Køge Bugt: Evidence of a Greenland Firn Aquifer Influencing Tidewater Glacier Dynamics?

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Køge Bugt - Introduction

- 3 TWG systems
  - Køge North (Pamiagtik Glacier)
  - Køge Central (Køge Bugt Glacier)
  - Køge South (Havhestens Bugt Glacier)
- Køge Central (3rd) and Køge South (7th) highest discharge in Greenland (Enderlin et al, 2014)
- Small retreat for most of 20th century except for small re-advance between 1972 – 1981 (Bjørk et al, 2012)
- Minimal retreat during Holocene (Dyke et al, 2017); suggest physical setting controls response to external forcing.
- Submarine beds vulnerable to warm Atlantic Water (Millan et al, 2018)
Køge Bugt - Introduction


- Køge South:
  - Seasonal speed variations triggered by melt, later sustained by bed topography and ice dynamics. (Moon et al, 2014)

- Køge Central:
  - Lacks seasonal variability and a response to melt (Moon et al, 2014)
  - Two major slowdown events occurred in recent years coincide with re-advance (Joughin et al, 2018)
  - Large along-flow variability in sliding, suggesting a complex relationship with meltwater (Stearns & van der Veen, 2018)
**Motivation:**

- "What’s going on at Køge Central?"

- What roles, if any, do the ice mélange and the firn aquifer play in ice dynamics?

- Why do glaciers in the same fjord with similar bed and ice surface geometries exhibit such different flow characteristics?

**Approach: Generated comprehensive record of ice dynamics**

- Speeds: 3 NASA derived datasets
  - MEaSUREs Radar *(Joughin et al, 2011)*
  - MEaSUREs Optical *(Howat, 2017)*
  - GoLIVE *(Scambos et al, 2016)*

- Terminus Positions
  - Landsats 1 & 5 (60-m)
  - Landsats 7 & 8 (15-m)
  - Sentinel-2 (10-m)

- Surface Elevations (Ice Thicknesses)
  - Time-tagged ArcticDEM
**Terminus History**

**Køge North: Stable**
- 1990 – 2000: Small ~1 km retreat

**Køge Central: ~3 km retreat**
- 1972 – 1998: Advanced position, ~750-m variations
- 1998 – 2003: Stable
- 2003 – Present: Large (>1 km), multi-year variability

**Køge South: ~1.2 km retreat**
- 1972 – 1992: Advanced position, ~500-m variations
- 2003 – Present: Increased annual variability
Terminus Speed

7.5 km along profile

8.2 km along profile

4.7 km along profile

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UNIVERSITY OF COLORADO BOULDER and NOAA
- **Prolonged increase in speed followed by rapid slow down**
- **Slowdowns initiate in summer and occur over 6-9 months**
- **2002 and 2012 slowdowns coincide with peak melt years (Steffen et al, 2004; Nghiem et al, 2012)**
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Sep 2015 - Apr 2016 (7 months)
1 winter: ~40 m elevation gain

Oct 2012 – Jun 2013 (8 months)
1 winter: 60 m elevation gain

Csatho et al, 2014: “Thinning ➔ Thickening ➔ Thinning with abrupt termination of initial thinning”

Coincident speed reductions, terminus advance & ice thickening
Large scale dynamic thickening events
Recall, Køge Central:

- lacks any melt-induced seasonal changes in ice flow. (Moon et al, 2014)
- Large along-flow variability in sliding parameter; suggests complex relationship with melt

**Q: What mechanism(s) are driving these changes?**

Coincident speed reductions, terminus advance & ice thickenings:

Large scale dynamic thickening events
Perennial firn aquifer ~30 km upglacier (Forster et al, 2013)

2013
- Water table increased 2 m
- 4 km inland expansion

2012: FA levels lower (draining) → glacier speeding up, thinning, and retreating

2013: FA levels higher (not draining and/or filling) --> glacier slowing, thickening, & advancing

2014: FA again lower (draining) → glacier again accelerating, thinning, and retreating.
**Conceptual Model: Firn aquifer mechanism for ice dynamics**

**Mode 1:** Persistent discharge from firn aquifer facilitates prolonged periods of ice dynamics that promote mass loss.

- **Surface Melt**
  - **Firn Aquifer “Buffer”**
    - **Basal Hydrology (Meltwater)**
      - \( \uparrow P_w, \downarrow P_e, \uparrow Sliding \)
      - Insufficient to incise large subglacial conduits
- **Controlled, multi-year increase in ice speed, thinning and terminus retreat**
**Mode 2:** Excessive melt inundates the hydrologic system, which incises large subglacial channels, decreases basal water pressure, increases effective pressure, and slows the glacier.
Additional Evidence

- Daily MODIS 250-m images
- Proglacial fjord typically ice free Jan – Mar
- **EXCEPTIONS:** 2007, 2013 & 2016 (years with a slower, thickening, and advancing terminus)
- This might suggest:
  - 1) an ice mélange influence
  - 2) low subglacial discharge (FA not draining?)
Additional Evidence

Hydraulic Potential

- $\Phi = \rho_w g Z_b + \rho_i g H_k_p$
Remaining Questions

• Do variations in the firn aquifer coincide with dynamic changes in 2003, 2007 and 2016?
• What mechanism(s) facilitate firn aquifer discharge/recharge?
• How does annual variability in surface melt affect firn aquifer?
• What is the buffering capacity of the firn aquifer?
• What role, if any, does ice mélangé play in dynamic change at Køge Central?

Future Work

• Simulate dynamic changes using an ice physics – basal hydrology coupled model; plan to use SHaKTi
• Collect additional in situ & satellite remote sensing data of firn aquifer variability (L-Band SAR, e.g. NiSAR?)
• Study regional climate models for patterns of melt, snow, precip, etc...
• Generate thermal SST record of fjord surface temperatures (winter ice mélangé proxy)
• Investigate plume detection methods
Summary

• Three Køge Bugt tidewater glaciers exhibit very different flow characteristics despite close proximity (<20 km apart) and similar bed and surface geometries.

• **Køge North**: Slowest, stable and lacks significant dynamic change.

• **Køge South**: Moderate speeds, exhibits small scale seasonal variations in flow, ice thickness, and terminus location; sensitivity to melt (Moon et al, 2014).

• **Køge Central**: Fastest, lacks seasonal variability, but exhibits prolonged periods of accelerated flow, dynamic thinning and retreat. These multi-year processes abruptly lead to decelerated flow, ice thickening, and re-advance before returning to previous mode.
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• **Køge Central changes coincide with variations in the firn aquifer, first known evidence of firn aquifer influence on TWG dynamics**

• **Firn aquifer induced large scale changes in ice dynamics along Køge Bugt produced 3rd highest volume of ice dynamic losses in Greenland 2000 – 2012**
Thank you!

Questions?
EXTRA SLIDES
\[ \Phi = \rho_w g Z_b + \rho_i g H k_p \]
Hydraulic Potential

\[ \Phi = \rho_w g Z_b + \rho_i g H k_p \]
Bed Geometries

Similar bed profiles along lower 22 km:
- 22 km (behind calving front): ~400 m ASL
- 3 km: at sea level
- 0 – 3 km: below sea level

Major Difference:
- Køge Central: Retrograde bed behind calving front
- Køge South: Prograde to the calving front
Køge North

- Negligible change in surface elevation

Køge South

- Some dynamic changes
- Smaller in magnitude
- Perhaps seasonal

+20-30 m Jul 2016 (1.5 yrs thickening)

+10-20 m May 2013 (winter thickening)
Surface Elevations Over Time

Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
Surface Elevations Over Time

Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 Jun 2013

Winter Thickening

Re-advance of terminus
Surface Elevations Over Time

Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013
Surface Elevation Change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013
- 3.3 yrs: +17 m 4 Jul 2014

- **Winter Thickening**
- **Summer Thinning**
- **Winter Thinning**
Surface Elevations Over Time

Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013
- 3.3 yrs: +17 m 4 Jul 2014
- 4.5 yrs: +1 m 23 Sep 2015

Winter Thickening
Summer Thinning
Winter Thinning
Multi-year Thinning
Surface Elevations Over Time

Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013
- 3.3 yrs: +17 m 4 Jul 2014
- 4.5 yrs: +1 m 23 Sep 2015
- 5.1 yrs: +44 m 12 Apr 2016
Multiple large-scale thickening events:
- Winters 2012 & 2016
- Thinning winter 2014
- Thickening summer 2016

Surface elevation change from Mar 2011
- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013
- 3.3 yrs: +17 m 4 Jul 2014
- 4.5 yrs: +1 m 23 Sep 2015
- 5.1 yrs: +44 m 12 Apr 2016
- 5.5 yrs: +50 m 17 Sep 2016