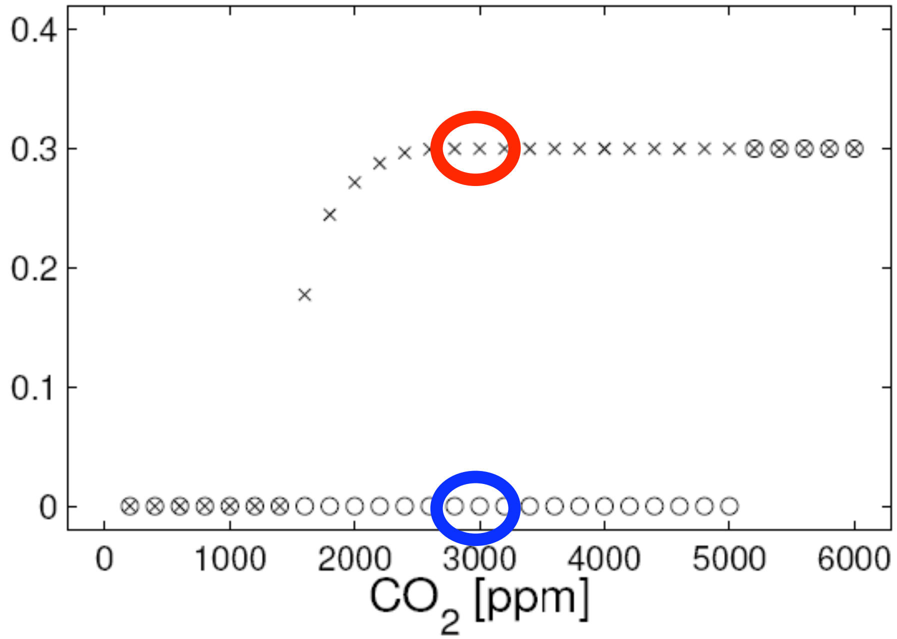
Results: 2 modes of atmospheric dynamics; [& multiple equilibria at a given co2, hysteresis]



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



Convective high cloud fraction, polar column.



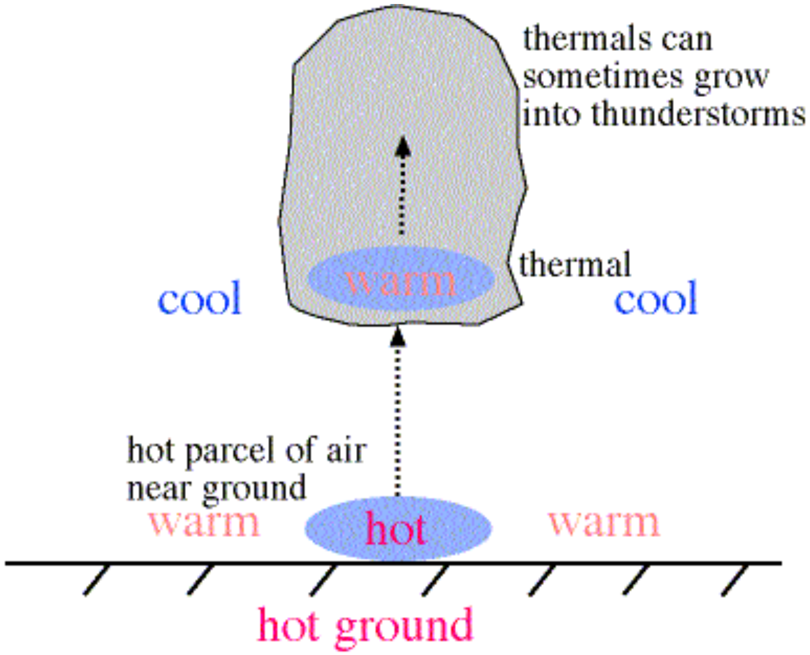
“Present-day: solution: non convecting, colder, high EPTD

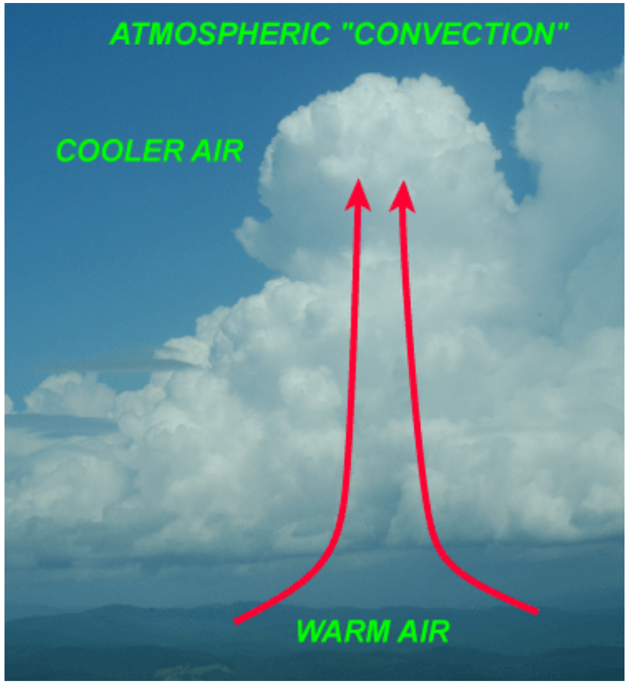
“Equable” solution: convecting, with high clouds, warm, low EPTD

Arrows: path of solution if CO2 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



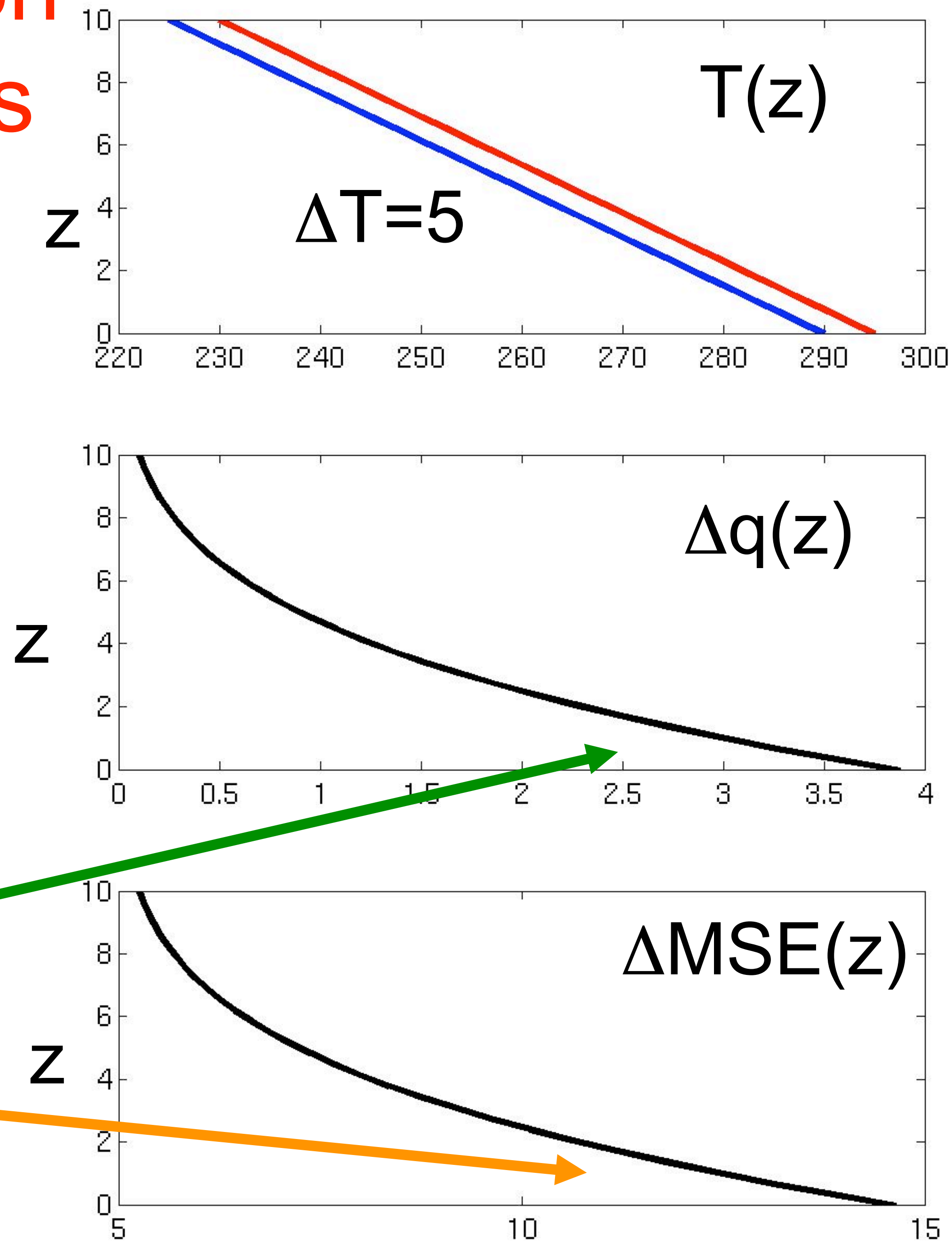


http://apollo.lsc.vsc.edu/classes/met130/

Why does convection start at high latitudes @ high CO2?

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

why: Clausius-Clapeyron
➔ increasing CO2 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)

Convection and high clouds…

Convective clouds: cover a small area & have a higher albedo; give rise to anvil & then cirrus clouds which cover a much larger area and have a strong greenhouse effect and small albedo.

- Mode with *high latitude deep convection*, high clouds, low equator to pole temperature difference at high co2 is interesting regardless of multiple equilibria issue.
- Relevant to equable climate? Robust result?

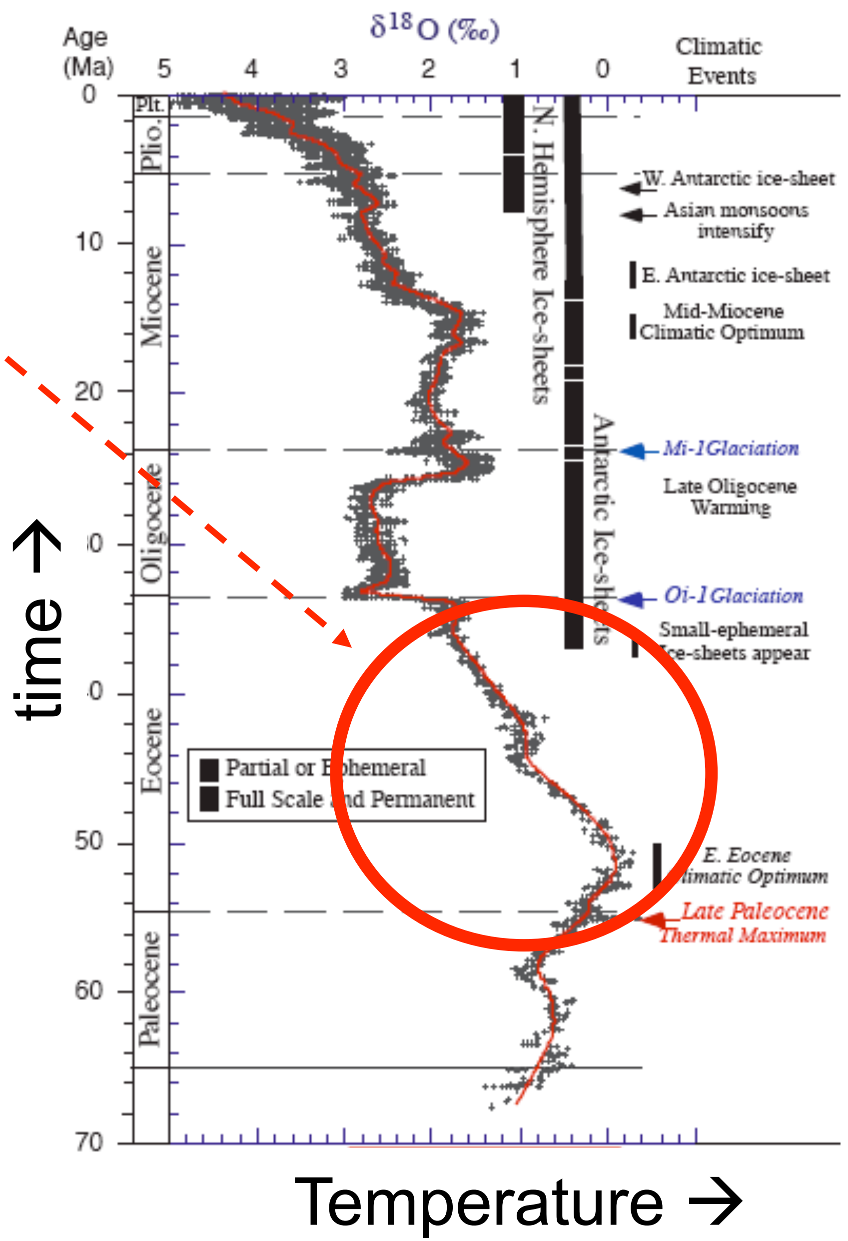
On the gradual cooling since the Eocene

Temperature gradually dropped since maximum in Eocene.

This does not look like a jump between two modes.

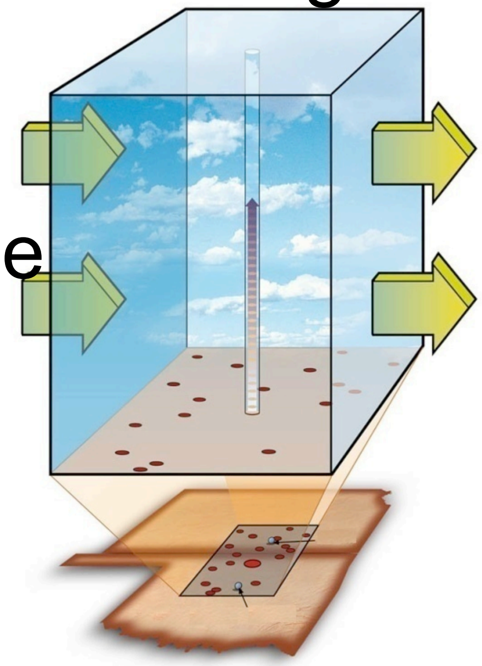
In a 30 box model version, convection onset *gradually* moves southward as CO2 decreases, and temperatures decrease gradually as well.

Even when convection does not occur at pole (arctic), it is heated via eddy fluxes from convecting mid-latitudes



Shocking news

- It seems not universally appreciated that simple toy climate models such as used here represent reality more reliably and accurately than the climate system itself. Some example of the enthusiastic reception.
- While searching for a more believable model, we have exposed (and considered using) the following shocking **SCAM**…



… but we eventually decided to use this one instead: The National Center for Atmospheric Research (NCAR) **SCAM**= **S**ingle **C**olumn **A**tmospheric **M**odel (Hack et al., 2004)

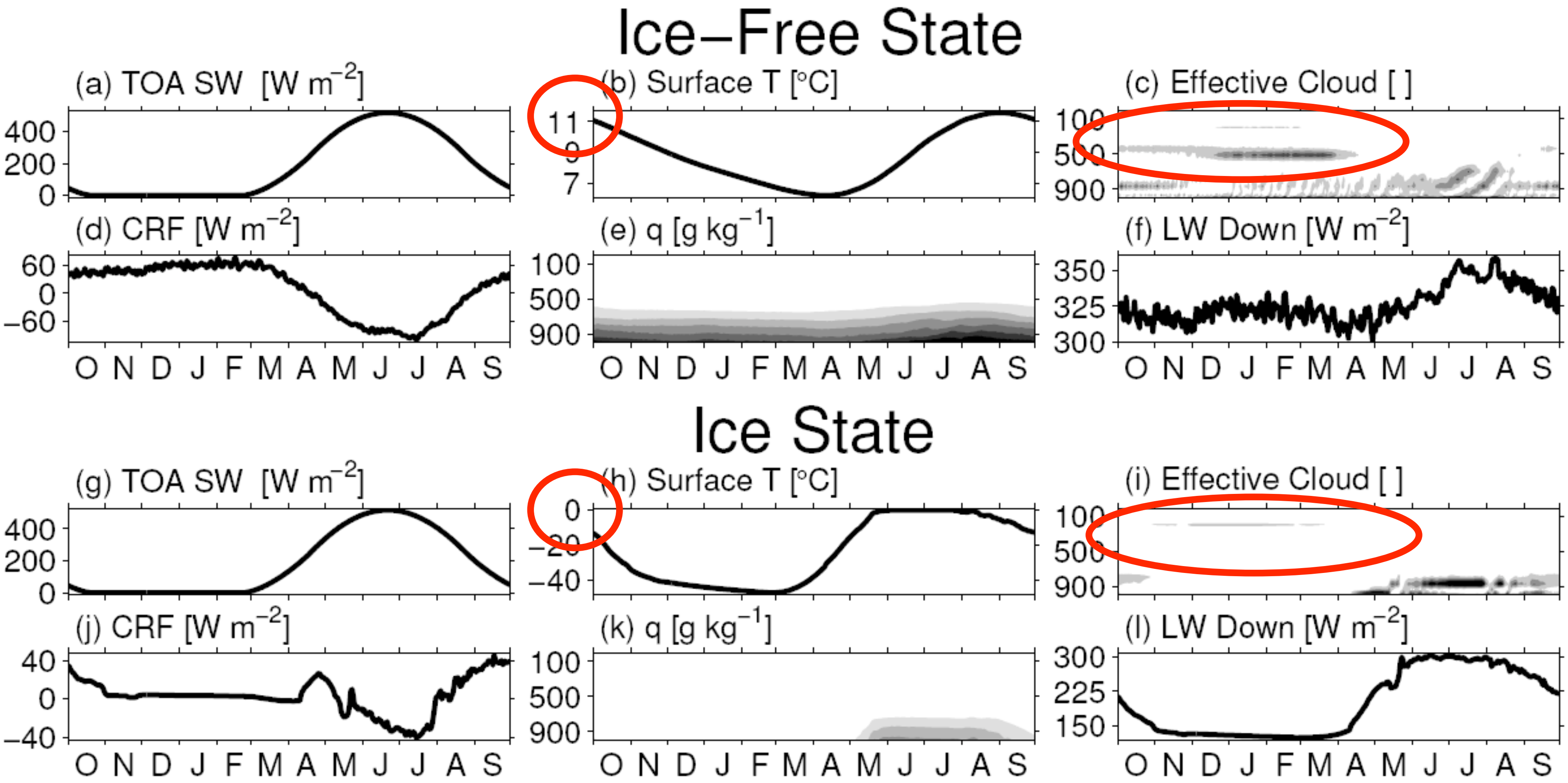
Date: Fri, 13 Jun 2007 08:58:18 -0700 (PDT)
From: Moses Odiaka [mosesadiaha@go.com]
To: Dorian Abbot, Eli Tziperman
Subject: CONFIDENTIAL PROPOSAL

Dear Sirs,
My name is Mr. Moses Odiaka from the Union Bank of Nigeria Plc, Lagos, Nigeria, department of *radiation and ocean mixing*. I write you in respect of a foreign customer with a Domiciliary account, Engineer Manfred Becker who died last year in a plane crash here in Nigeria.

So far, no one has come to claim the *18.5 million lines of code* in this account, *representing one of the largest GCMs in our bank*. *However, I have discovered that this complex state-of-the-art GCM is in fact a wrapper to the Budyko (1969) 1d climate model.* Only an insider such as me could produce the code or access to the deposit particulars.

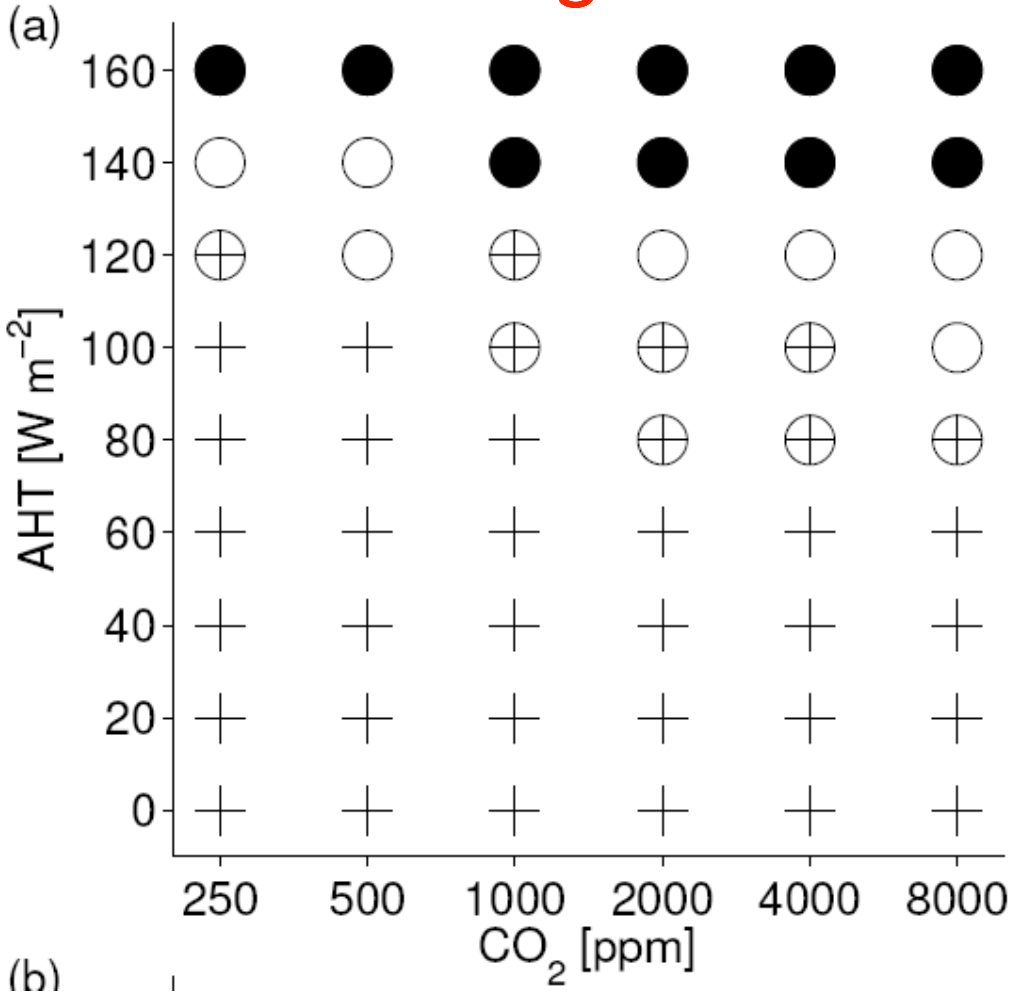
I hereby ask for your cooperation in using your name as the next of kin to the deceased to *send this code out to a foreign offshore modeling center for mutual sharing between myself and you.*

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

Multiple equilibria in seasonally forced SCAM due to the convection/ high cloud feedback



+: ice-state stable; ○: ice-free state stable; ●: ice-free state is stable even with long wave cloud radiative forcing artificially set to zero between September 1 and April 1.

Seasonality and continental interiors

Winter/ polar night: ocean heat storage can supply heat to sustain atmospheric convection through winter/ polar night (SCAM&CAM).

Continental interiors: preliminary results: latent heat release of drifting moisture from above-ocean convection can heat continental interiors. Speculation: drifting clouds could provide greenhouse effect over continents; weaker eddies in equable climate ➔ less drying by vertical eddy motions (thanks to Kerry).

Mature thunderstorm cloud with typical anvil shaped cloud.
http://www.physicalgeography.net

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

1) **Observations**: very warm climate 146-34 Myr ago

2) **The mystery**: Warm high-lats & warm continental winters cannot be reproduced by GCMs even at *very* high CO2 levels. Even when they do get close, it is not clear why…

3) **Previous explanations…**

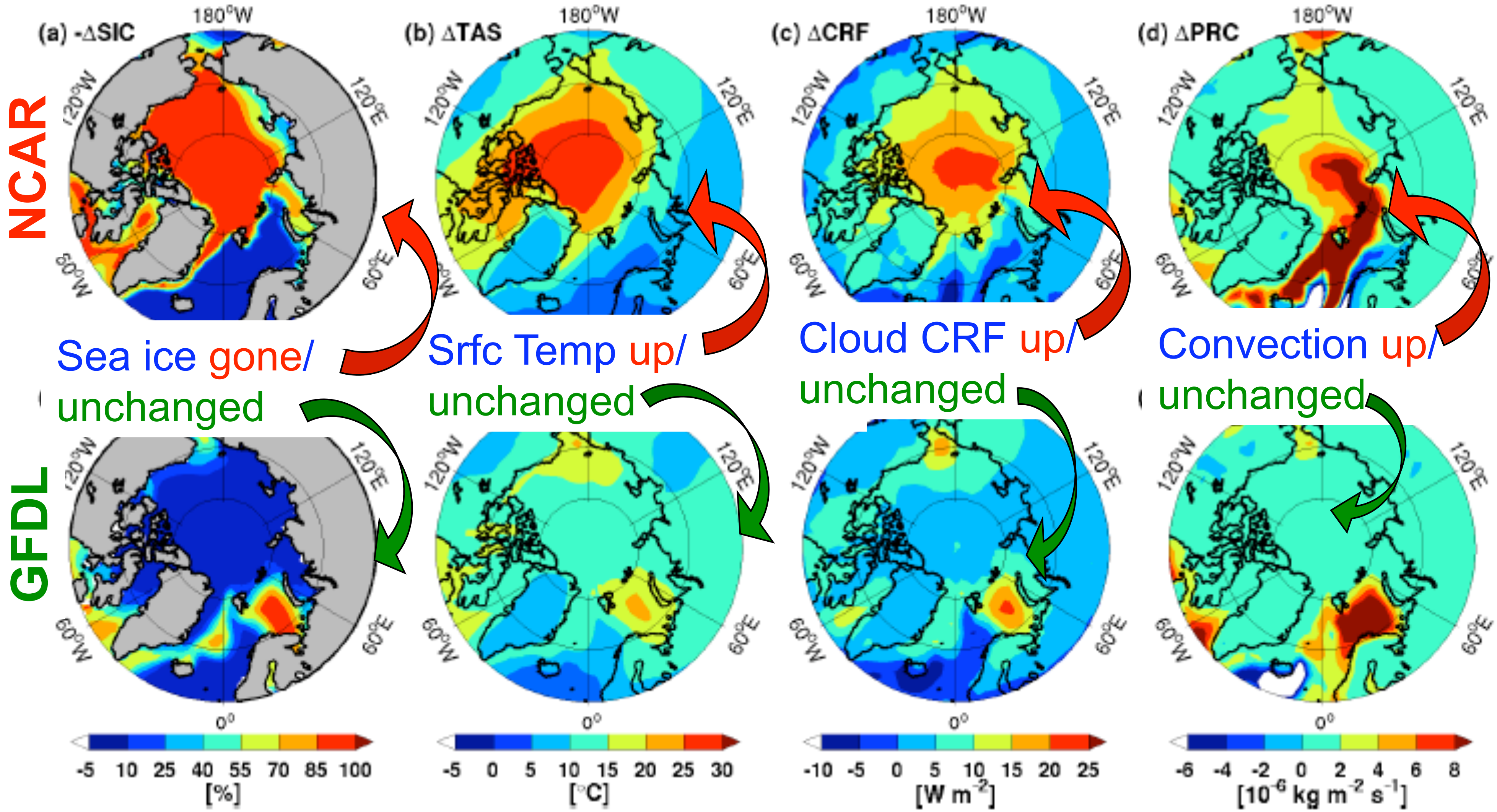
4) **Our mechanism**: a qualitatively different state of the atmosphere, with tropical-like deep atmospheric convection and high tropospheric clouds at mid- to high-latitudes providing a strong greenhouse effect.

5) **Why should you care**

Back to the future

Enticing 3D IPCC Model Simulations 1st/3

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



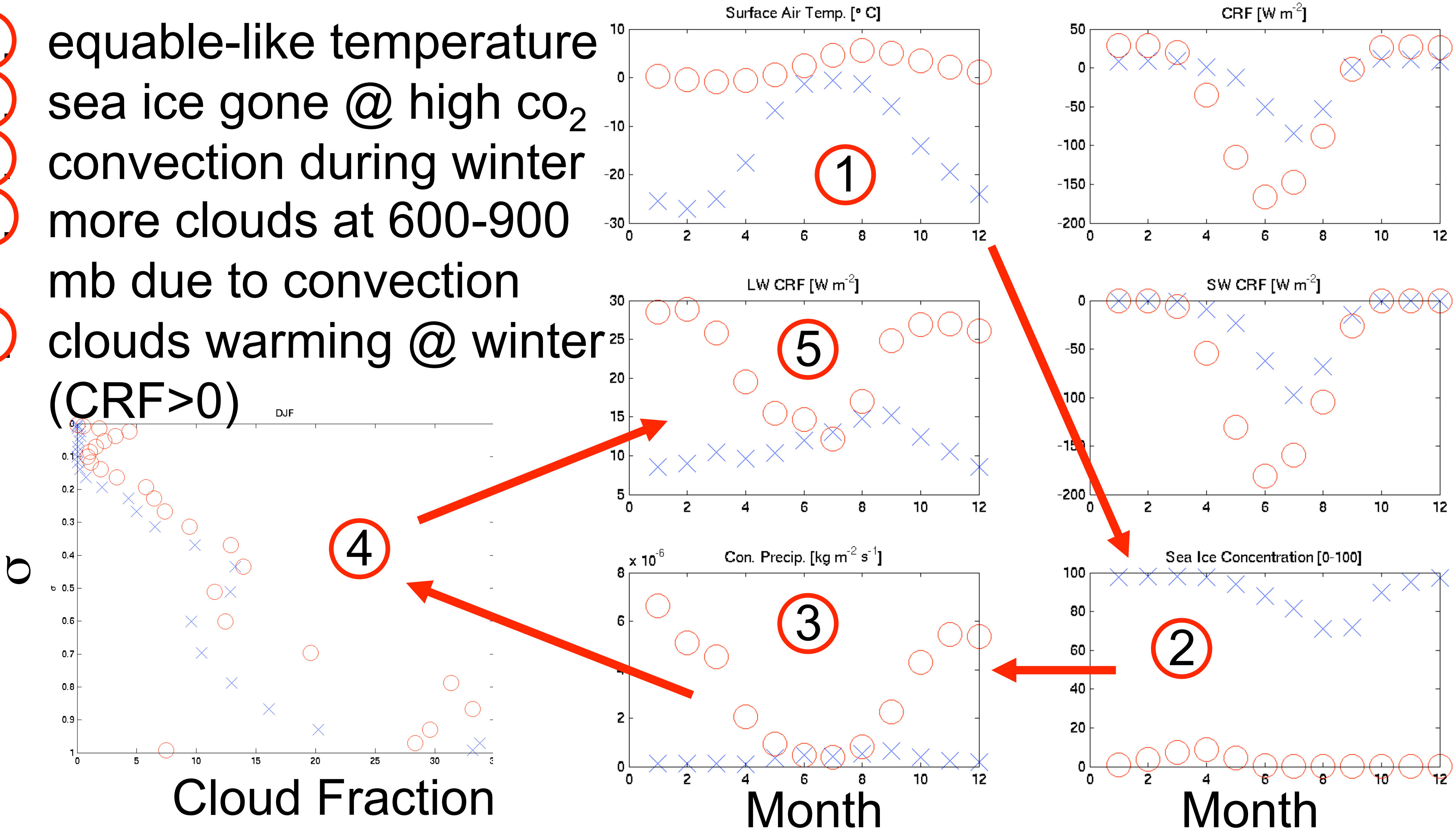
➔ IPCC NCAR 3d model behaves like toy model & 1d SCAM!!

➔ Enticing 3D IPCC Model Simulations 2nd/3

Exactly like 1d SCAM & toy model!

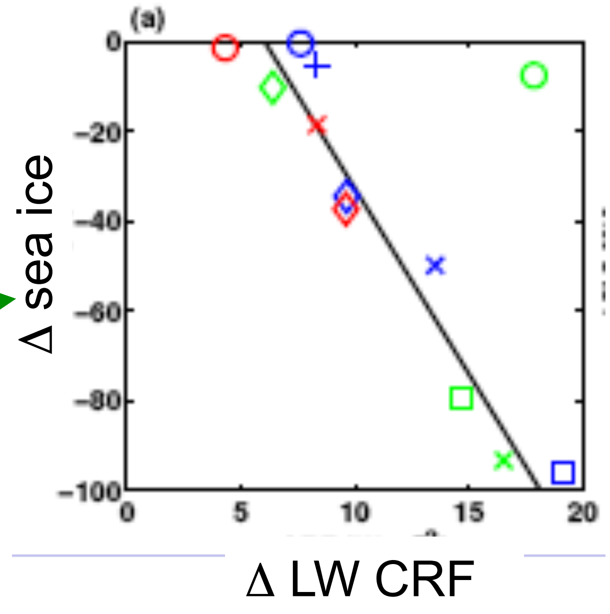
Consider the solutions of the NCAR 3d coupled ocean-atm model, north of 80N for pre-industrial (x) & at x4 CO_2 (o):

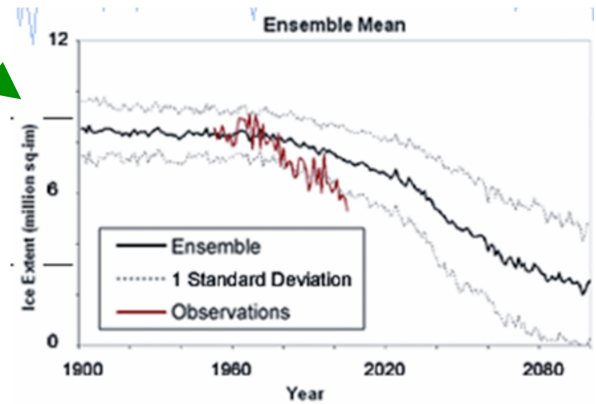
1. equable-like temperature
2. sea ice gone @ high co_2
3. convection during winter
4. more clouds at 600-900 mb due to convection
5. clouds warming @ winter (CRF>0)

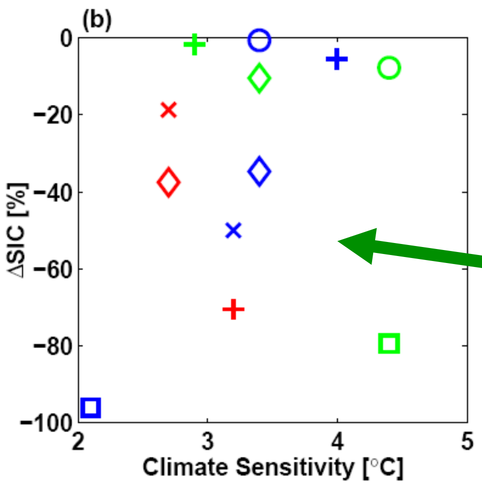


3D IPCC model confirmation; & why should you care…? 3rd/3

- All IPCC models show the proposed cloud-radiative feedback to some extent
- The IPCC models underestimate rapidity of summer sea ice reduction
- Do models underestimate the cloud feedback proposed here? ➔ Could winter sea ice disappear sooner than @ x4 CO_2?



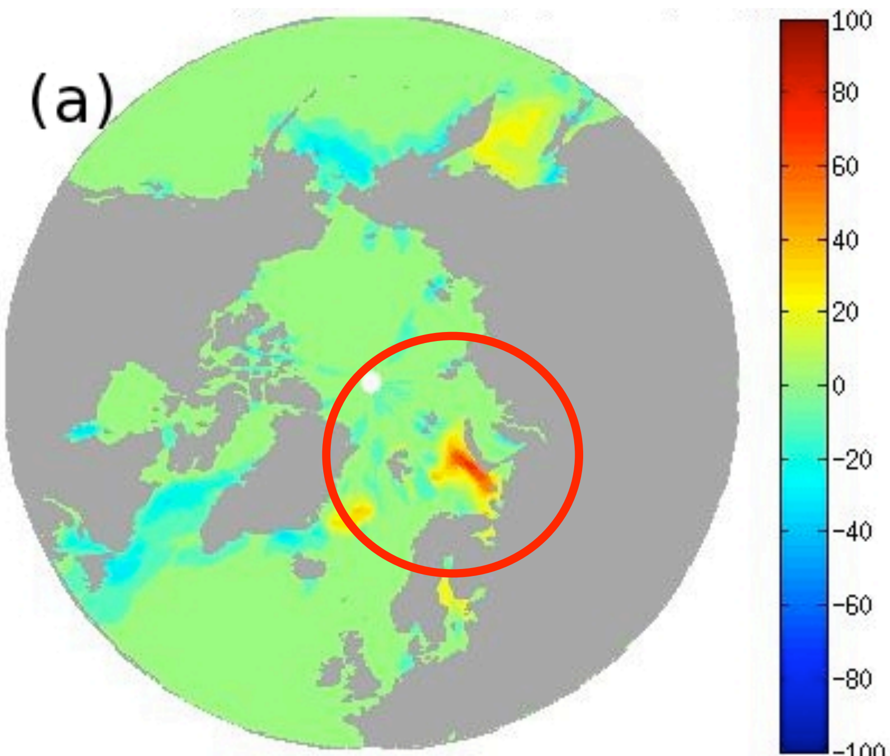




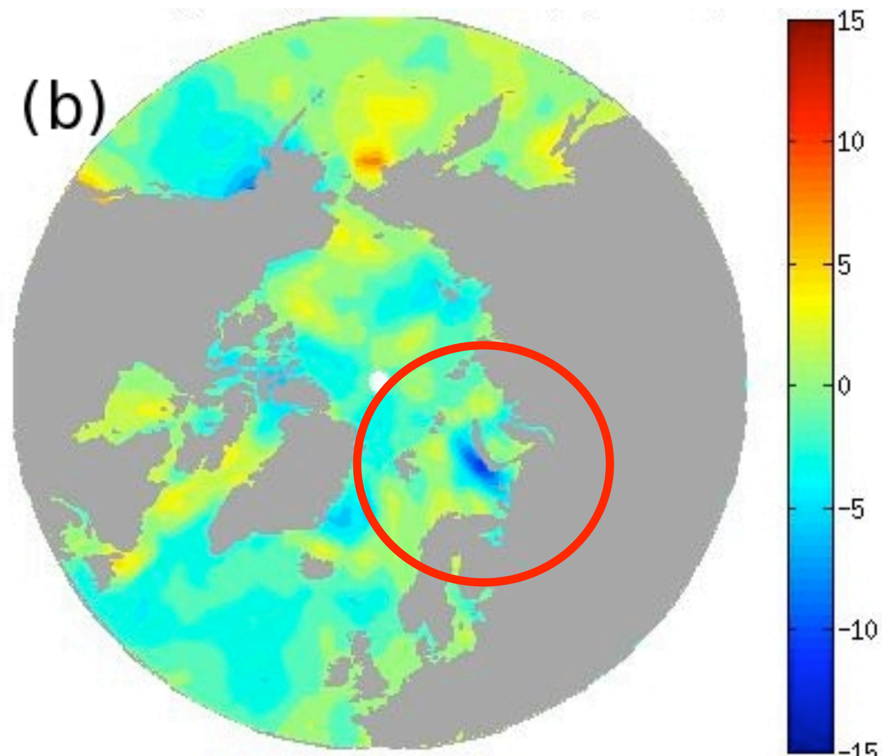
- Arctic sensitivity to this feedback is completely uncorrelated with global sensitivity to X2 CO2 ➔ onset of proposed feedback is difficult to predict…!

Confirmation using modern observations
with Kerry Emanuel, Ben Leibovitch

- 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

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.
- Why don't all GCMs see this? convection/ cloud parameterizations? Perhaps haven't been analyzed sufficiently?
- Future…? Arctic uncertainty may mean *more* warming …

In progress: explicit mechanism for continental interiors

[Abbot & Tziperman, 2008a,b,c,d: QJRMS, GRL, JAS, submitted]

More…

Pliocene (1.8-5.3 Myr) "*permanent El Nino*" & atmospheric superrotation
OR
How to get in trouble without doing any work

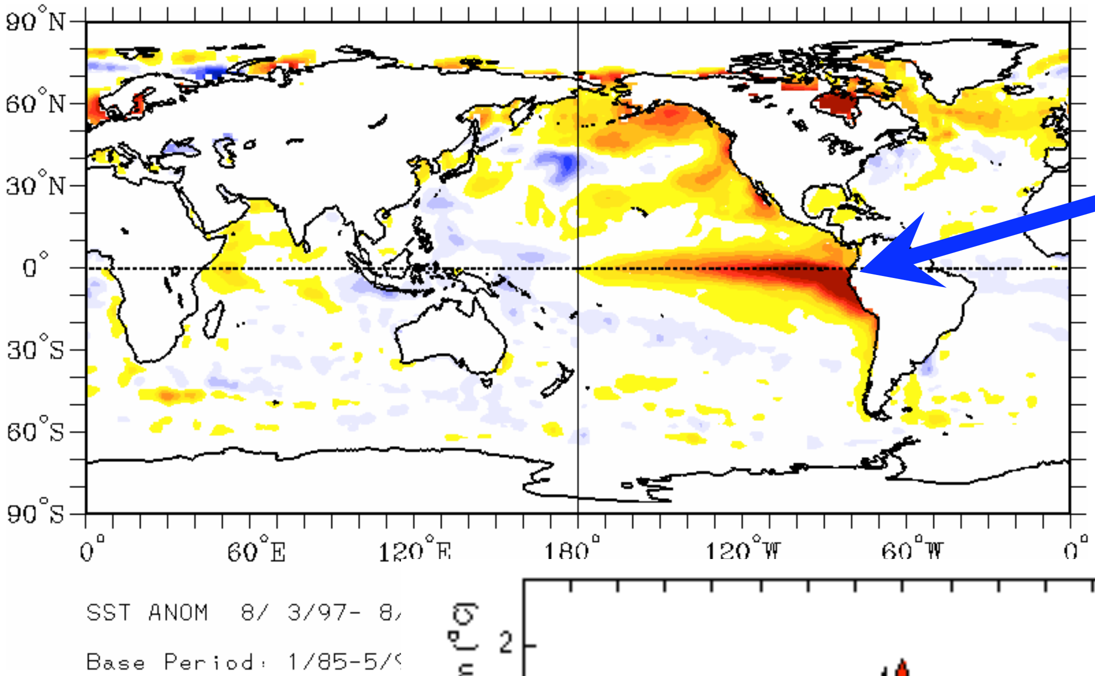
with: **Brian Farrell**

LESSON 2

Outline

- El Nino, thermocline, easterlies
- Pliocene, "permanent El Nino"
- Some previous attempts
- Superrotation! turning off those easterlies
- Why climate models don't get it this time?
- Do we care…?

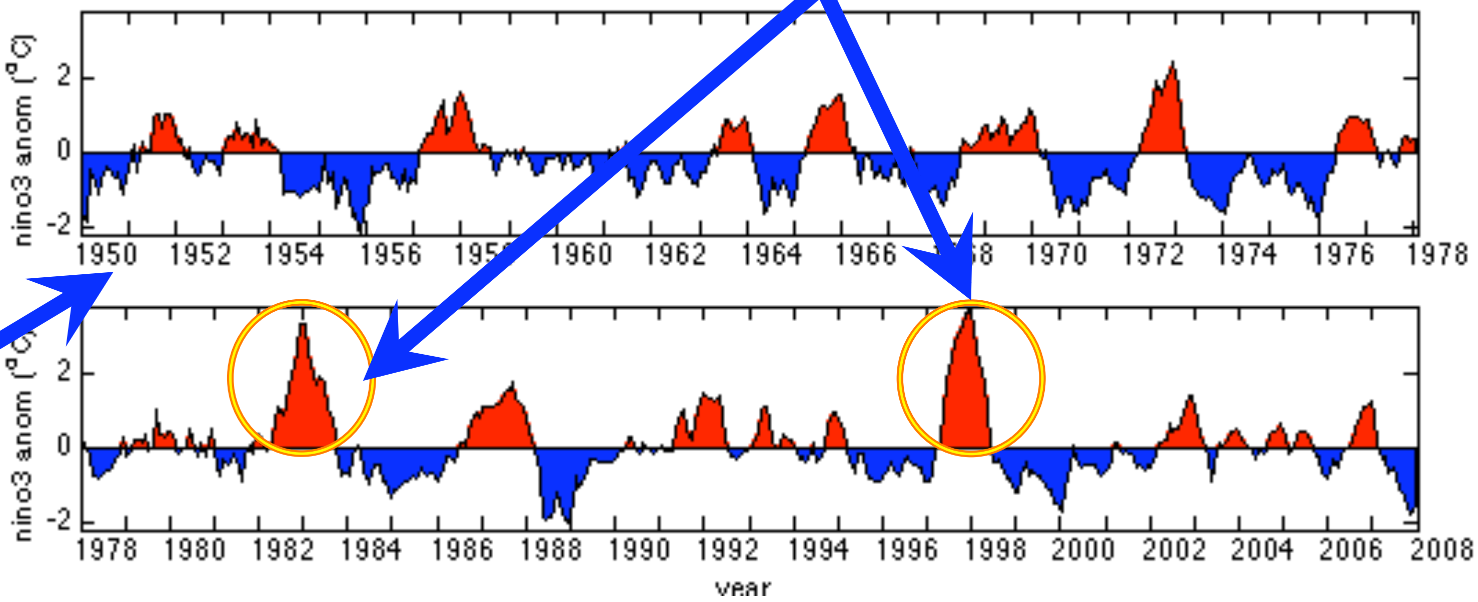
El Nino, the equatorial Pacific easterlies & thermocline (1st/2)



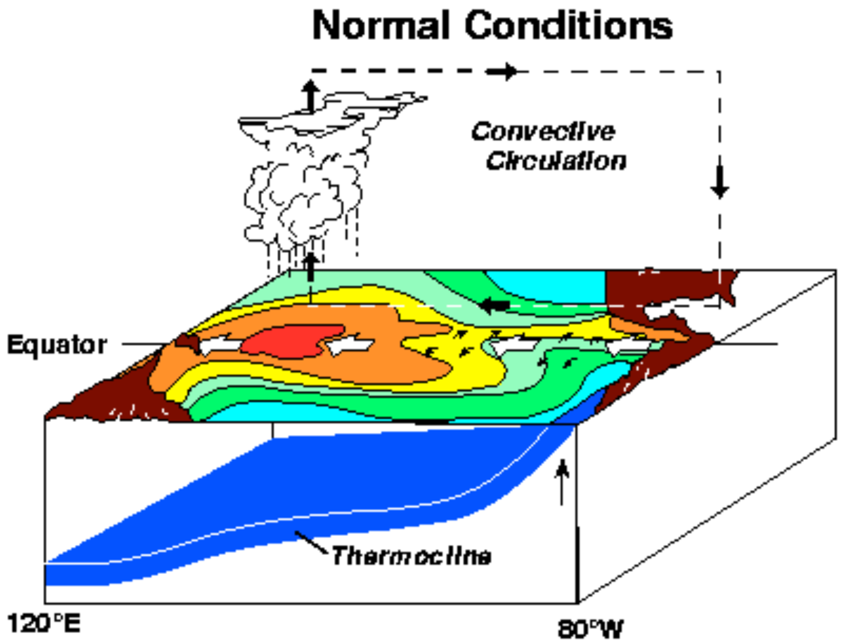
East Pacific warming during El Nino

1982, 1997, strongest El Ninos of past 100 years

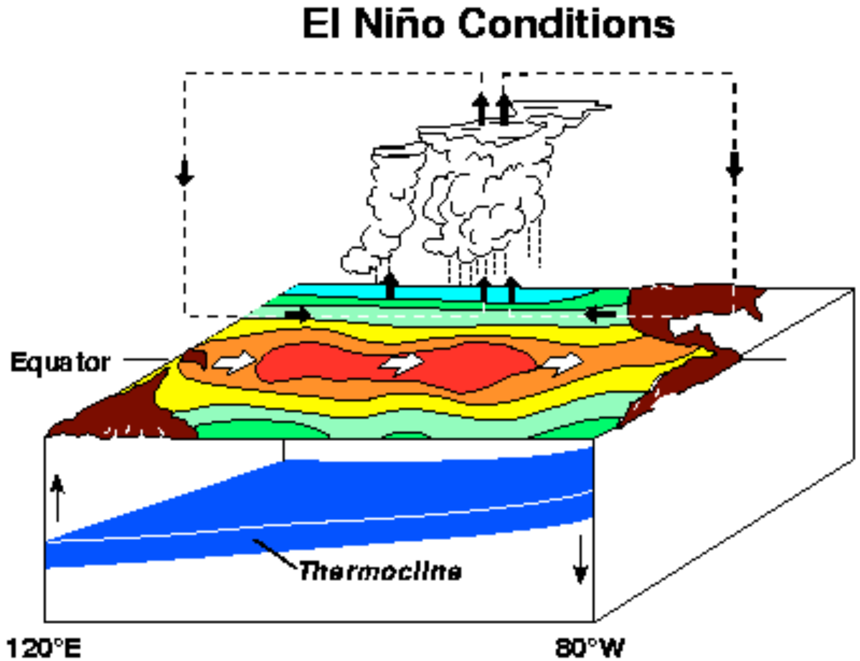
East Pacific temperature time series, 1950-2008; El Nino: every 3-6 years



El Nino, the equatorial Pacific easterlies & thermocline (2nd/2)



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.

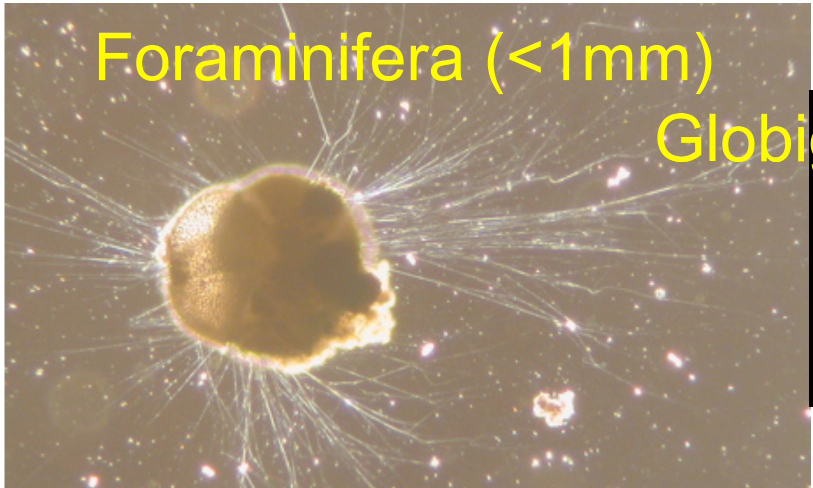
The Pliocene

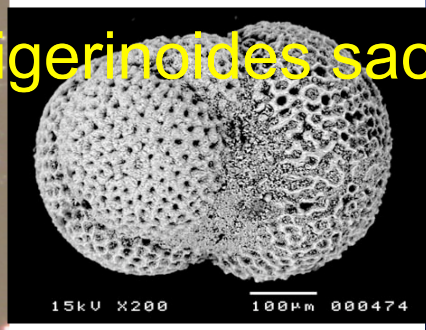
Some general mid-Pleistocene climate characteristics:

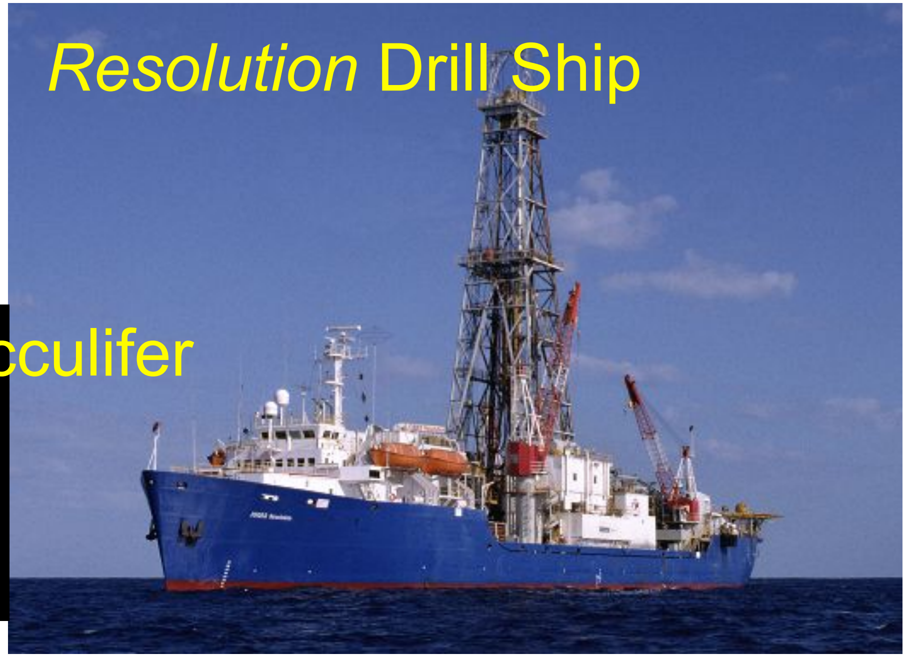
- Atmospheric CO_2 concentration: **???** Possibly 350-500ppm?? (Today: 380; preindustrial: 280; in 50 years: …)
- Global average surface temperature: ≈3° warmer than today??
- Ice: covers Antarctica, but not much in northern hemisphere (ice ages started ≈2.7 Myrs ago)

How do we know:

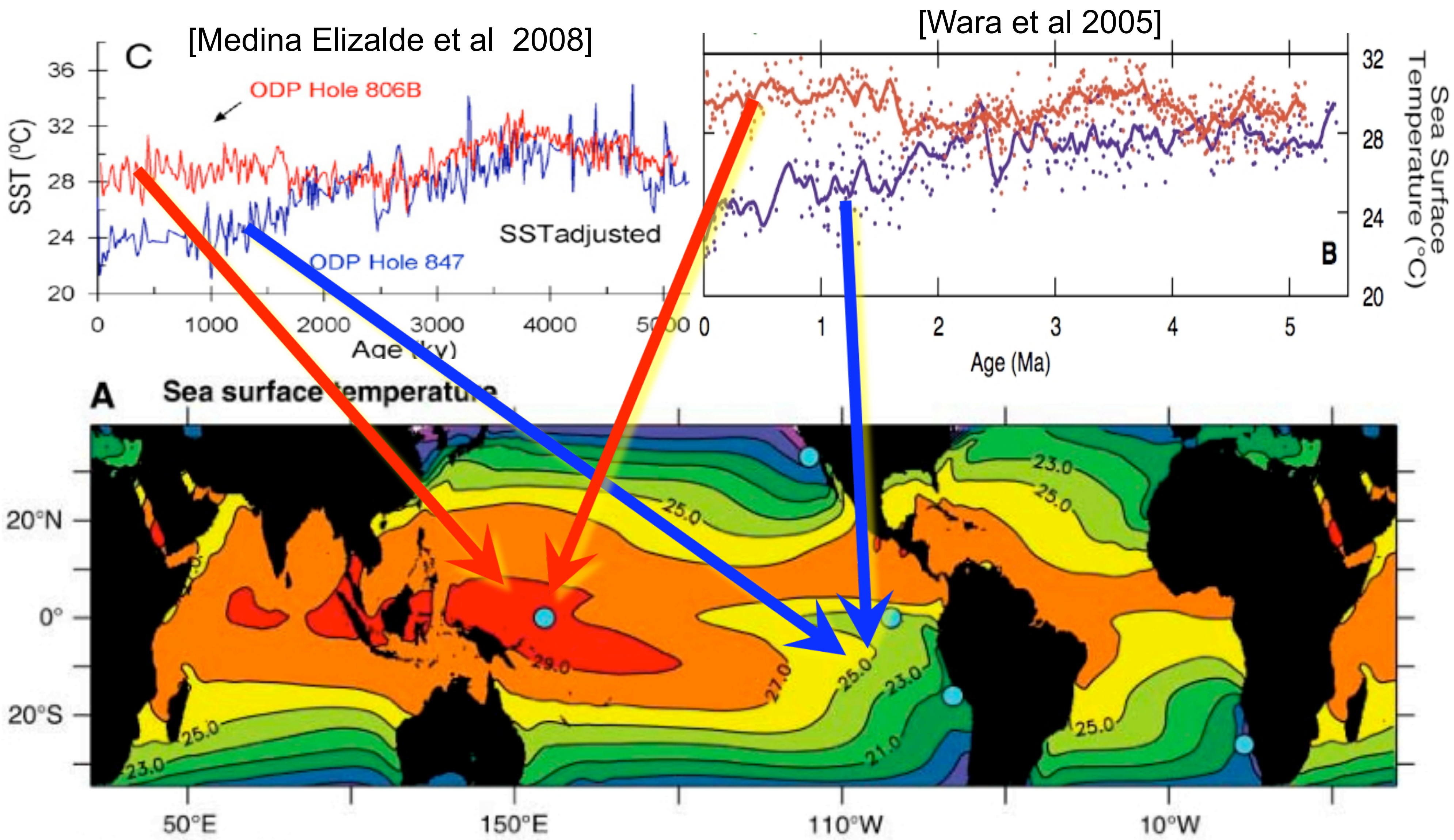
- Isotopic/ other proxy records from deep sea drilling.







The equatorial Pacific during the Pliocene



➔ **The east-west temperature gradient in the equatorial Pacific did not exist during the Pliocene (3-5 Myr ago)**

Was there actually a "*permanent El Nino*" during the Pliocene?

Data resolution is very coarse in both space and time, O(1000s yrs), can we really be sure?

Alternatively, it could have been:

- A higher frequency of El Nino
- Longer El Nino events
- An artifact due to some uncertainties with the proxy observations…

Anyway…, suppose it ***was*** a permanent El Nino, how could that happen?

Should we call it “*permanent El Nino?*

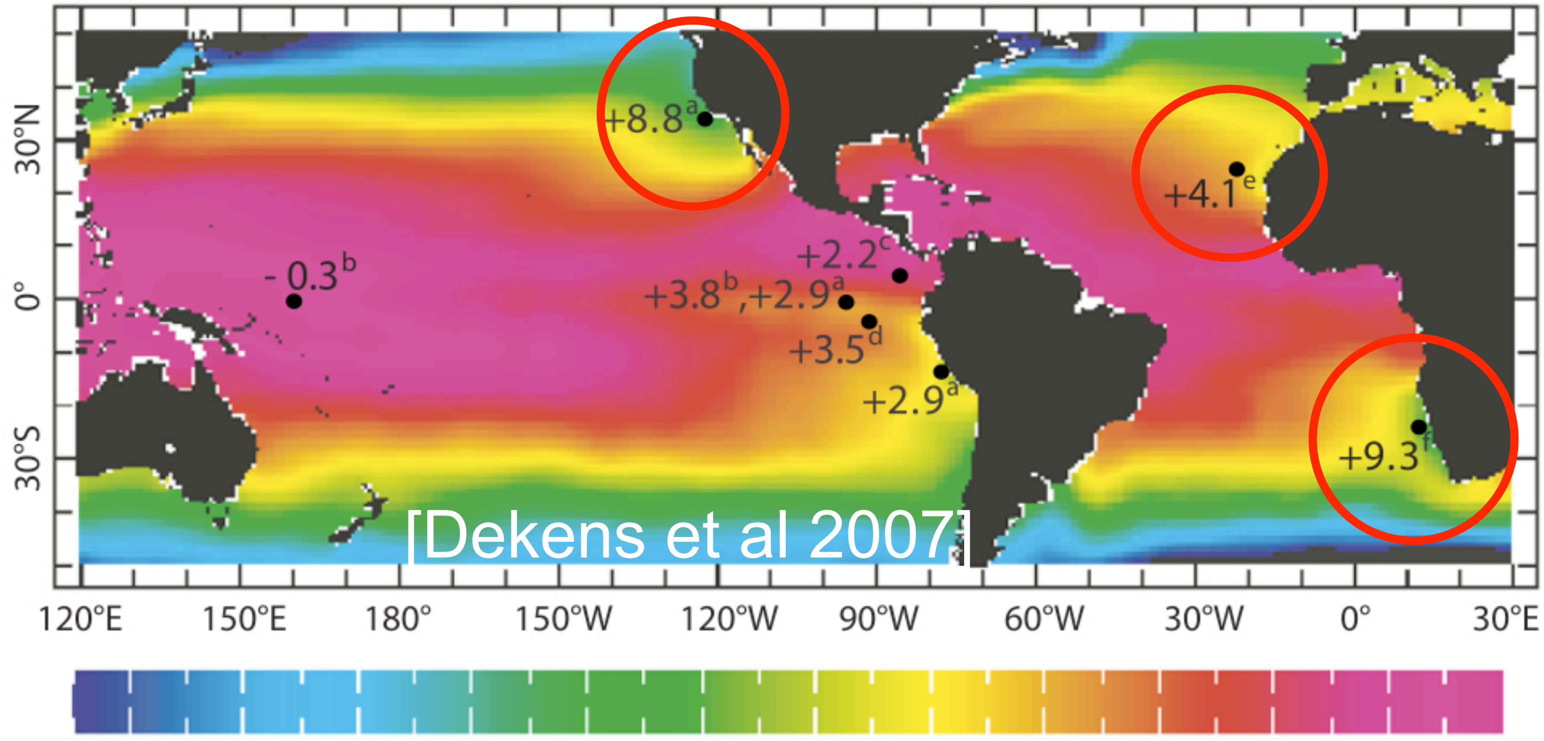
Mechanism must be different, so perhaps a different name…?

Alternatives:

- El Padre? (Christina Revelo)
- Jose? (Joe Pedlosly)
- (padre putativo ➔ P.P ➔)
  Pepe? (our own Mauricio)

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

- Deeper thermocline, possibly globally?
- Evidence: significant warming also in upwelling sites off Africa, California, South America:

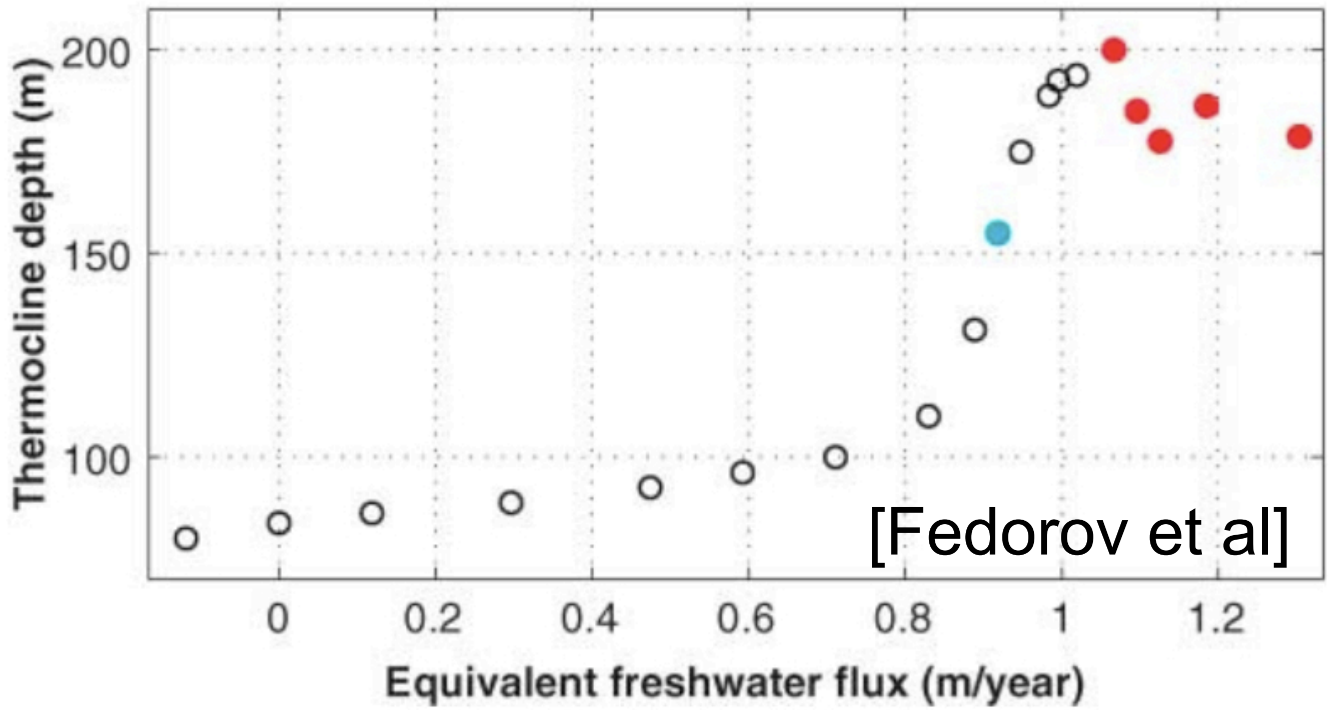


[Dekens et al 2007]

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

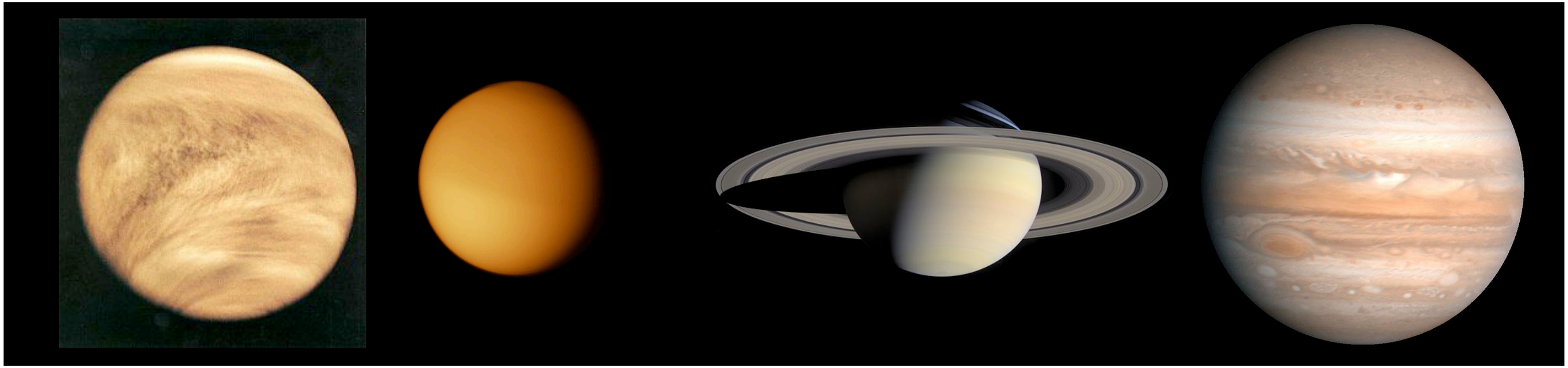
Previous explanations of the Pliocene "*permanent El Nino*"

- Deeper thermocline, possibly globally?
- Proposed Mechanism [Fedorov et al]: a collapse of the thermocline by a very strong fresh water forcing [in the north Pacific?]



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.

Hide's theorem

Schneider 2006, (also Lindzen's book)

A steady axisymmetric circulation in which angular momentum disperses diffusively, however weak the diffusion, cannot have an extremum of absolute angular momentum away from boundaries, which constrains zonal winds to be weaker than or at most equal to the zonal winds implied by an angular momentum–conserving circulation (Hide 1969, Schneider 1977). If there were an angular momentum extremum away from boundaries, there would exist a closed contour of constant angular momentum surrounding it in the meridional plane. The advective flux of angular momentum across the contour would vanish because, in a steady state, the mass flux across the contour would vanish. But diffusion of angular momentum—typically, vertical diffusion representing small-scale turbulent fluxes—implies that there would be a downgradient flux of angular momentum across the contour, which could not be balanced, so angular momentum extrema away from boundaries are impossible.

Angular momentum must attain its maximum value in a region of easterlies at the surface, where the surface drag on the easterlies transfers angular momentum from the surface to the atmosphere immediately above it, from where it can diffuse into the interior atmosphere.

The angular momentum per unit mass M = (Ω a cos phi + u) a cos phi must therefore be everywhere less than or equal to Ω a^2, and the zonal winds must be less than or equal to the angular momentum–conserving zonal wind uM = Ω a $\sin^2$ phi/cos phi corresponding to M = Ω a^2, a result known as Hide's theorem. A steady state with stronger eastward winds—for example, equatorial westerlies (superrotation) such as seen on the giant planets—can only be maintained if diffusion of angular momentum is balanced by upgradient eddy fluxes of angular momentum.

Superrotation dynamics: Rossby Wave reminder…

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

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

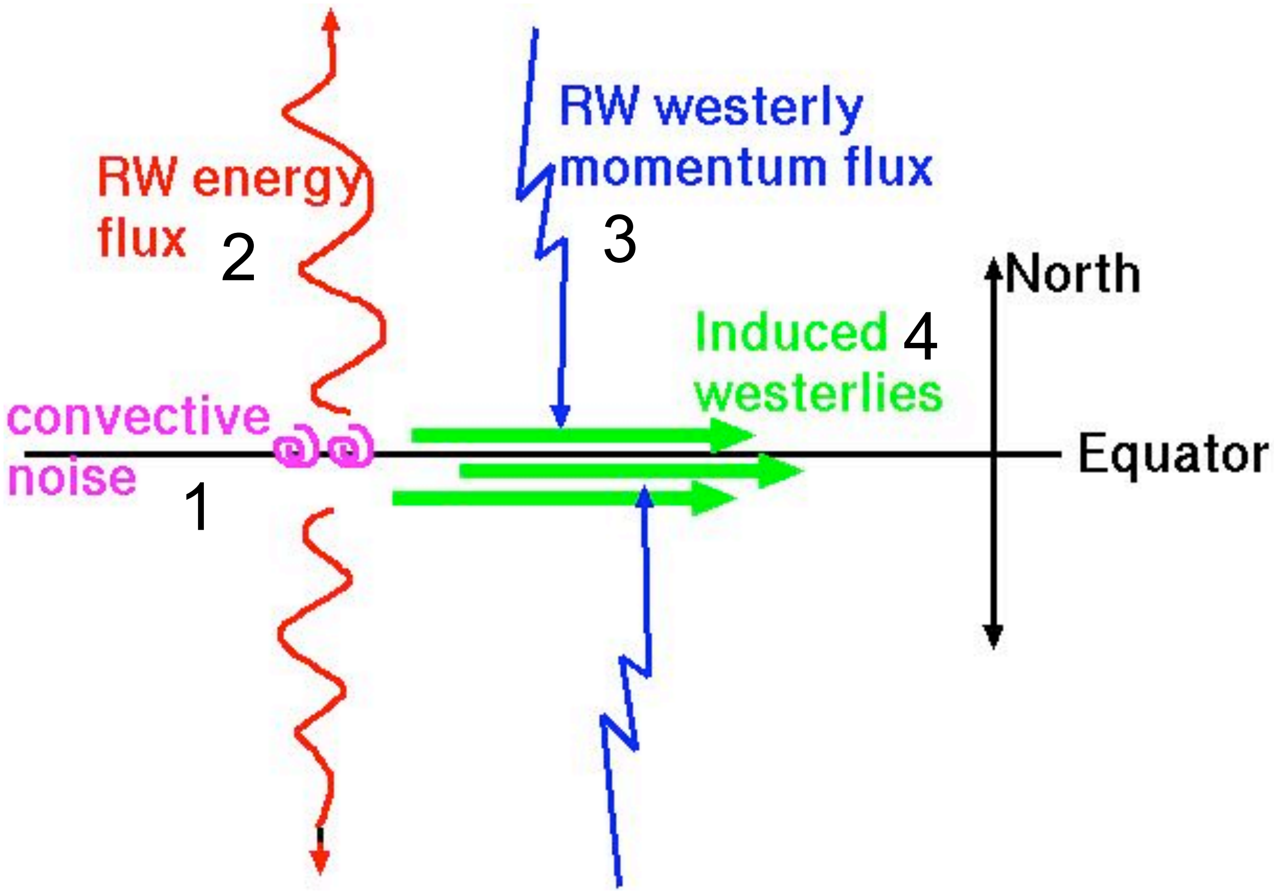
Meridional group velocity $$c_g^{(y)} = \frac{2\beta kl}{(k^2 + l^2 + L_R^{-2})^2}$$

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…

Bifurcations, hysteresis & multiple equilibria again

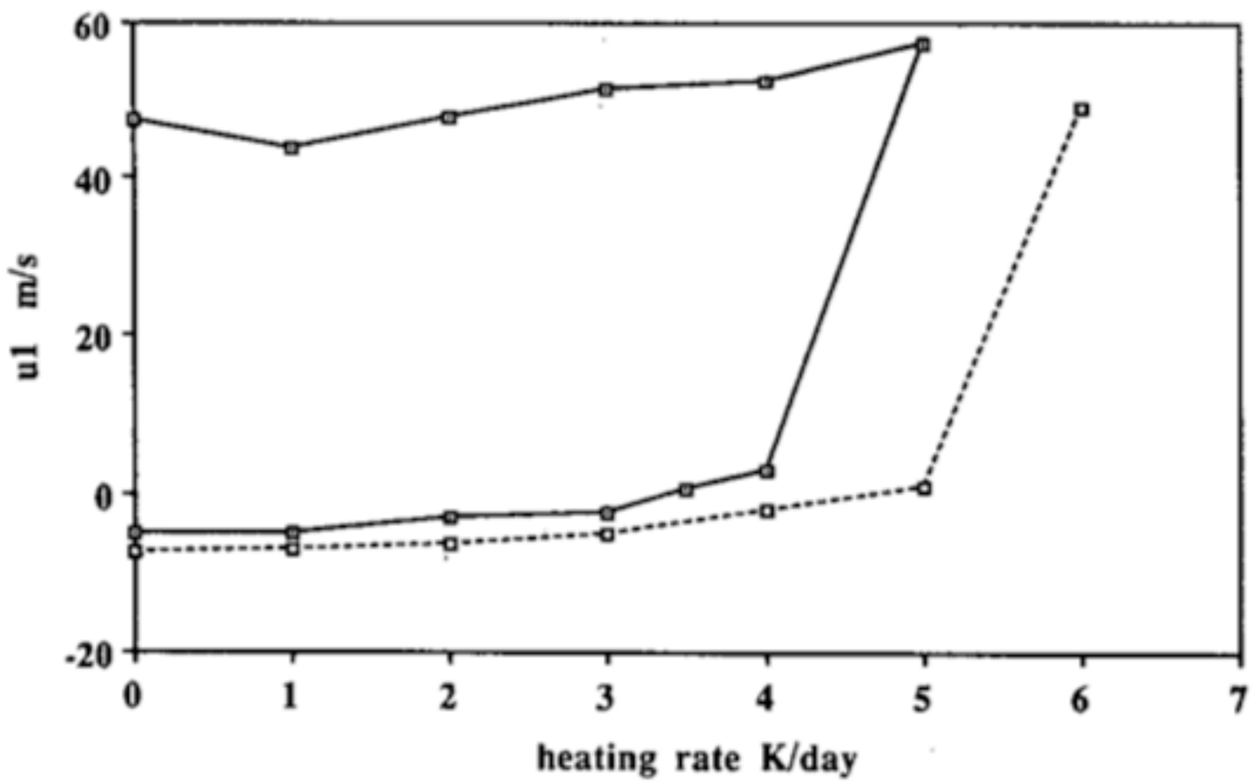


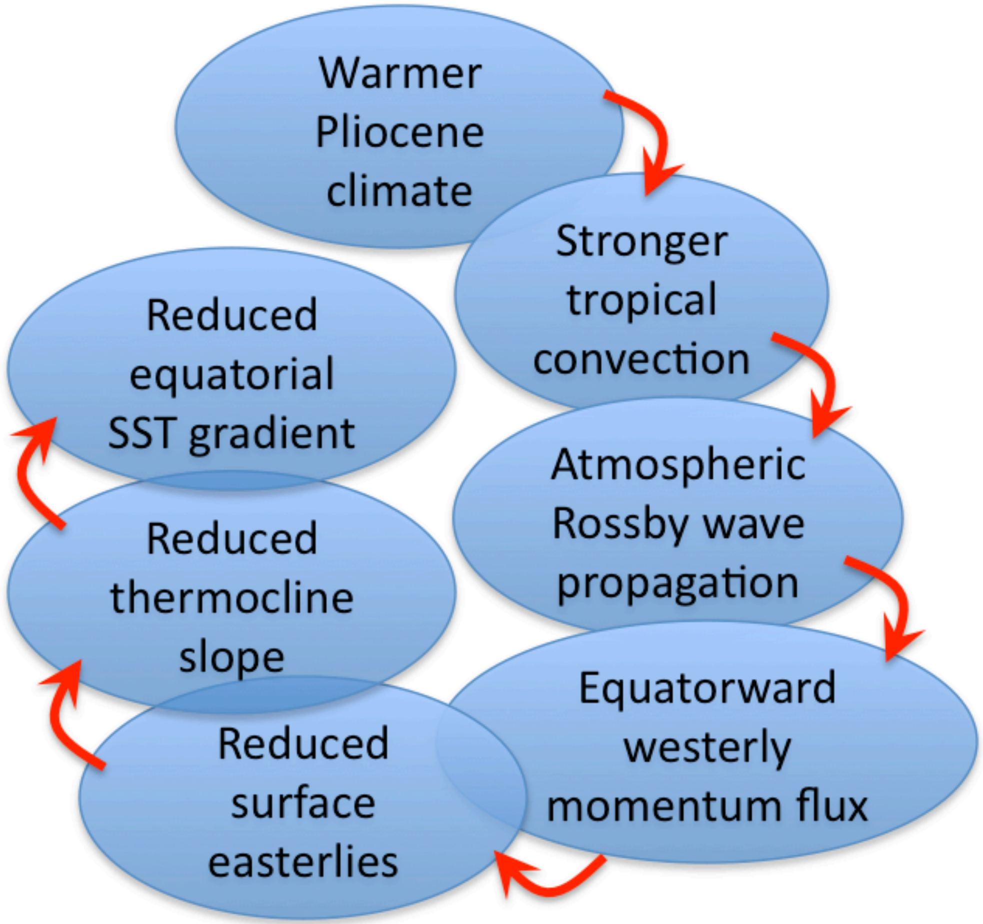
FIG. 2. Equatorial $[u_1]$ for model integrations with different values of the tropical eddy heating rate A_T (K day^{-1}), averaged between day 600 and day 1000. Solid line denotes T21 integrations; dashed line denotes T42 integrations. Note the hysteresis in the solid curve. (The various initial conditions for these integrations are described in the text.)

Much of the superrotation literature is concerned with the existence of multiple equilibria and bifurcations, again…

Superrotation during Pliocene?

Summary of proposed scenario:

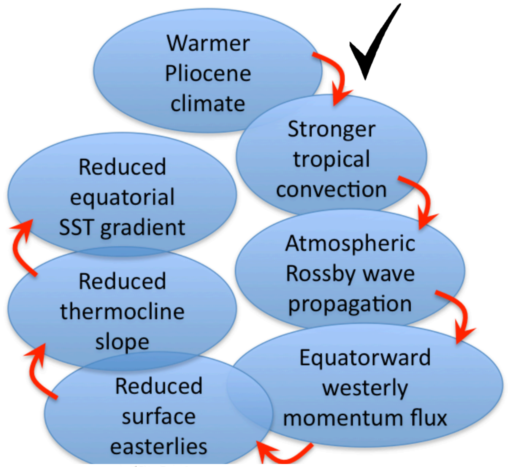
1. Warmer Pliocene ➔ stronger/ rearranged MJO & WWB-like tropical convection activity = stochastic forcing at equator.
2. Rossby wave energy flux away from equator ➔ equatorward westerly momentum flux ➔ weaken equatorial easterlies.



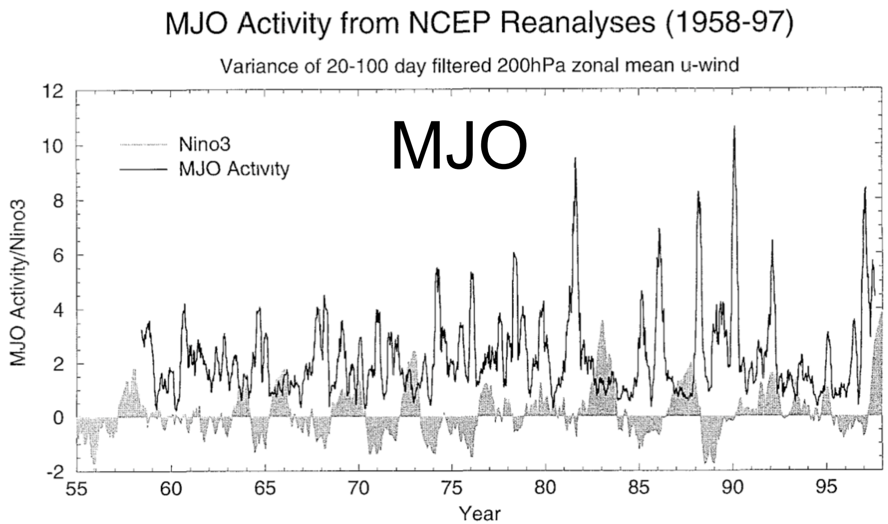
3. Weaker easterlies ➔ decreased E-W thermocline slope ➔ eliminate East Pacific cold tongue & E-W SST gradient ➔ further weakened the Walker circulation, strengthened East Pacific convective activity

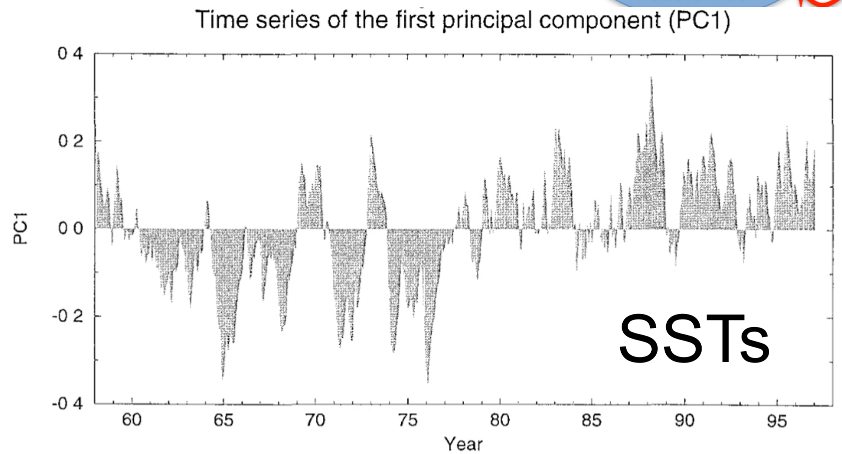
Superrotation dynamics Pliocene: the evidence

Warner climate ➔ more/ stronger/ rearranged convective activity:

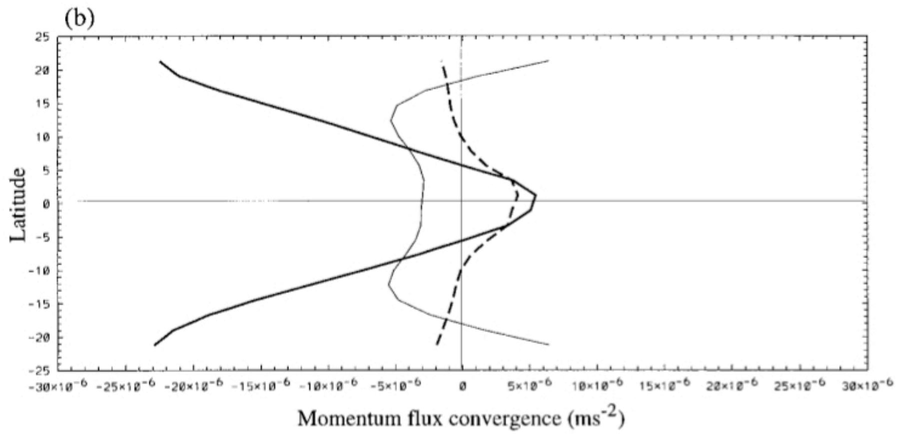


(1) Slingo et al. [1999]: increased MJO activity since 1970s; due to decadal tropical SSTs warming



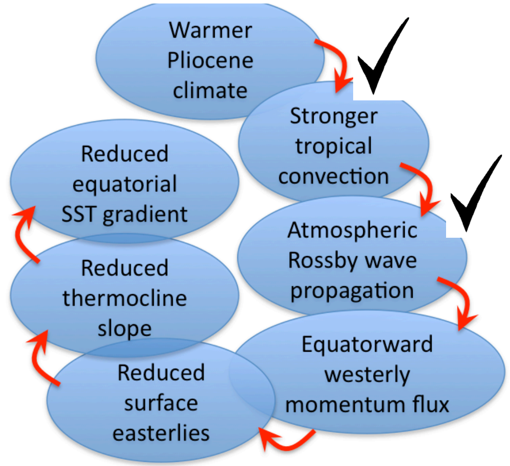


(2) Idealized AGCM [Lee, 1999]: eddy flux convergence due to MJO twice as strong due to a uniform 3 degree warming ➔ equatorial westerlies (upper atm, though)



Superrotation dynamics Pliocene: the evidence

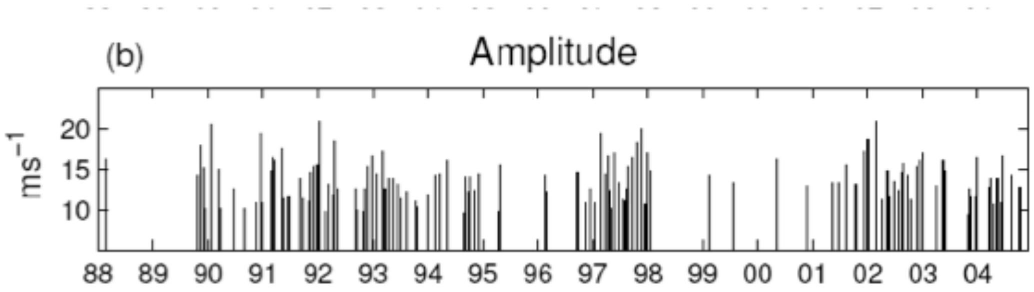
More/ stronger/ rearranged convective activity
➔ stronger Rossby Wave (RW) propagation



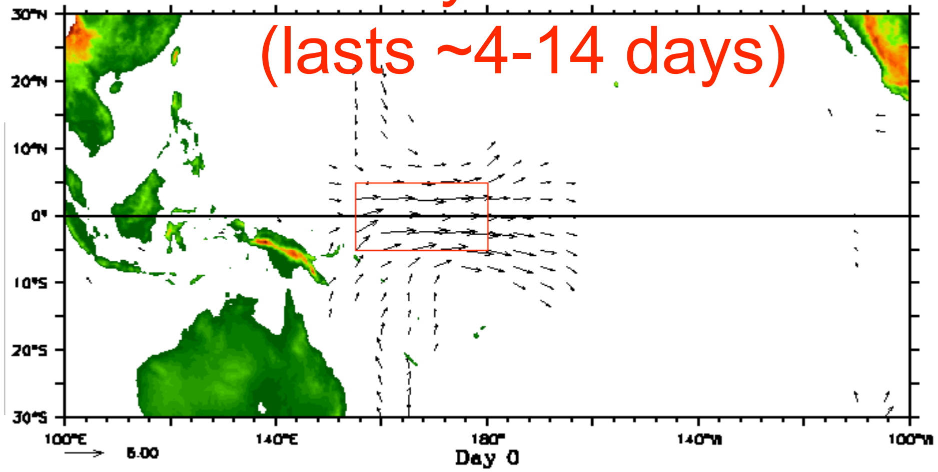
Many more questions than answers here:

Theoretically: what convective activity could produce barotropic Rossby Waves? MJO? WWBs?
Numerically: current models cannot reproduce observed range of convective phenomena. Nor predict changes in warmer climate.

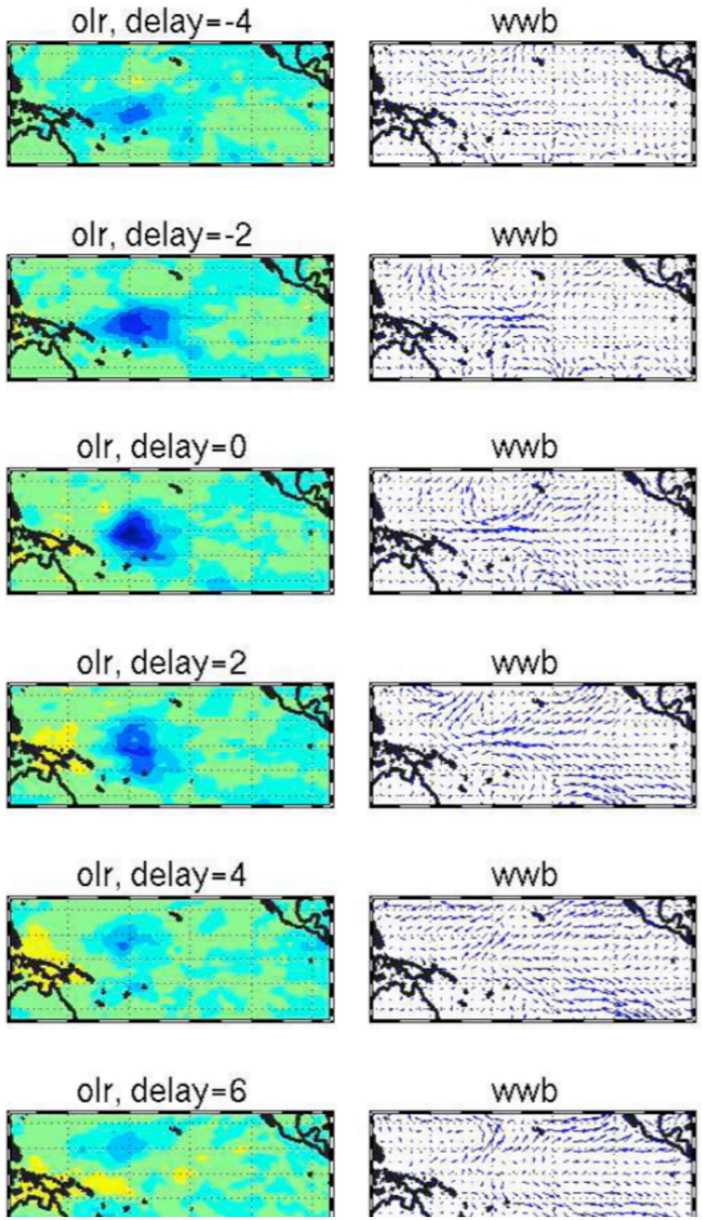
Good news: plenty barotropic RW escaping from tropics & remote teleconnections [Hoskins&Karoly, 1981].



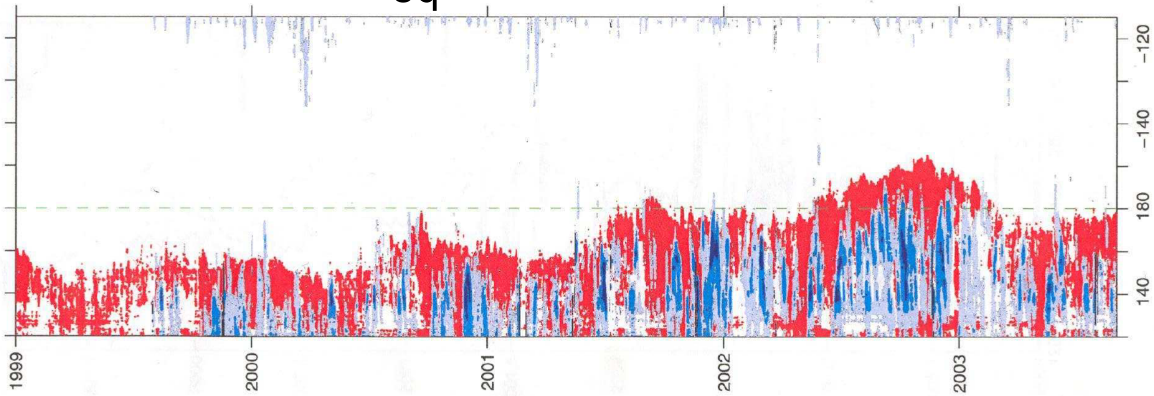
A Westerly Wind Burst
(lasts ~4-14 days)



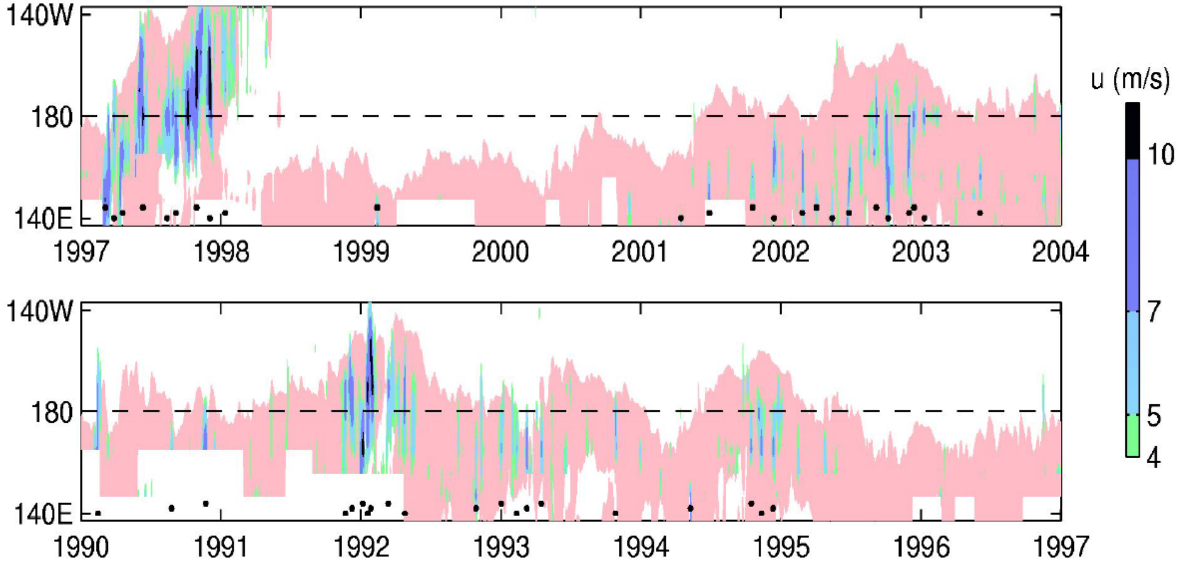
Example of convective "noise": WWBs



QuikSCAT u_{eq}>2m/s; SST=29°:



TAO $u_{eq\ anom}$>4m/s (green, blue) on SST=29° (pink):

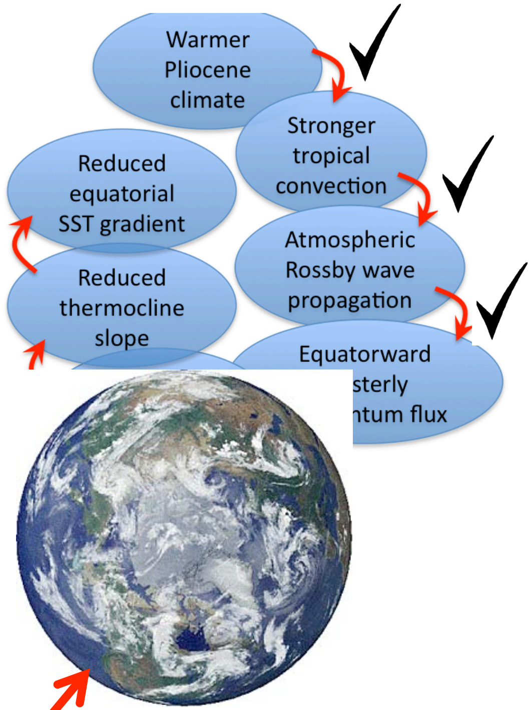


More/ stronger WWBs during warm El Nino events.

➔ Also more during a "permanent" El Nino?

Superrotation dynamics Pliocene: the evidence

Stronger Rossby Wave (RW) propagation
➔ (1) equatorward westerly momentum flux
➔ (2) westerlies/ reduced easterlies (at surface!)

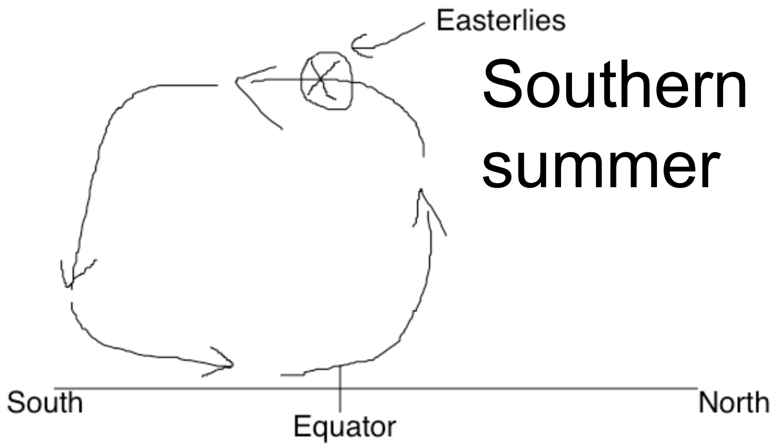


The westerly wave momentum flux must dominate sources of easterly momentum. What are these sources?

In upper atm: commonly believed to be transient eddies, but in fact, [Lee, 1999] transient seasonal cycle of Hadley cell dominates. (i.e. rising motion is off the equator):

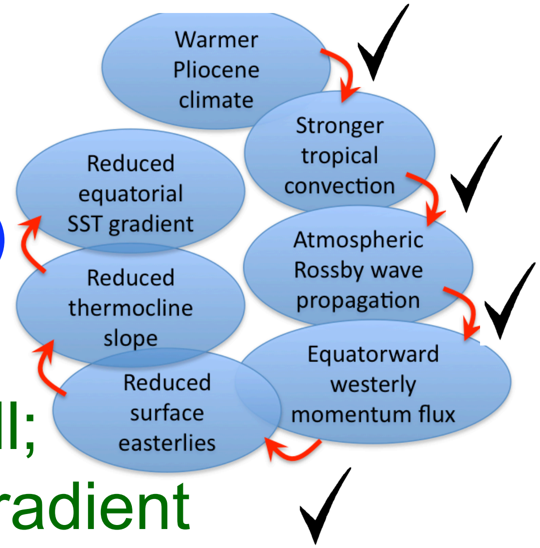
$$r\overline{u} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x} - \frac{\partial}{\partial y}\overline{u'v'}$$

So RW must overcome this effect.



Southern summer

Superrotation dynamics Pliocene: the evidence



Stronger Rossby Wave (RW) propagation

➔ (1) equatorward westerly momentum flux

➔ (2) westerlies/ reduced easterlies (at surface!)

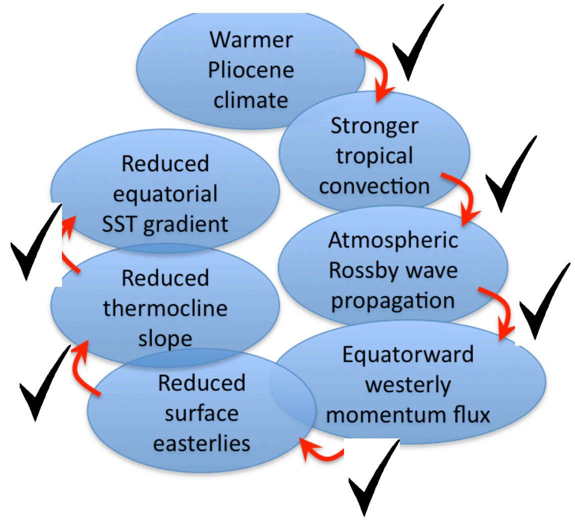
In lower atm: Pacific easterlies are due to
(1) Coriolis force on returning flow of Hadley cell;
(2) east-west SST/ pressure gradient

$$\frac{\partial \bar{u}}{\partial t} - f\bar{v} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} - \frac{\partial}{\partial y}\overline{u'v'} - r\bar{u}$$

Bottom line: most SuperRotation work is about Rossby Wave propagating from *mid-latitudes*, but there are also examples of *equatorial* RW driving SR: Lee [1999]: warming → MJO → SR; Huang et al. [2001]: tendency to SR in greenhouse simulation, possibly bec of tropical convection. Held & Suarez [1978], Held [1999]: noisy convection parameterization led to SR via RW radiation.

Superrotation dynamics Pliocene: the evidence

westerlies/ reduced easterlies (at surface!)
➔Elimination of thermocline slope,
➔Reduced east-west SST gradient



This, for a change, is something that's pretty much obvious…?

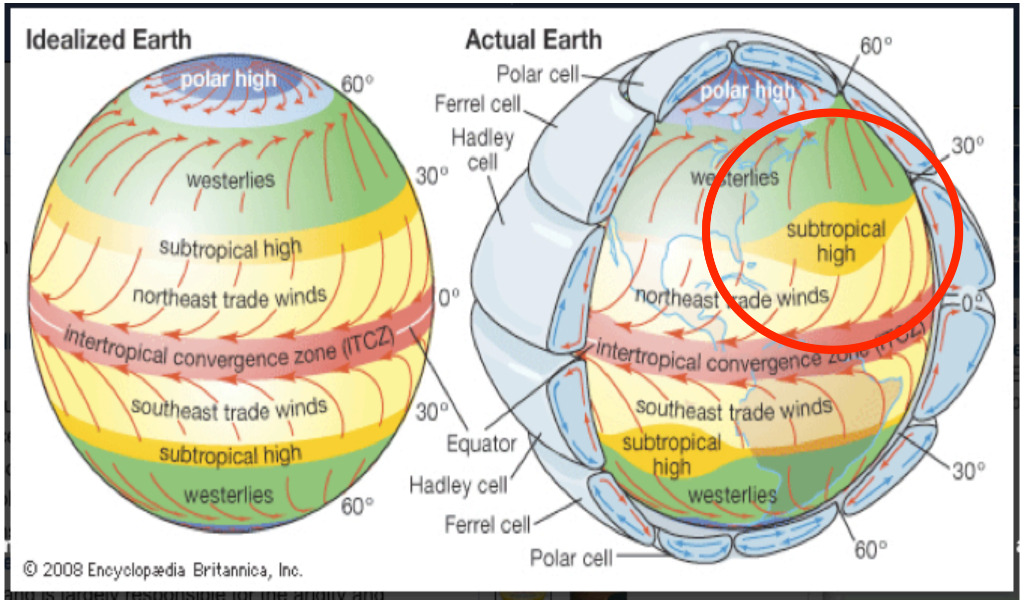
Or is it? Superrotation typically happens at height in models.
How do we get the westerlies to extend to the surface??
Via convective momentum transfer? Another mechanism?

To be continued…

Upwelling zones warming due to superrotation?

Benguela upwelling off southwest Africa, 10C warmer in Pliocene. Increased fraction of upwelling diatoms suggests an increased upwelling, not changed thermocline depth [Marlow et al 2000].

➔Upwelling favorable wind in mid-lats is due to:
(1) subtropical high;
(2) land-sea contrast



➔Upwelling sites warming could indicate a shift in wind/ subtropical high, perhaps due to superrotation-related change (RW absorption in mid-lats)?

➔**A falsifiable prediction** of the superrotation idea: examine sampling sites along coastal zones to look for meridionally shifted rather than eliminated upwelling sites during Pliocene.

Conclusions from Lesson 2: Pliocene permanent El Nino due to superrotation?

- We tried to make the case for superrotation as a mechanism for the vanishing equatorial Pacific SST gradient 3-5 Myr ago.
- Mechanism: more convective "noise" at equator, radiating Rossby waves and inducing westerlies at equator.
- Our strongest "argument" is "Anything that is physically possible, will happen". (physics examples: earth magneto reversals, snowball earth, … black holes); a private case of Murphy's law: "Anything that can possibly go wrong, does"
- This is all very speculative, not even based on a specific model calculation, most likely just wrong.
- Wouldn't it still be fascinating (…) if this were right and if such convective (storminess?) activity accelerated due to increased CO2 and led to a permanent El Nino in the future…? [Held 1999; Pierrehumbert 2002]