• Past Arctic Ocean Climate Evolution

• High-Latitude Marine Paleoclimatology

• Crustose coralline algal-based marine climate reconstructions

Jochen Halfar, University of Toronto
Past Arctic Ocean Climate Evolution
How to cool a planet?

Let's isolate Antarctica!
How to cool a planet?

- Oceanic Gateway Opening
- Initiation of Circumantarctic Current

~34 Ma
How to cool a planet?

1. \( \text{CaSiO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + \text{SiO}_2 + \text{H}_2\text{O} \)

- Main collision India-Asia \( \sim 35 \text{ Ma} \), and European Alps in Eocene (56-35 Ma)
- Weathering of Mountain Belts
- Drawdown of \( \text{CO}_2 \)
- Arctic glaciation contemporaneous with Antarctica

→ Bipolar glaciation

- Points to CO₂ as main driver
ACEX – Arctic Coring Expedition

IODP - Integrated Ocean Drilling Program

Stoll 2006
Paleocene-Eocene Thermal Maximum (PETM - 56 Ma)

- Massive carbon release to atmosphere in short time (<5 ka)
- Comparable to today's CO$_2$ increase (amount and timing)
- Caused short global scale warming (duration ~200ka)
Paleocene-Eocene Thermal Maximum (PETM - 56 Ma)

- Arctic sea surface temperatures increased from 18 to 23°C
- Supergreenhouse
- Invasion of subtropical marine species
- Before, after and during PETM Arctic ice free

Sluijs et al. 2011
First evidence for the establishment of an offshore winter sea-ice regime in the Arctic Ocean (Stickley et al., 2009)
Freshwater Lake (49 Ma ago)

Brinkhuis et al. 2006
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  (grows only in less than 0.2% salt)

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- Arctic freshwater overflowed into adjacent basins

- Often anoxic conditions at seafloor

*Brinkhuis et al. 2006*
First evidence for the establishment of an offshore winter sea-ice regime in the Arctic Ocean (Stickley et al., 2009)
First Sea Ice at 47.5 Ma

Evidence A: Sea Ice Algae (Diatom – Synedropsis sp.)
First Sea Ice at 47.5 Ma

Evidence B: Ice Rafted Debris (IRD)

Stickley et al. 2009
First Sea Ice at 47.5 Ma

- Shore-fast ice at 47.5 Ma
- Seasonal sea ice at 46.9 Ma
- Icebergs at 46.25 Ma
- Slightly earlier than onset of glaciation in Antarctica
- Less saline waters in Arctic
First evidence for the establishment of an offshore winter sea-ice regime in the Arctic Ocean (Stickley et al., 2009)
Greenland glaciers at 38 Ma

- Ice rafted debris in sediment core off Eastern Greenland
- Glacial Ice
First evidence for the establishment of an offshore winter sea-ice regime in the Arctic Ocean (Stickley et al., 2009)
Miocene Sea Ice Evolution

- Ice decline at Mid-Miocene Climate Optimum
- Continuous ice since 14 Ma

Stein et al. 2012
Opening of Fram Strait

Late Early Miocene ~17.5 Ma

Bering Strait only opened 5.3 Ma years ago

Jakobsson et al., 2007
Opening of Fram Strait
Opening of Fram Strait

Oxygen poor ‘lake stage’ \((Azolla \ – \ 49 \ \text{Ma})\)

Transitional ‘estuarine sea’ phase with variable ventilation

Fully ventilated ‘ocean’ phase starting 17.5 Myr ago

Jakobssen et al. 2007
Opening of Fram Strait

- Onset of modern circulation regime

- Warm salty currents feed into the Arctic

- After releasing heat, waters become dense enough to sink as North Atlantic Deepwater (driver of thermohaline circulation)

- Fluctuations in the intensity of these currents and deepwater formation participated in causing or amplifying climate change events
Why little IRD in early Pleistocene?

- Stable ice pack reduces transport and melting
- Lower inflow of Atlantic-derived warm water reduces basal melting of sea ice
Pleistocene Ice Ages (2.6 Myr)

Coarser ice rafted material during glacial

IODP Core

533 ka

Bulk density (Mg m$^{-3}$)

Sound velocity (km s$^{-1}$)

Moran et al. 2006
Last Glacial Maximum

Modern Sea Ice Thickness  Last Glacial Maximum Sea Ice Thickness

Staerz et al 2012
Last Glacial Maximum (~20ka)

Summer Ice Extent

Past glacial

Present

Future?

Stein et al. 2012
Past 1500 years (late Holocene)

Kinnard et al. 2011
Past 1500 years (late Holocene)