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Modelling Past Rapid Climate Change events

Identification and analysis of critical climate risks

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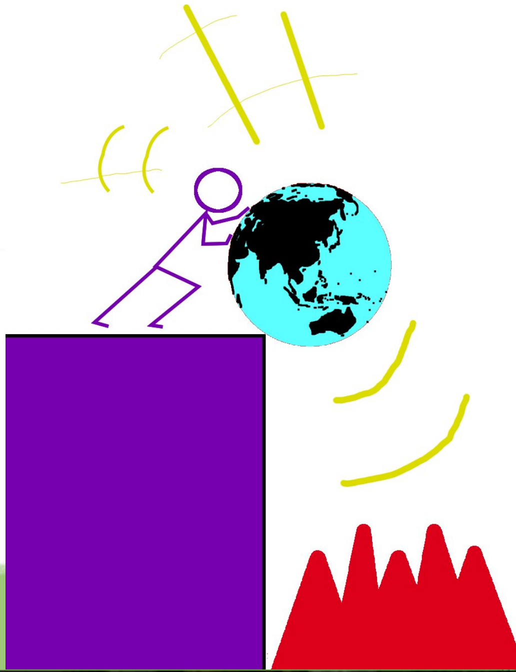
With help from James Annan and Julia Hargreaves



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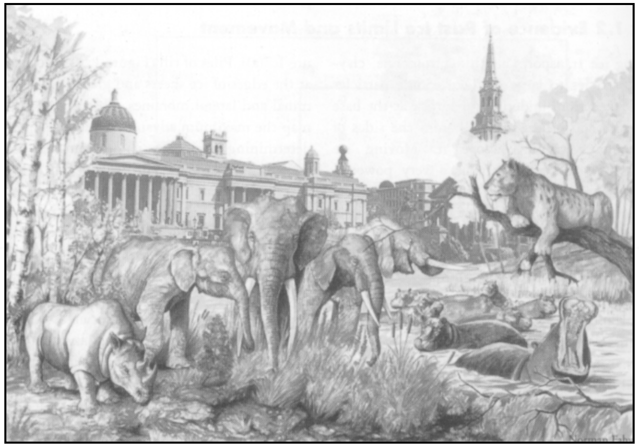
Structure of Talk

120 million years ago

Reconstruction based on PhD work of Jodie Howe, University of Leeds/BAS, painted by Robert Nichols.

125,000 years ago



From Wilson et al, 1999

21,000 years ago

- Introduction
- Brief review of some key time periods
- Two Case Studies
- Summary

How can we predict the future climate risk?

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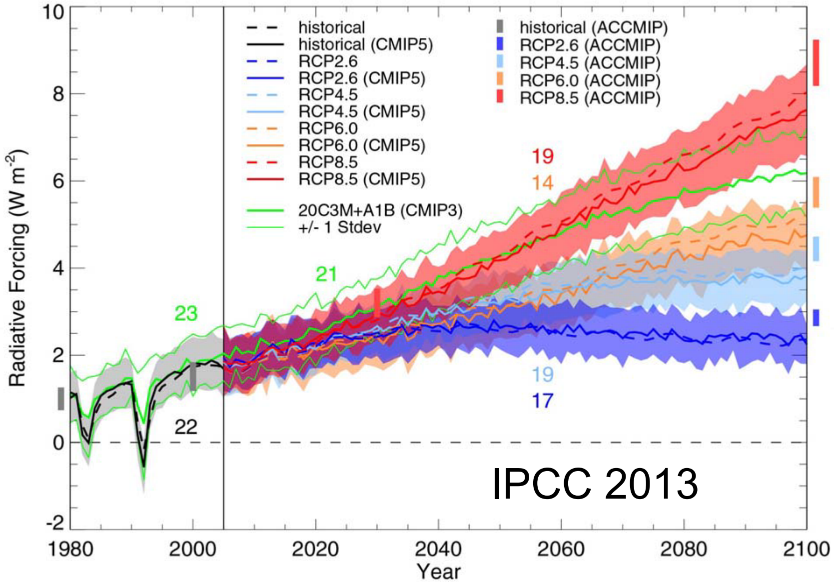


- All climate change predictions of the future are based on Earth System models.
- Based on fundamental physics but need many approximations.
    - **Can we believe the models?**

"Prediction is very difficult, especially if it's about the future." -- Nils Bohr, Nobel laureate in Physics

"Those who have knowledge, don't predict. Those who predict, don't have knowledge. " --Lao Tzu, *6th Century BC Chinese Poet*

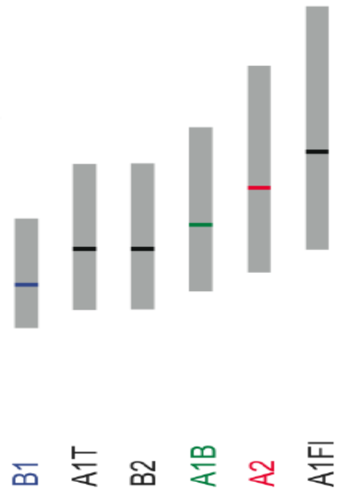
"This is the first age that's ever paid much attention to the future, which is a little ironic since we may not have one. " --Arthur C. Clarke

"The herd instinct among forecasters makes sheep look like independent thinkers. " --Edgar R. Fiedler

How can palaeoclimate help with critical climate risks?

- What are the strengths of palaeoclimate studies?
  - Highlighting new processes and mechanisms that could be important: giving context for the future.
  - Identifying past "rapid" climate change events and investigating different "states" of the Earth system
  - Providing data to test and evaluate models

A Longer Term Perspective of climate change



21st Century Temperature Projections

Million years BP

How can palaeoclimate help with critical climate risks?

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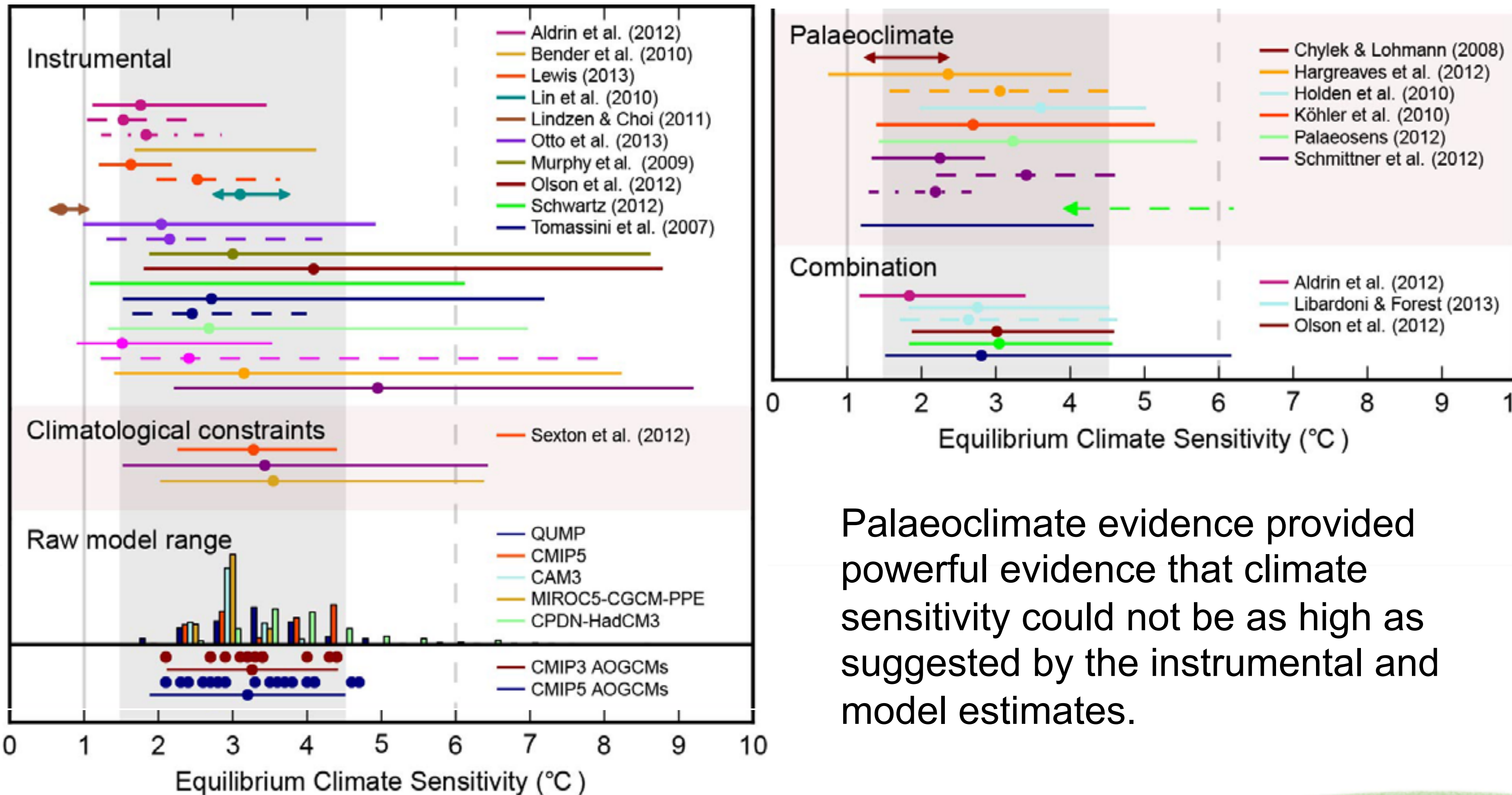
- What are the weaknesses of palaeoclimate studies?
  - Palaeo-observations give indirect measurement of climate
    - Must embrace the uncertainties in both model and data
  - No perfect direct analogue of next century so difficult to make conclusions about future change without linking to modelling

Constraints on the Mean Climate Change



Palaeoclimate evidence provided powerful evidence that climate sensitivity could not be as high as suggested by the instrumental and model estimates.

IPCC, WG1, 2013

Critical Risks/Tipping Points and the palaeo perspective

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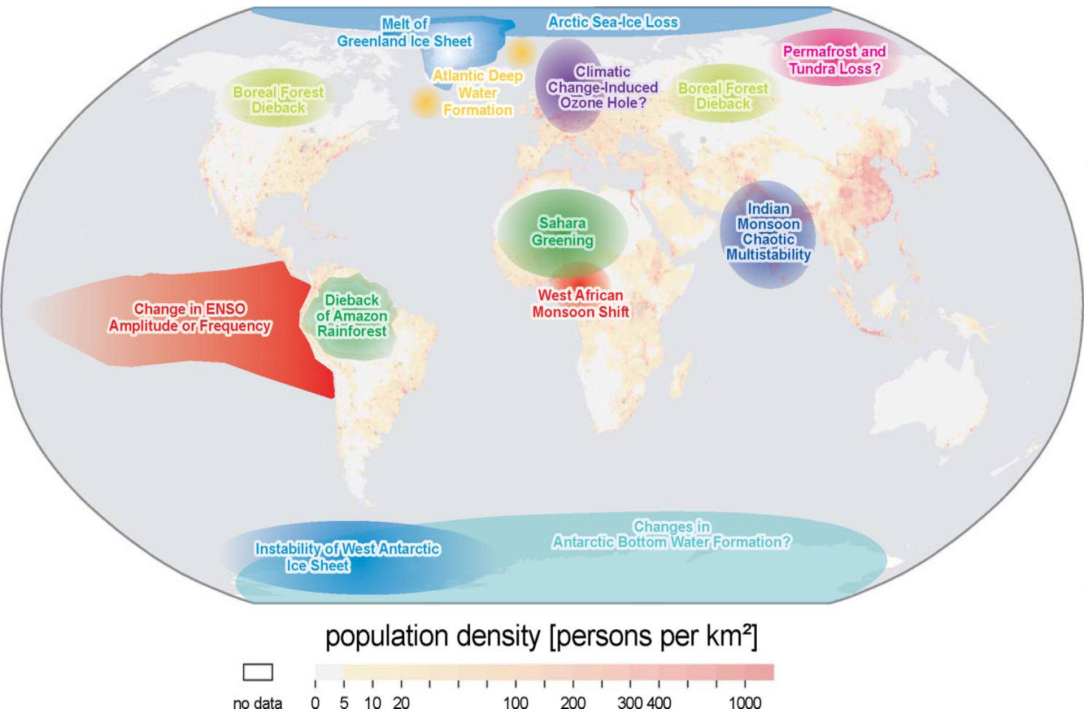
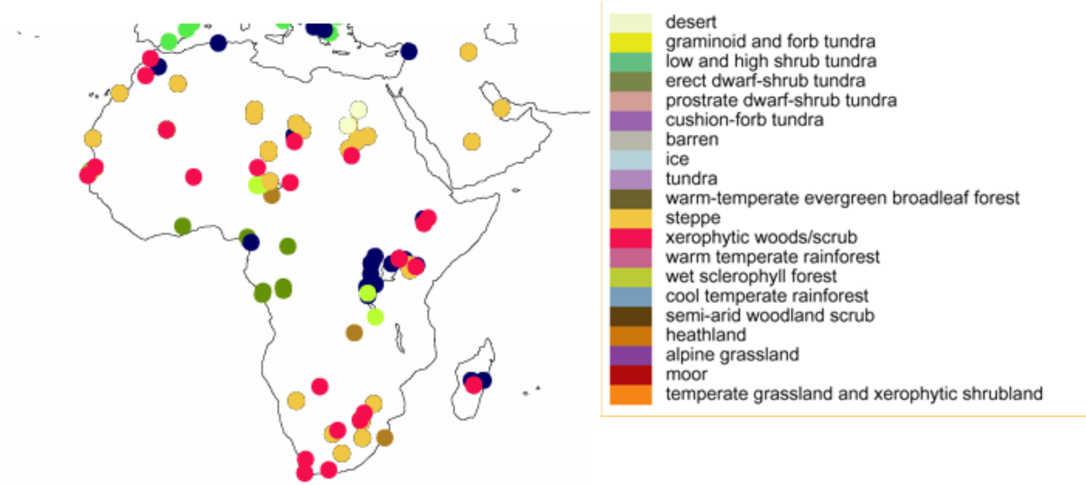


Tipping points: Lenton et al 2008

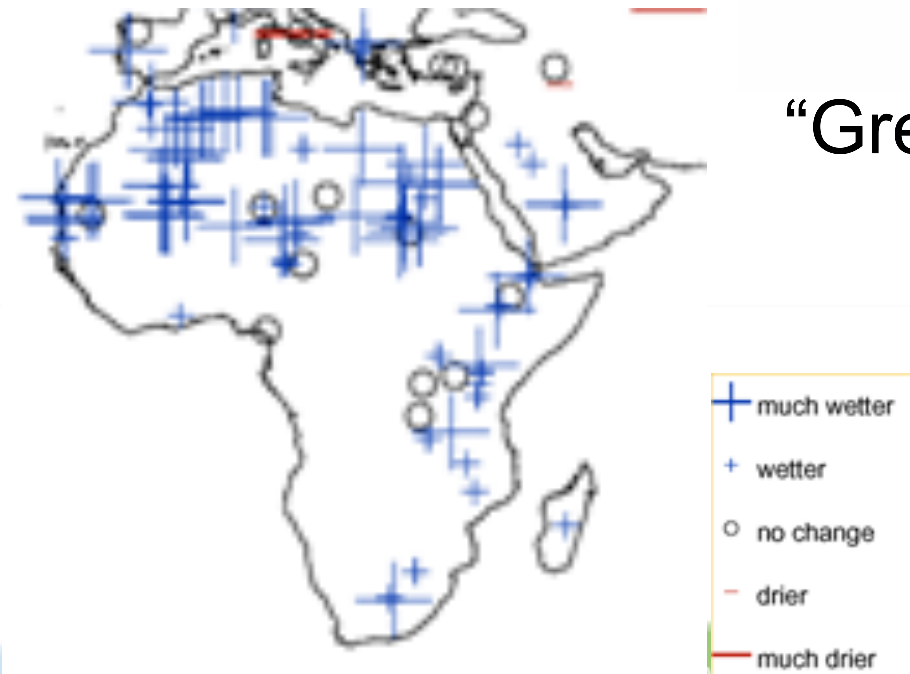
- West African Monsoon
  - Mid-Holocene (6000 years BP)
- ENSO variability
  - Pliocene (3 million years ago)
- Gas Hydrates
  - Paleocene-Eocene thermal maximum (~55 million years ago)
- Atlantic Meridional Overturning Circulation
  - Stage 3 (60,000 years onwards)
- Ice sheet stability
  - Eemian (125,000 years ago)
- Amazon Rainforest
  - Last 21,000 years

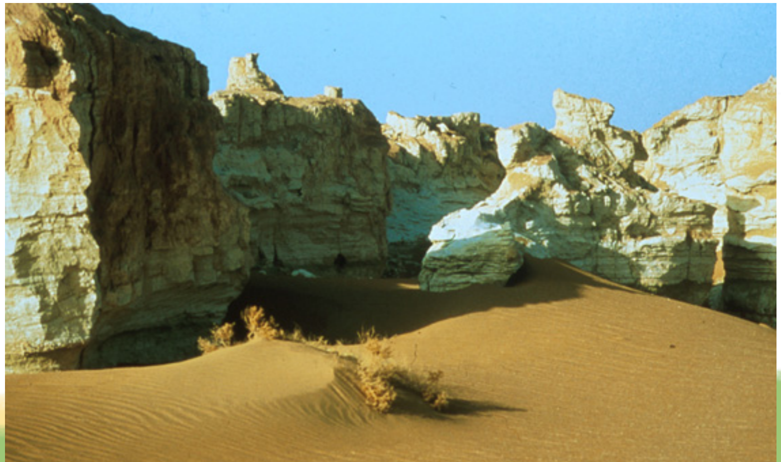
Mid-Holocene climates (6000 years ago)

Very strong evidence to suggest that the Sahara was a lot wetter 6000 years ago

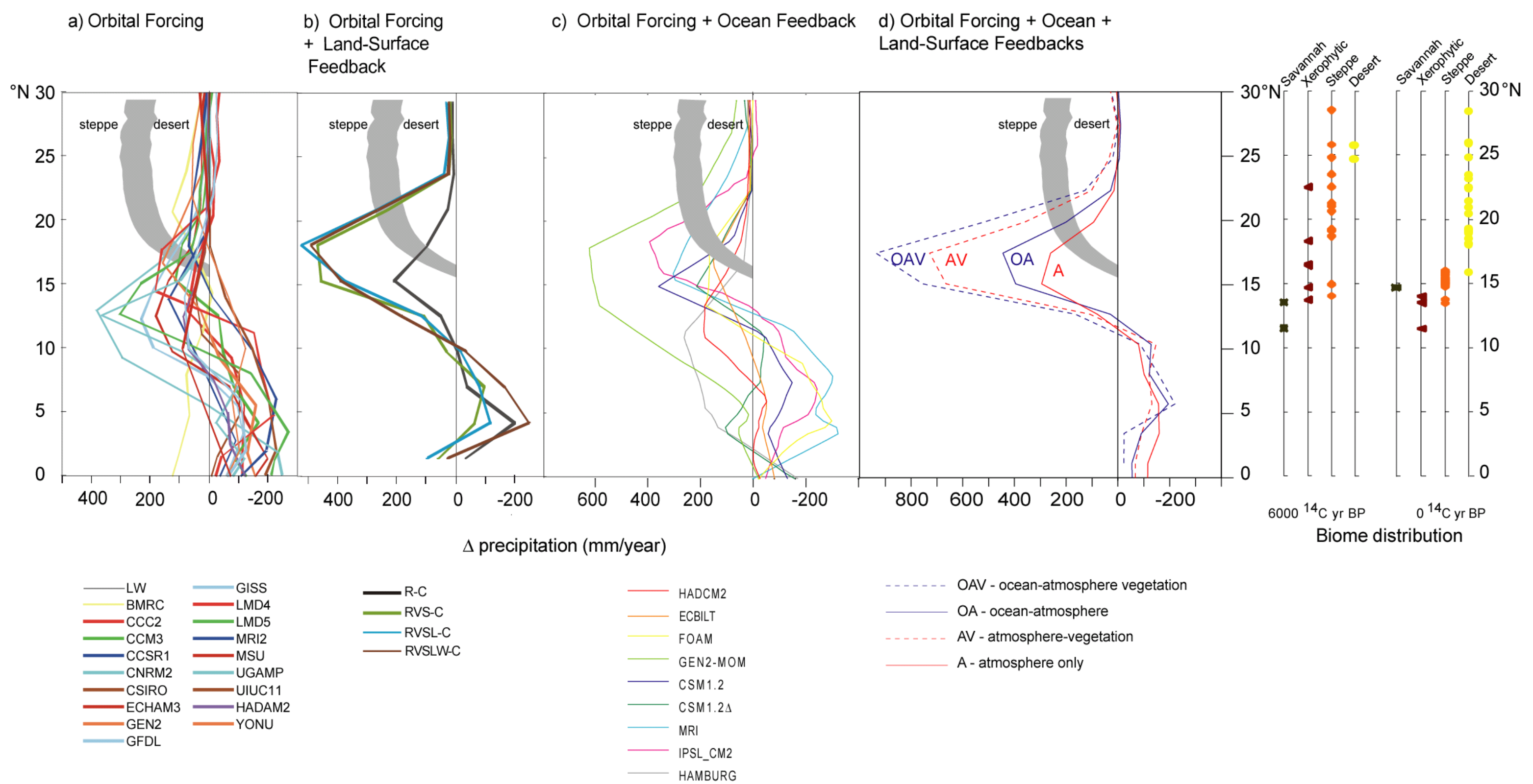


"Green Sahara"



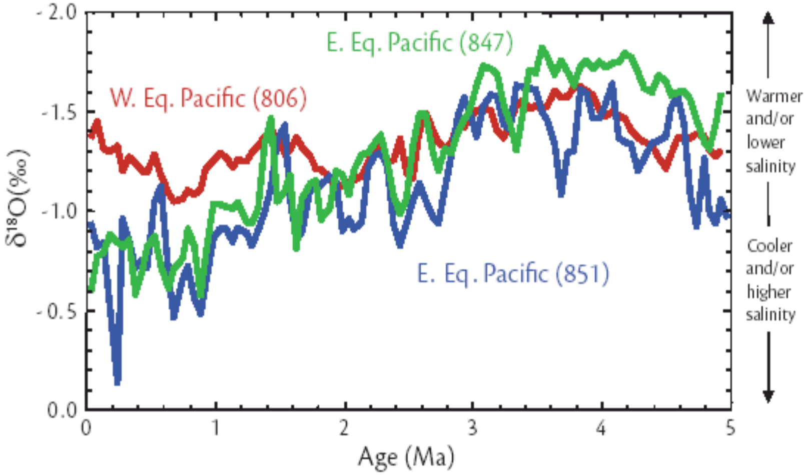


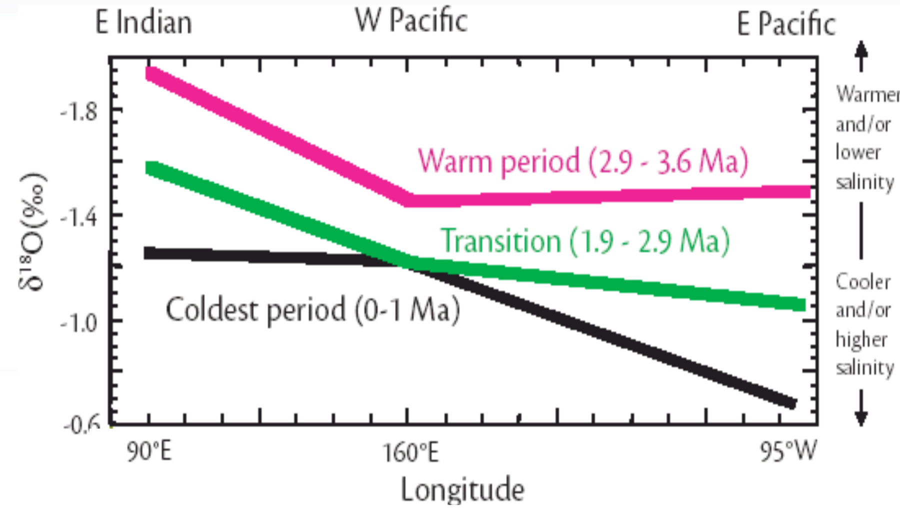
Can models simulate changes to the N.African monsoon?

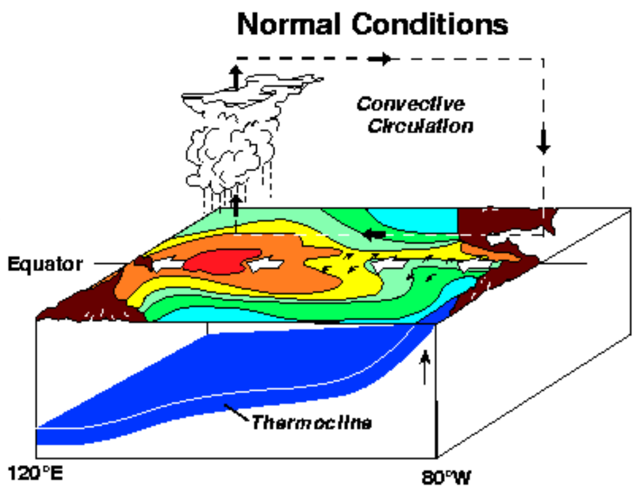


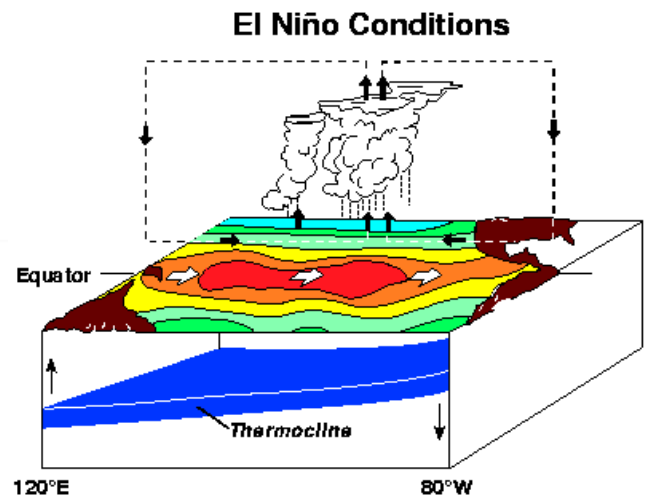
To date, all IPCC-class models have failed to reproduce “green Sahara” during mid-Holocene and hence cannot be used to investigate subsequent “tipping point”

The Pliocene (3 million years ago) a Permanent ENSO?









To date, all IPCC-class models have failed to reproduce permanent ENSO

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Case 1: Paleocene-Eocene Thermal Maximum

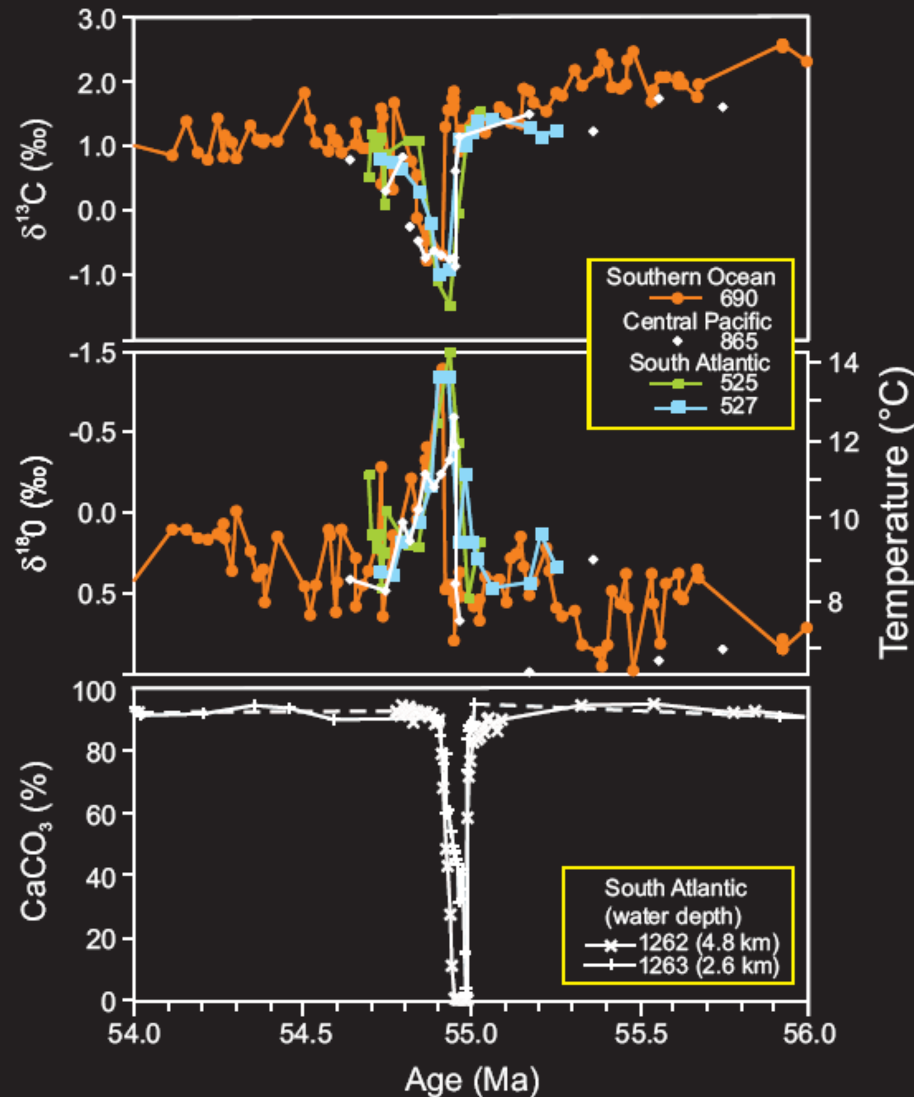
Features similar to future changes

Carbon release

Warming

Ocean acidificatoin

Most plausible mechanism for large carbon isotope change is hydrates release



Zachos et al. [2008] (Nature 451)

Most Recent Extreme Warm Earth Climate

Key Features

Common throughout 220-50 million years ago but Early Eocene (~55Ma) was most recent example

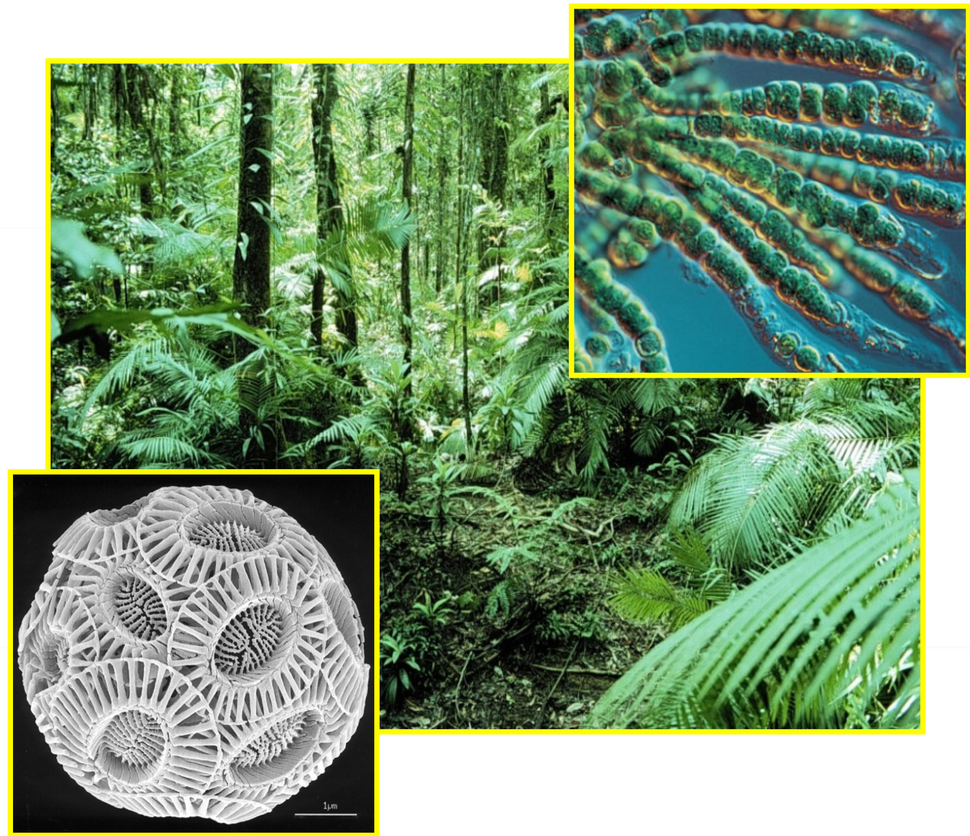
No / small permanent ice sheets

Warm ocean bottom waters

Reduced continentality

Probable high atmospheric CO_2 concentrations

Changed continents



Model-Data Comparison

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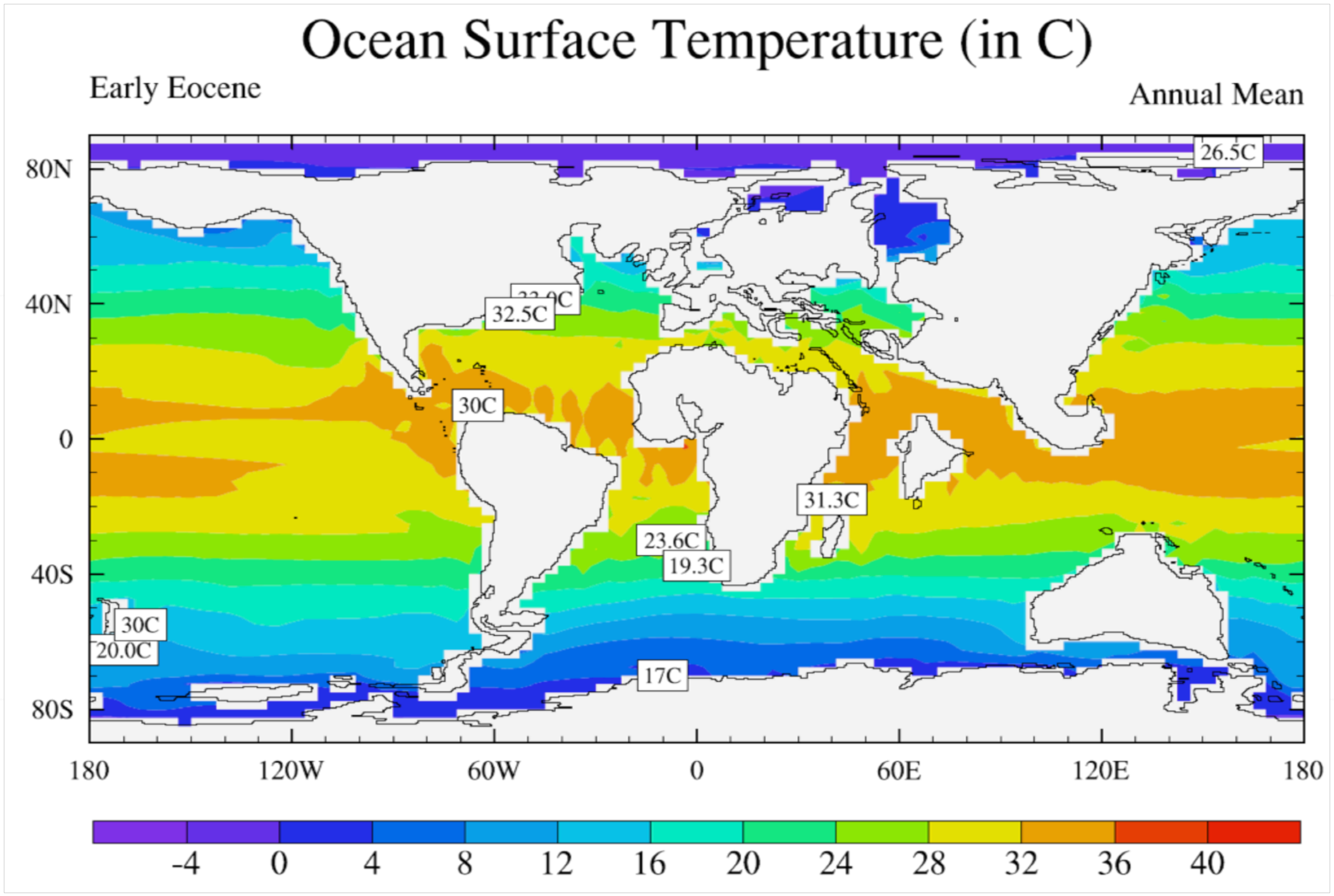

Stott et al., 1991
Bilj et al., 2009
Barrera & Huber, 1991
Shackleton et al., 1984
Oberhansli et al., 1991
Pearson et al., 2007
Sluijs et al., 2007
Zachos et al., 2007
Sluijs et al., 2009

To date, all IPCC-class models have failed to reproduce warm poles

Valdes, 2011, Nature GeoSci

“Perturbed Physics” Simulations

Climate models are based on physics of climate, but inevitably include parameters that are relatively poorly defined We need to know sensitivity to these uncertain parameters

Method

- Select 10 key model parameters
- Select reasonable possible ranges for each parameter
- Vary them together (using a Latin-hypercube sampling method)
- Use low resolution (FAMOUS) version of HadCM3
- **Clouds:**
  - Threshold of relative humidity for cloud formation (RHcrit)
  - Precipitation ice fall out speed (VF1)
  - Conversion rate of cloud liquid water droplets to precipitation (CT)
  - Threshold value of cloud liquid water for formation of precip. (CW)
- **Convection** : Convective roughness length over the sea (Z0FSEA)
- **Gravity wave** parameters (WAVE)
- **Sea ice** low albedo (ALPHAM)
- **Diffusion** in ocean and atmosphere

Range of values from literature (Murphy et al. 2004)

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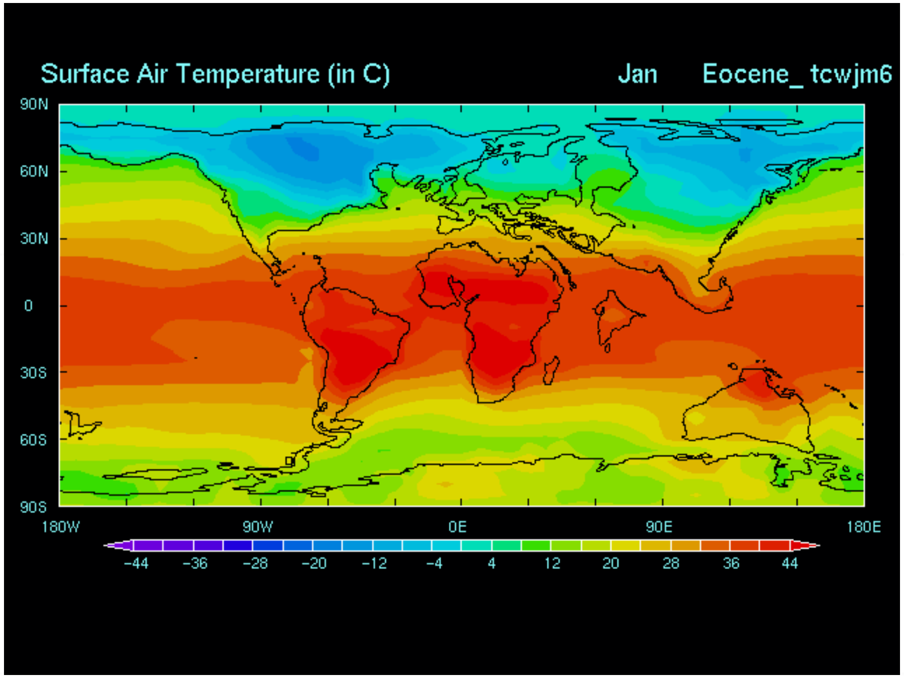
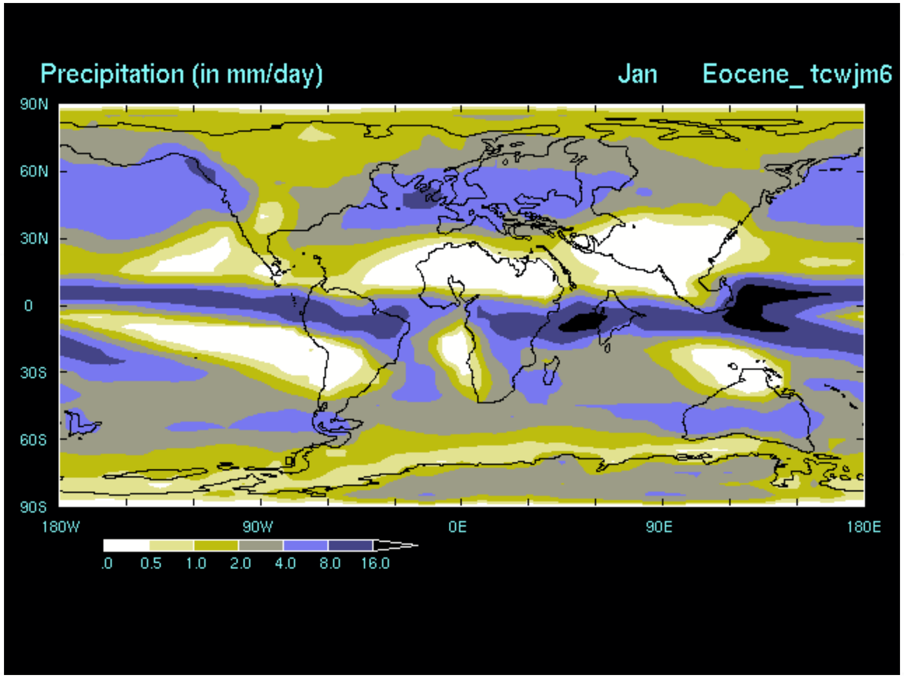
A "warm poles" example Ensemble Member

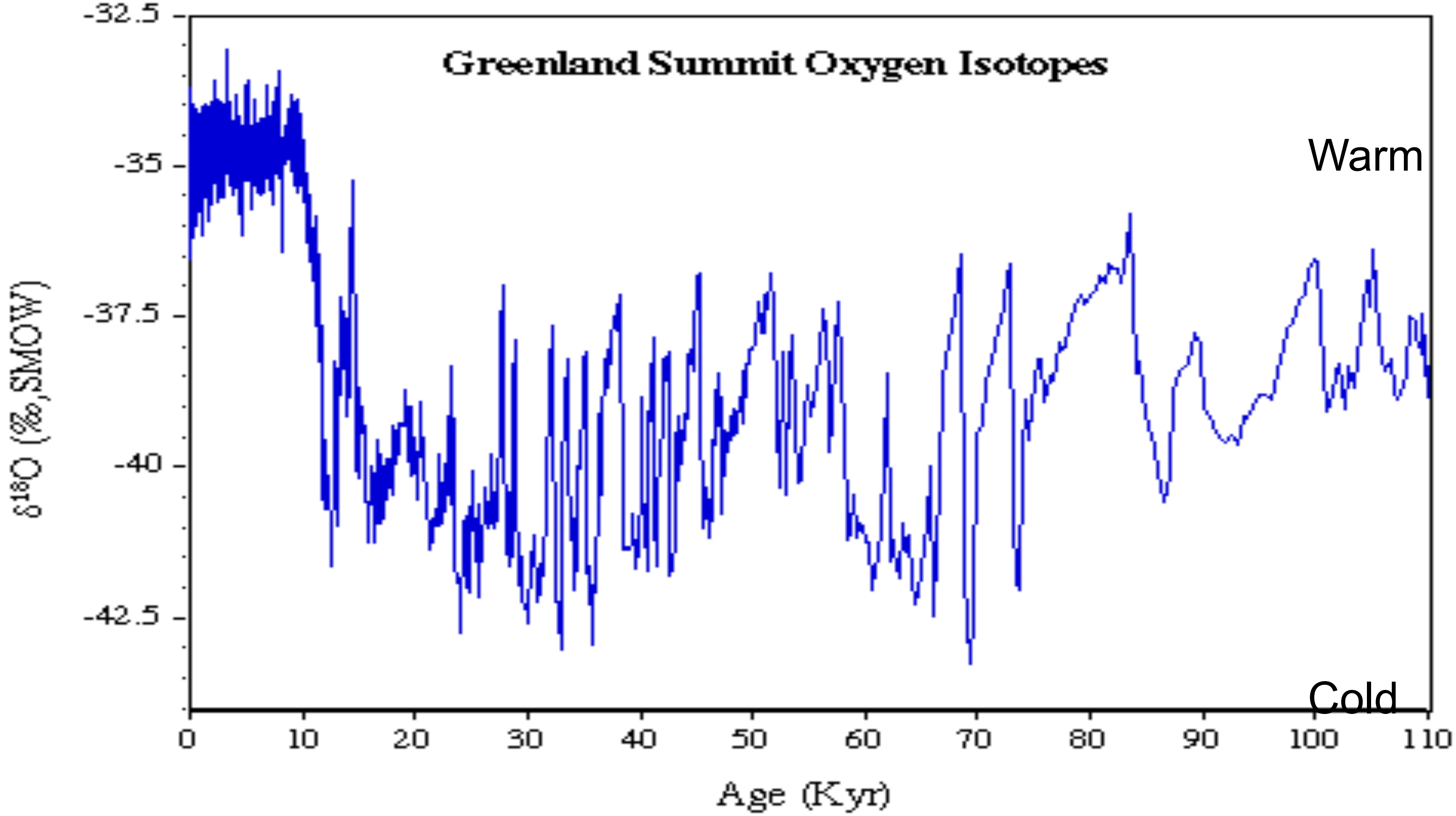




- Large part of change related to cloud cover
- Revised model now fits the data reasonably well (and ALOT better than older model)
- With this model, future climate change sensitivity ~3.1C (c.f. 2.7 from standard model)

Sagoo et al 2013

Case 2: Past Rapid Climate Change Events



Heinrich events (rapid cooling) and Dansgaard-Oeschger Cycles (rapid warming)

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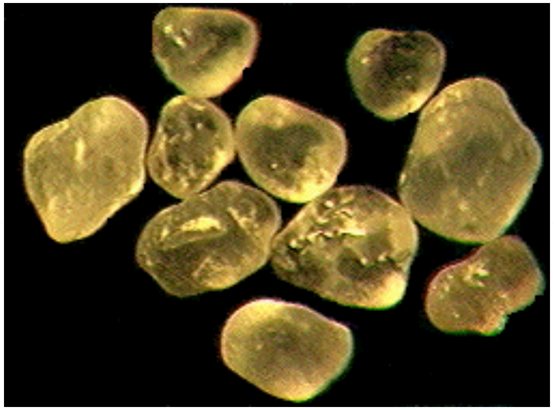
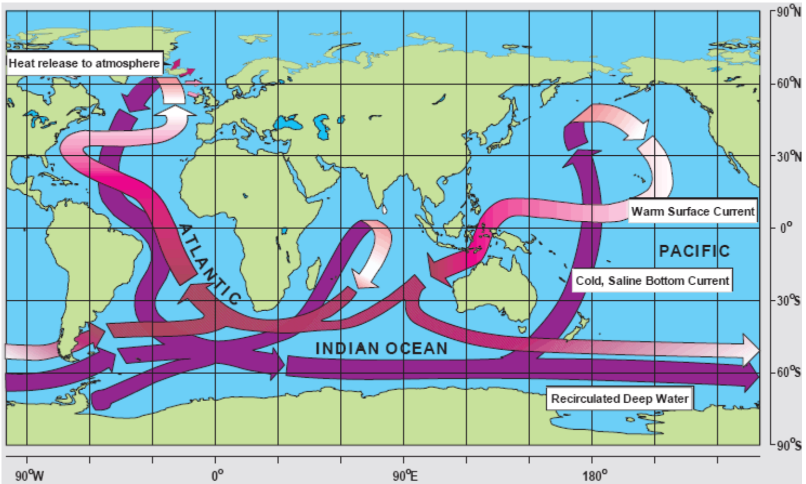
Heinrich Layers and Events

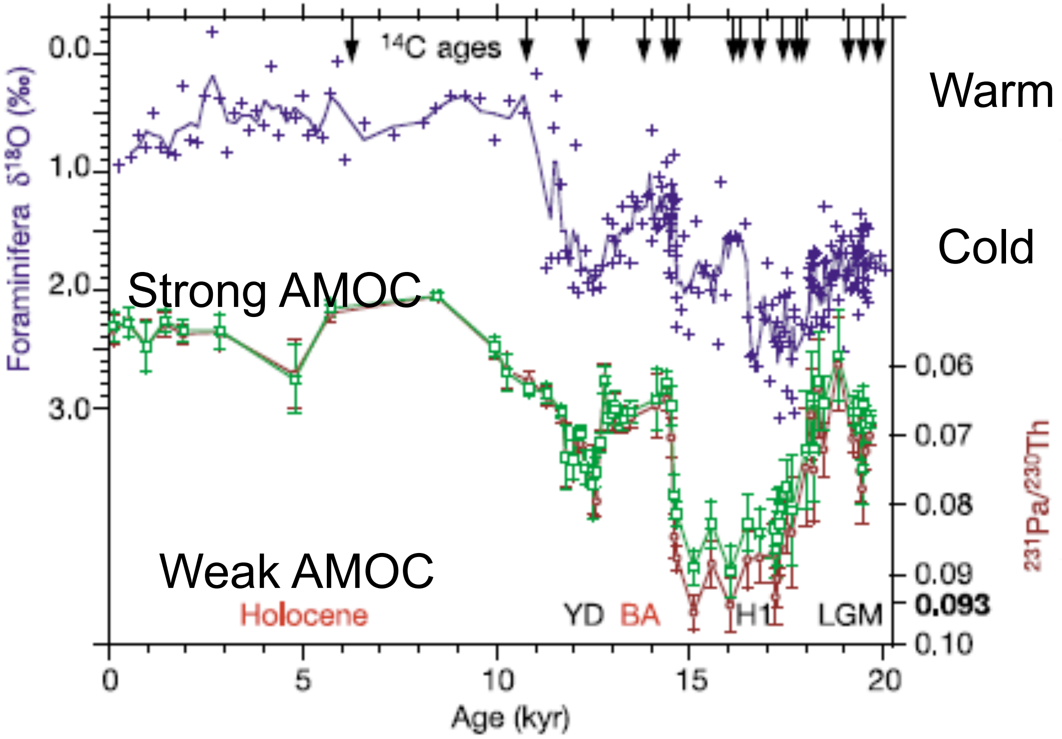
- Heinrich Layer (Heinrich, 1988)
  - layers with anomalously high lithic fraction in North Atlantic sediment cores
  - North American source (generally)
  - Evidence of Heinrich Layers right across the Atlantic as far as Iberian Peninsular
- Heinrich Events
  - Anomalously large discharge of ice that gives Heinrich Layer
- Possible Mechanism
  - Binge-purge cycle of Ice Sheets or ice shelf collapse results in collapse of Atlantic ocean circulation and big climate change



Debris from glacial icebergs found in ocean sediment

N. Atlantic Ocean Circulation: A paradigm of palaeo change and tipping points

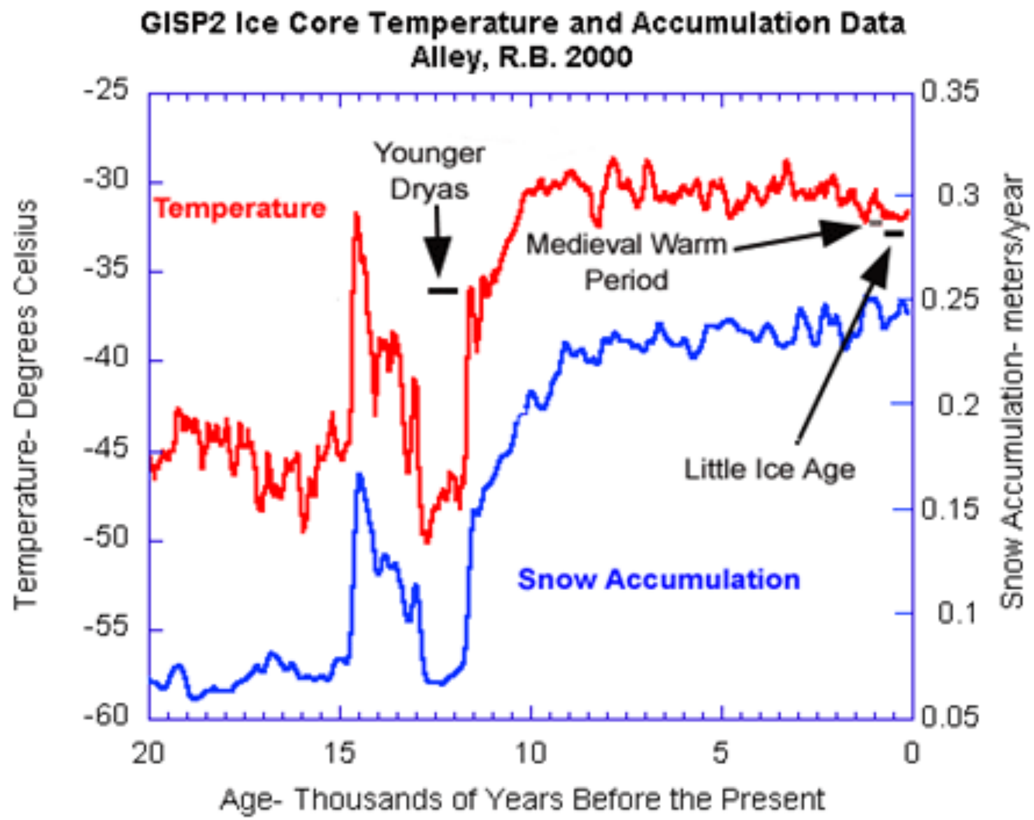




McManus 2004

Atlantic Meridional Overturning Circulation (AMOC) could be a major critical risk (tipping point)

Can GCM's simulate these events?



Simulate the last "deglaciation", from 21,000 years ago to 10,000 years ago.

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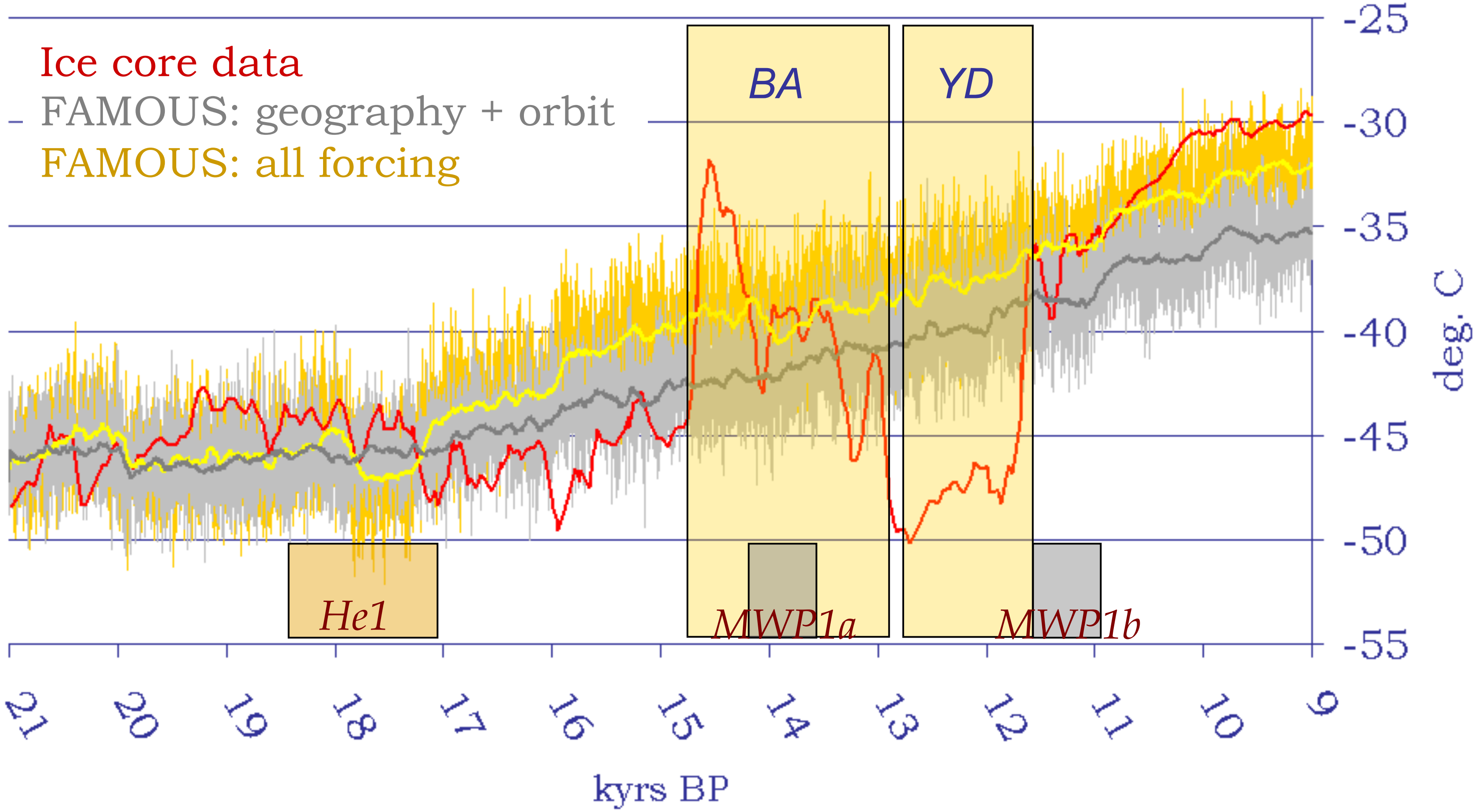
Model simulation of Greenland temperatures

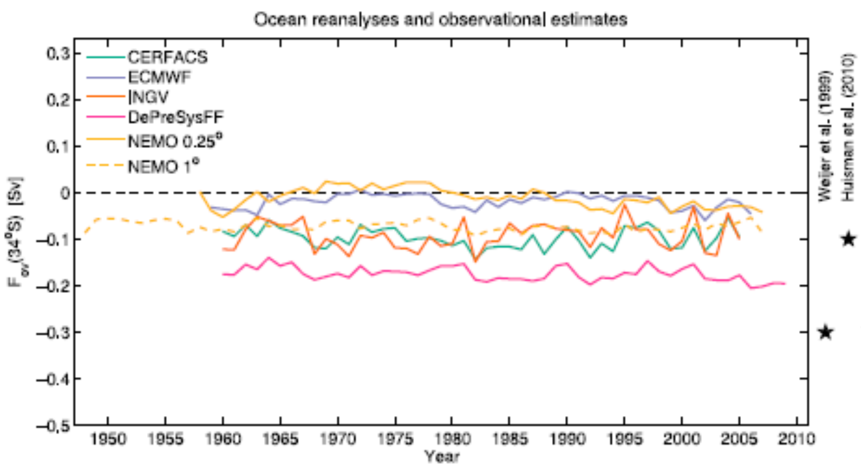


Ice core data : Alley, R.B.. 2004. GISP2 Ice Core Temperature and Accumulation Data. IGBP PAGES/World Data Center for Paleoclimatology. Data Contribution Series #2004-013. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA

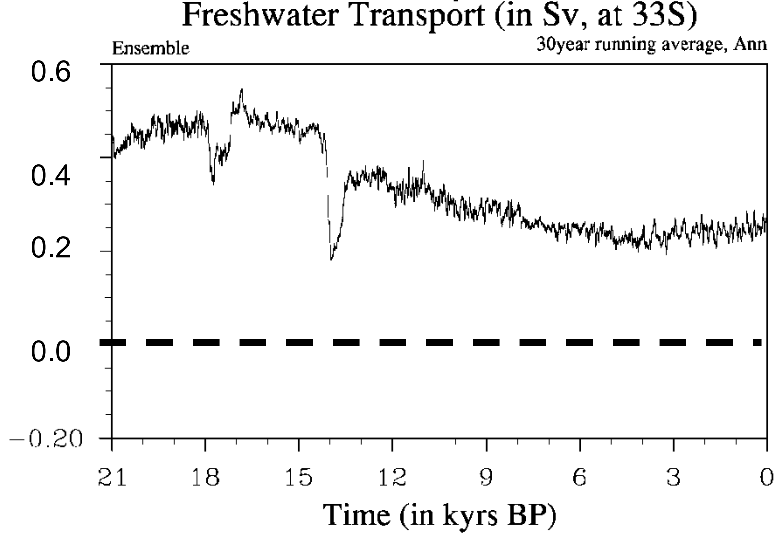
So what are we missing: Are the models tuned badly?

Salt Export (Fov) from Atlantic good indicator of stability of AMOC (e.g. Rahmstorf 1996, Dijkstra 2007)

Observations



Standard setup of model



Import of freshwater into Atlantic

Export of freshwater into Atlantic

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Re-tuning the model

- New skill score = Good climate + good AMOC + good Fov
- Target parameters which may have an impact on AMOC strength
  - Ocean parameters : Horizontal and vertical diffusion
  - Sea ice parameters: albedo, strength of ice, maximum coverage
  - Heat, momentum and moisture transfer (all potentially have impact on buoyancy flux) : ocean roughness, bulk aerodynamic coefficients of momentum and heat …
- Initial single parameter sweeps.
- Subsequently use iterative Importance Sampling method (Annan and Hargreaves 2010)   (In progress)

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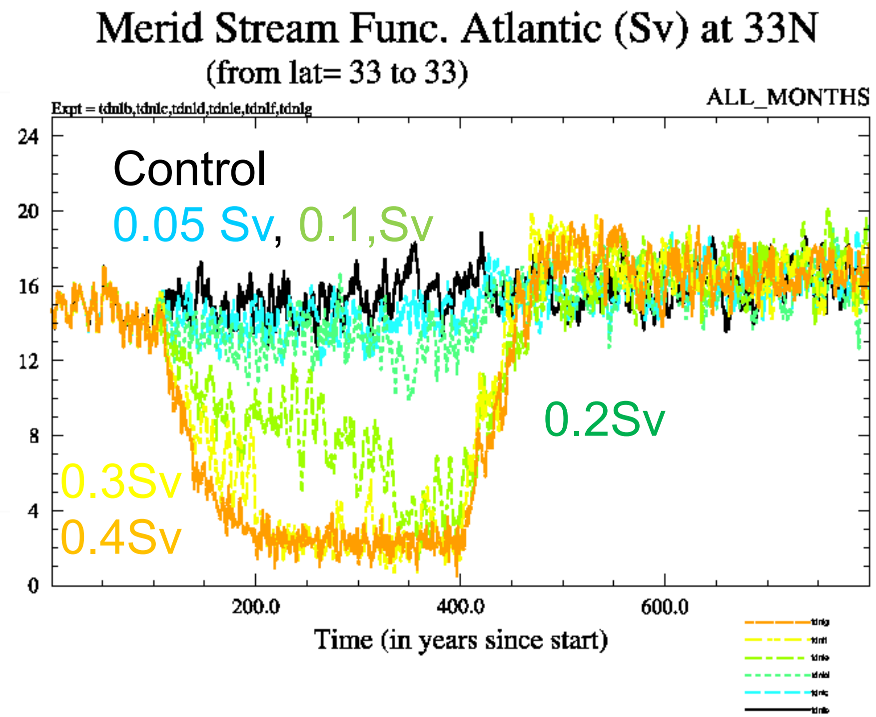
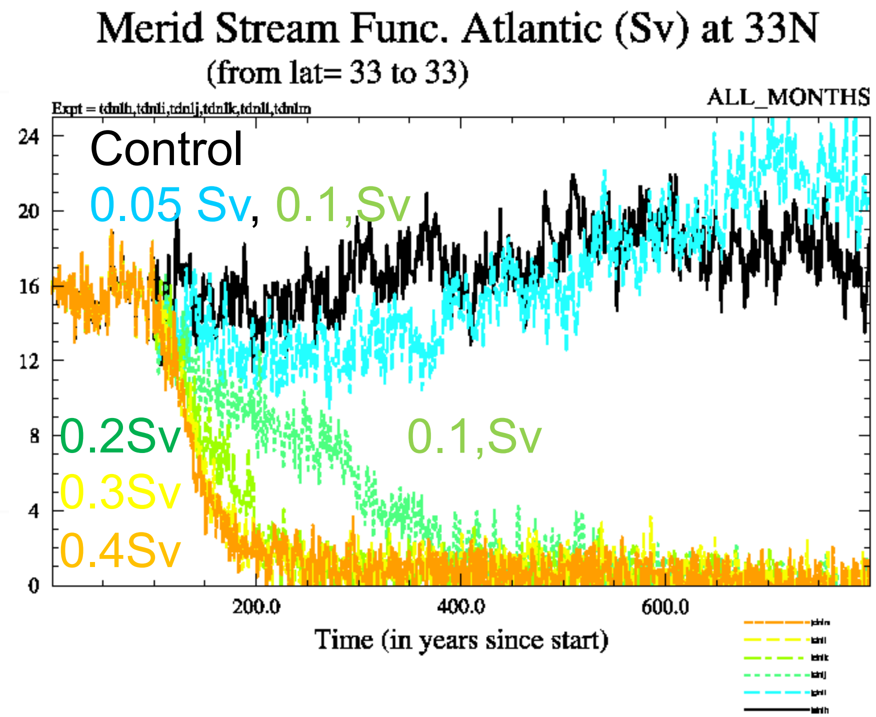
Impact of Changing Model Parameters

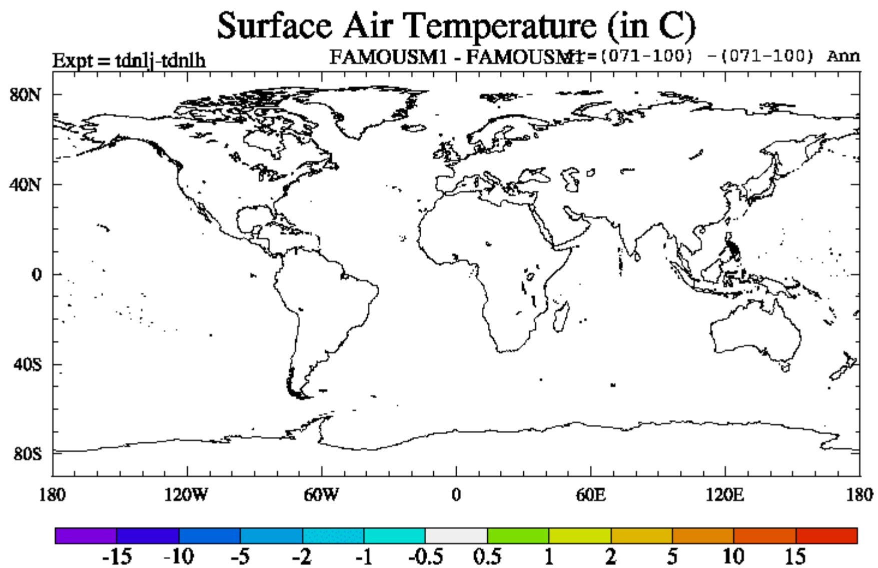
Fresh Water Hosing Experiment:
Add fresh water into N. Atlantic (50-70N).
Turn on at year 100, turn off at year 400
Different maximum amounts of fresh water

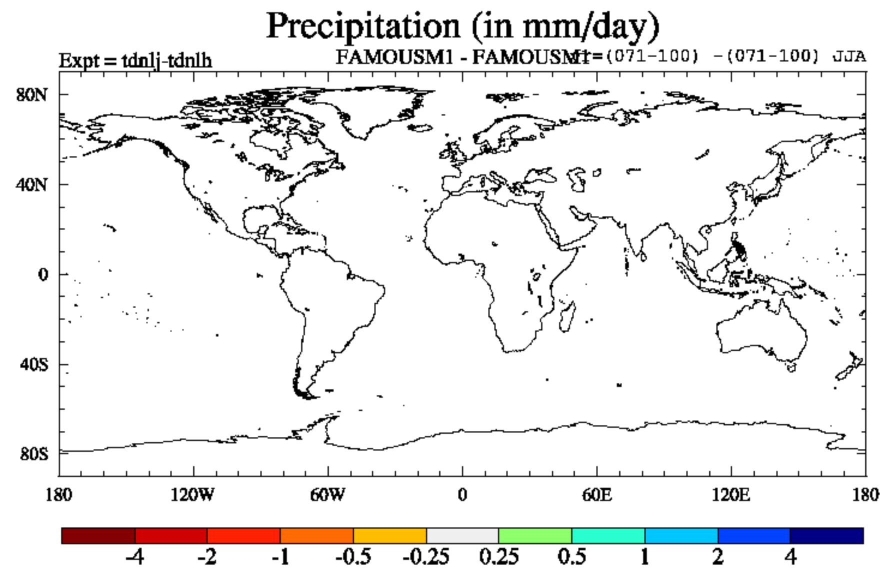




Be careful: Work in progress!

Resulting Changes in Climate





Change of climate due to an (idealised) increase in melting of 0.1Sv
c.f. best estimate of Greenland melt will be ~0.05Sv

Be careful: Work in progress!

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Summary

- Palaeodata can tell us huge amounts about the stability of various components of the Earth System
  - For a few cases, more detailed analysis can examine the ability of climate models to simulate critical risk/tipping points.
- In many cases, IPCC-class models have failed to reproduce basic characteristics of past extreme/rapid changes – they are too stable
  - Suggests that we may be underestimating some critical climate risks
  - But progress can be made in "tuning" the models for some of these test cases (although we are still struggling to match speed of change)
  - And I have highlighted the cases where there are clear problems!