

# EPS 231, Climate dynamics

Eli Tziperman; Museum building, room 456, 24 Oxford. [eli@eps.harvard.edu](mailto:eli@eps.harvard.edu)

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Course web page, teaching notes, and downloads: Canvas or <http://www.seas.harvard.edu/climate/eli/Courses/EPS231/2025spring/>

Misc papers & notes posted to the website, plus some textbooks:

*Vallis*: Atmospheric and oceanic fluid dynamics,

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**NCAR/Derecho jupyter server account**: For GCM runs/analysis

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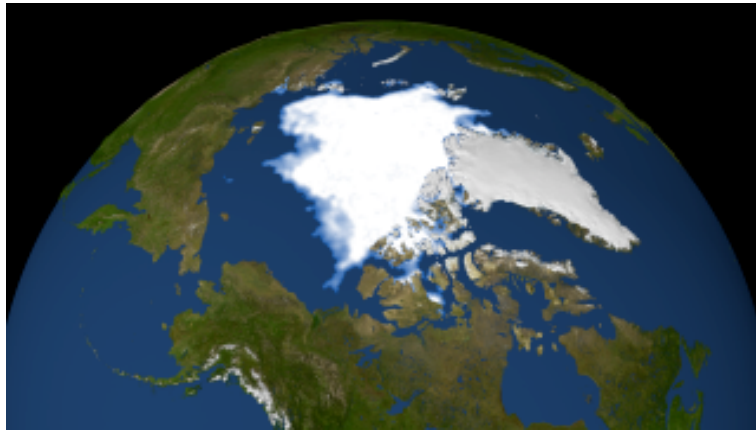
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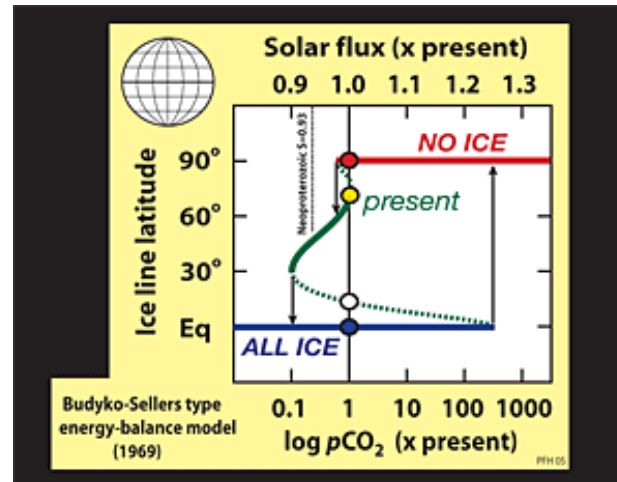
**Requirements**: HW every 9–10 days (50%); final project (50%)

EPS 231, Climate dynamics, review!

# Energy balance, greenhouse effect



NASA

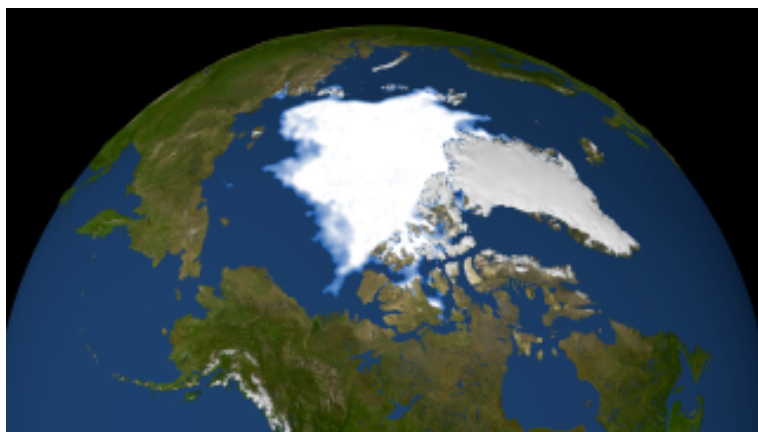


[snowballearth.org](http://snowballearth.org)

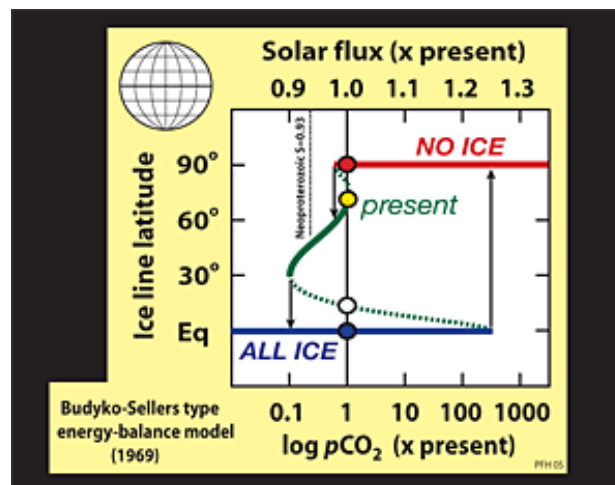
## Run away ice albedo, snowball events:

- Ocean frozen to a depth of ~1km, land ice-covered for Myrs
- Initiation: Termination: CO<sub>2</sub> emissions from volcanoes+clouds
- Predicted by Budyko-Sellers (1969) energy-balance model

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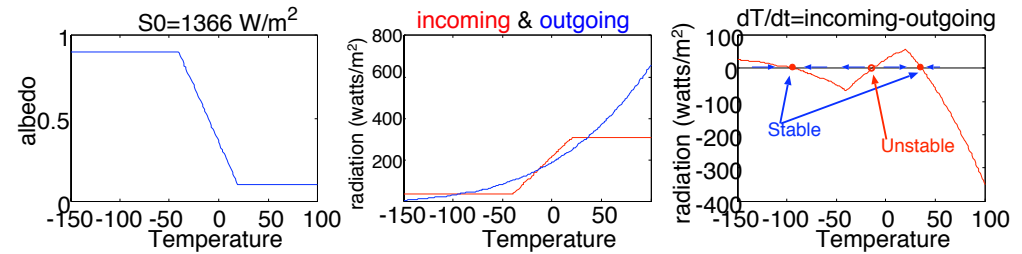
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## Greenhouse:

- Natural greenhouse effect: a 2-level model,
- Anthropogenic: The lapse rate & changes to the emission height

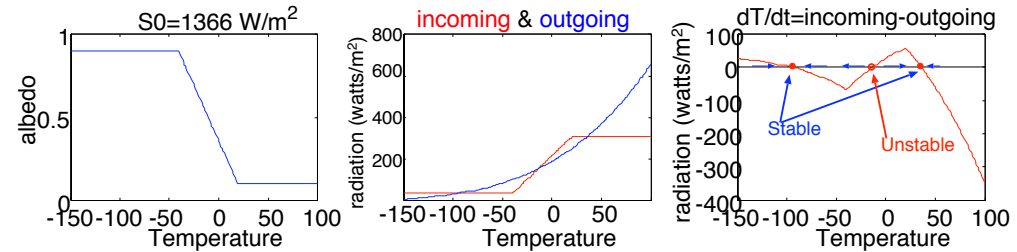
# Energy balance and Greenhouse: Summary

## 1. Energy balance of Earth, the Snowball bifurcation



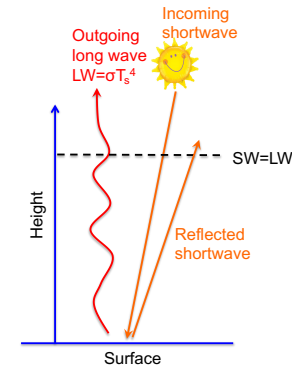
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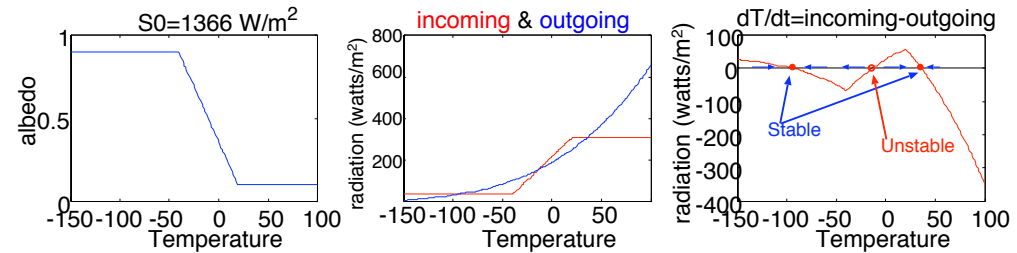
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### A. Two-layer model of the natural greenhouse effect



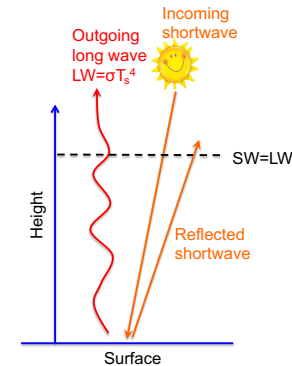
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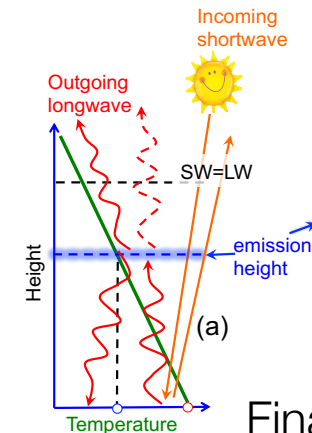


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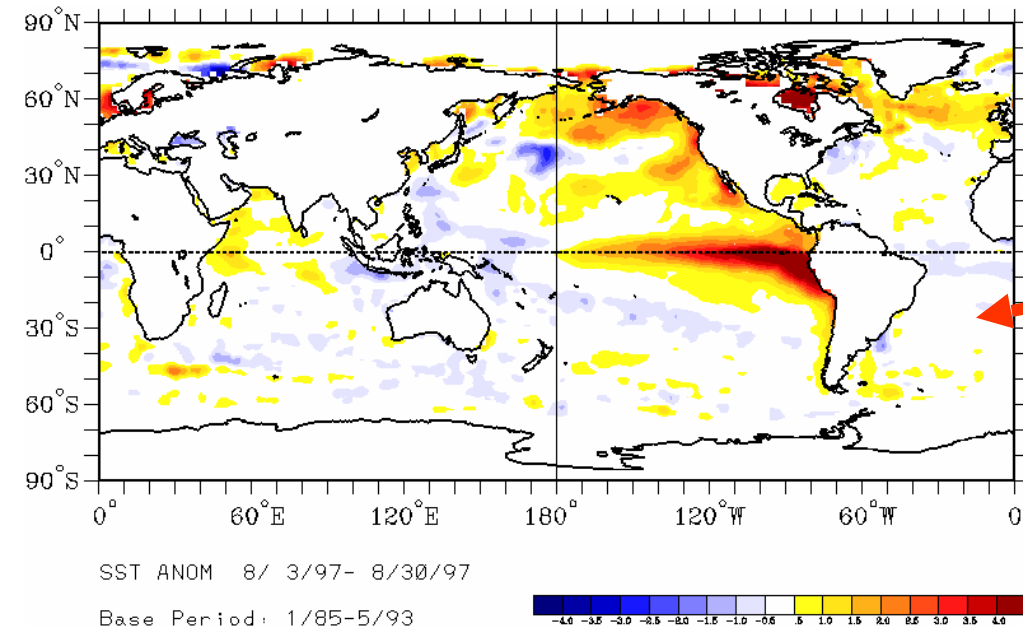
B. Lapse rate, emission height, & anthropogenic greenhouse



## In-class workshop

Why is the 2-level model not a good description of the anthropogenic greenhouse effect?

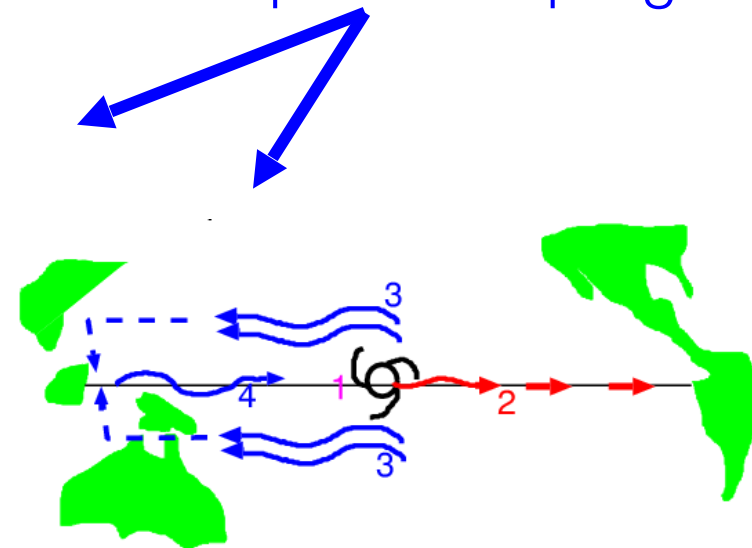
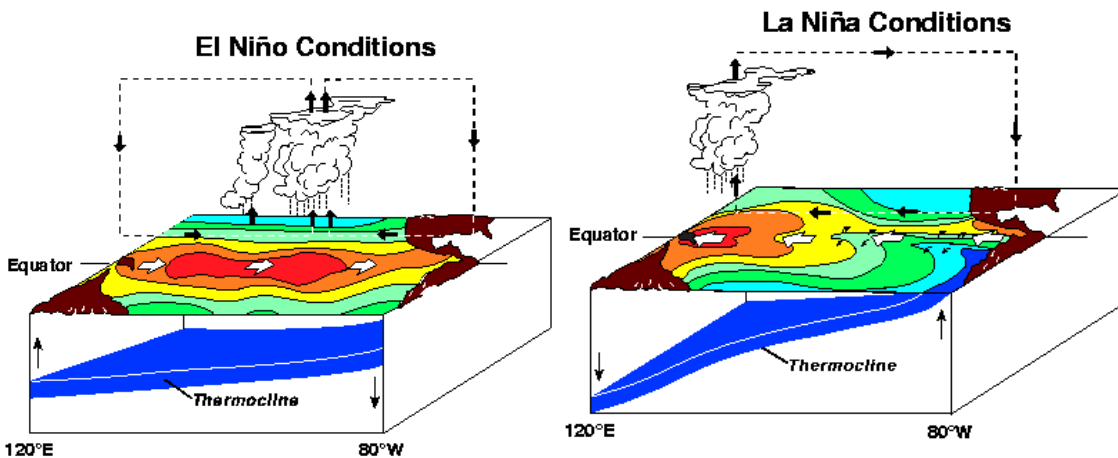
# El Niño – Southern Oscillation (ENSO)



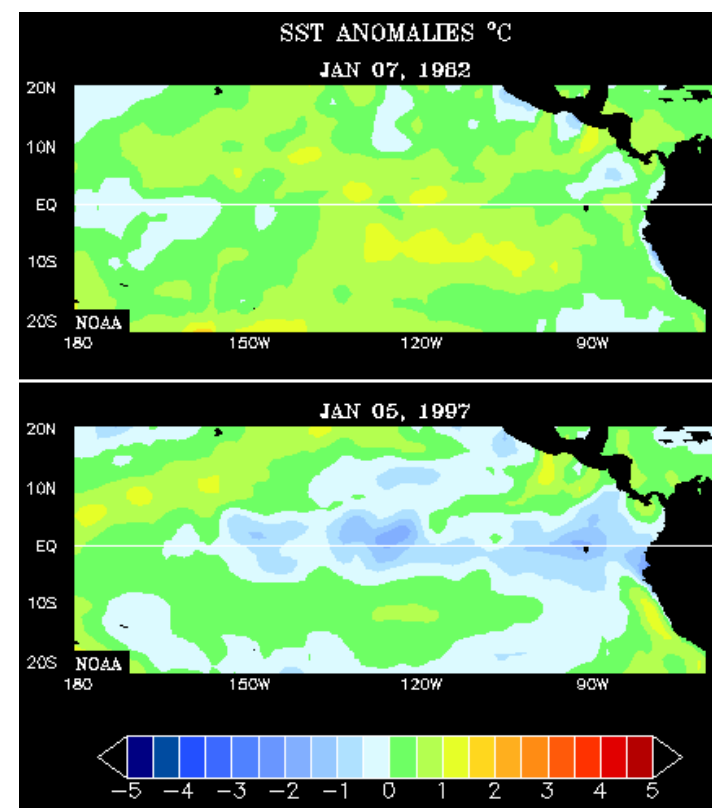
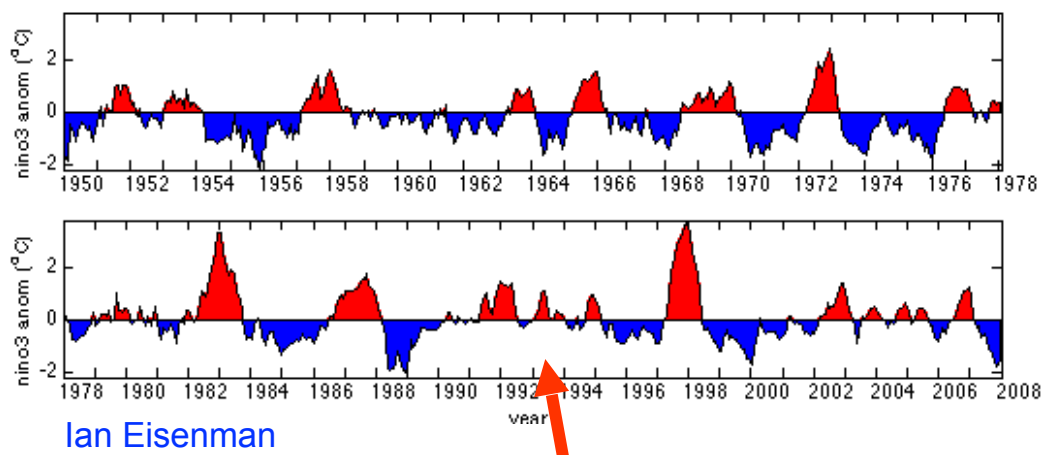
Sea surface temperature, 1997: strongest El Niño in 100 years

Mechanism: ocean waves, thermocline, SST; atmospheric heating, winds; & ocean-atmosphere coupling

[www.pmel.noaa.gov/elnino](http://www.pmel.noaa.gov/elnino)

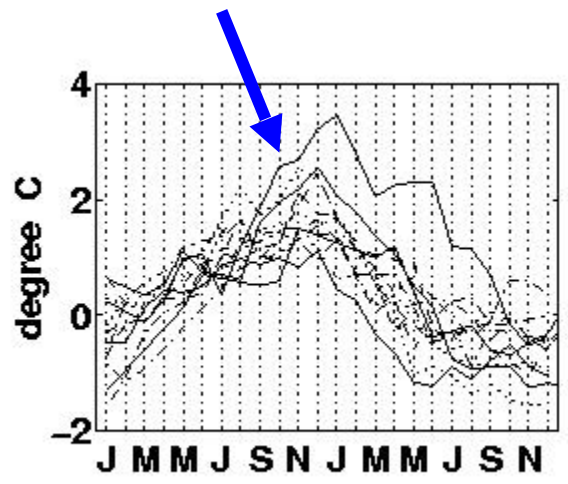


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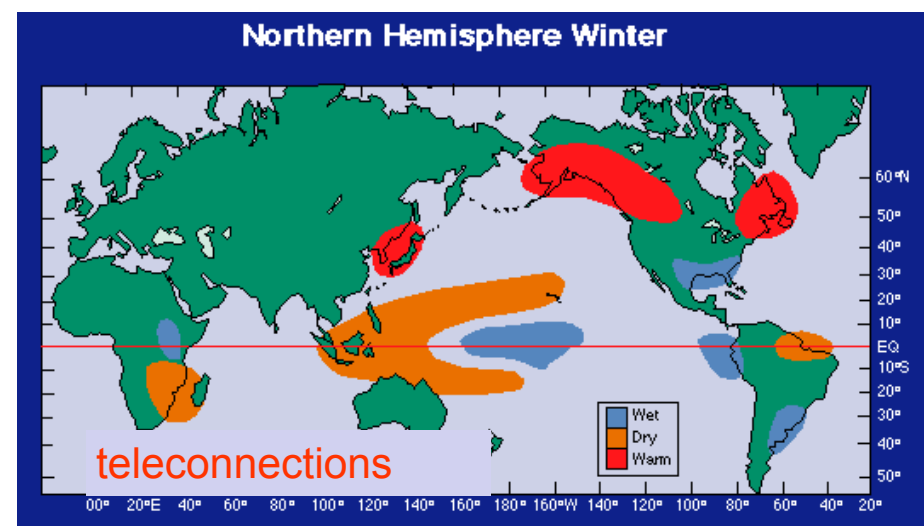


[https://psl.noaa.gov/map/clim/sst\\_olr/old\\_sst/sst\\_anim\\_2panel.shtml](https://psl.noaa.gov/map/clim/sst_olr/old_sst/sst_anim_2panel.shtml)

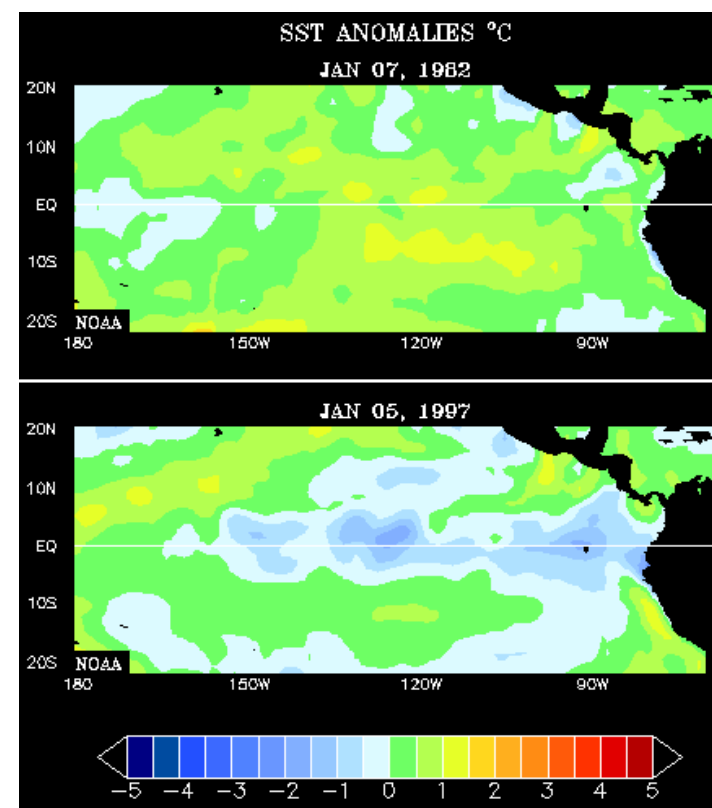
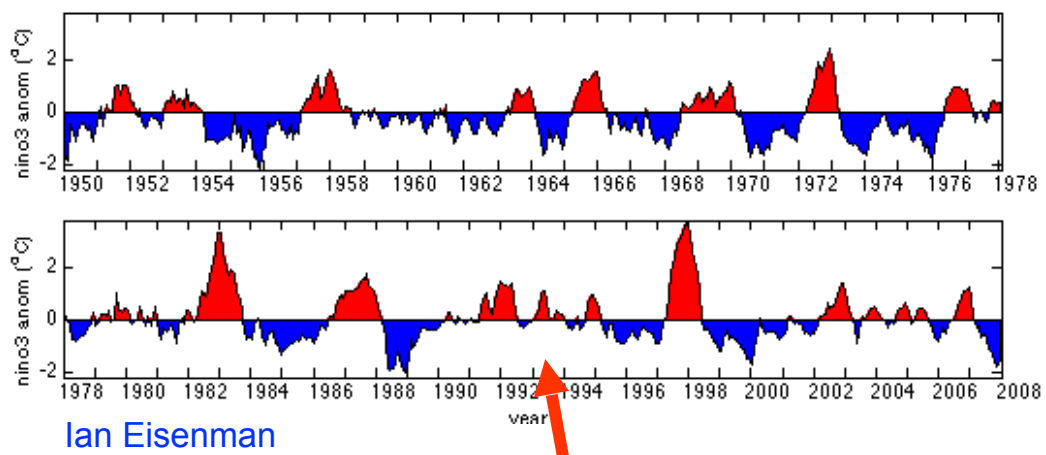
ENSO is irregular (NINO3 SST), yet locked to seasonal cycle



NOAA

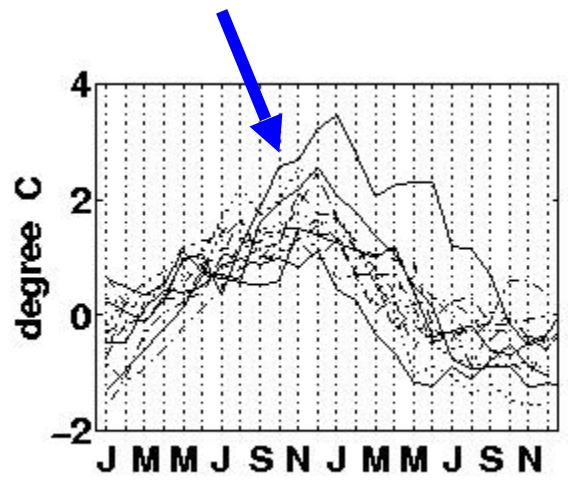


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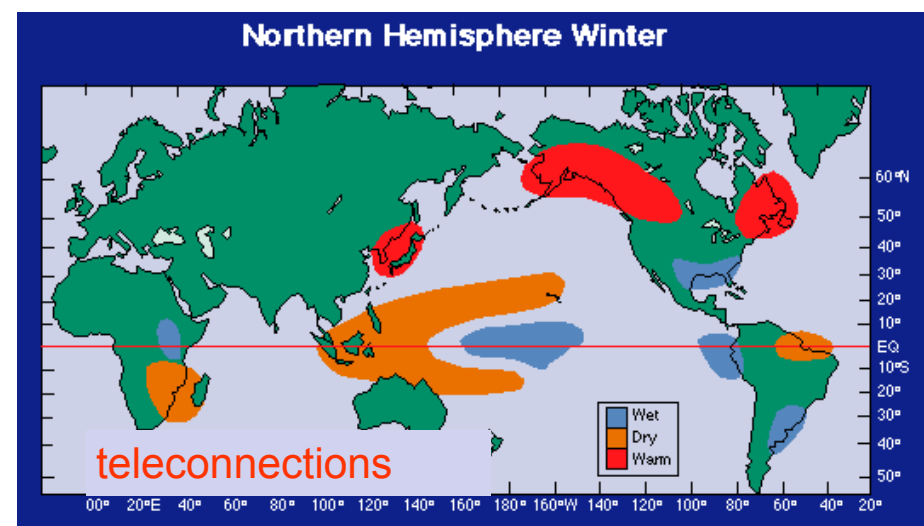


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Weather as stochastic forcing vs nonlinearity & large-scale chaos

- **ENSO diversity:** CP vs EP, different mechanism & teleconnections

- **Future projections:** unclear how frequency/ amplitude will change

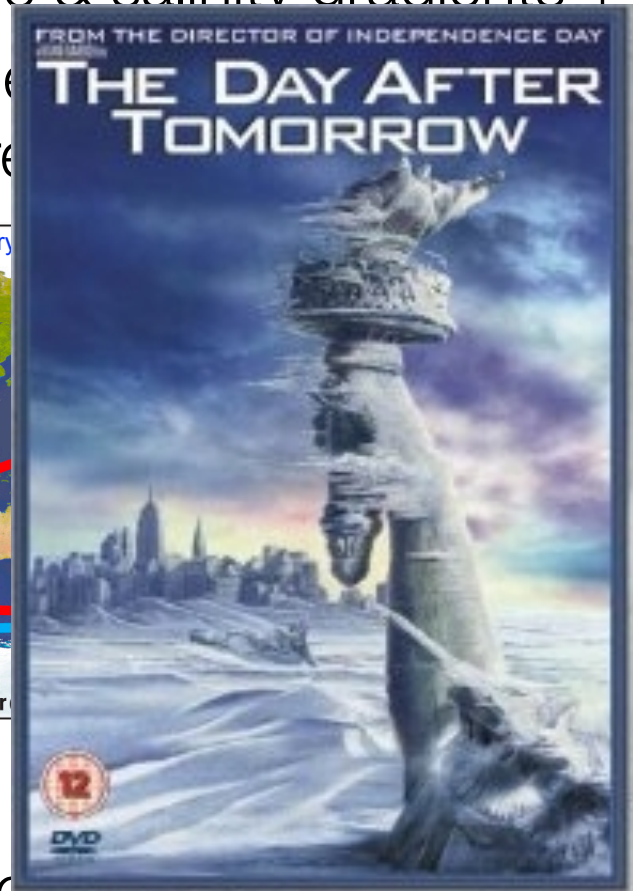
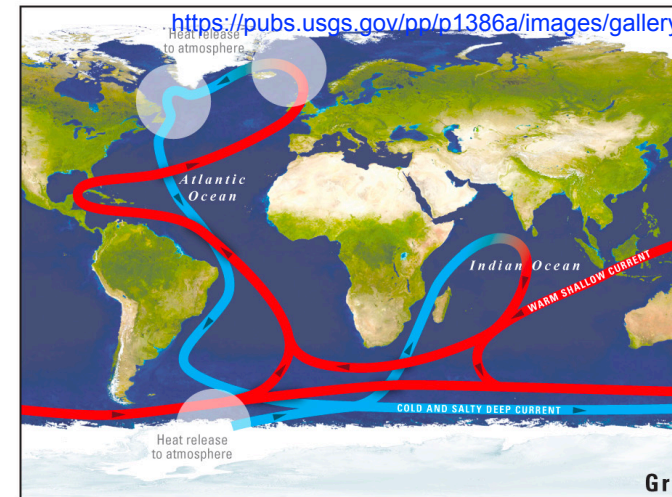
## In-class workshop

Describe the recharge oscillator mechanism



# Atlantic Meridional Overturning Circulation (AMOC)

- Transport: 20 x world rivers combined. Warms Europe...?
- Driven by temperature & salinity gradients + wind + mixing + more
- May become unstable multiple equilibria, tipping points, hysteresis -year time scale



A winter scene in Europe's Little Ice Age, 14th Century  
Pieter Breugel the Elder.

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  - Stochastic resonance

## In-class workshop

What is transient amplification, how is it relevant to ENSO and AMOC variability?

# Dansgaard-Oeschger Events

## DO events in Greenland ice cores:

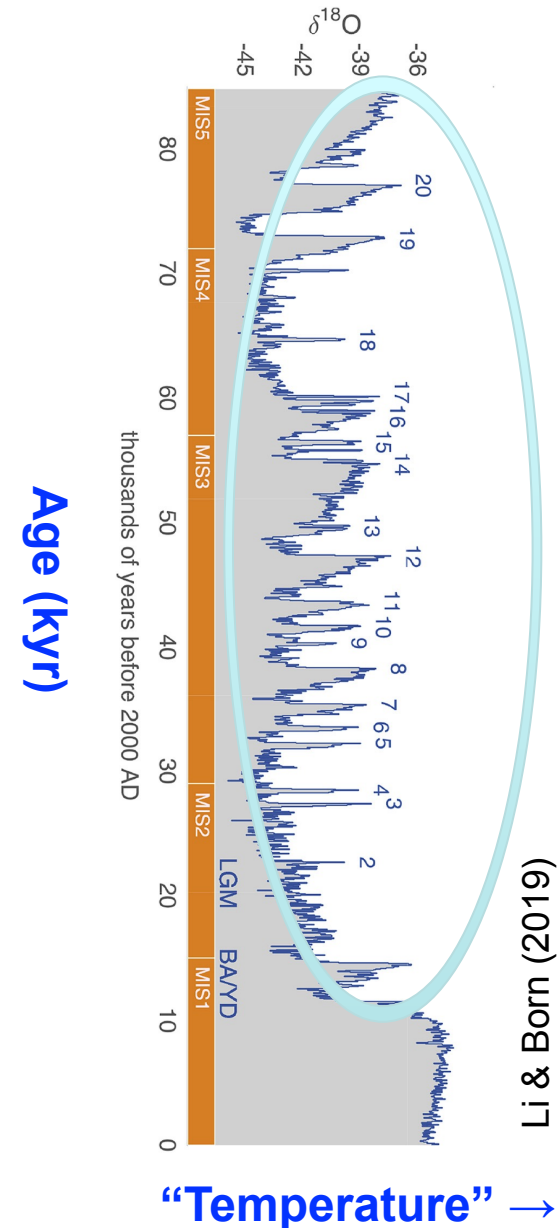
- Warmings every ~1500yr
- ~10 deg C warming
- Start & end within 20 yrs!
- Warmings last 500-1000 yrs

## Mechanism:

- AMOC + sea ice? Future relevance?

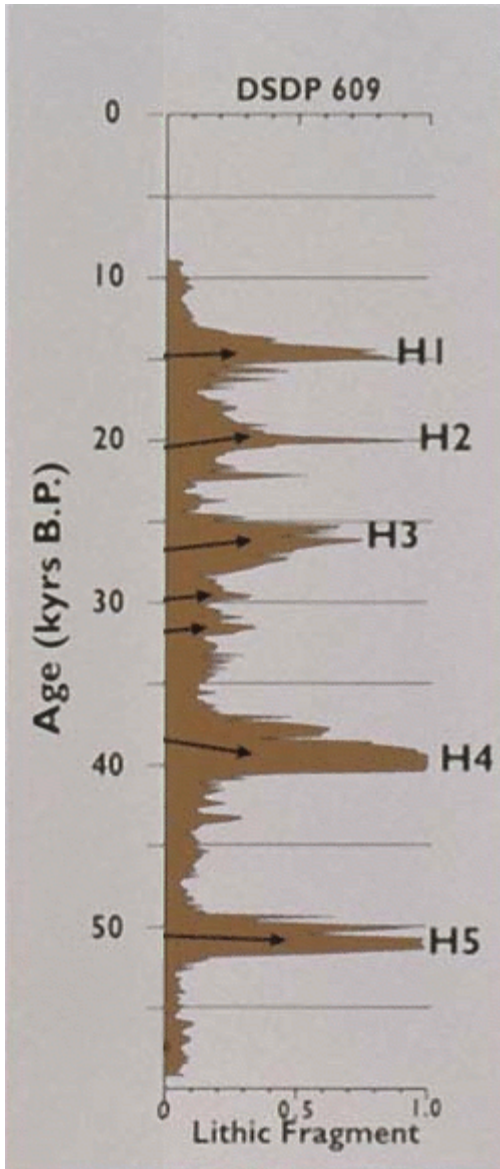


[https://en.wikipedia.org/wiki/ice\\_core#/media/File:Icecore\\_4.jpg](https://en.wikipedia.org/wiki/ice_core#/media/File:Icecore_4.jpg)



# Heinrich events

- Ice Rafted Debris (IRD) sediment layers due to massive glacier discharges from Laurentide & other ice sheets, every 7–10,000 yr.
- Occurred 20–60,000 ago
- Possibly synchronous collapses/ discharges of several ice sheets
- Mechanism: Bing/purge + AMOC + sea ice?

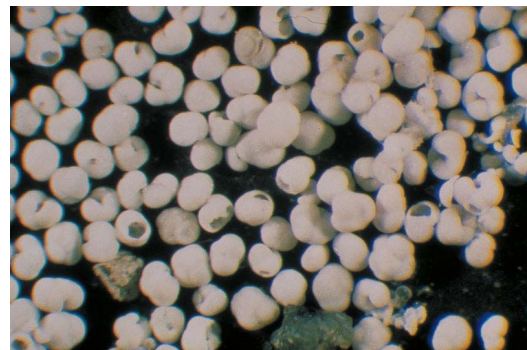


Micrograph of sand-size fraction in core HU87033-009

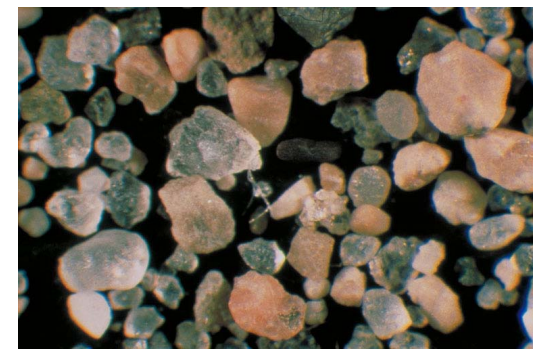
Sand-size fraction from the same core at 670-672 cm depth, within H-2.

from <https://slideplayer.com/slide/12822818/>

or <https://slidetodoc.com/environmental-geosciences-natural-global-change-some-special-events/> Andrea Koschinsky



Typical sediments



Ice rafted debris

## Conclusions: DO and Heinrich events

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## Conclusions: DO and Heinrich events

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- “Precursor events,” a large collapse seemingly triggered by earlier collapse of a smaller ice sheet: may be part of nonlinear phase locking instead.

## In-class workshop

Can abrupt DO-like events happen due to anthropogenic global warming?

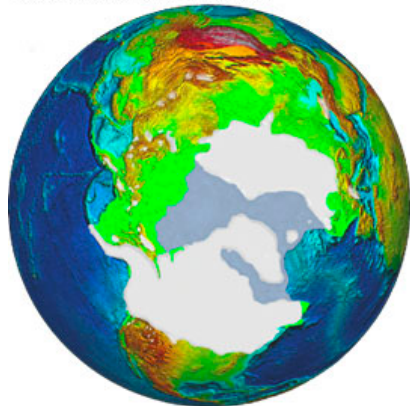
# Glacial cycles

Largest climate signal in past 3 Myrs.

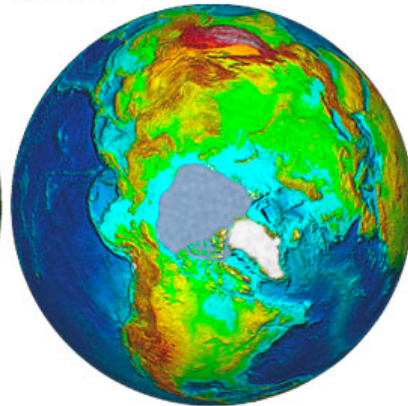
Still not understood:

- Mechanism/ forcing?

Pleistocene (18,000 Years Ago)

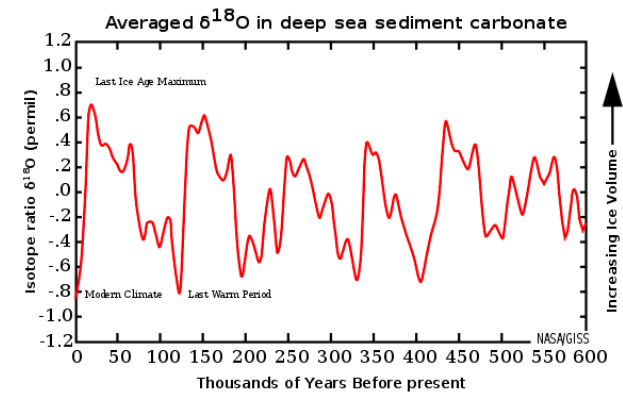


Modern Day



□ Glacial Ice    ■ Sea Ice

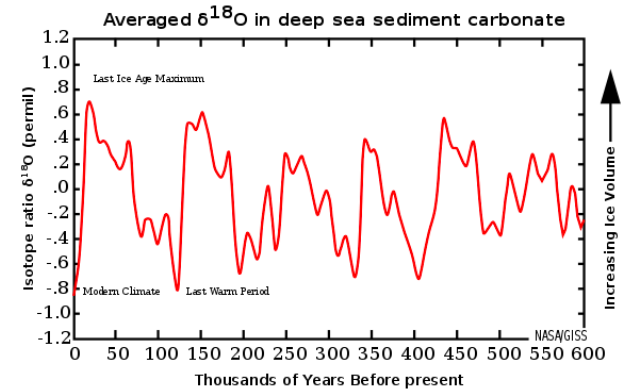
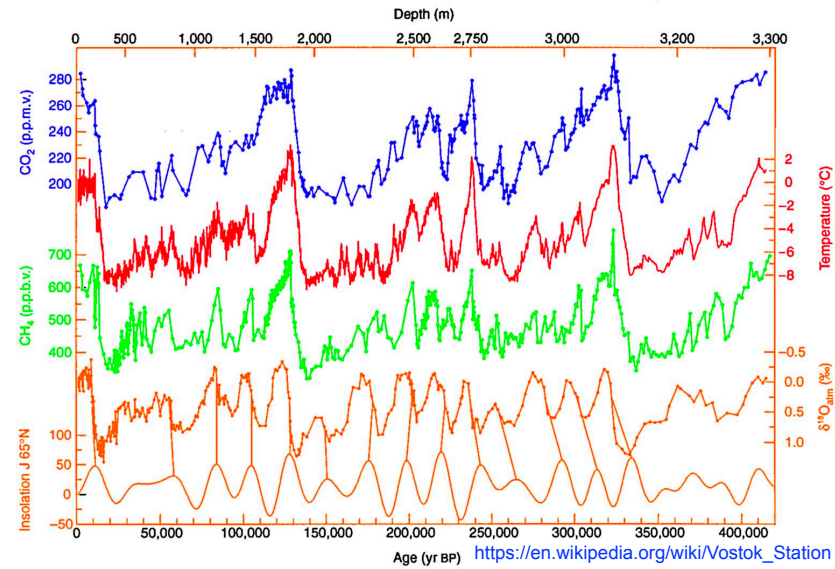
[https://en.wikipedia.org/wiki/100,000-year\\_problem](https://en.wikipedia.org/wiki/100,000-year_problem)



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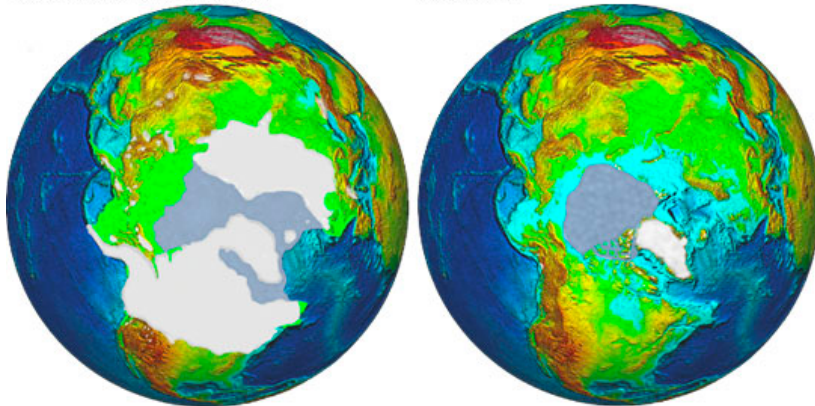
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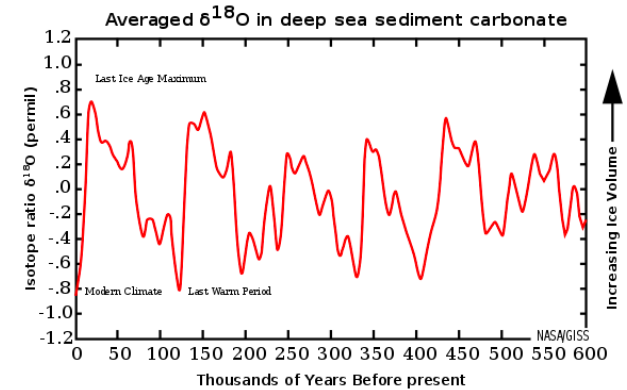
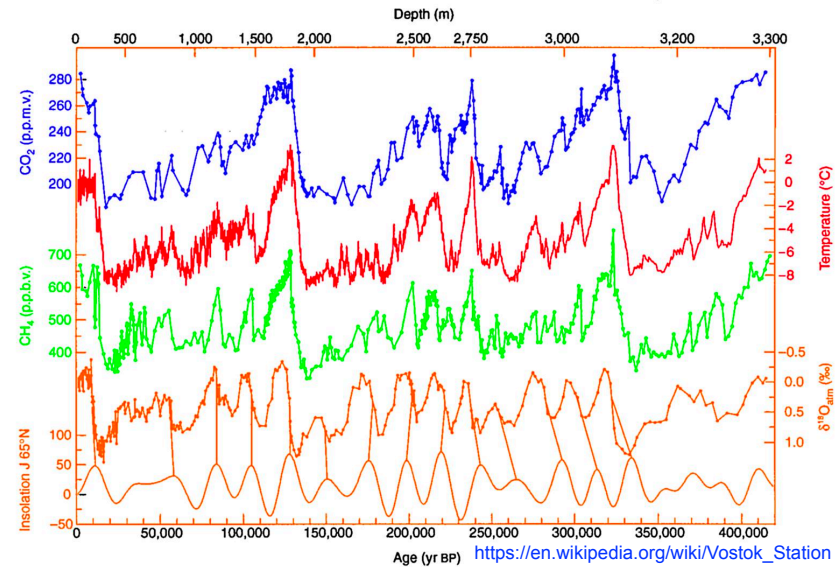


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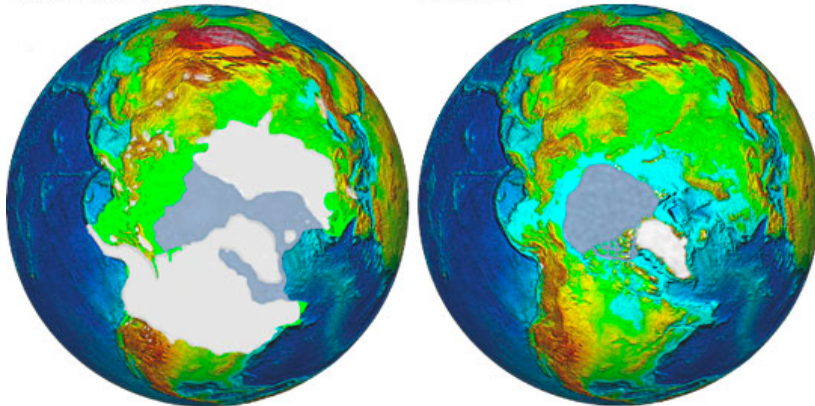
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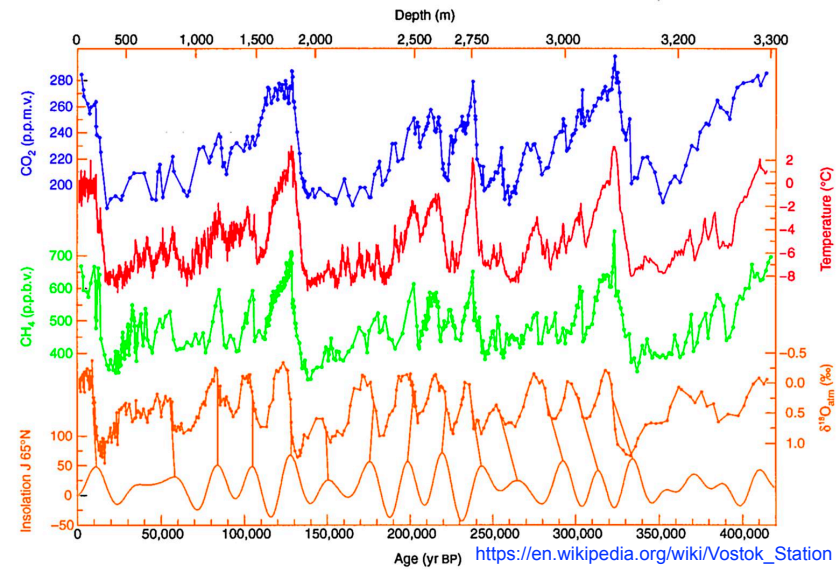


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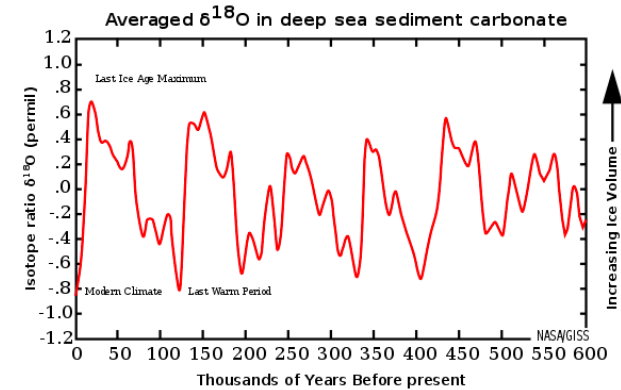
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- Change from 41 kyr to 100 kyr?

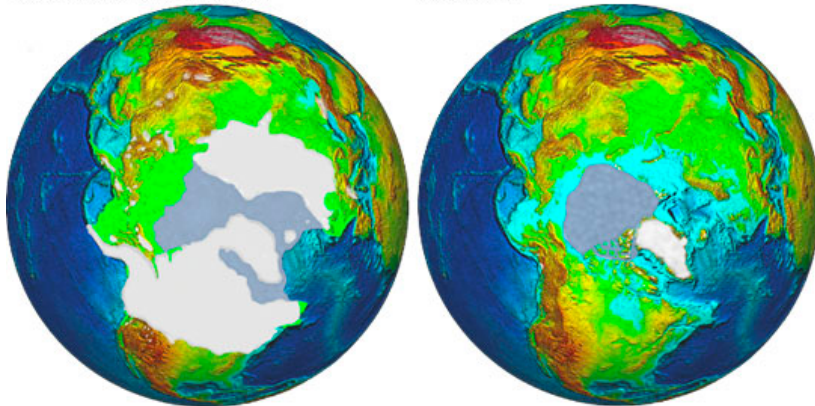


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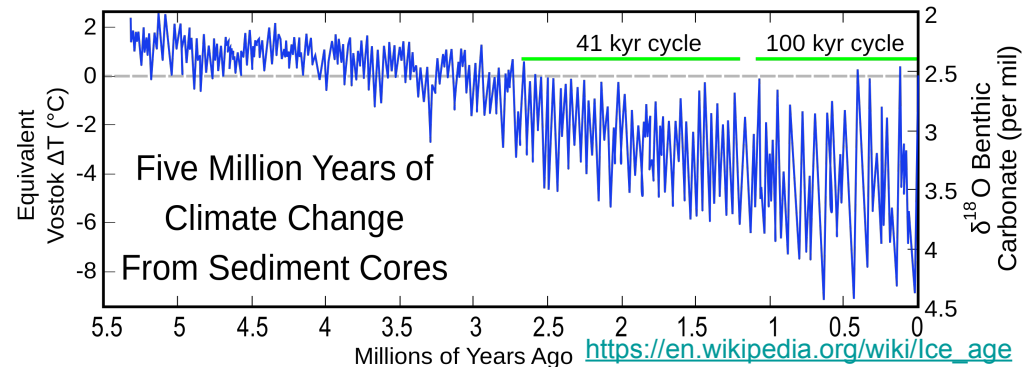


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**Features to be explained:**

## Glacial cycles, summary

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- 100 kyr time scale
- Saw-tooth structure: long glaciations (~90,000 yr), short deglaciations (10,000 yr)
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- Fitting ice volume record vs. a falsifiable mechanism
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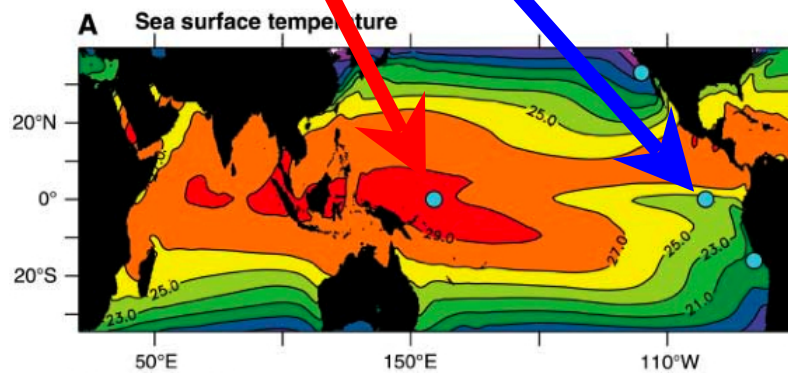
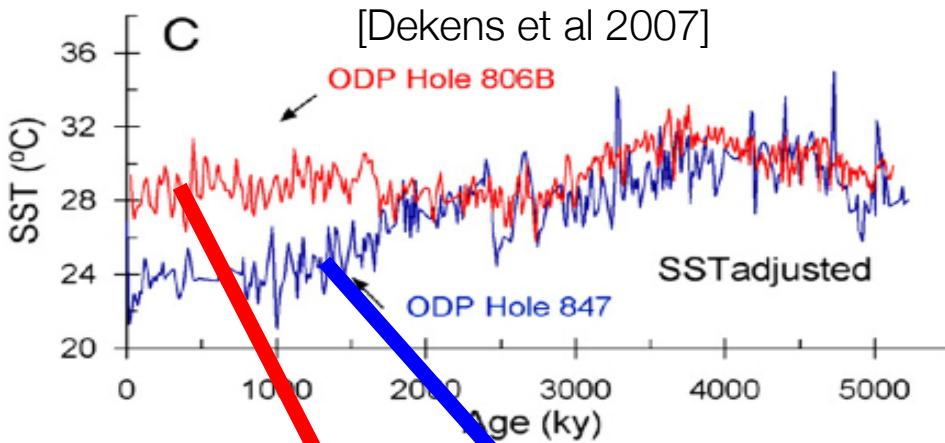
- Likely a self-sustained relaxation oscillation that would have existed without Milankovitch and CO<sub>2</sub> variations
- Phase locked by obliquity (3:1) of precession (4:1 or 5:1)
- 41 kyr oscillation likely driven by integrated summer insolation
- Amplified by CO<sub>2</sub> variations; CO<sub>2</sub> varies due to solubility & biological pumps

Mechanism for glacial cycles is still unresolved, although this is the largest climate variability signal over the past 1 Myr; Mechanism for CO<sub>2</sub> variations also still not clear

## In-class workshop

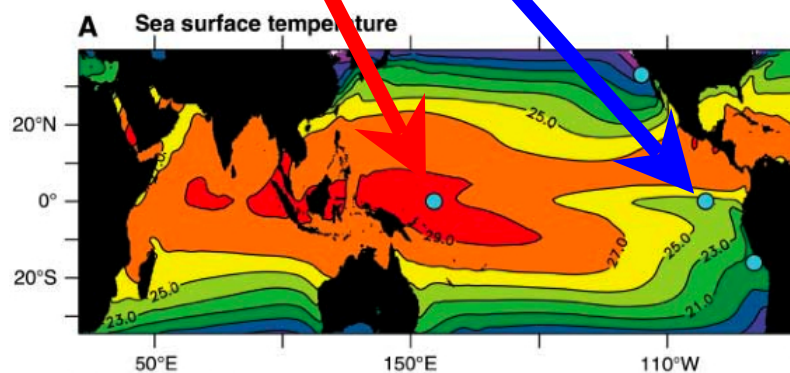
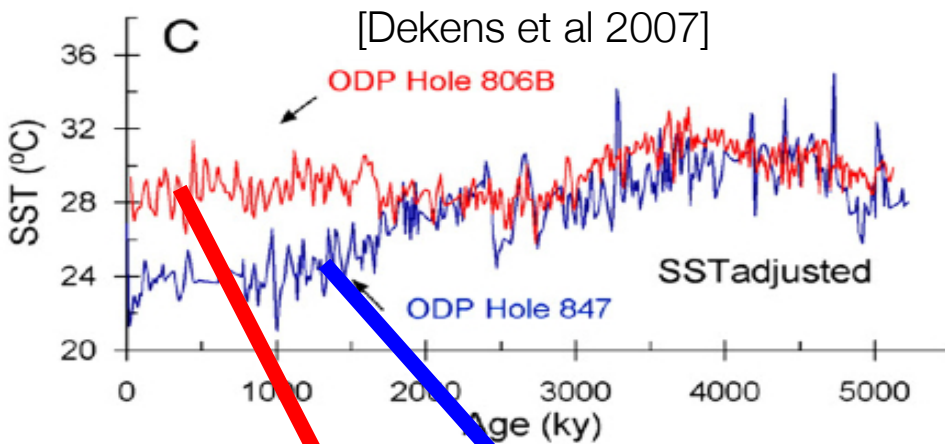
What is a relaxation oscillation? What phenomena that we covered might it be relevant to?

# The Pliocene, 2–5Myr: “Permanent El Niño” & warm upwelling sites

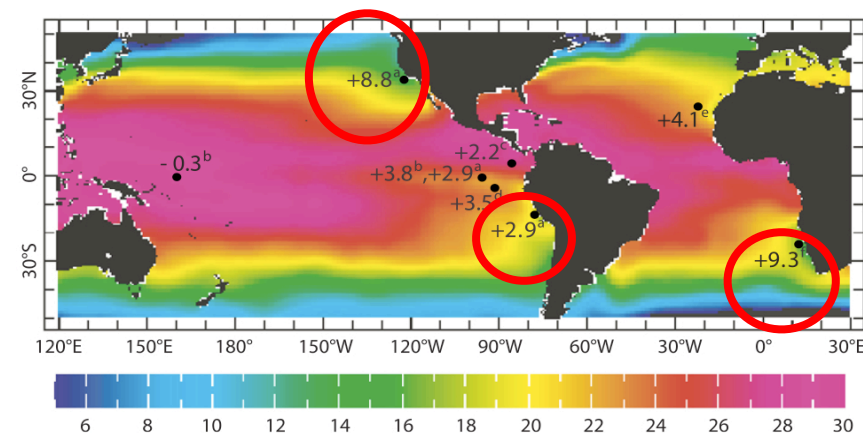


➡ East-west temperature gradient in equatorial Pacific was weaker 2–5 Myr

# The Pliocene, 2–5Myr: “Permanent El Niño” & warm upwelling sites



➡ East-west temperature gradient in equatorial Pacific was weaker 2–5 Myr



**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

Proxy evidence shows strong 10 °C warming in upwelling sites off California, Africa, & South America

# The Pliocene, 2–5Myr: “Permanent El Niño” mechanisms



Move Papua/ New  
Guinea;

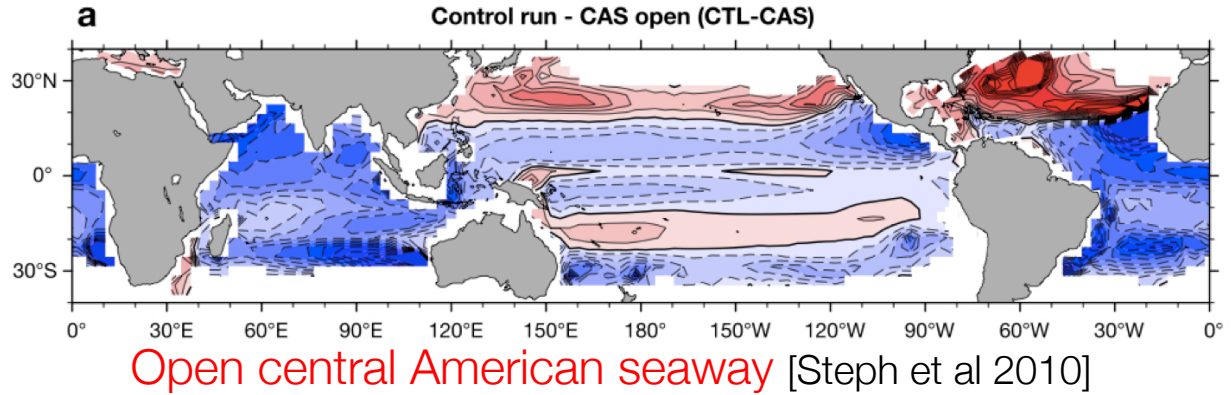
[Cane & Molnar 2001;

Final review

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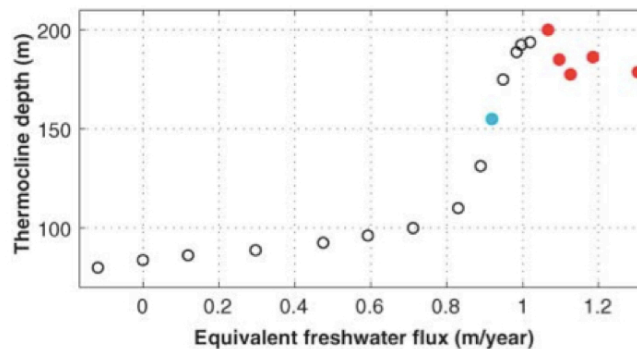
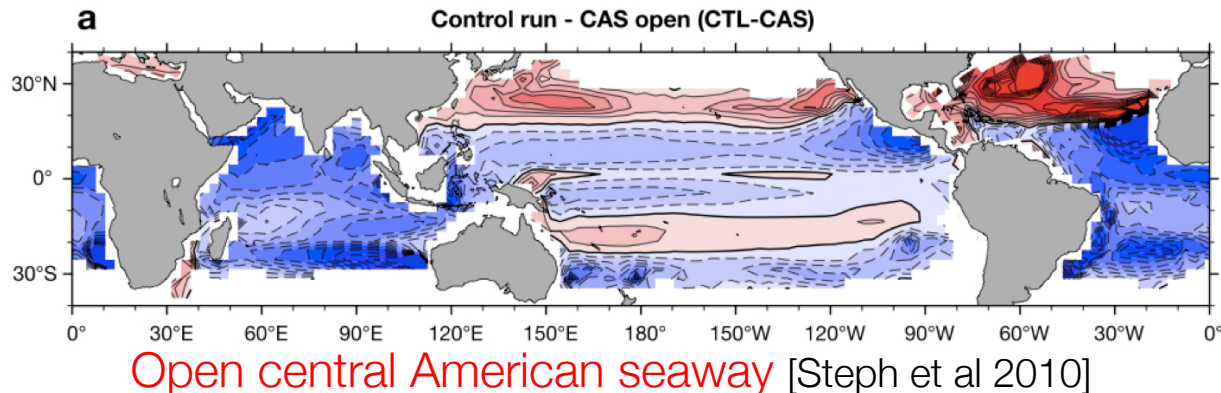


Final review

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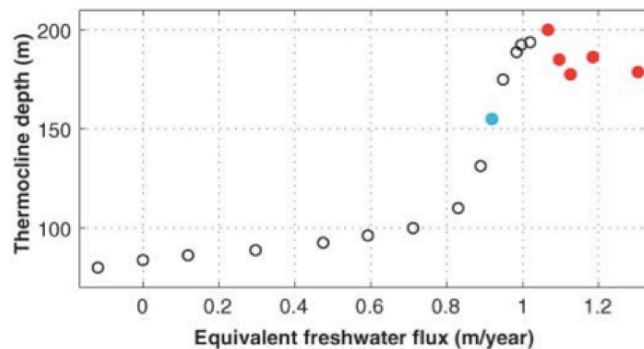
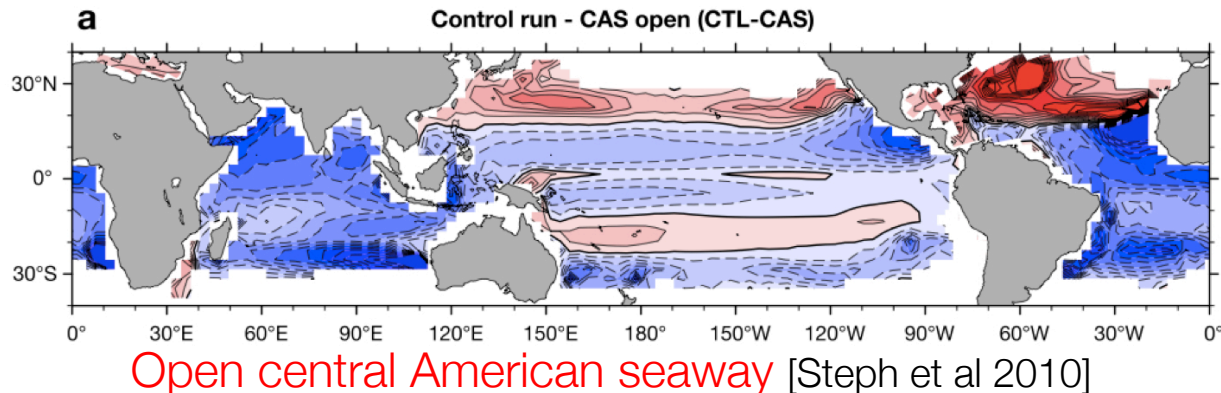
collapse equatorial thermocline w/ N. Pacific fresh water flux [Fedorov et al 2004/2006]

Final review

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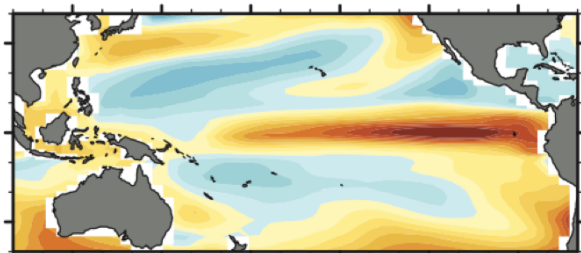


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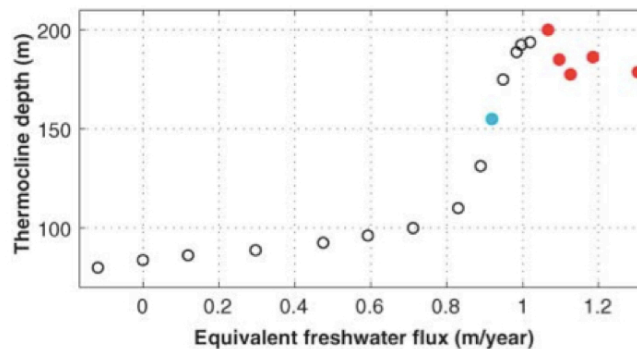
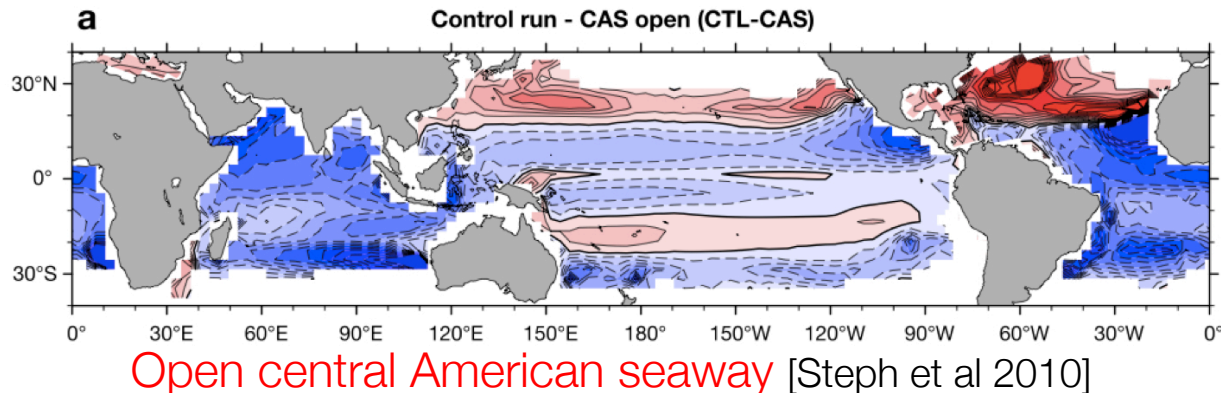


Hurricanes/ ocean mixing [Emanuel 2002... Fedorov et al 2010/2013]

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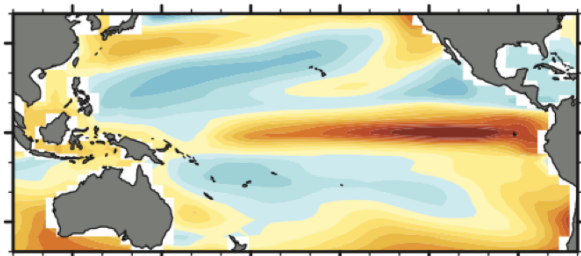


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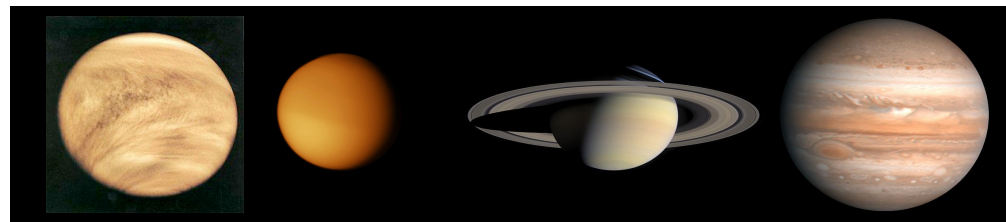


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Final review



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



Change easterlies via R.W. induced Superrotation [Tziperman & Farrell 2009, Arnold, Tziperman & Farrell 2012]

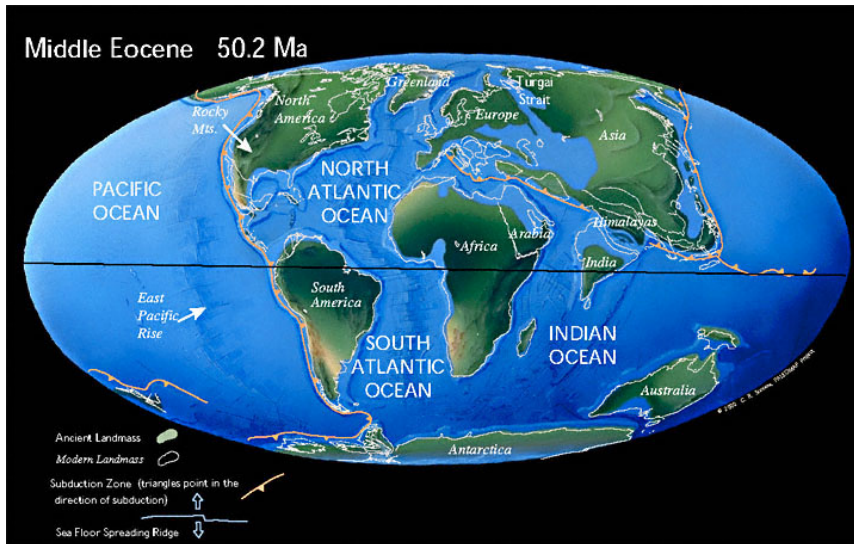
# Equable climates: Eocene (55.8–33.9 Myr) and beyond

**Observations:** very warm climate ~146–34 Myr ago: deep ocean ~15 °C; above freezing **winter** temperatures at 60N, Greenland, Wyoming, and Canada (now -30 °C); equator to pole Temp gradient: ~25 °C (present-day: >40 °C).

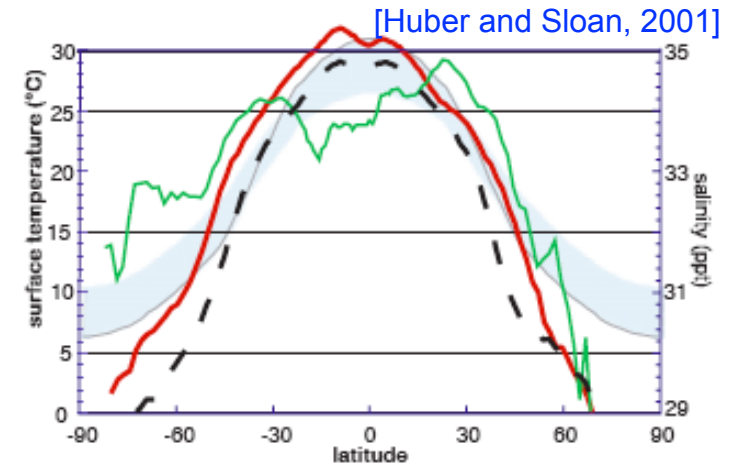
**The mystery:** Warm continental winter climate cannot be reproduced by GCMs even at very high CO<sub>2</sub> levels.

A surprising relevance to future warming.

<http://www.scotese.com/newpage9.htm>



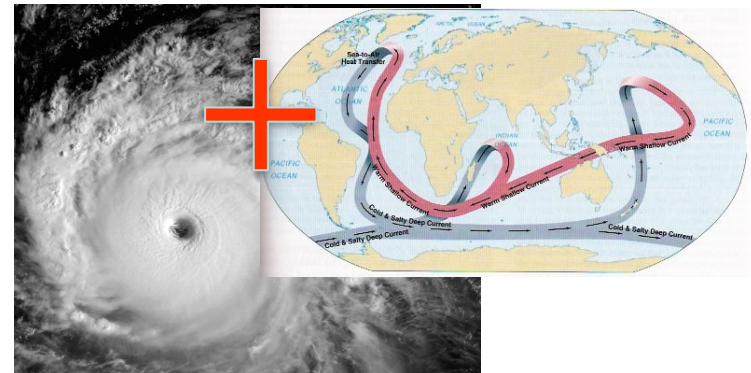
Present-day like geometry



[Huber and Sloan, 2001]

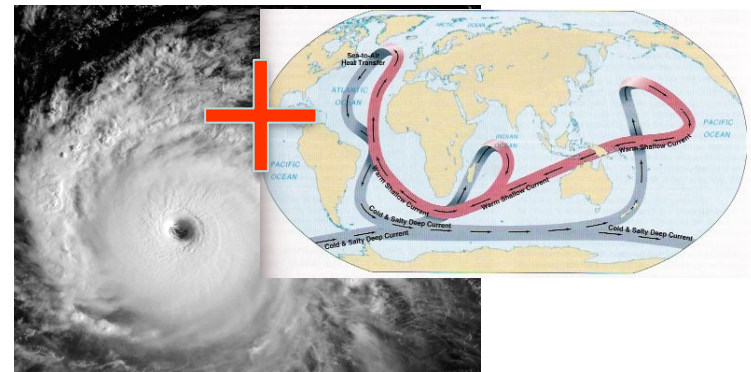
- - Modern Model SST
- (red) - Eocene Model SST
- (green) - Eocene Model SSS
- (shaded blue) - Eocene Proxy SST

# Equable climate ideas

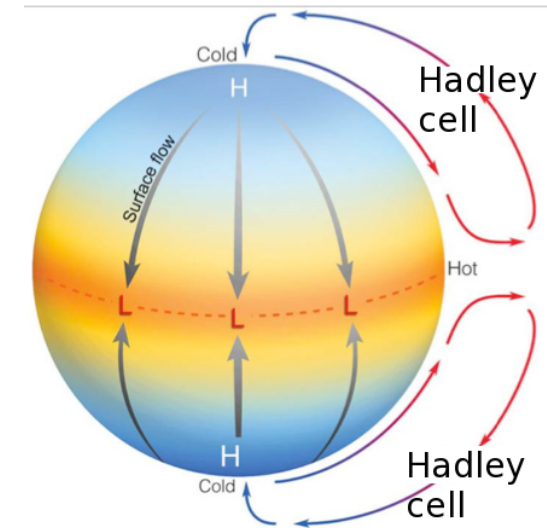


Hurricanes & ocean mixing/  
MOC (Emanuel 2002)

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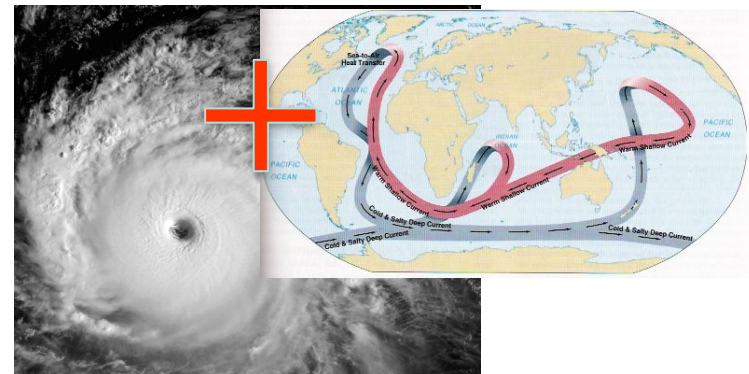


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Equator-to-Pole Hadley cell (Farrell 1990)

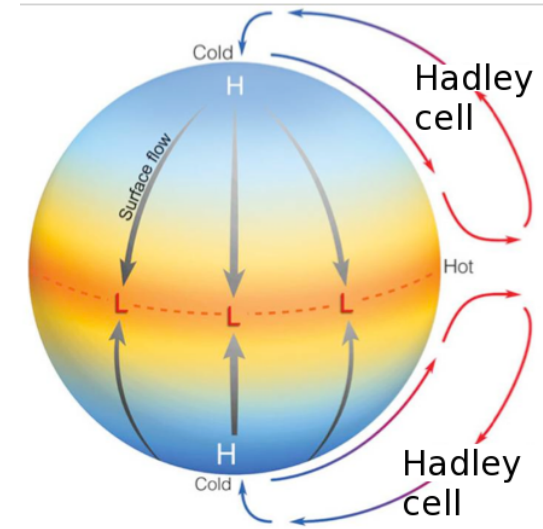
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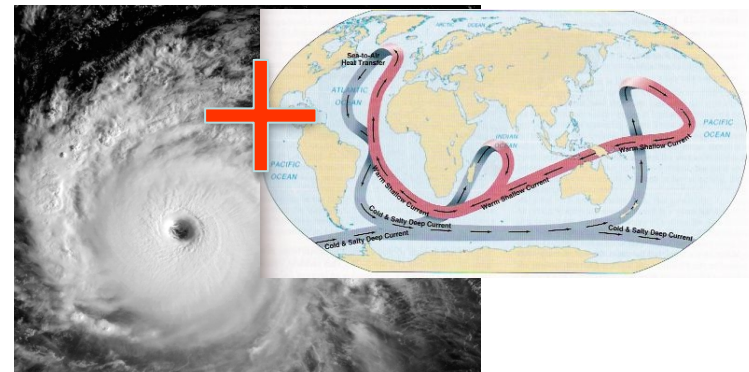


Polar stratospheric (15–25  
km) clouds (Sloan et al  
1992; Kirk-Davidoff et al  
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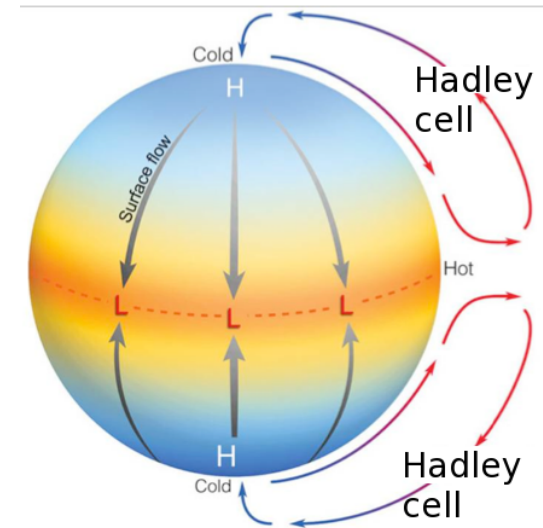
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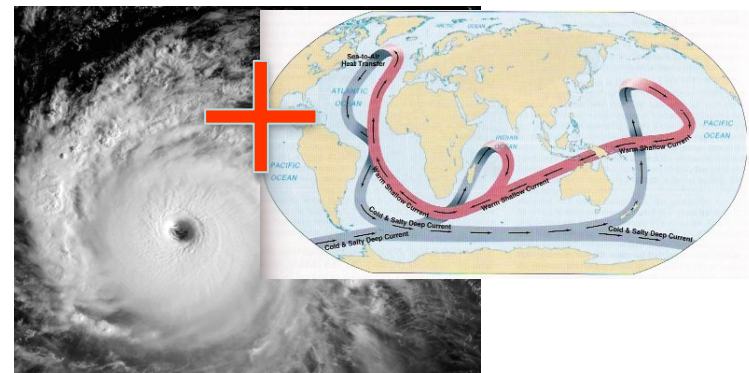


Arctic convective tropospheric cloud feedback (Abbot & Tziperman 2008)

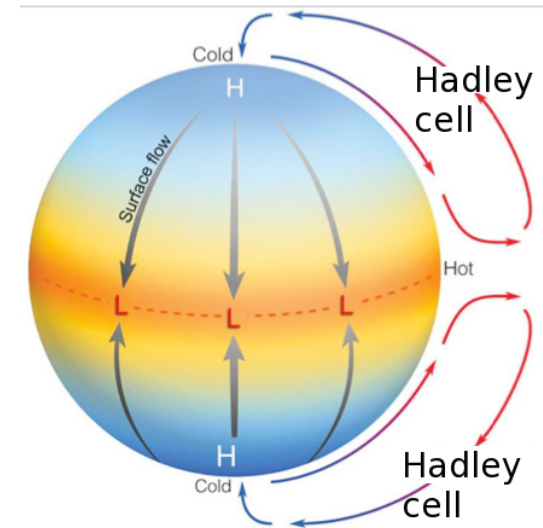


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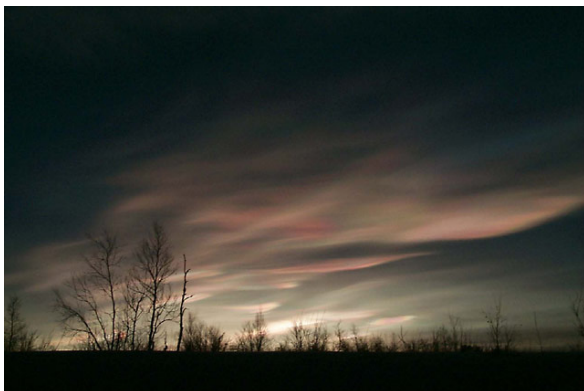
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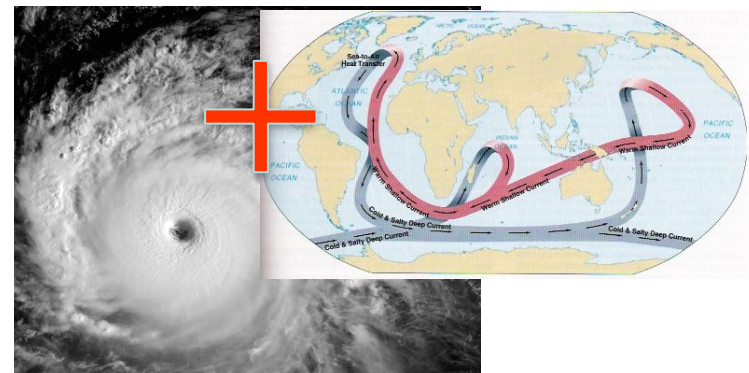


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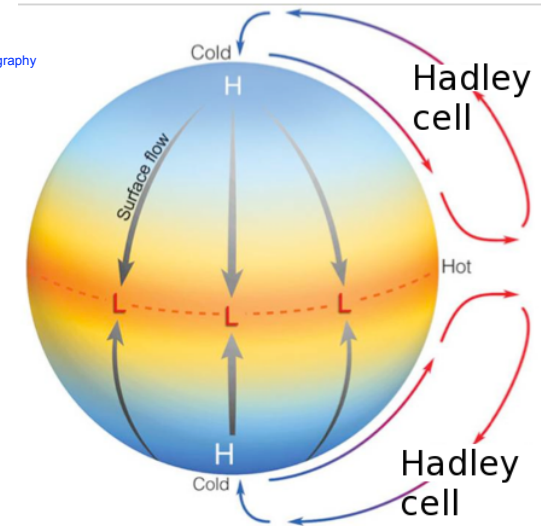


Hurricanes & ocean mixing/  
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<https://iceland-photo-tours.com/articles/photography-tutorials/how-to-improve-your-fog-photography>



Low clouds suppress  
Arctic air formation (Cronin  
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breakup of mid-latitude  
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## In-class workshop

Why do clouds play so prominently in proposed mechanisms for equable climate? Why is the reason relevant to future climate projections?

## **Climate modeling!**

Students will learn and gain experience with running and analyzing a global climate model (GCM, Community Earth System Model CESM2). Activities will include class-time hands-on introduction (Andrea!) and guided HW assignments.

### **A variety of climate applications/ scenarios will be used:**

- Simulations of the El Niño-Southern Oscillation (ENSO),
- Atlantic meridional overturning circulation (AMOC),
- Abrupt CO<sub>2</sub> change,
- Preindustrial climate,
- High CO<sub>2</sub> scenarios.

# Final discussion... objectives of climate dynamics

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- Simulation vs understanding: is it important to understand?
  - Toy models vs realistic Earth System Models: why do we need simple models...?

The End

**Thanks, Andrea!**

And thanks for a great semester...