Abrupt Climate Change & the Thermohaline Circulation During the last Glacial: Concepts, Data & Models

IMPRS Lecture in Hamburg

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Outline

1. **Introduction**
   - Motivation, Data & Concepts

2. **Deglacial amplification of the Thermohaline Circulation (THC)**

3. **Conceptual framework for cooling induced climate instabilities**

4. **Outlook**

Why do we care about rapid climate changes?

- Sea-ice
- Ice sheets and ice shelves
- Sea level
- Hydrologic cycle/droughts
- Ecosystems
- El-Nino dynamics
- Ocean circulation
- Methane hydrates
- Ocean anoxia
- etc…

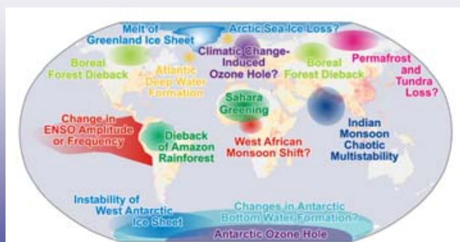
Motivation

• Rapid climate changes have happened in the past.

• They will happen in the future.

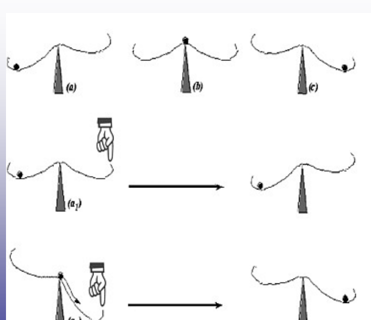
When, Where, Why and How?

Vulnerable Regions in the Earth system



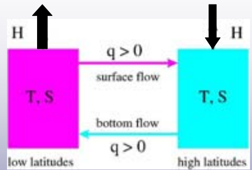
Lenton et al., 2008

A Mechanical analogy for rapid climate change

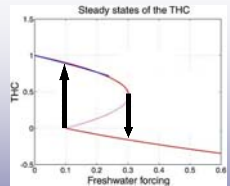


A temporary influence can have permanent effects!

Non-linear behaviour in a Box Model



Marotzke, 2000



Flow strength increases with high latitude salinity

High latitude salinity increases linearly with the flow strength

Abrupt climate change:

-Transition to a new state

- Rate determined by the system itself & faster than the cause

The Ocean as a Global Heat Pump

1. Differential heating of the earth surface by the sun
2. Positive energy balance in the latitude belt equator-wards of 30° and a deficit pole-wards

→ heat transport from the tropics to the mid and high-latitudes by the atmosphere-ocean system

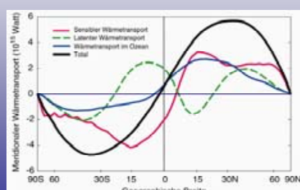


Figure after after Bryden & Imawaki, 2001

The Global Ocean Circulation

- Thermohaline circulation (THC) is maintained by heat and freshwater fluxes between atmosphere & ocean

- northward heat transport at all latitudes

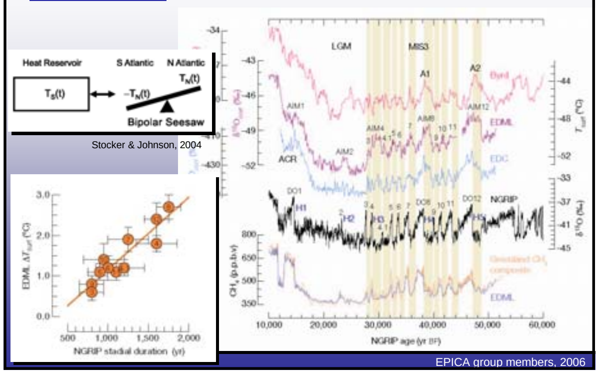
→ Relative mildness of western European climate

Potential THC weakening in response to rising CO_2

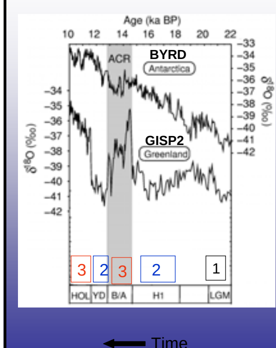
Modified version from Broecker (1991); IPCC, 2001

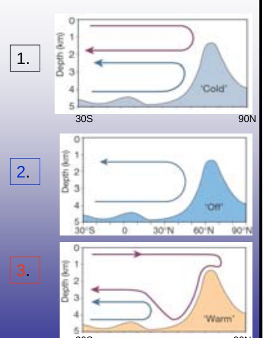
Millennial-scale climate variability during the last glacial

A bipolar seesaw



Different Modes of the AMOC during the Last Deglaciation





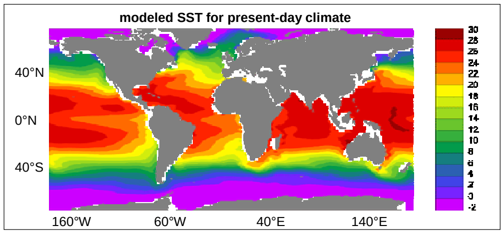
Millennial-Scale climate variability during the Last Glacial

1. What causes the abrupt warmings in the North?

2. How to explain the AMOC amplification in a dynamical framework?

The Ocean Model

- Based on the Hamburg *LSG (Maier-Reimer et al., 1993)*
- Dynamical equations for T, S, u, v, ^{14}C, …
- 3.5° horizontal resolution, 11 vertical levels
- Background climate: ECHAM3/ T42 for present-day and glacial conditions
- Coupling: air temperature; hydrological cycle and wind; Q = $Q = (\lambda_1 - \lambda_2\nabla^2)\,(T_a - T_s)$



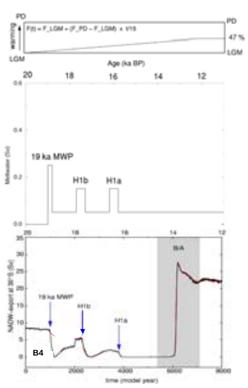
Lohmann & Lorenz, 2000; Prange et al., 2003

Global Deglacial Warming Scenario

Thermal Forcing
- Temperature
- Sea ice (South)
- Wind stress

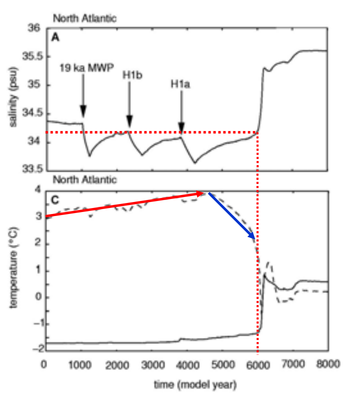
Freshwater Forcing

Simulated THC response



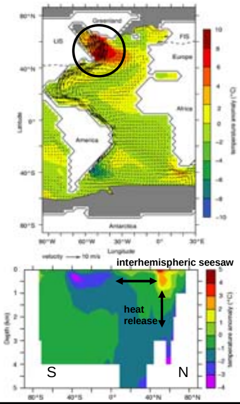
Knorr & Lohmann, 2007

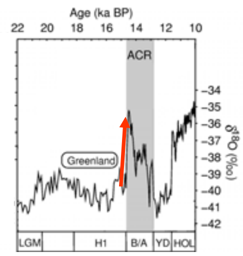
Transition to the B/A



Knorr & Lohmann, 2007

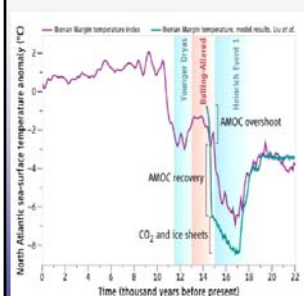
Abrupt Warming Signature at the B/A onset

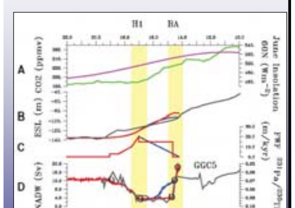




Knorr & Lohmann, 2007

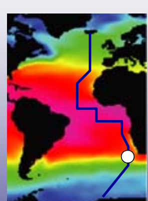
An AMOC overshoot during the B-A?

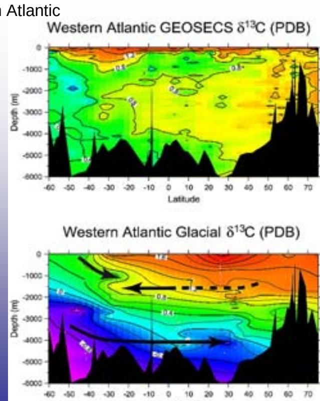




Liu et al., 2009

New results from the deep South Atlantic





Graphics: ODV, Schlitzer, 2009 Data: GLODAP, Key et al., 2004

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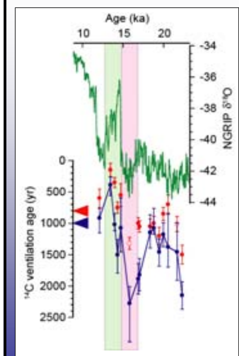
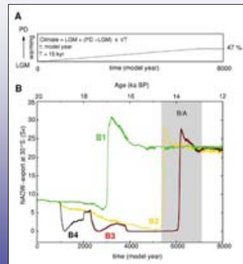


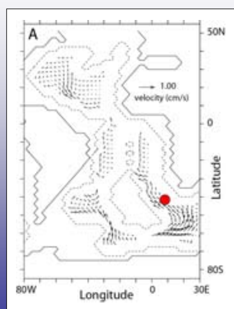


Barker et al., 2010

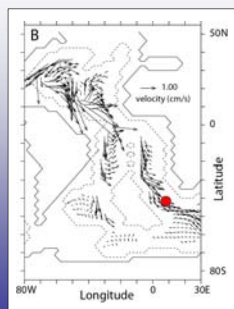
Model of the AMOC overshoot

Average velocity below 4000m

HS1

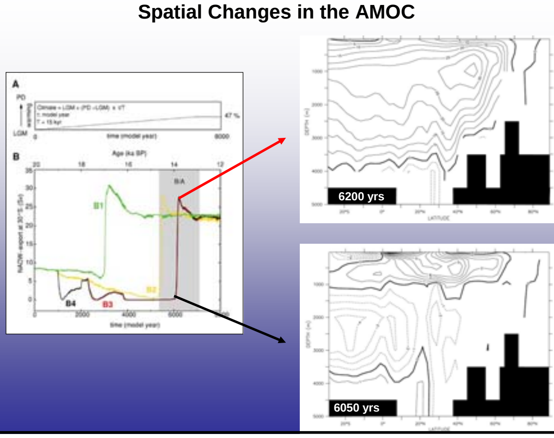


B-A



Barker et al., 2010

Spatial Changes in the AMOC



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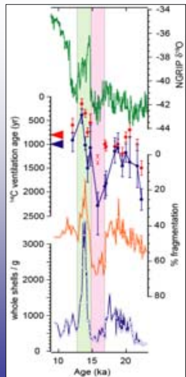
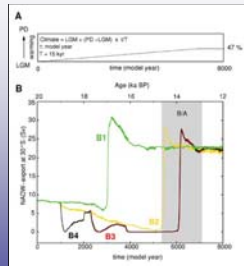


Barker et al., 2010



Knorr and Lohmann, 2007

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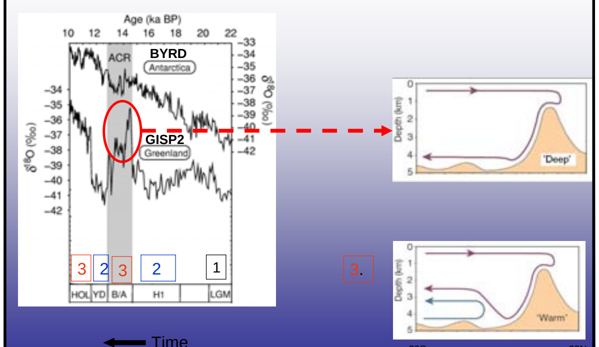


Blunier & Brook, 2000

Rahmstorf, 2002

I. Conclusions

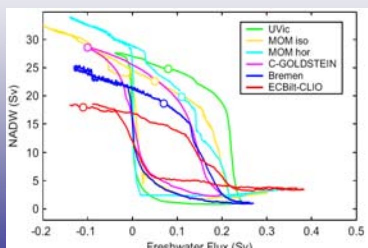
1. What causes the abrupt warming in the North?

- Gradual Global warming induces an abrupt switch from a weak to a strong THC
- Global warming enables a transition directly from a weak MOC-mode by the generation of a temperature inversion which overcomes the salinity stratification
- THC changes might be strongly related to changes in the background climate with freshwater only modulating the transitions

How to explain the AMOC amplification in a dynamical framework?

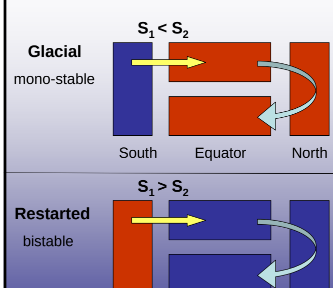
1. Non-linear Transition between two Stable states
2. Largely linear response to a strong and rapid forcing
3. Internal Oscillations in an intermediate climate State

Freshwater Hysteresis Curves

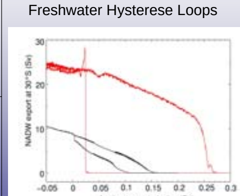


Rahmstorf et al. (2007)

Conceptual Picture of the THC Stability



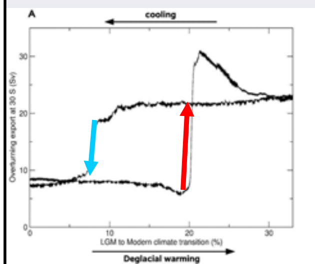
Freshwater Hysterese Loops

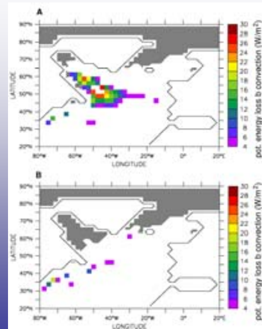


⟶ Importance of the "warm water route"

(Gordon et al., 1992; Knorr & Lohmann, 2003; Peeters et al. 2004)

Background climate and changes in the THC stability





Knorr & Lohmann, 2007

II.Conclusions

- Cooling induces a weaker THC by increased sea ice cover
- Ocean heat transport feedback becomes positive
- THC bifurcates at a threshold

Instability of the thermal component can be an indirect result of a freshwater flux to the North Atlantic and associated changes in ocean heat transport !

Outlook

1. Use of complex models

2. Integration and direct simulation of proxy data

3. Understanding of the stability behaviour of the MOC at different climate states beyond freshwater forcing & changes in the hydrological cycle
- e.g. thermal component and sea ice