Observed Pliocene (~2–5 Myr) features

Big picture:

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

Main features:

- A permanent El Niño
- Warm coastal upwelling sites
- Wet North America

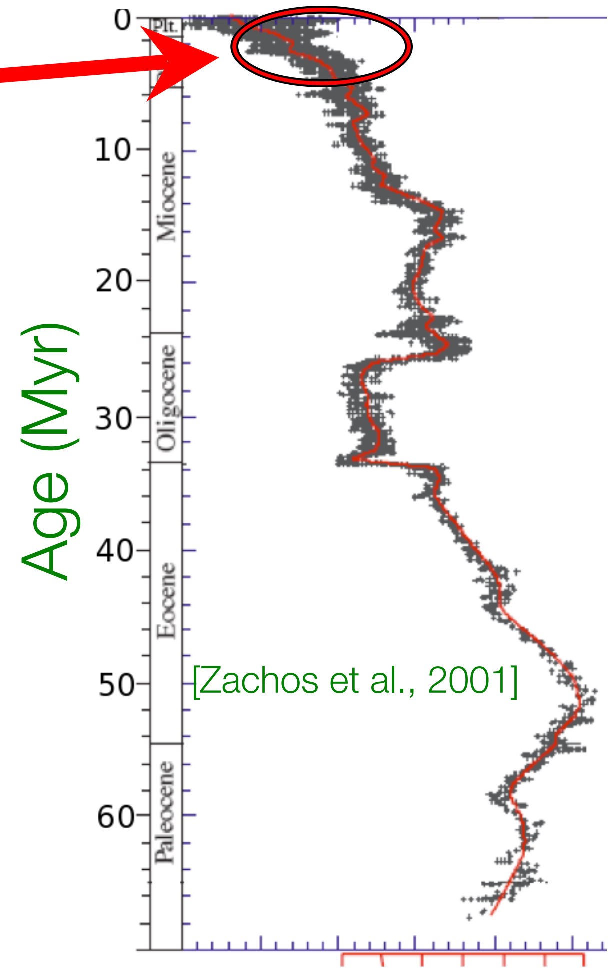
The Pliocene within the bigger picture

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

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

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

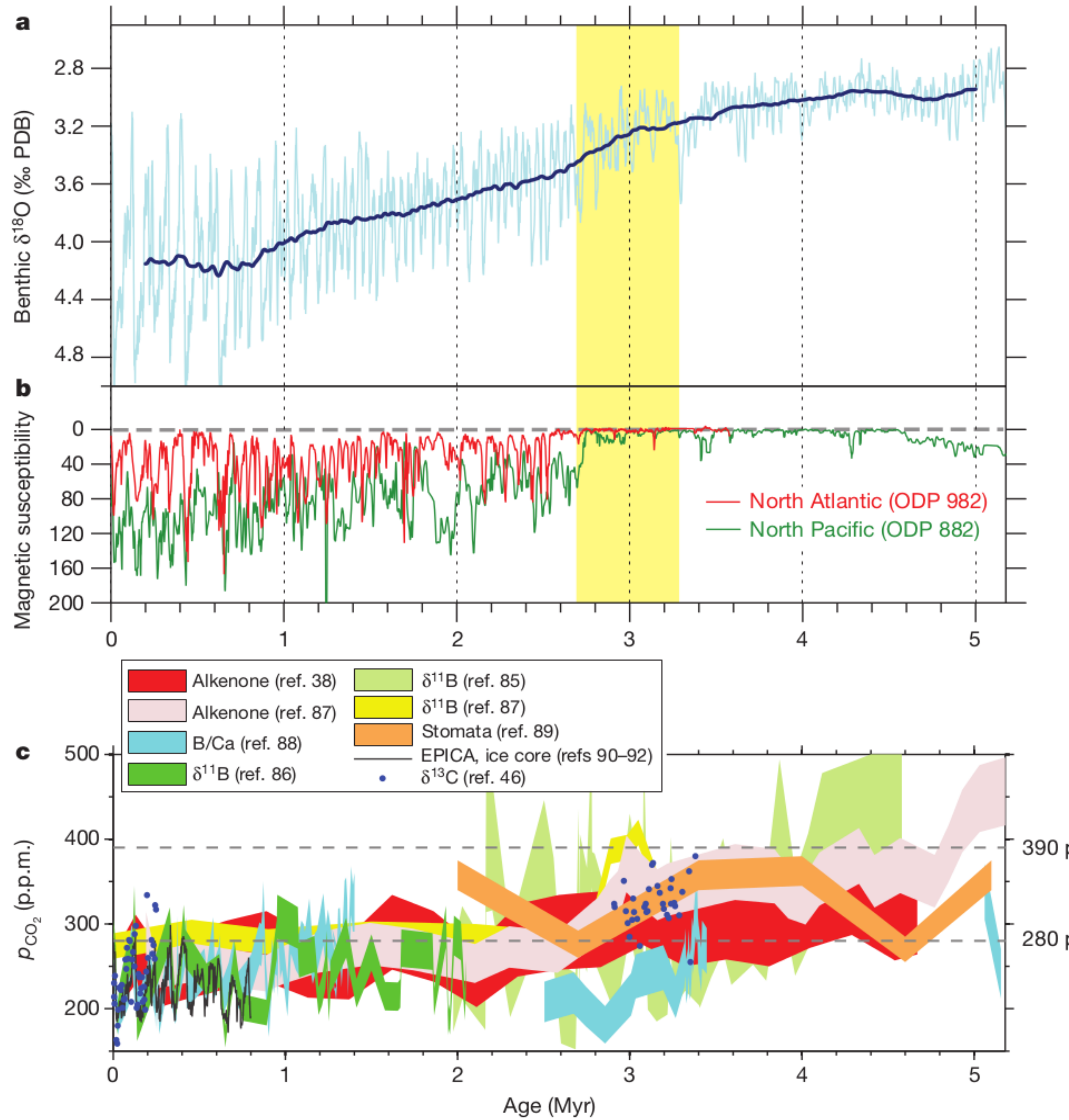
Gradual cooling over past 55Myr



Deep ocean Temperature

Pliocene proxy obs:

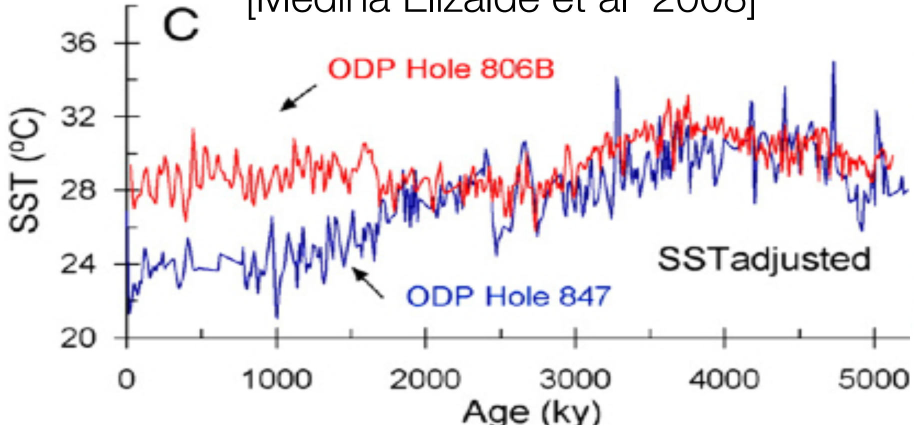
Temperature, ice, CO_2



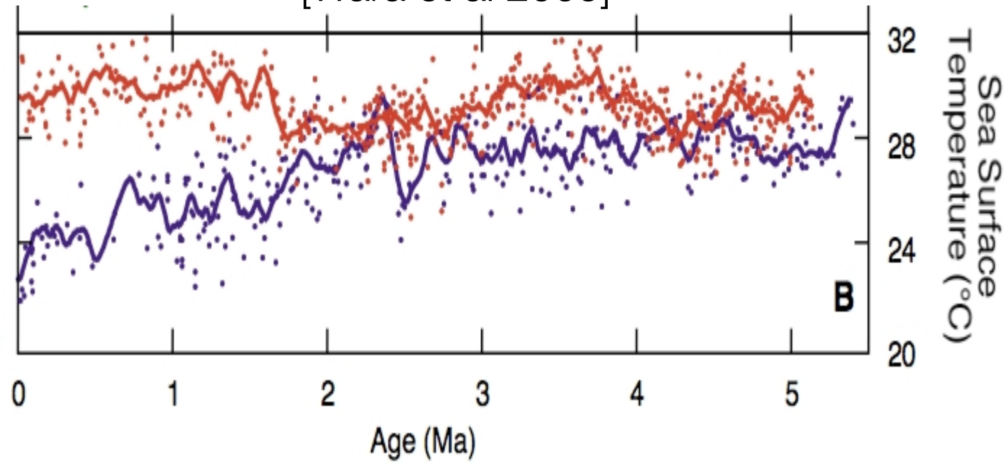
Fedorov et al 2013

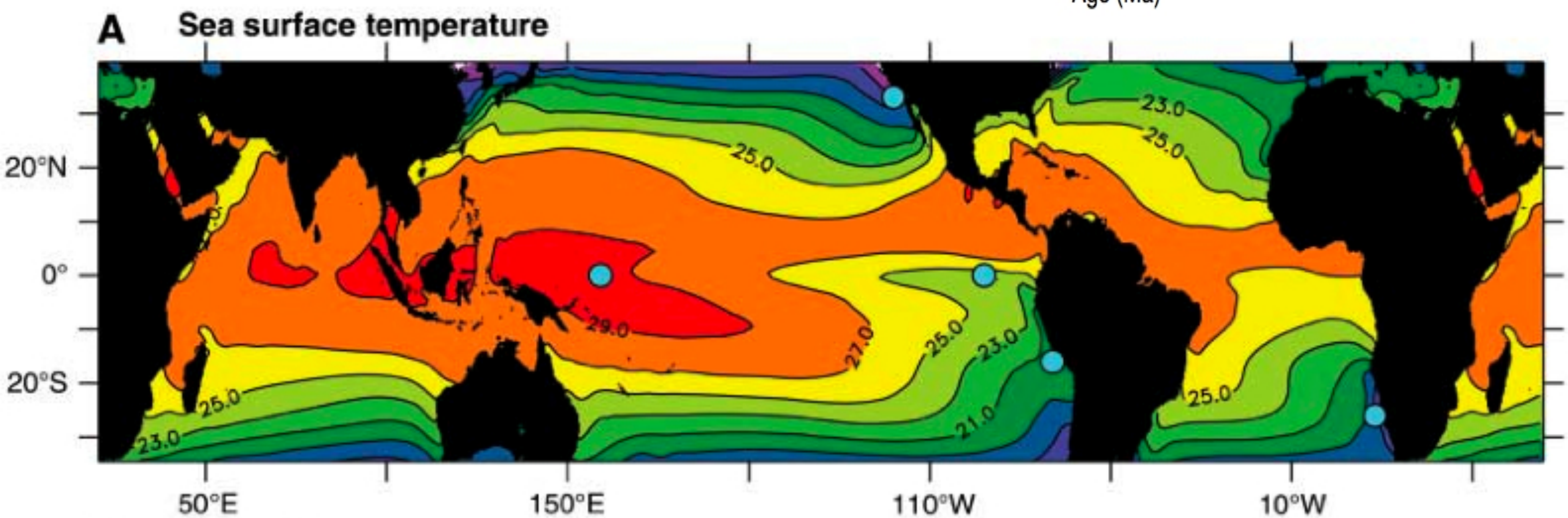
The equatorial Pacific during the Pliocene

[Medina Elizalde et al 2008]



[Wara et al 2005]





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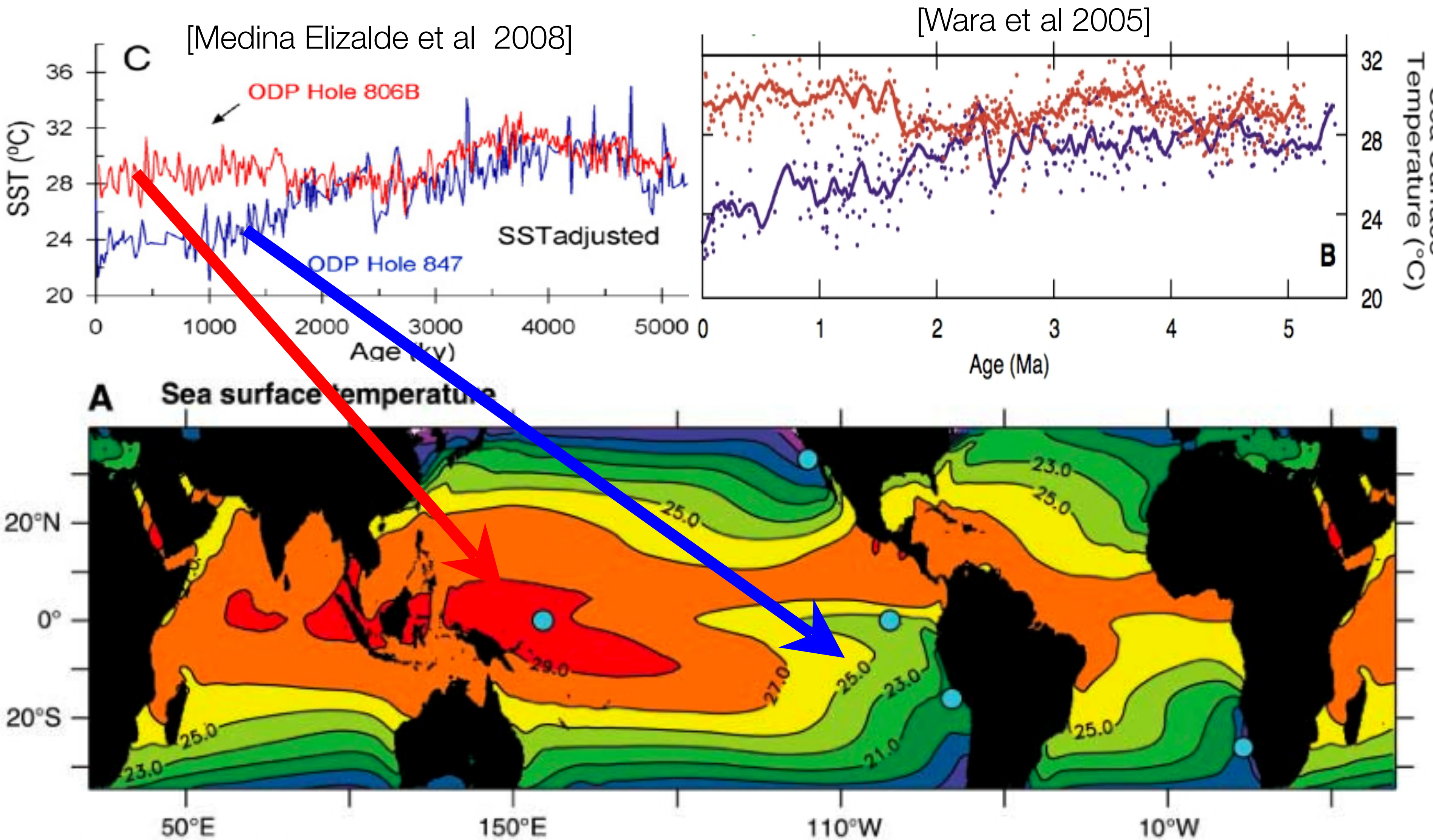

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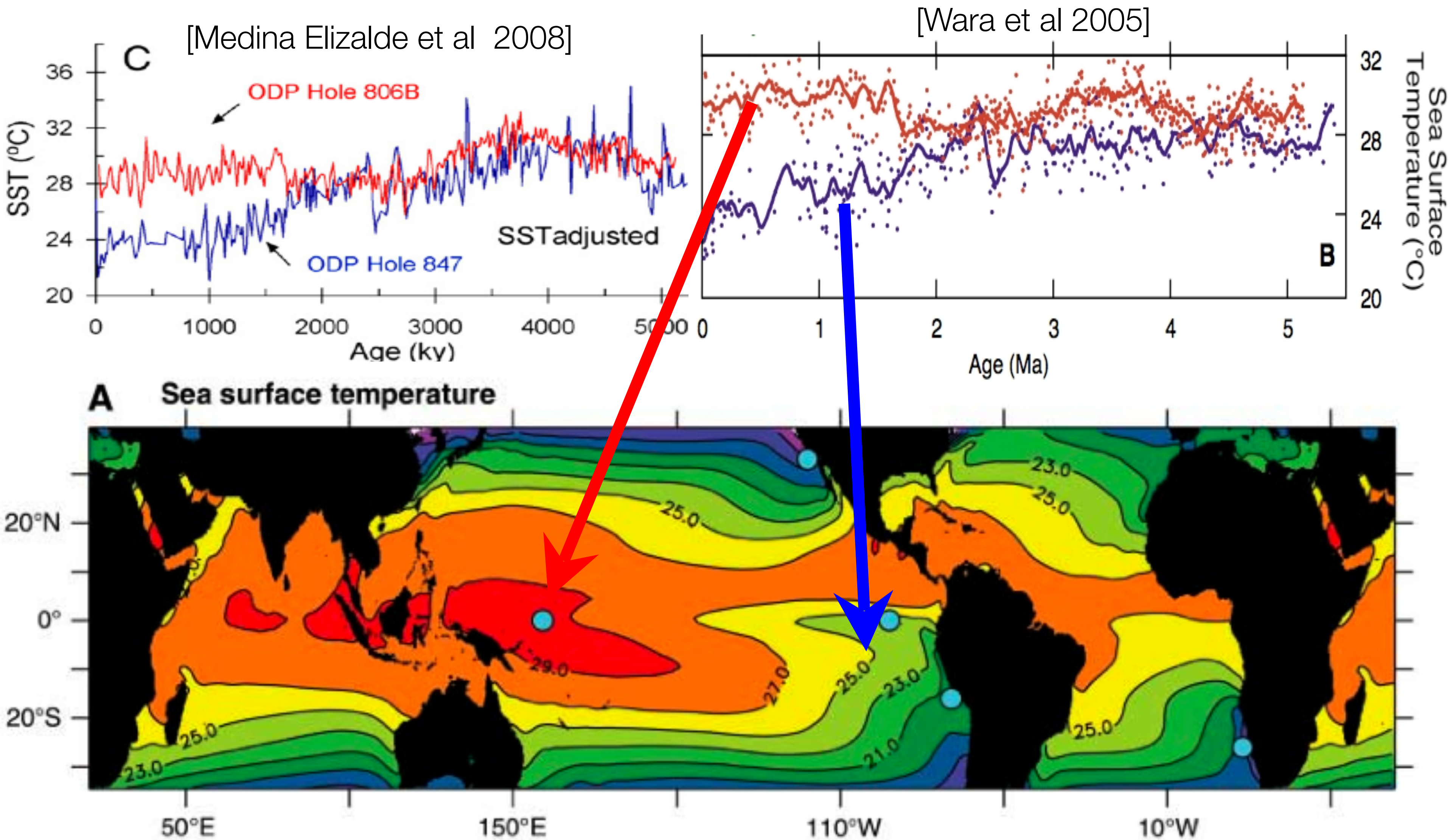
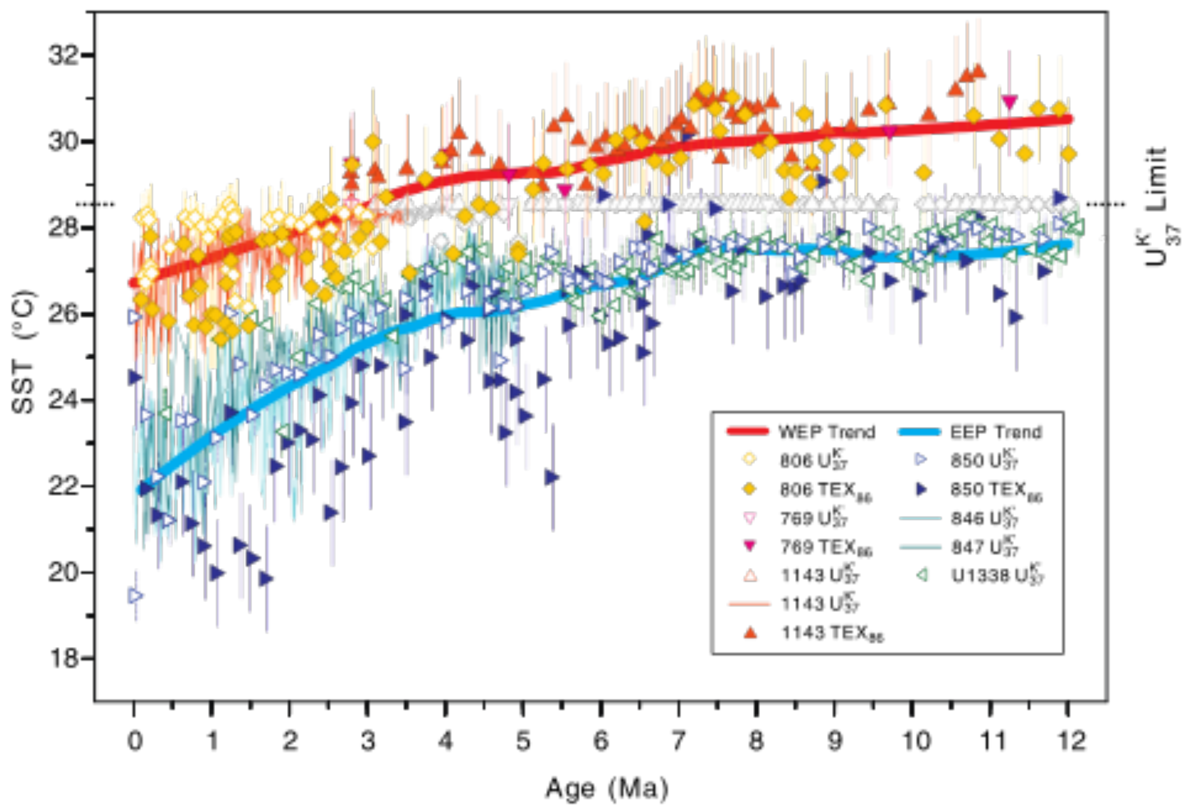


➔ Strong east-west temperature gradient in the equatorial Pacific did not exist during the Pliocene (~2–5 Myr ago)

No permanent El Niño?

(Zhang, Pagani & Liu 2014)



East and west pacific temperatures do not converge in this reconstruction; SST gradient exists all the way to 12 Myr

Warmth of Pliocene upwelling sites

[Dekens et al 2007]

Proxy evidence shows strong warming in upwelling sites off California, Africa, and South America

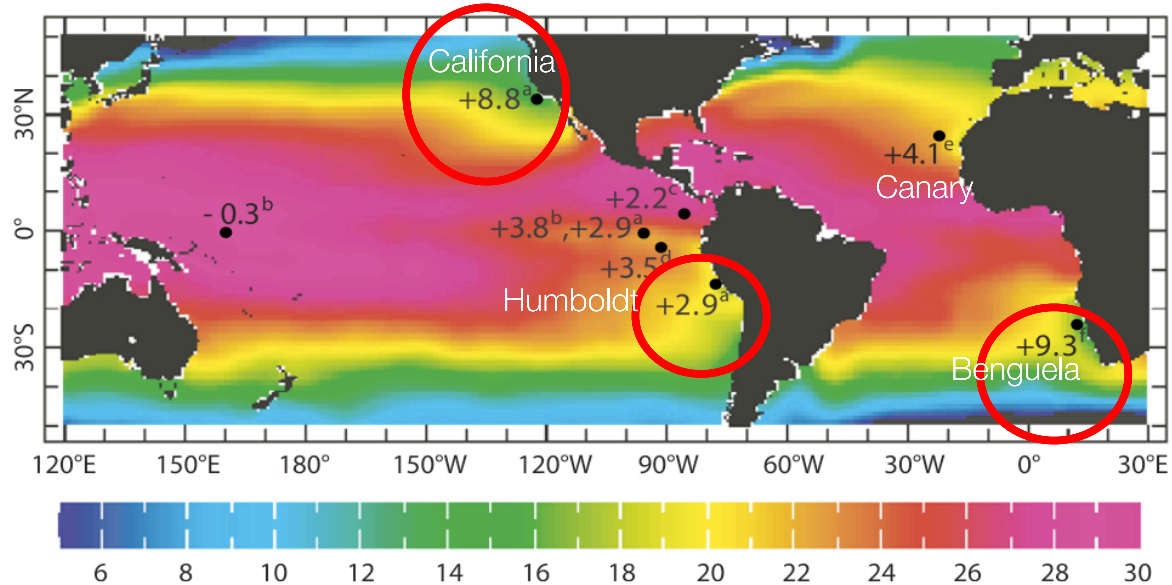


Figure 1. Difference in sea surface temperature (SST) between Pliocene and modern SST. The colored map shows modern mean annual SST [*Levitus and Boyer*, 1994]. Superimposed is the difference between

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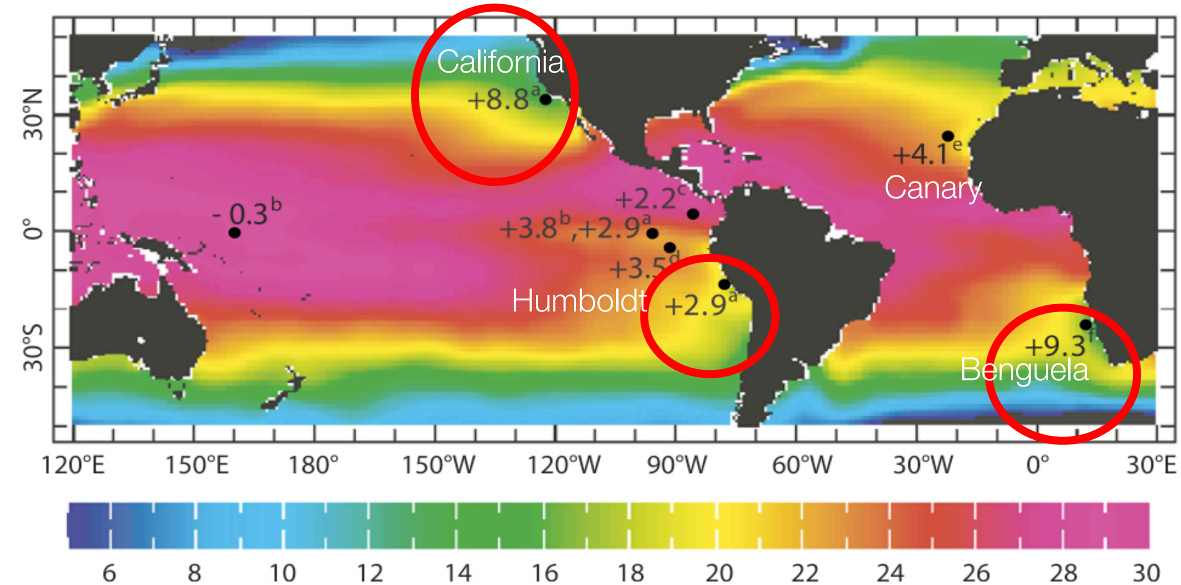
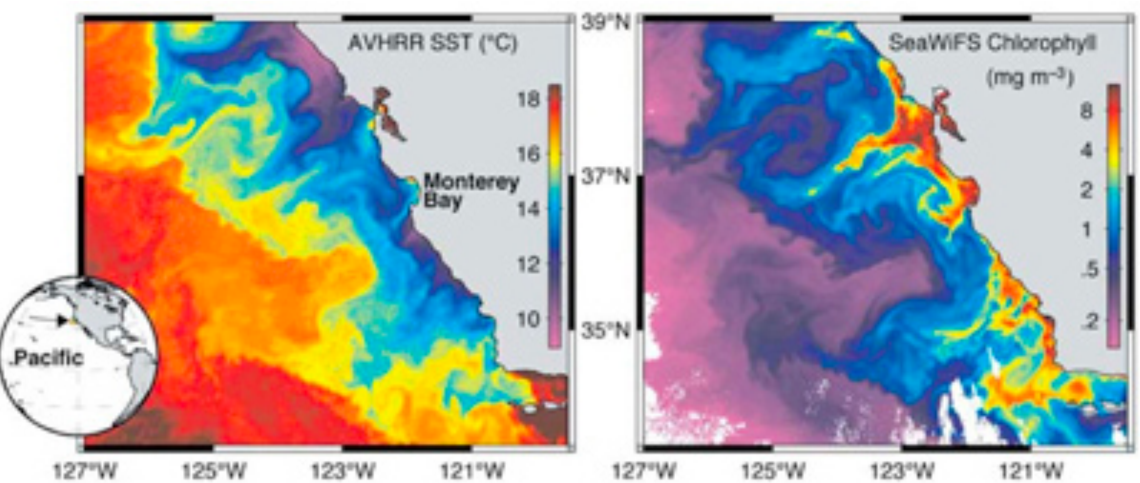


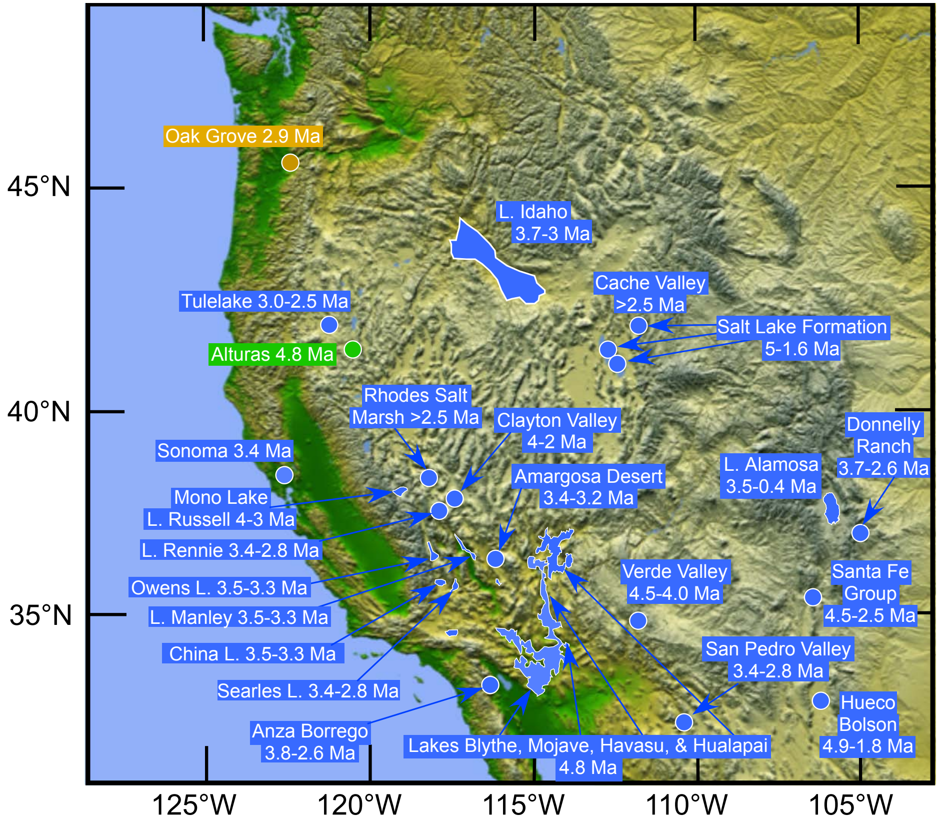
Figure 1. Difference in sea surface temperature (SST) between Pliocene and modern SST. The colored map shows modern mean annual SST [*Levitus and Boyer*, 1994]. Superimposed is the difference between

(Ryan et al. 2005).



As opposed to present-day: Satellite imagery of central California upwelling system: cool SST & high surface chlorophyll

Wet southwest US during Pliocene (2–5 Myr)



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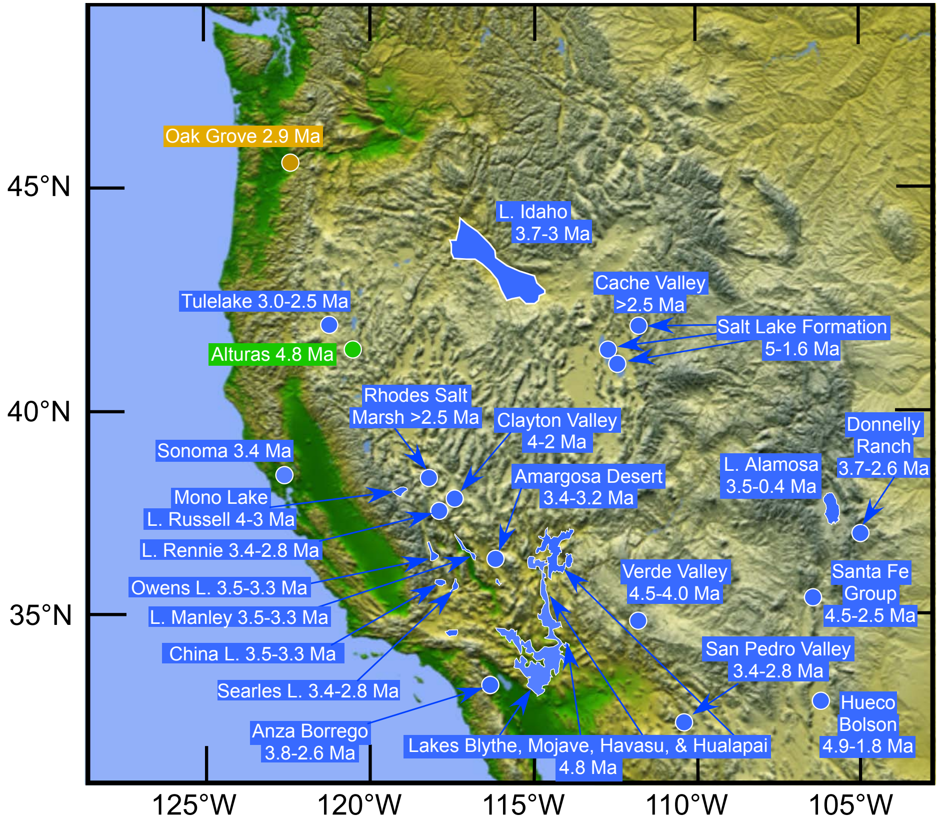
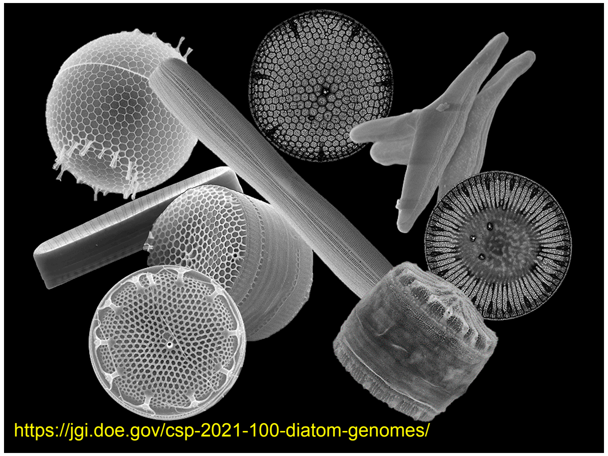


- lacustrine sediments,
- fish fossils,
- mega-plant fossils,
- fossils of animals,
- pollen,
- diatoms,
- ostracod

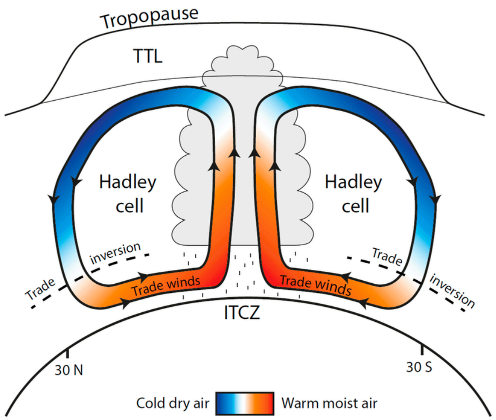


The evidence:

lake sediments
fossils of: fish,
freshwater shrimp,
and plankton

Wet California/ warm upwelling sites

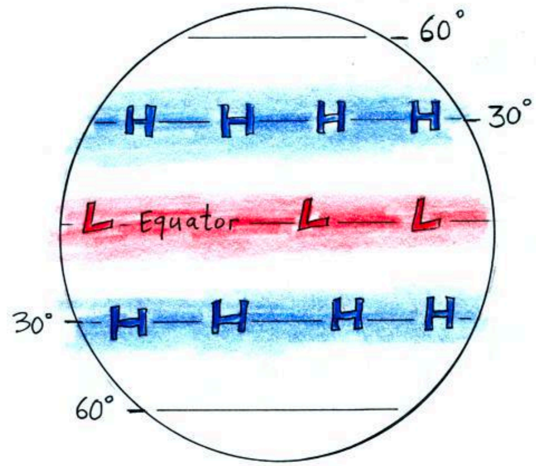
Subtropical high & coastal upwelling zones



Hadley cell

Alina Fiehn Phd, 2017

https://www.researchgate.net/figure/Schematic-of-the-Hadley-circulation-Abbreviations-TTL-Tropical-tropopause-layer_fig1_322886947

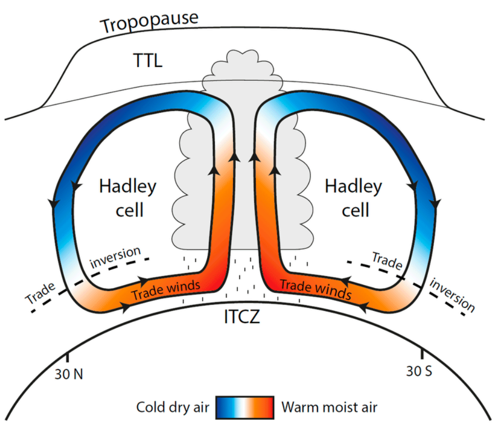


without continents:
belts of high & low pressure

Images and text from:

http://www.atmo.arizona.edu/students/courselinks/spring14/atmo170a1s4/lecture_notes/apr18.html

Subtropical high & coastal upwelling zones



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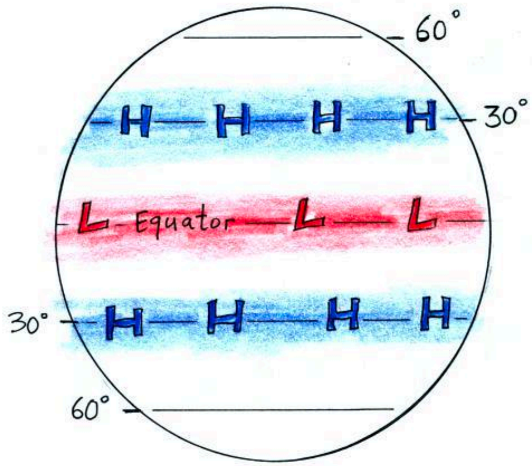

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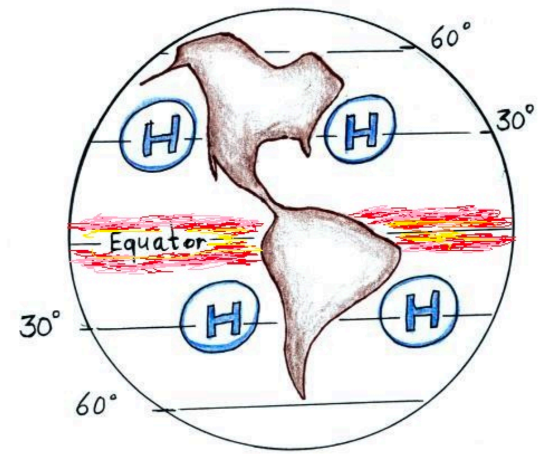

adding continents ➨ centers of high pressure & a belt of low pressure at equator

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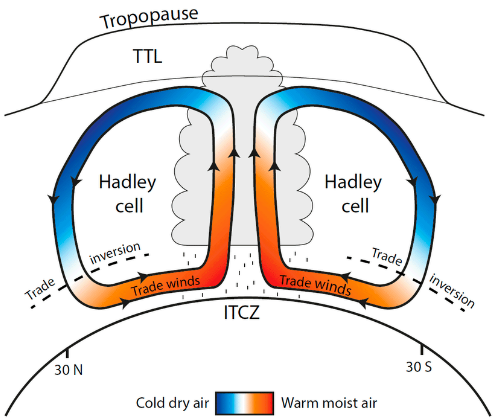

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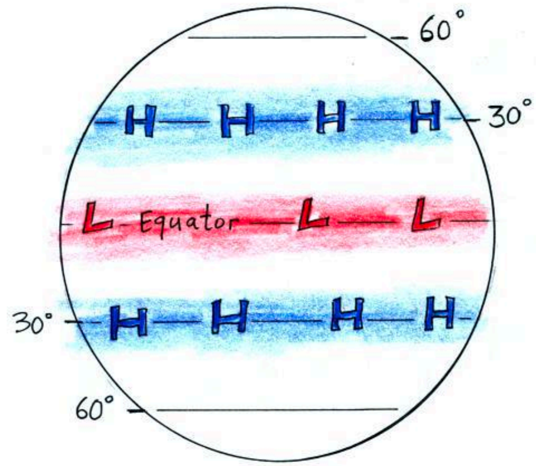

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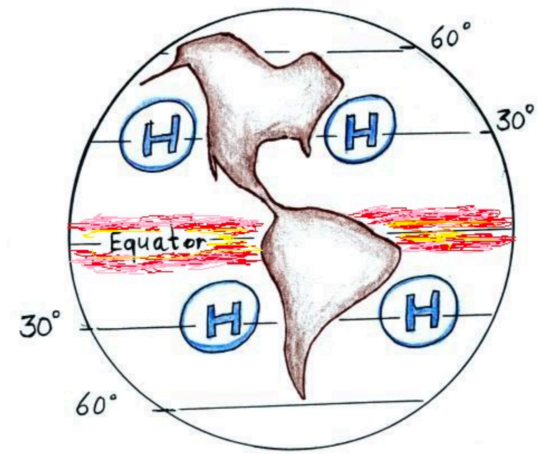

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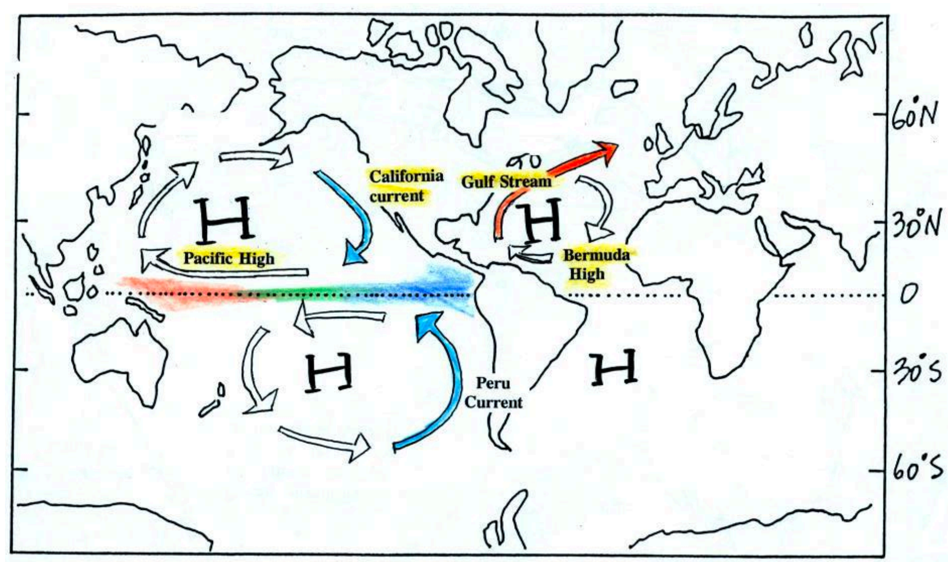

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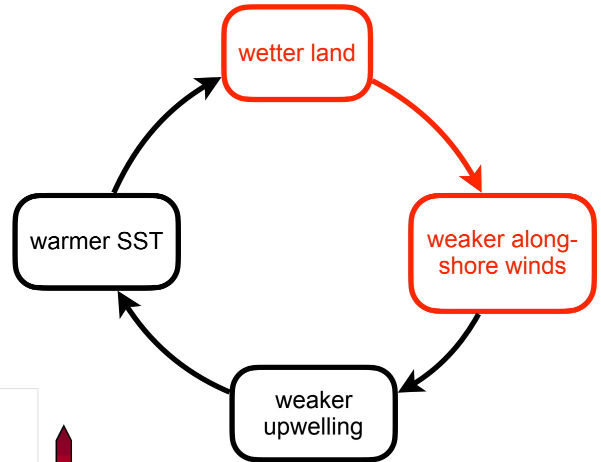
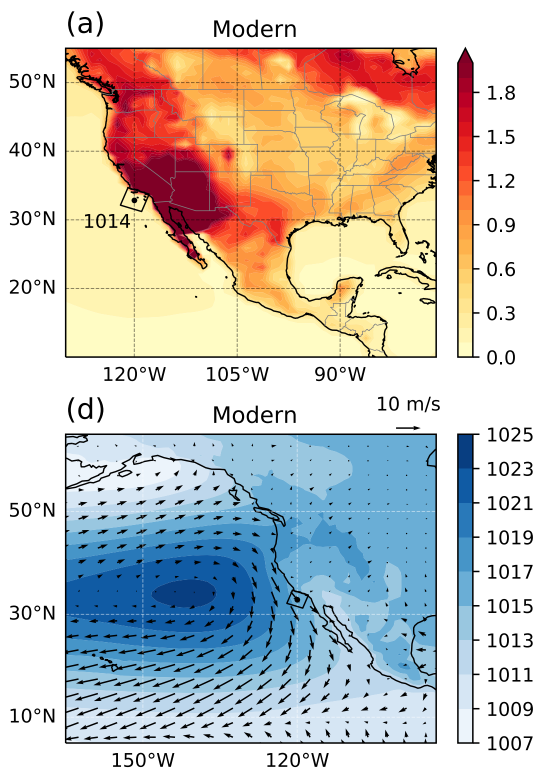
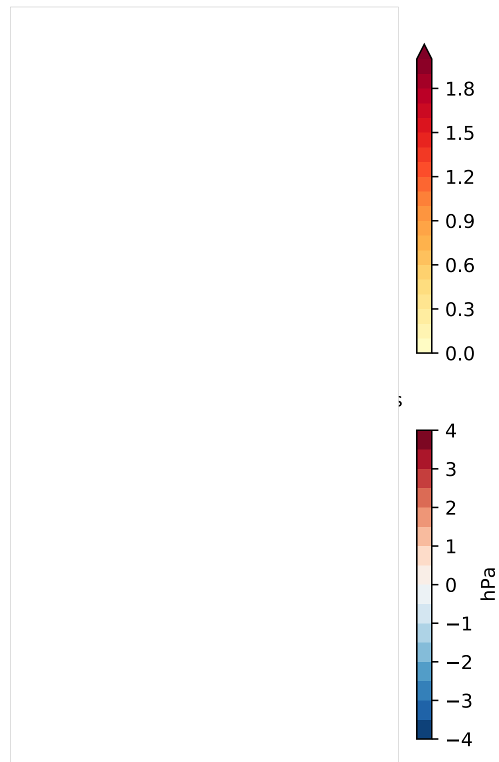
Wetter land ➡ weaker coastal upwelling-favorable winds







(a) Bowen ratio (sensible over latent heat flux) in Modern run. **(d)** Climatology SLP (hPa) & surface winds for Modern.

Minmin Fu, Mark Cane, Peter Molnar, Eli Tziperman, 2021, 2022

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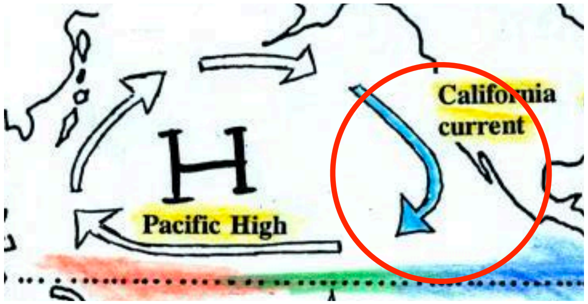

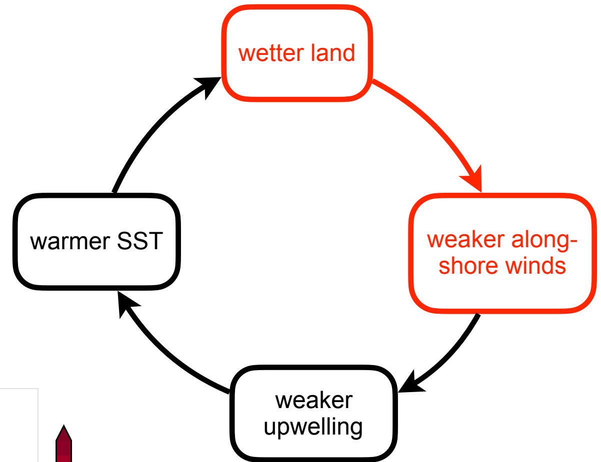

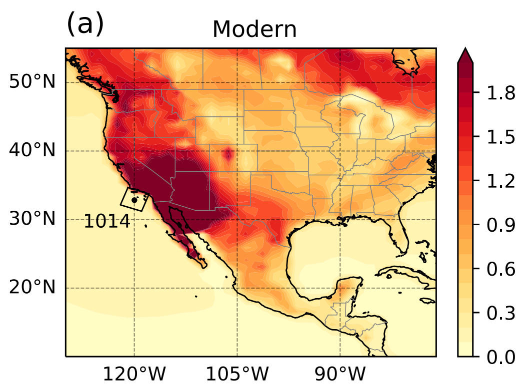

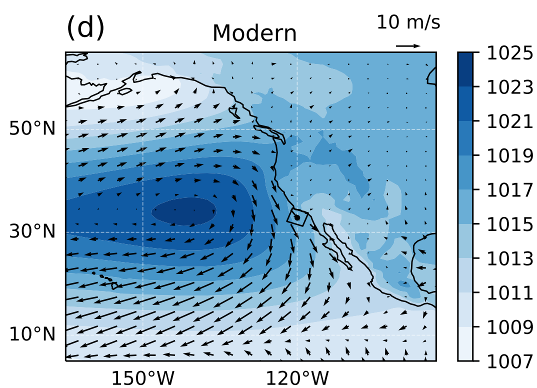

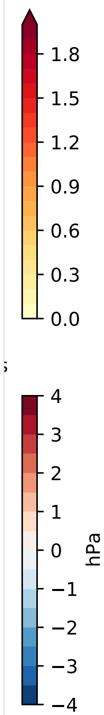

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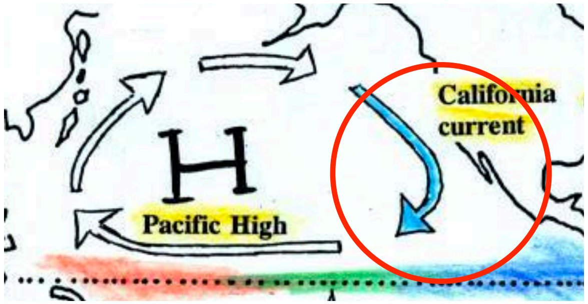

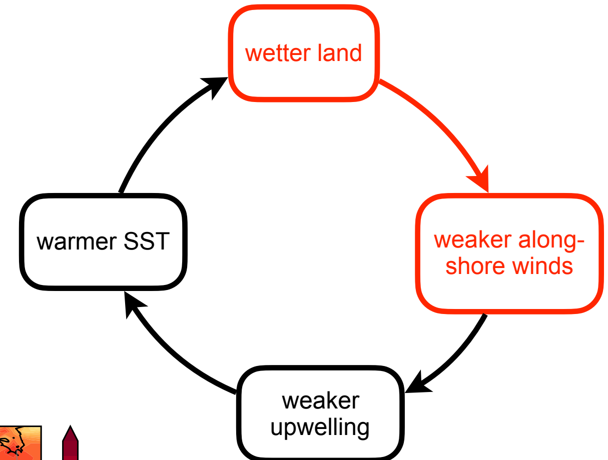

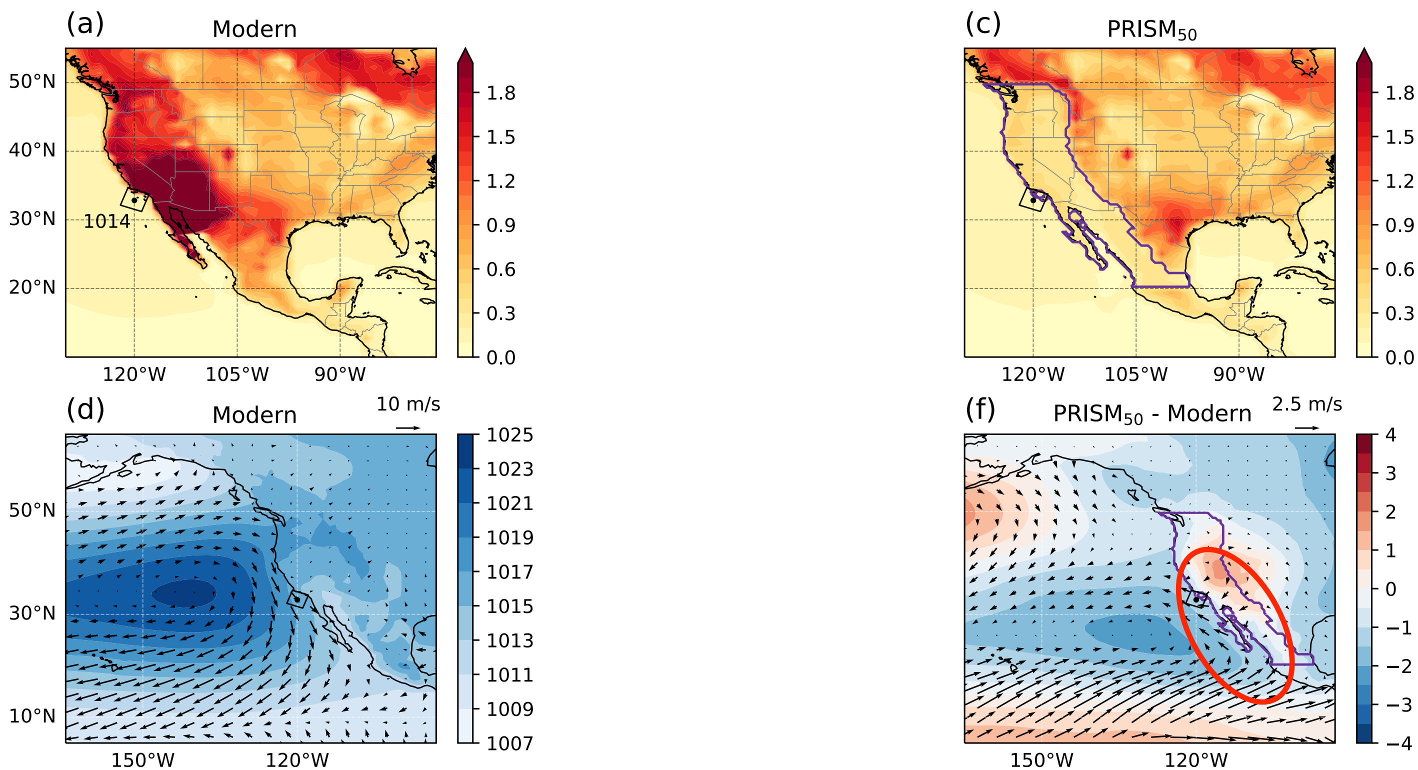

(a) Bowen ratio (sensible over latent heat flux) in Modern run. **(d)** Climatology SLP (hPa) & surface winds for Modern.

(c) Bowen ratio, PRISM50. **(f)** SLP and winds: diff between PRISM50 & Modern.

Minmin Fu, Mark Cane, Peter Molnar, Eli Tziperman, 2021, 2022

Wetter land ➨ weaker coastal upwelling-favorable winds

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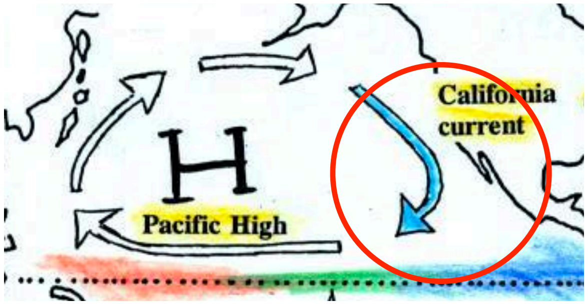

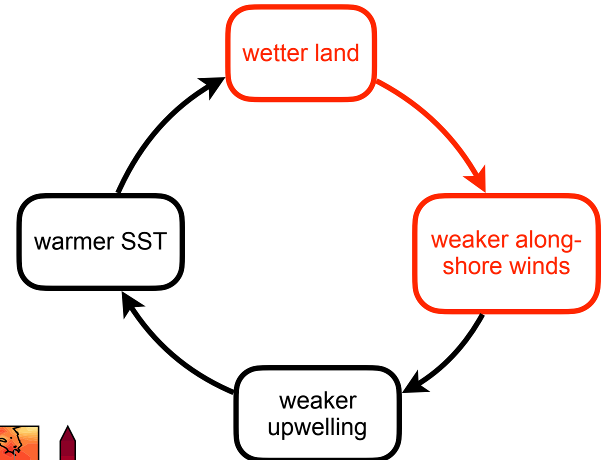

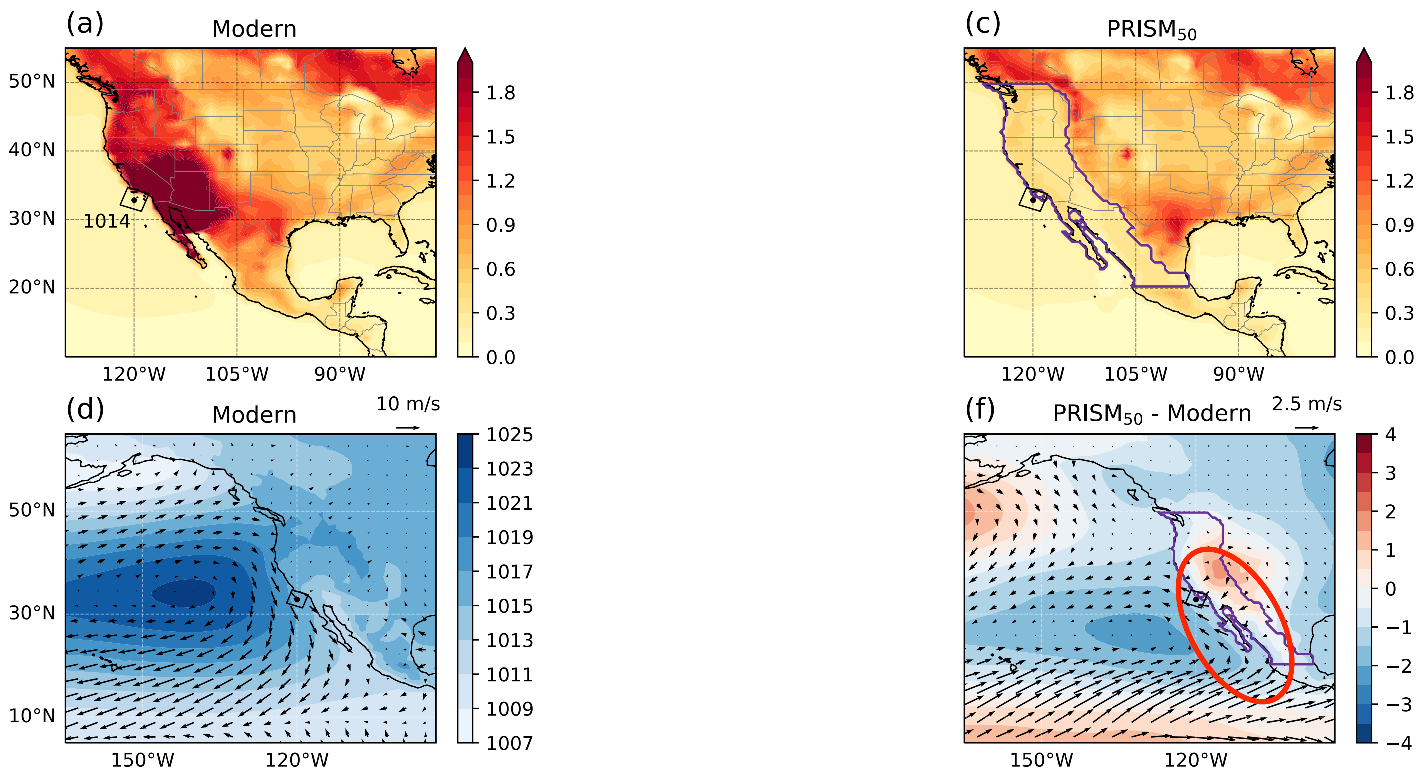

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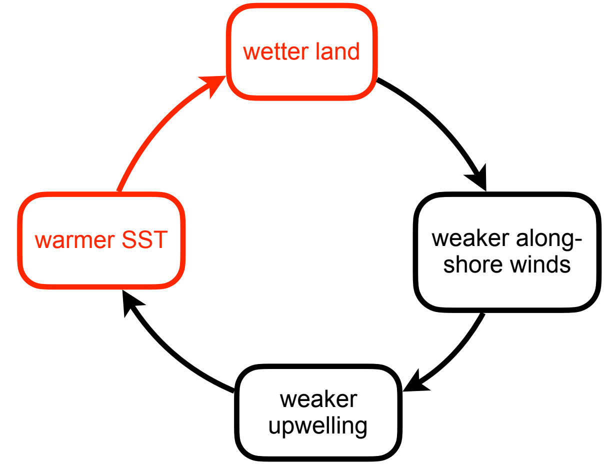
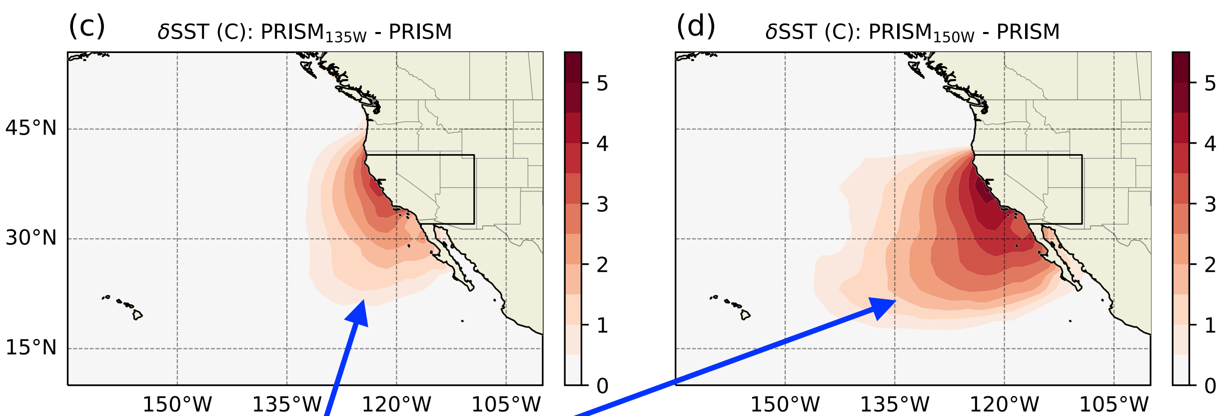
➨ East-west pressure gradient is weakened by wetland presence, and along-coast winds weaken

Minmin Fu, Mark Cane, Peter Molnar, Eli Tziperman, 2021, 2022

2nd set of experiments: Warmer SST ➡ wetter land



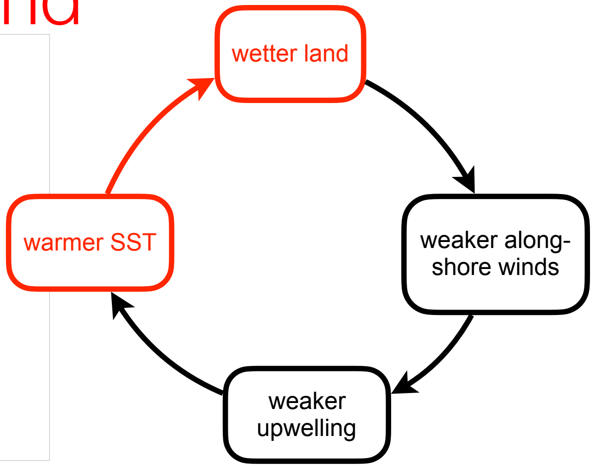
The experiment: modify SST to emulate weakening of upwelling and examine atmospheric response

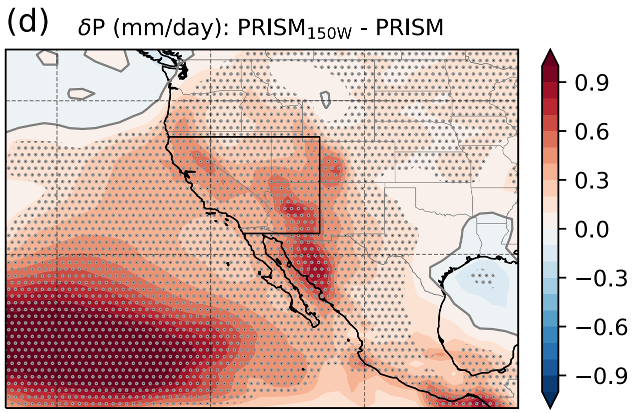


Two examples of imposed SST perturbations emulating the results of a weakening upwelling

Minmin Fu, Mark Cane, Peter Molnar, Eli Tziperman, 2021, 2022

Warmer SST ➡ wetter land

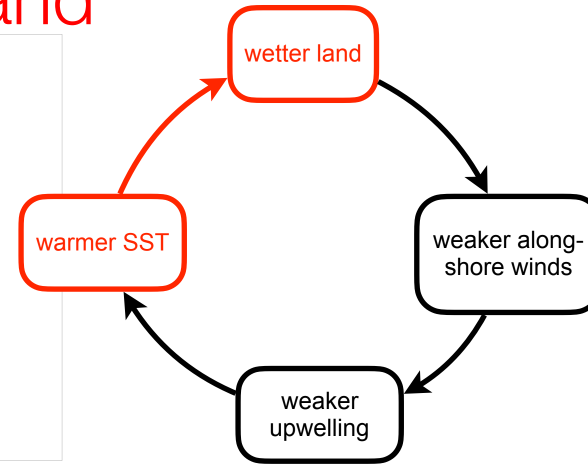


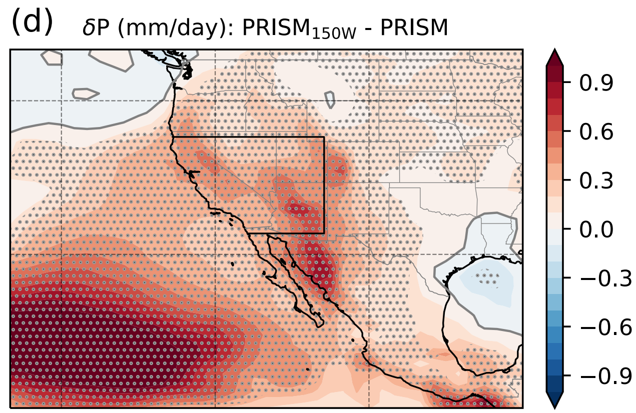


Increased precipitation over land for warmer coastal SST,

Minmin Fu, Mark Cane, Peter Molnar, Eli Tziperman, 2021, 2022

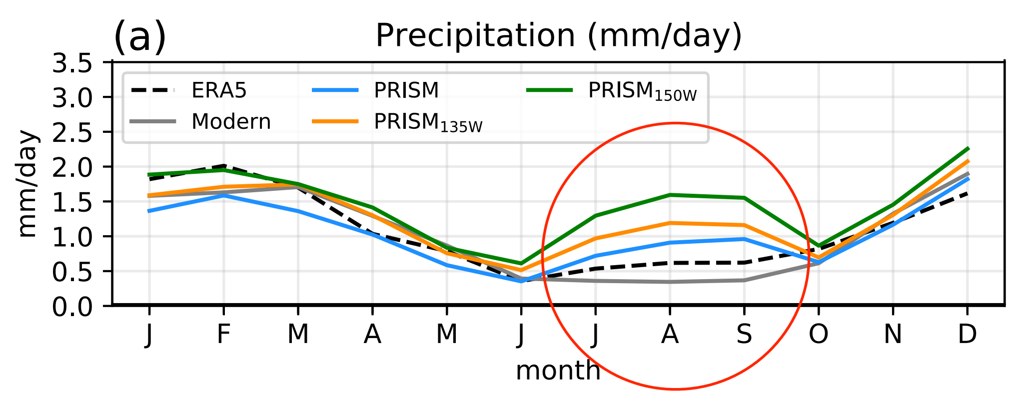
Warmer SST ➡ wetter land





Increased precipitation over land for warmer coastal SST,

especially in summer



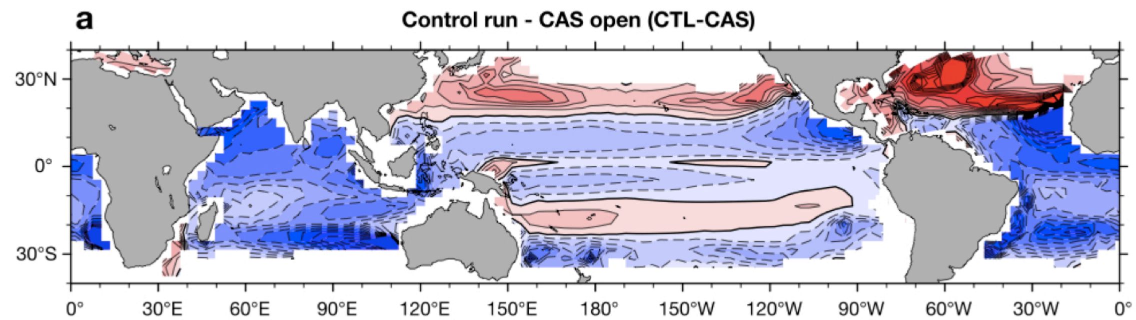
Minmin Fu, Mark Cane, Peter Molnar, Eli Tziperman, 2021, 2022

Permanent El Niño

Permanent El Niño ideas

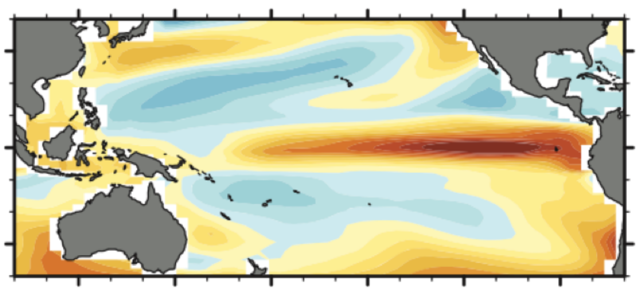
Move Papua/ New Guinea;

[Cane&Molnar 2001; Fedorov et al 2013]



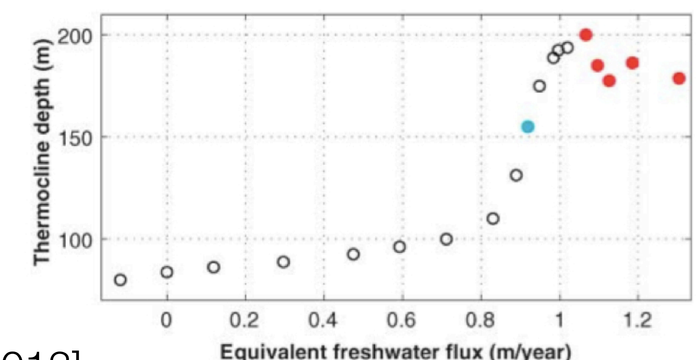
Open central American seaway

[Steph et al 2010]



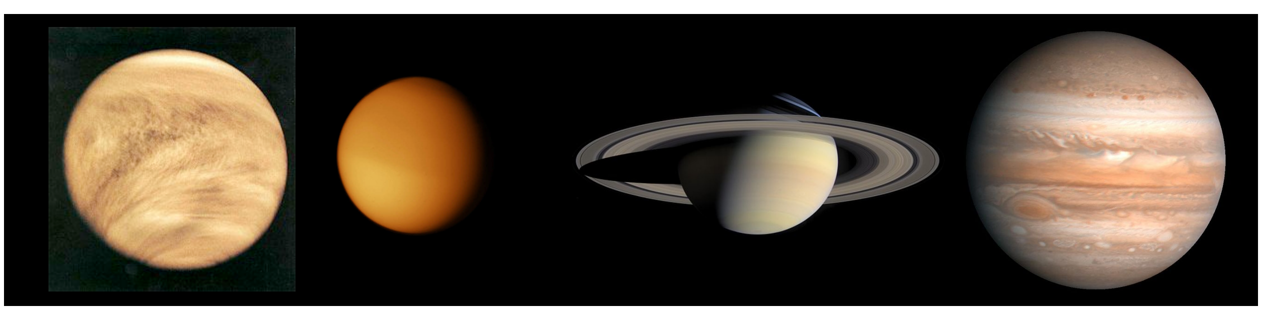
Hurricanes/ ocean mixing

[Emanuel 2002… Fedorov et al 2010/2013]



collapse equatorial thermocline w/ N. Pacific fresh water flux

[Fedorov et al 2004/2006]

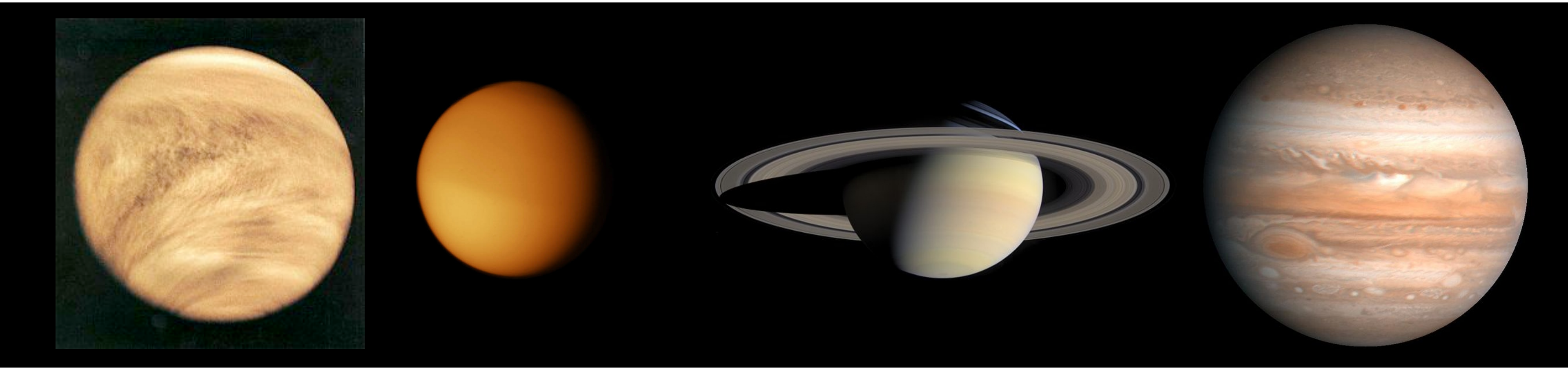


Atmospheric superrotation due to stronger MJO

Tziperman & Farrell 2009,
Arnold et al 2012, 2014.

Weakening the easterlies: 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 QBO
- "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 $$\psi = A\cos(kx + ly - \sigma t)$$

Superrotation dynamics: Rossby Wave reminder…

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

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

Superrotation dynamics: Rossby Wave reminder…

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

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Meridional flux of zonal momentum

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

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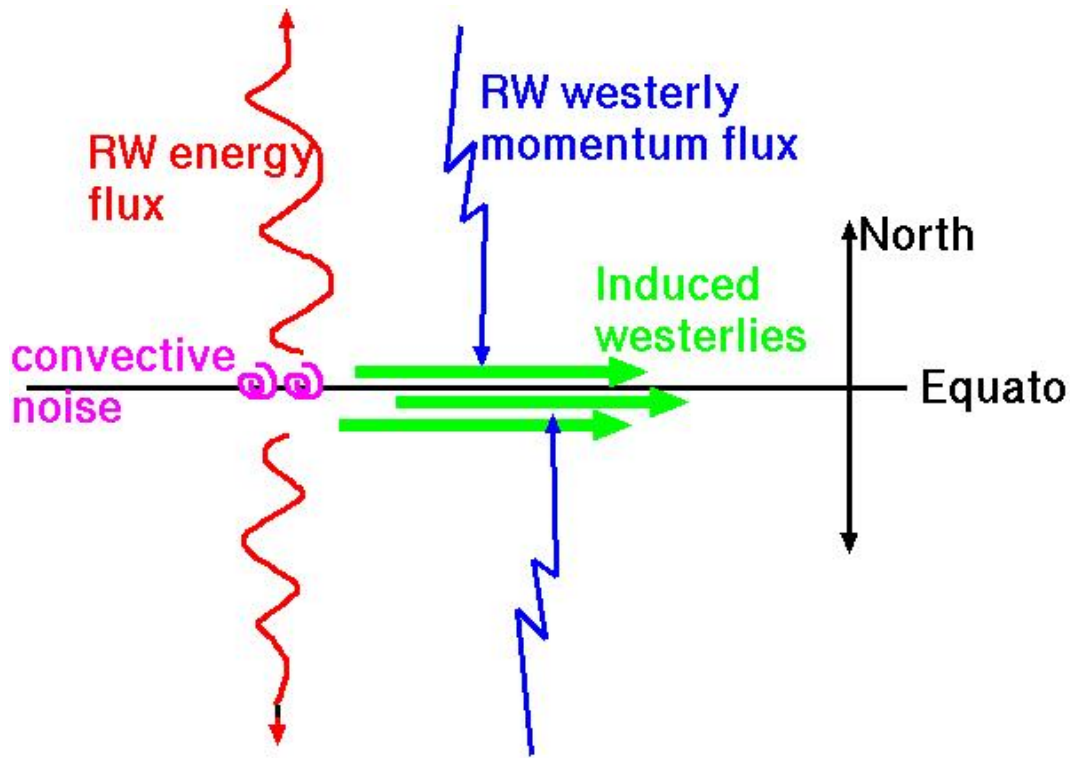
Meridional flux of zonal momentum

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

➔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.

A summary of the superrotation mechanism for a permanent El Niño

1. Warmer Pliocene ➔ stronger Madden-Julian Oscillation (MJO) at equator

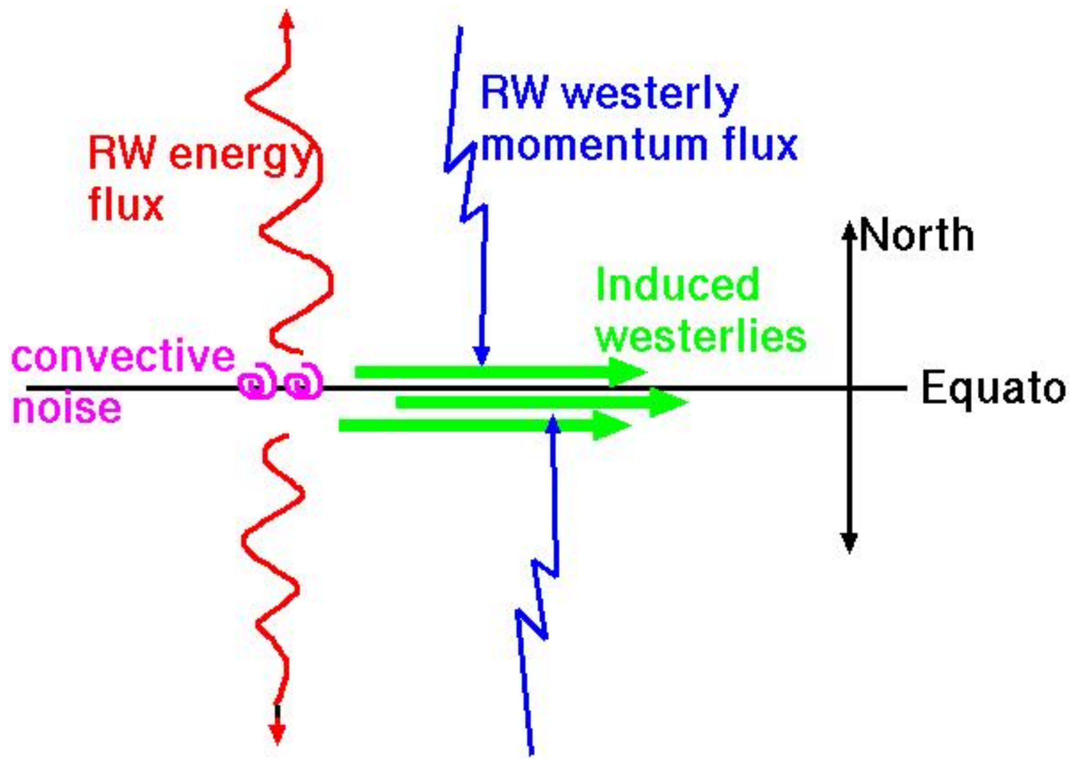


Tziperman & Farrell 2009, Arnold et al 2012, 2014.

A summary of the superrotation mechanism for a permanent El Niño

1. Warmer Pliocene ➔ stronger Madden-Julian Oscillation (MJO) at equator

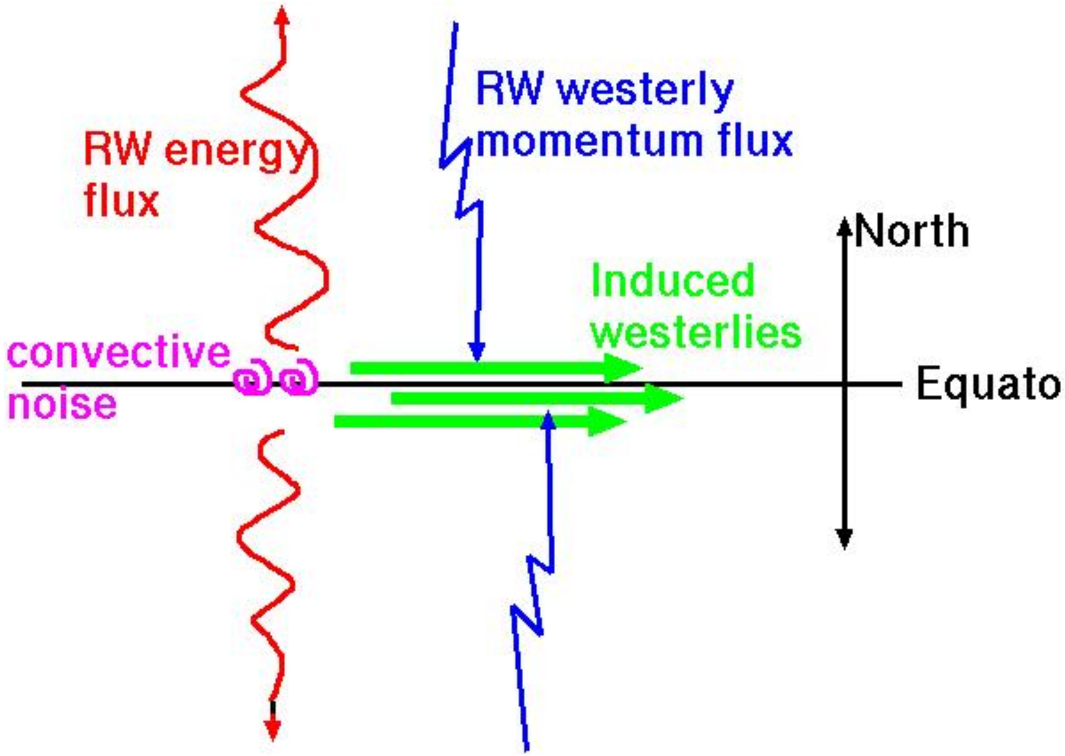
2. ➔ Excited Rossby waves ➔ equatorward westerly momentum flux ➔ weaken equatorial easterlies.



Tziperman & Farrell 2009, Arnold et al 2012, 2014.

A summary of the superrotation mechanism for a permanent El Niño

1. Warmer Pliocene ➔ stronger Madden-Julian Oscillation (MJO) at equator



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

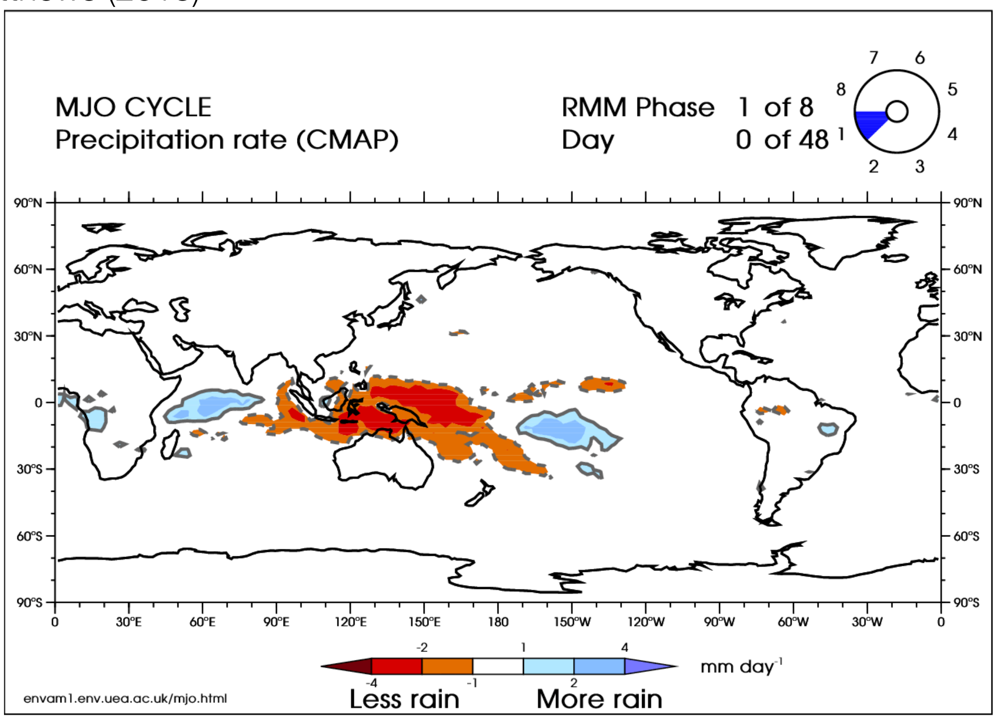
3. ➔ decreased E-W thermocline slope ➔ eliminate East Pacific cold tongue ➔ Permanent El Nino!

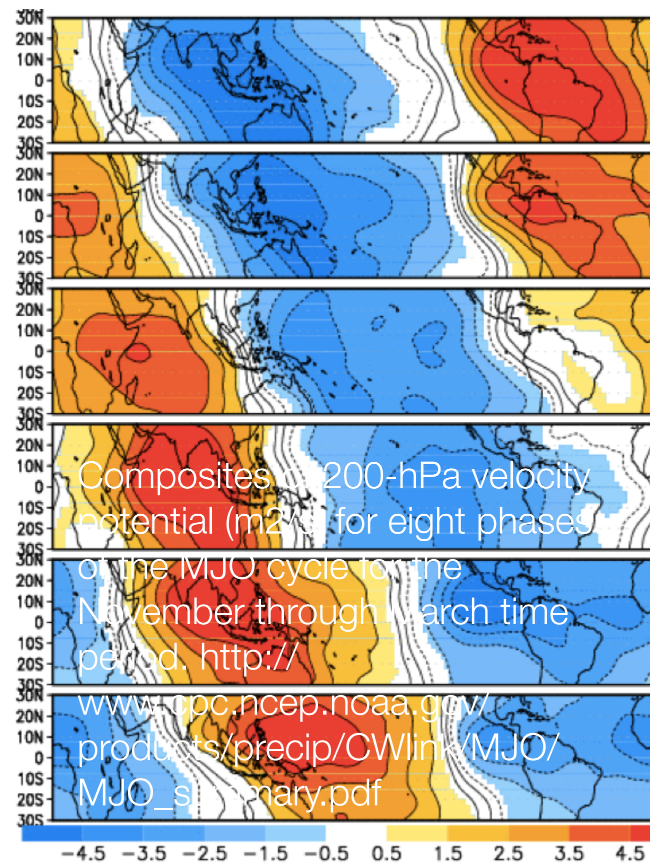
Tziperman & Farrell 2009, Arnold et al 2012, 2014.

The Madden-Julian Oscillation (MJO)

The Madden-Julian Oscillation (MJO): a tropical disturbance that propagates eastward around the global tropics 30-60 day period. Impacts ENSO, tropical & extratropical precipitation, atmospheric circulation, and surface temperature.

Matthews (2013)





Composites of 200-hPa velocity potential (m2/s) for eight phases of the MJO cycle for the November through March time period. http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/MJO_summary.pdf

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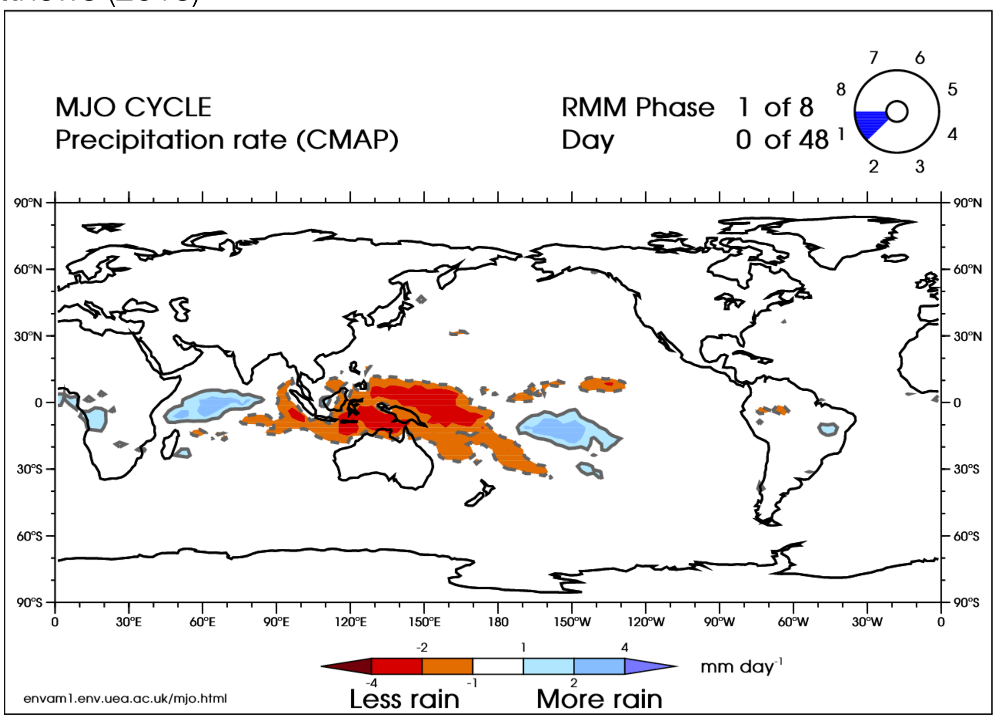

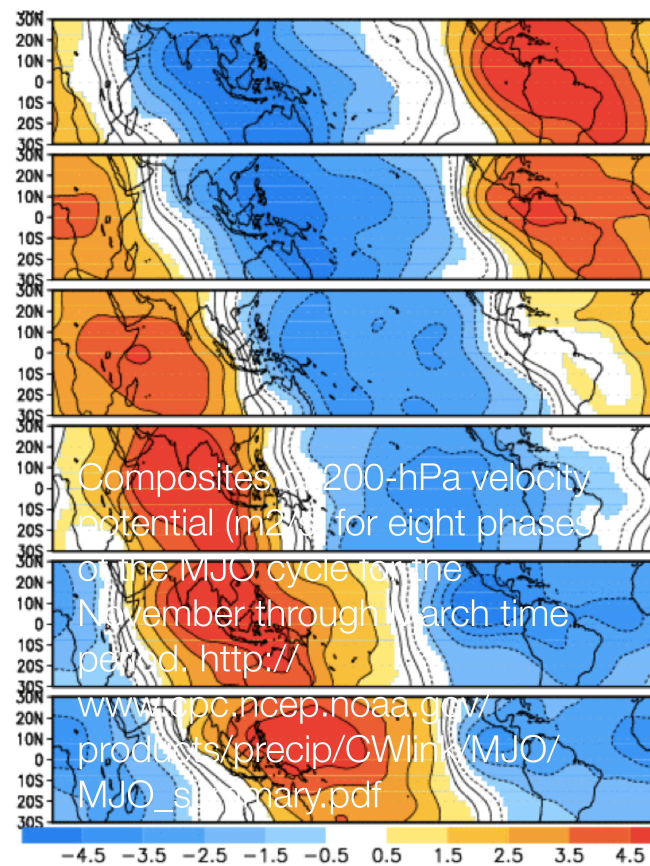

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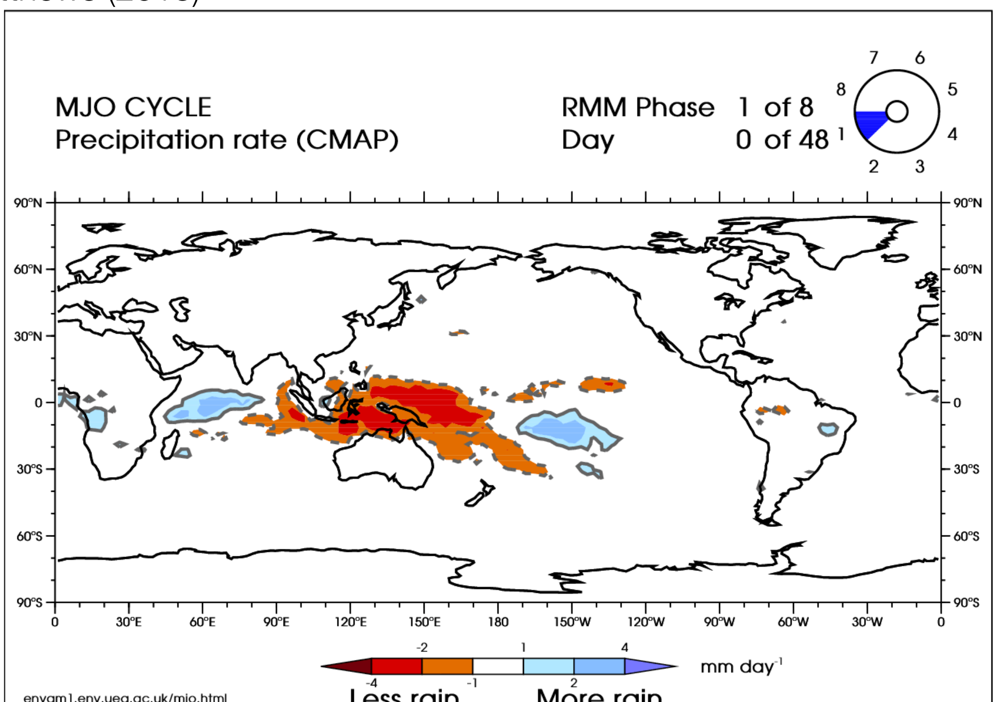

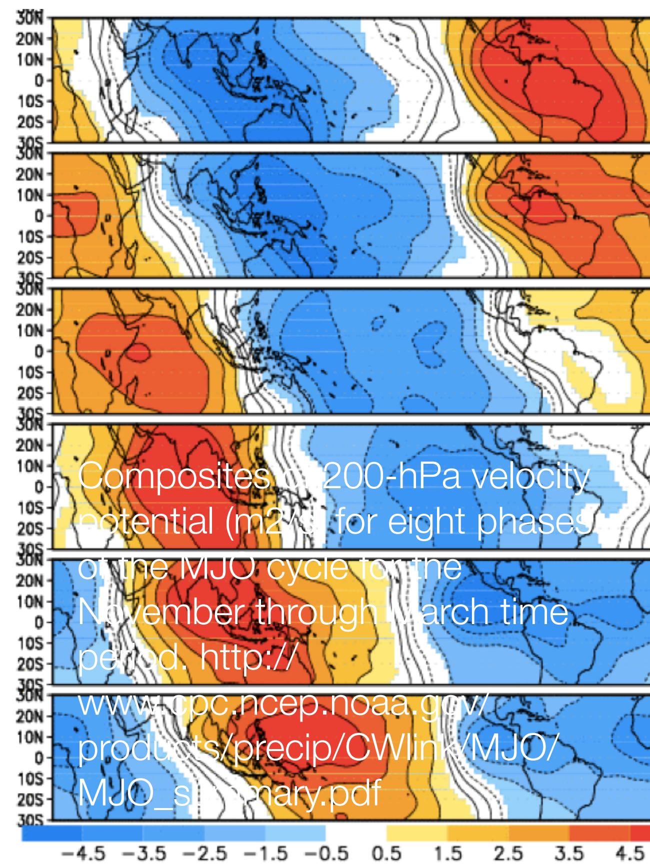

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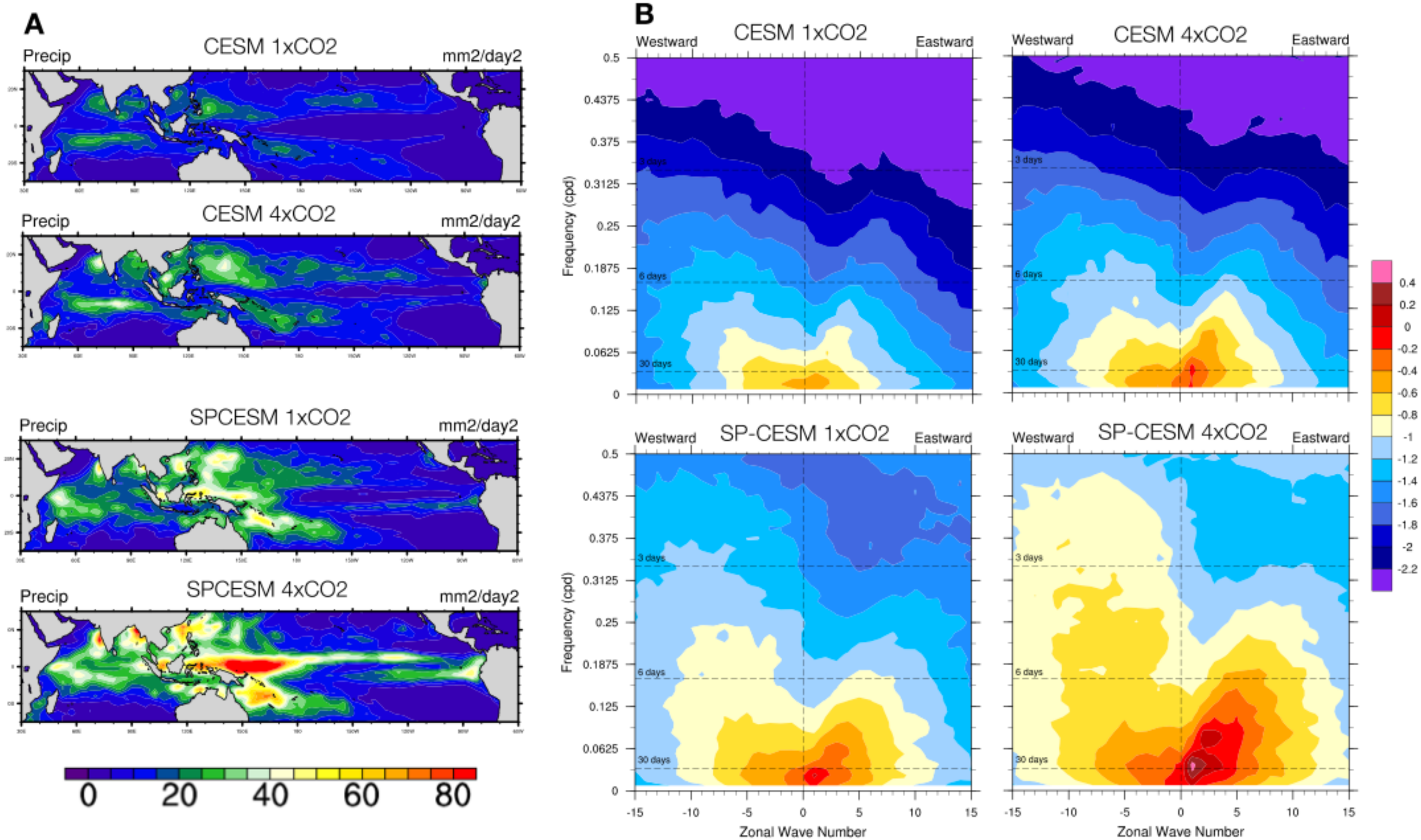
Enhanced MJO in a x4CO_2 greenhouse scenario, SP-CESM, ‘realistic’ configuration



Tziperman & Farrell 2009,
Arnold et al 2012, 2014.

Stronger MJO in fully coupled ocean-atm SPCESM at x4

The End