Linking glaciers, ocean and atmospheric variability – lessons from marine sediment archives

Camilla S. Andresen

Work in collaboration with amongst others: Andreea Elena Stoican, Kristian K. Kjeldsen, Kurt H. Kjær, Antoon Kuijpers, Fiamma Straneo, Dave Sutherland, Jerry Lloyd, Mette Juncker Hansen, Aleksandra Grycel, Marie-Alexandrine Sicré, Anne Jennings, Sabine Schmidt
Greenland Ice sheet reconstructions
- and its interaction with ocean, sea ice and climate
Findings

1. The climate drivers behind outlet glacier instability during the past 100 years

2. The late 1930s and early 2000s glacier retreat events

3. Fjord circulation intensity changes on inter-annual time scales

4. The potential effect on submarine glacier melt of ambient ocean water
Findings

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4. Fjord circulation intensity changes on inter-annual time scales
Subsurface water by Disko Bay
Bottom-living foraminifera

Subsurface water by Disko Bay

Lloyd et al. 2011
Constructing a calving record for Helheim Glacier

Meltwater plume
Fine mud

Iceberg rafting
All sediment grain sizes
Incl. sand

Helheim Glacier

ER11-22
ER11-23
ER11-24
ER11-25
ER13
ER07
ER11
Fox04G/05R

Tasilaq

Laminated mud
Massive mud
Diamicton
Constructing a calving record for Helheim Glacier

Retreat rate from marine-terminating glaciers in southeast Greenland increases (Bjørk et al. 2012)

Calving from Helheim Glacier increases (Andresen et al. 2012)
Comparing the calving record with climate indices
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Multi-decadal variability

Warming of summer air

Negative Index

Reconstructed SST on shelf

Combined increase in Atlantic Water influence on shelf

Decrease in Polar Water influence

Increase in Atlantic Water influence

Helheim Glacier calving

Date

1900 1920 1940 1960 1980 2000

10 9 8 7 6 5 4 3 2 1
Comparing the calving record with climate indices

AMO
Atlantic Multidecadal Oscillation

(From Knight et al., 2005)
Comparing the calving record with climate indices

Short-term variability

- Warming of summer air
- Negative Index
- Reconstructed SST on shelf
- Combined increase in Atlantic Water influence on shelf
- Decrease in Polar Water influence
- Increase in Atlantic Water influence

Helheim Glacier calving

Nares Strait - Davis Strait - Bering Straits - Queen Elizabeth II - Greenland - Svalbard - Norwegian Seas - Denmark Strait - Subpolar Gyre - North Polar Current

Graph showing time series of climate indices and their relationship with calving events.
Comparing the calving record with climate indices

North Atlantic Oscillation

Positive index

Negative index
Comparing the calving record with climate indices

North Atlantic Oscillation

Positive index

Negative index
Comparing the calving record with climate indices

Warming climate → calving

Subglacial discharge

Temperature of ambient (subsurface) water

Circulation intensity

Thickness AW layer

(Double cell circulation proposed by Sciascia et al. JGRC)
Timing of instability of Jakobshavn Isbræ and Helheim Glacier concurs with:

- a positive Atlantic Multi-decadal Oscillation
- a negative North Atlantic Oscillation index
- changes in sea ice occurrence around Greenland
Findings

1. The climate drivers behind outlet glacier instability during the past 100 years

2. The late 1930s and early 2000s glacier retreat episodes

3. The potential effect on submarine glacier melt of ambient ocean water

4. Fjord circulation intensity changes on inter-annual time scales
The late 1930s and early 2000s marked glacier retreats.
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The late 1930s and early 2000s episodes of marked glacier retreat of Jakobshavn Isbræ and Helheim Glacier may stand out due to the coincidence of:

- Subsurface warming of the ocean around Greenland
- Record low sea ice occurrence
- Record warm summer air
Findings

1. The climate drivers behind outlet glacier instability during the past 100 years

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3. The potential effect on submarine glacier melt of ambient ocean water

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Warming climate → calving

Subglacial discharge

Temperature of ambient (subsurface) water

Circulation intensity

Thickness AW layer

PW

AW

(Double cell circulation proposed by Sciascia et al. JGRC)
Little Ice Age submarine melt

**LIA scenario**

**Cold atmosphere**

Minimal subglacial discharge submarine melt?
Onset LIA
Associated oceanographic change

Baffin Bay sea ice increase

EGC Intensifies

1150 AD
1200 AD?
1250 AD
1190 AD
1250 AD
1250 AD
1250 AD
1250 AD
Little Ice Age submarine melt

Sea surface temperature
Mg/Ca in planktonic foraminifers
(Richter et al. 2009)

Sea surface salinity
$\delta^{18}O$ in planktonic foraminifers
(Thomalley et al. 2009)

Air temperature
Cave deposits
(McDermott et al. 2001)

LIA cooling....?
Little Ice Age submarine melt

Subsurface ocean warming
inferred from benthic foraminifera

Ameralik Fjord
(Sørenkrantz et al. 2008)

Igaliku Fjord
(Lasson et al. 2004)

Sermilik Trough
(Andresen et al. 2012)

Kangerdlugssuaq Trough
(Andresen et al. 2012, Jennings et al. 2011)

LIA subsurface ocean warming
Little Ice Age submarine melt

Subsurface ocean warming

- **Ameralik Fjord**
  - *Siedenkranz et al. 2008*

- **Igaliku Fjord**
  - *Lasson et al. 2004*

- **Sermilik Trough**
  - *Andresen et al. 2012*

- **Kangerdlugssuaq Trough**
  - *Andresen et al. 2012, Jennings et al. 2011*

LIA subsurface ocean warming

Subsurface ocean cooling
Onset LIA
Associated oceanographic change

- **Baffin Bay sea ice increase**
- **WGC cools**
- **EGC Intensifies**

**LIA:**
subsurface ocean warming along with surface ocean cooling
Little Ice Age submarine melt

Warm subsurface water intrusion outside Sermilik Fjord
(Foraminifera flux)

Warm subsurface water intrusion inside Sermilik Fjord
(Foraminifera flux)

(Andresen et al. 2013)

(Stoican et al. In prep)
Little Ice Age submarine melt

LIA scenario

Cold atmosphere

Minimal subglacial discharge
submarine melt?
What happened to the large outlet glaciers during the LIA?
Mass loss since the LIA (1900 AD) until 1980s

- Jakobshavn Isbræ
- Helheim Glacier
- Kangerdlugssuaq Glacier

(Kjeldsen et al., submitted)
Little Ice Age submarine melt

![Diagram of LIA scenario]

*Cold atmosphere*
Little Ice Age submarine melt

*Cold atmosphere*

**LIA scenario**

Minimal subglacial discharge

‘Moderate’ submarine melt
Little Ice Age submarine melt

**Cold atmosphere**

**LIA scenario**

Minimal subglacial discharge

‘Moderate’ submarine melt
So in spite of atmospheric cooling Helheim Glacier did not advance during the LIA - maybe because of the warming subsurface layer in the fjord in relation to high SSTs in the Irminger Sea.
In regions with quite warm subsurface waters these have the potential to trigger glacier instability even with minimal glacier discharge.
Findings

1. The climate drivers behind outlet glacier instability during the past 100 years

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4. Fjord circulation intensity changes on inter-annual time scales
Circulation intensity – Sermilik Fjord

Shelf  Fjord

Along coastal northeasterly winds

Straneo et al. 2010
Warming climate $\rightarrow$ calving

Subglacial discharge

Temperature of ambient (subsurface) water

Circulation intensity

Thickness AW layer

(Double cell circulation proposed by Sciascia et al. JGRC)
Mass flow deposits

Meltwater plume
Very fine grained material (clay and silt)

Iceberg rafted debris
All grain sizes

Circulation intensity – Sermilik Fjord

Laminated mud
Massive mud
Diamicton

Depth in core (cm)

591 m 591 m 558 m 550 m Water depth
Circulation intensity – Sermilik Fjord

Positive NAO index
Increase in storm passage

Storis Index
Increase in PW influence

Helheim Glacier calving

(Andresen et al. In prep)
Circulation intensity – Sermilik Fjord

Increasing current strength by sea bed
Mean grain size sortable silt

Positive NAO index
Increase in storm passage

Storis Index
Increase in PW influence

Helheim Glacier calving

(Andresen et al. In prep)
On inter-annual time scales episodes of increased fjord circulation are linked with a positive NAO index and increased sea ice occurrence on the shelf - thus a climatic setting impeding calving rates in spite of marked renewal rate
Summary of findings

1. Timing of instability of Jakobshavn Isbørn and Helheim Glacier concurs with:

- a positive Atlantic Multi-decadal Oscillation
- a negative North Atlantic Oscillation index
- decreased sea ice occurrence around Greenland

2. The late 1930s and early 2000s episodes of marked glacier retreat of Jakobshavn Isbørn and Helheim Glacier may stand out due to the coincidence of: Subsurface warming of the ocean around Greenland, record low sea ice occurrence and record warm summer air

3. In regions with quite warm subsurface waters these have the potential to trigger glacier instability even with minimal glacier discharge

4. On inter-annual time scales episodes of increased fjord circulation are linked with a positive NAO index and increased sea ice occurrence on the shelf - thus a climatic setting impeding calving rates in spite of marked renewal rate
Comparing the calving record with ocean temperature proxy.

Temperature reconstruction via alkenone analysis.
Comparing the calving record with ocean temperature proxy

(Andresen et al. submitted)
Comparing the calving record with ocean temperature proxy

Oceanographic data

Tasiilaq

Straneo et al. (2010)
Sutherland et al. (2013)
Comparing the calving record with ocean temperature proxy

(Andresen et al. submitted)
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Comparing the calving record with ocean temperature proxy

Warming climate $\rightarrow$ calving

Subglacial discharge

Temperature of ambient (subsurface) water

Circulation intensity

Thickness AW layer

(PW)

(Double cell circulation proposed by Sciascia et al. JGRC)
The Little Ice Age – climate scenario

EGC influence

- Disko Bay (Ribeiro et al. 2012)
- Ameralik Fjord (Seierckrantz et al. 2008)
- Igaliku Fjord (Jensen et al. 2004)
- Nansen Trough (Jennings and Weiner, 1996)

Baffin Bay sea ice influence

LIA surface ocean cooling
The Little Ice Age – analysing fjord cores

Mud

Mud with sand and pebbles

Dowdeswell et al. 2000

Decreasing iceberg rafting in Sermilik Fjord clay content core

Cooling
The Little Ice Age – analysing fjord cores

Nansen Trough

Sermilik fjord

Icelandic sea ice (weeks/year)

Polar water conditions
foraminifera inferred
(Jennings and Weiner, 1996)
The Little Ice Age – analysing fjord cores

Polar water influence Nansen Trough
(Jennings and Weiner, 1996)

Decreasing iceberg rafting in Sermilik Fjord clay content core
Cooling

600 +/- 200 AD

1900 AD
The Little Ice Age – analysing fjord cores

Nansen Trough
Sermilik fjord

Polar water influence Nansen Trough
(Jennings and Weiner, 1996)

Decreasing iceberg rafting
in Sermilik Fjord
clay content core

800-1200 AD
1350 AD 1750 AD
600 +/- 200 AD
1900 AD

Date (A.D.)
Depth (m)
XRF-based correlation of two mid-fjord cores

The Little Ice Age – analysing fjord cores

Depth (cm) Core ER07

Depth (cm) Core ER11

Ca/Fe↓
K/Ti↓
Si/Al↑

1900 AD

Stone

Tassilaq

ER07

ER11
The Little Ice Age – analysing fjord cores

XRF-based correlation of two mid-fjord cores
The Little Ice Age – analysing fjord cores

Warm subsurface water intrusion inside Sermilik Fjord
(Foraminifera flux)
The Little Ice Age – analysing fjord cores

Warm subsurface water intrusion inside Sermilik Fjord (Foraminifera flux)
The Little Ice Age – analysing fjord cores

Warm subsurface water intrusion outside Sermilik Fjord
(Foraminifera flux)

Warm subsurface water intrusion inside Sermilik Fjord
(Foraminifera flux)
Caused by warm SSTs in the vicinity of Greenland?

Maximum sea ice occurrence around Greenland

Higher precipitation level
Average sedimentation mm yr⁻¹
Cores c. 150-200 cm

- Core top intact
- Core top lost

Uncertain (only 100 cm long core)

- Zone where plume sed. rapidly decreases
Grain size distributions

Comparing the calving record with current strength proxy

Sediment rates:
- 16 - 17 mm/yr
- 20 - 36 mm/yr
- 2.3 mm/yr
- 2 mm/yr

Grain size distributions

Meltwater plume deposits
Iceberg rafted sediment

Volume %

Grain size (micron)

Clay | Silt | Sand
Comparing the calving record with current strength proxy

$^{210}$Pb dating of the meltwater plume sediment

$y = 60.075e^{-0.021x}$
$R^2 = 0.9216$

$y = 68.407e^{-0.025x}$
$R^2 = 0.7413$
Comparing the calving record with current strength proxy

K/Ti ratios

Date

ER11-25

ER11-24
Comparing the calving record with current strength proxy
Comparing the calving record with current strength proxy

Helheim Glacier calving
Reconstructed from

Knut ratios
Comparing the calving record with current strength proxy

Helheim Glacier calving
Reconstructed from mid-fjord cores

K/Ti ratios

Current strength by sea bed
Increases---->
Comparing the calving record with climate indices (Andresen et al. 2012)
near Ilulissat, Greenland (69.23°N, 51.07°W)
Annual Mean Temp 1886 to 2001
Comparing the calving record with climate indices

Verifying the Shelf Index

(Andresen et al. 2012)
Constructing a calving record

Retreat rate from marine-terminating glaciers in southeast Greenland increases

Calving from Helheim Glacier increases

Constructing a calving record (Andresen et al. 2012)

Retreat rate from marine-terminating glaciers in southeast Greenland increases (Bjørk et al. 2012)

Calving from Helheim Glacier increases

Composite of ER13, ER07 and ER11

ER13

ER07

ER11

(Andresen et al. 2012)