Climate Dynamics (PCC 587): Paleoclimate/Cryosphere I

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12-3-09

History of Earth, Part I

- We'll look at this timeline:
  - Lifetime of Earth (4.5 billion years)
  - Past 100 million years
  - Past million years
  - Past 20,000 years
- Equivalent timeline for 25 yr old student:
  - Whole life
  - 100 million yrs = last 6 months
  - 1 million yrs = last 2 days
  - 20,000 yrs = last hour

In The Beginning

- Planets & the Sun formed in a collapse of gas & dust
  - 4.5 billion yrs ago (Bya)
  - Stuff like methane, water, ammonia was in the collapsing cloud
    - A lot boiled out in the hot collapse though
  - Immediately after collapse, Earth = big ball of rock w/ little atmosphere
- Hadean epoch: first 700-800 million yrs
  - Constant bombardment by planetesimals
  - Released methane, water, etc into the atmosphere/ocean
- Most of the bombardment stopped around 3.8 Bya
  - Although obviously these collisions still happen

The Sun

- Sun was weaker when it first started
  - Stars increase in strength over their lifetime
  - Sun is thought to have increased in strength by 30% or so over its lifetime
- Earth has not been ice-covered much in its history though
  - Only three times?
- "Faint Young Sun Paradox"
  - How was Earth not ice-covered when Sun was weaker?
  - Must have been high greenhouse gas concentrations

Volcanoes

- Volcanoes are important for recycling atmospheric composition over the Earth lifetime
- Current composition of gases in volcanic eruptions:
  - 80-90% steam
  - 6-12% CO_2
  - 1-2% SO_2
  - Traces of H_2, CO, H_2S, CH_4, N_2
  - Trace composition could have been higher in the past

Rise of Oxygen

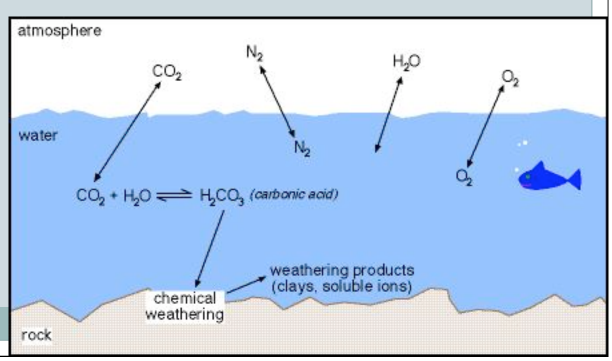
- Cyano-bacteria first seen 3.8-3 Bya
  - Their photosynthesis could create oxygen
- Oxygen didn't accumulate until 2.4-2.2 Bya. Why?
- Oxygen released early on would have been consumed by **reactions w/ H_2** or **oxidation of minerals** at the surface
  - Once the above slowed, oxygen could accumulate
  - Weathering of rocks is also key to setting the carbon dioxide in the atmosphere

Rise of Oxygen

- Accumulation of oxygen happened rapidly once it got going
  - 0.01% of current concentrations 2.4 Bya, 2% of current values by 1.9 Bya
- Ozone layer forms with a small amount of oxygen
  - Photochemical breakdown of O2
  - Key to protecting life from UV radiation

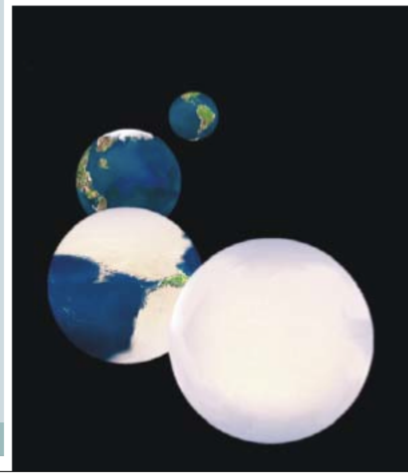
Carbon Cycle over Very Long Timescales

- Carbon dioxide emitted by volcanoes
- Carbon taken up by (chemical) "weathering" of rocks
  - CO2 dissolves into ocean & forms carbonic acid
  - Chemical weathering of minerals (silicates & carbonates) at the surface occurs
  - Eventually this carbon gets subducted underground and comes back up in volcanoes



"Snowball Earth"

- The Earth seems to have frozen over 3 times:
  - 2.4-2.2 Bya (decrease of methane in atmosphere led to freezing?)
  - 750-600 Mya
  - 280 Mya
- How could the Earth ever unfreeze?
- "Freeze-fry" scenario



Freeze-fry

- Earth freezes.
- Frozen ocean means no weathering out of carbon. CO_2 builds up from volcanoes.
- Enhanced greenhouse effect + blackening of ice sheets leads to eventual unfreezing.
  - Requires huge CO_2 values though.
- Unfrozen climate is extremely hot! (due to combination of high GHGs and much smaller albedo)

Past 100 Million Years

- Cretaceous (ended 65 Mya)
  - High temps, esp at high latitudes
  - 10x CO_2 distribution?
- Followed by period of cooling, culminating in Pleistocene Glaciation (2.5 Mya)
  - Why the cooling over this period?
  - Changes in plate tectonics thought to be important
    - Plate movements have slowed over last 100 My

Fig. 2.30 Continental configuration 65 million years ago, at the end of Cretaceous epoch. Note the separation between the Indian and Eurasian pla

Past 100 Million Years

- Slower plate movement → reduced limestone/clay subduction (so eventually less CO_2 outgassed by volcanoes)
- Forming of Himalayas created more minerals available for weathering → more CO_2 uptake

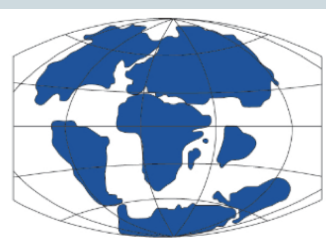


Fig. 2.30 Continental configuration 65 million years ago, at the end of Cretaceous epoch. Note the separation between the Indian and Eurasian pla

Other Factors in Past 100 Million Years

- Antarctica shifting to high latitudes and glaciating → more reflection of solar radiation
- Opening of Drake Passage and joining of N. & S. America at Panama
  - Influenced ocean circulation and heat transports, leading to glaciation in Arctic & cooling?

Fig. 2.30 Continental configuration 65 million years ago, at the end of Cretaceous epoch. Note the separation between the Indian and Eurasian pla

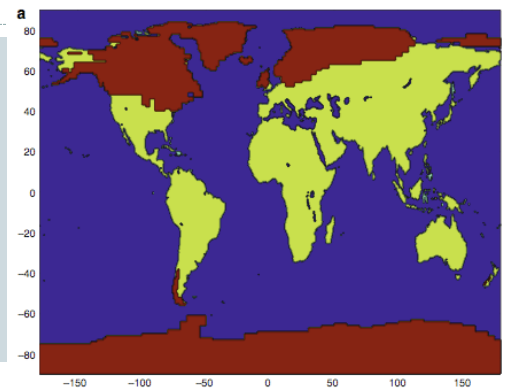
Past 2.5 Million Years

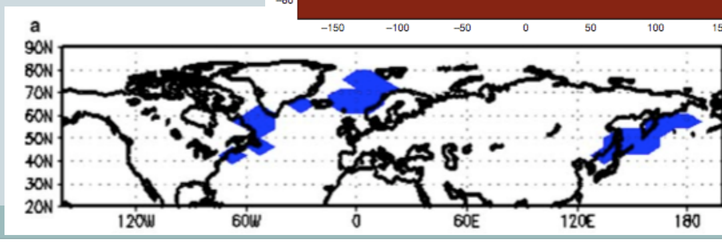
- Past 2.5 million years: oscillating between glacial and interglacial climates
- Next time: why these are thought to happen
  - Influence of orbital changes on climate
- Now: influence of glacial conditions on **tropical climate**!

Last Glacial Maximum

- Land ice extent (red) and extra sea ice (blue)

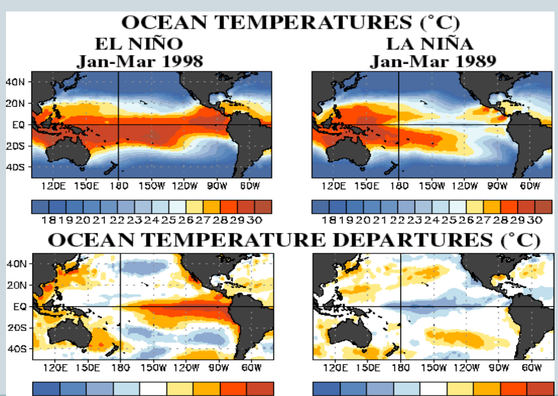
  Why would this affect tropical climate?





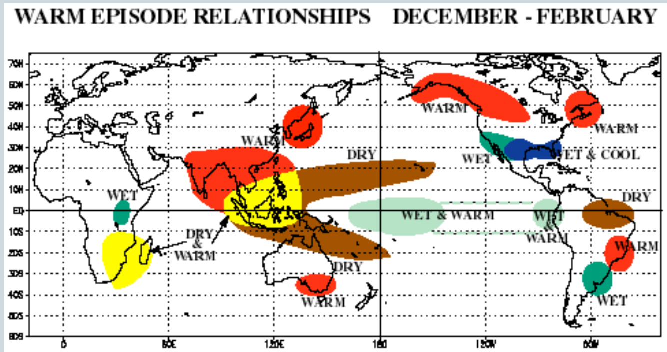
Trop.-Extratrop. Interactions: Traditional View

- **Tropics forces extratropics**:
  - E.g., El Nino causes large changes to midlatitude weather patterns



El Niño/Southern Oscillation

- Impacts are global:

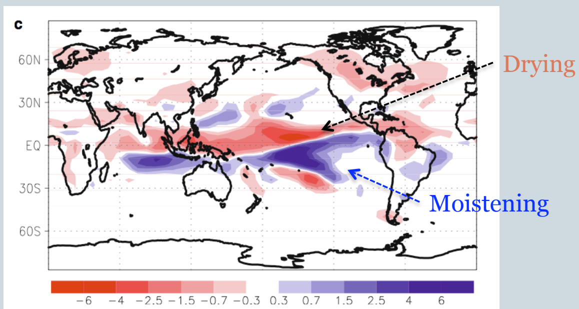


Trop.-Extratrop. Interactions: Traditional View

- **Tropics forces extratropics**:
  - E.g., ENSO causes large changes to midlatitude weather patterns
- We also think of “El Nino-like” responses to global warming:
  - Perhaps not such a good analogy though:
    - El Nino is associated with a contraction of Hadley cell
    - Global warming is associated with an expansion of Hadley cell
    - See Lu, Chen and Fri. (2008, J. Climate) for more

ITCZ Response to **High Latitudes**

- Pioneering work by Chiang, Biasutti and Battisti (2004) and Chiang and Bitz (2005):
  - Showed strong sensitivity of ITCZ to high latitude sea ice and land ice in LGM simulation using CCSM



Southward displacement of ITCZ occurs in LGM climate

Paleoclimate data is consistent with such a shift

From Chiang and Bitz (2005)

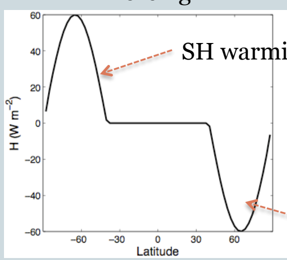
Simplified GCMs

- Full GCM simulations:
  - Often too hard to interpret
  - Hard to isolate dynamical feedbacks
  - Sensitive to parameterizations
- Simplified GCMs:
  - Useful for developing theories
  - Can then compare with full GCMs

Extratropical Influences on ITCZ

- Sarah Kang's thesis (2009):
  - Effect of high latitude forcing on ITCZ location/structure/ intensity
  - **Aquaplanet full GCM (AM2)** and **simplified moist GCM** runs w/ idealized forcing:

Forcing



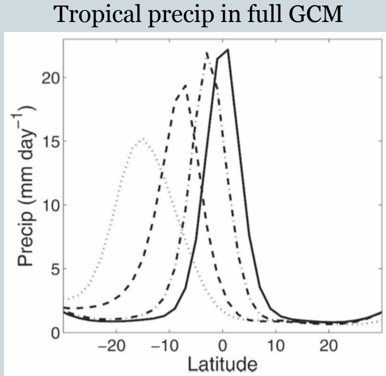
Think glaciers + sea ice in NH, plus warming in SH (to keep global mean temperature the same)

From Kang, Held, Fri., & Zhao (2008, J Clim) and Kang, Fri. & Held (2009, JAS)

ITCZ Changes

- In both models, ITCZ precipitation shifts towards warmed hemisphere

Tropical precip in full GCM

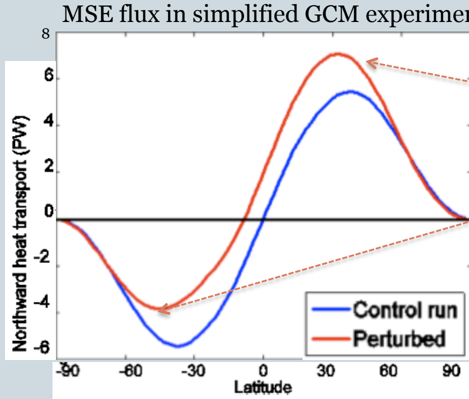


From Kang, Held, Fri., & Zhao (2008, J Clim) and Kang, Fri. & Held (in press, JAS)

Mechanism for ITCZ Response

- We argue energy flux is of key importance

MSE flux in simplified GCM experiments



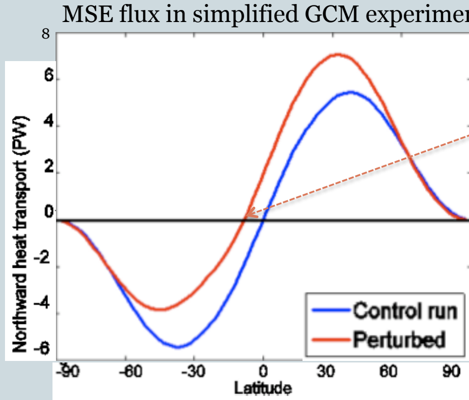
Anomalous energy flux into cooled region

Less flux into warmed region

Mechanism for ITCZ Response

- ITCZ latitude ~ "Energy flux equator"

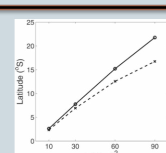
MSE flux in simplified GCM experiments



Define "**energy flux equator**" as zero crossing of energy flux

Shifted into SH in perturbed case

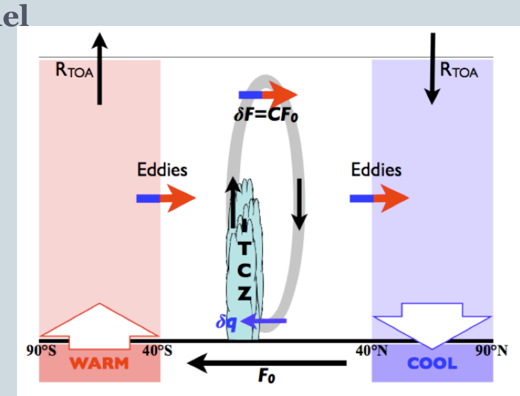
In tropics, mean circulation does most of the flux => v=0 there => ITCZ is nearby



ITCZ location (-) is approximately same as energy flux equator (--) for full GCM

Mechanism for Energy Flux Change

- Eddies modify fluxes in midlatitudes
  - Quasi-*diffusively*: they can be well-approximated with a moist **energy balance model**
- Anomalous Hadley circulation modifies fluxes in tropics



See Kang, Held, Fri., & Zhao (2008, J Clim) & Kang, Fri. & Held (in press, JAS) for more

Role of Cloud-Radiative Forcing

- Differences in **cloud-radiative forcing** (CRF) affect ITCZ as follows:
  - CRF = extra forcing at certain latitude bands
  - Forcing is again propagated away by eddies quasi-diffusively
  - Changes in energy flux equator then result in changes in ITCZ location
  - Result in massive differences in ITCZ shift **for same forcing**!