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

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Land Ice Working Group

National Center for Atmospheric Research

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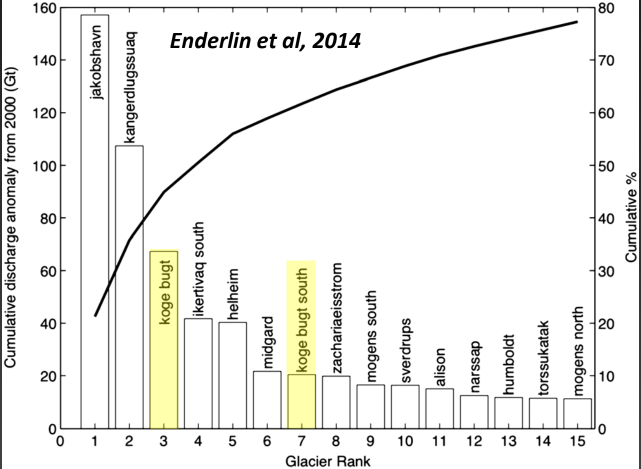
CIRES

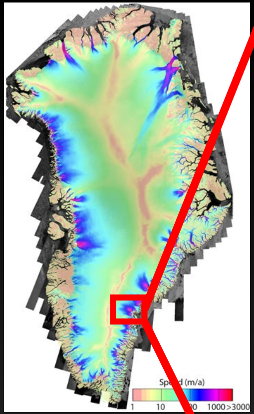
Cooperative Institute for Research in Environmental Sciences

UNIVERSITY OF COLORADO BOULDER and NOAA

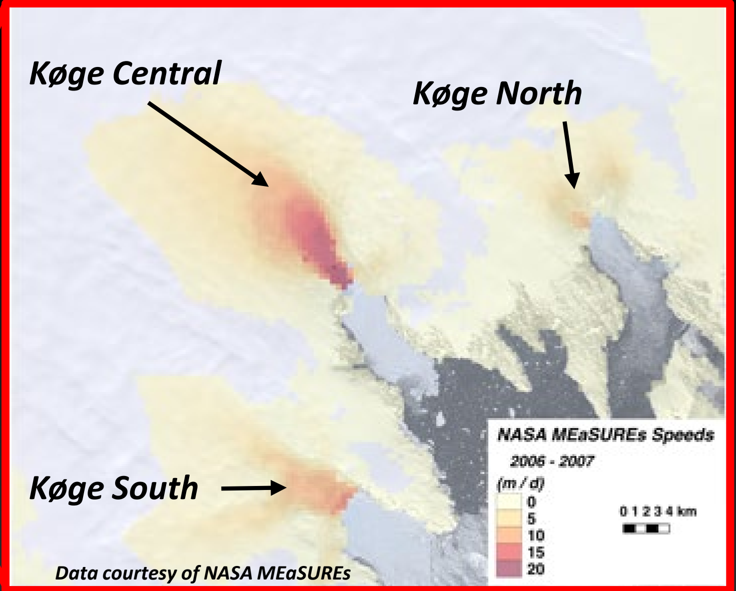
Køge Bugt - Introduction

- 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*)





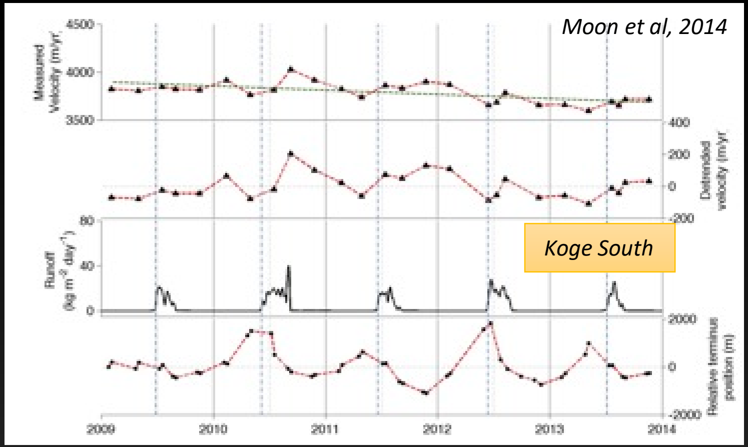
Joughin et al, 2018

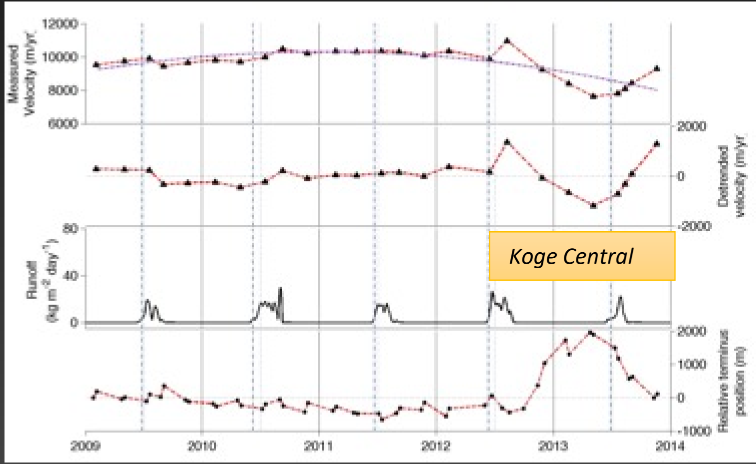


- Small retreat for most of 20th century except for small re-advance between 1972 – 1981 (*Bjørk et al, 2012*)
- Minimal retreat during Holocene (*Dyke et al, 2017*); suggest physical setting controls response to external forcing.
- Submarine beds vulnerable to warm Atlantic Water (*Millan et al, 2018*)

Køge Bugt - Introduction

- 2003-09: experienced thinning-thickening-thinning pattern *(Csatho et al, 2014)*
- 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

<u>Køge North: Stable</u>

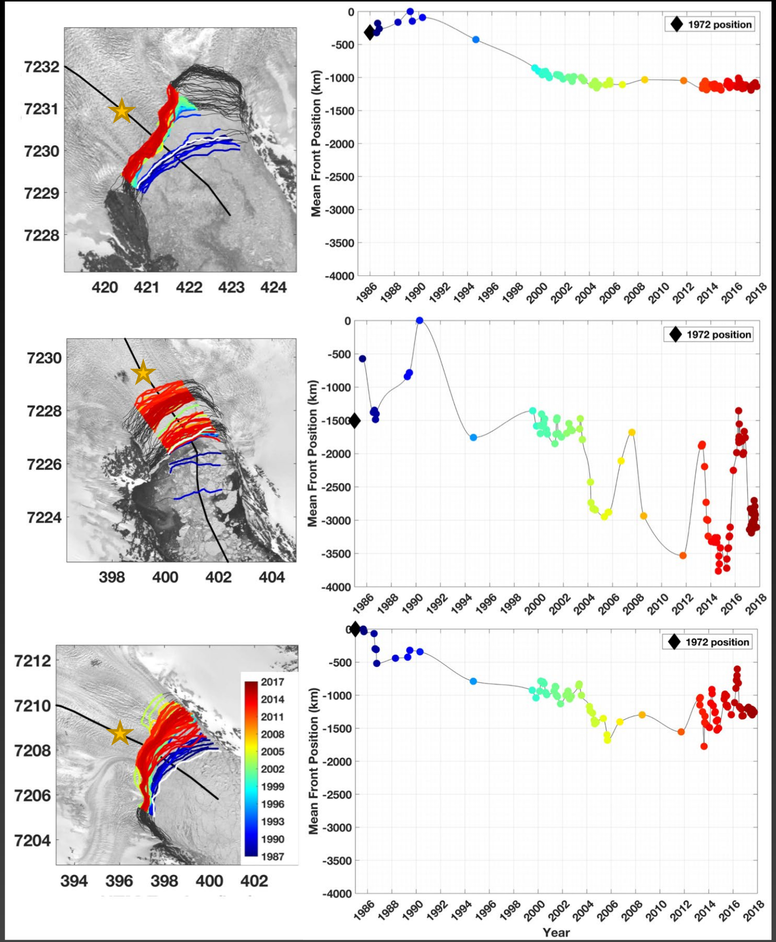
- **1990 – 2000: Small ~1 km retreat**

<u>Køge Central: ~3 km retreat</u>

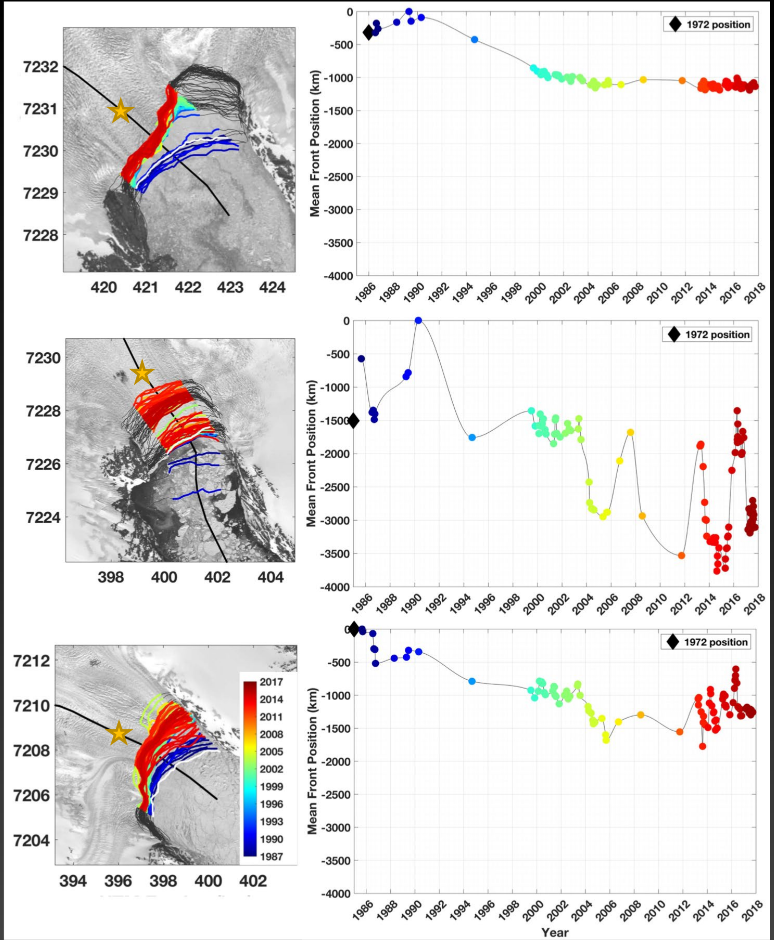
- **1972 – 1998: Advanced position, ~750-m variations**
- **1998 – 2003: Stable**
- **2003 – Present: Large (>1 km), multi-year variability**

<u>Køge South: ~1.2 km retreat</u>

- **1972 – 1992: Advanced position, ~500-m variations**
- **1992 – 2003: Stable**
- **2003 – Present: Increased annual variability**



Terminus Speed



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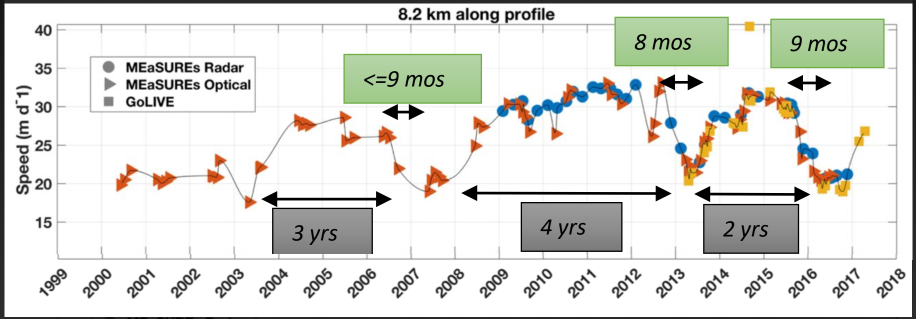
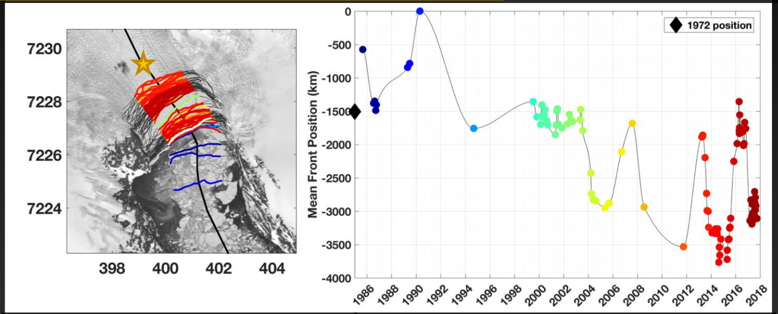
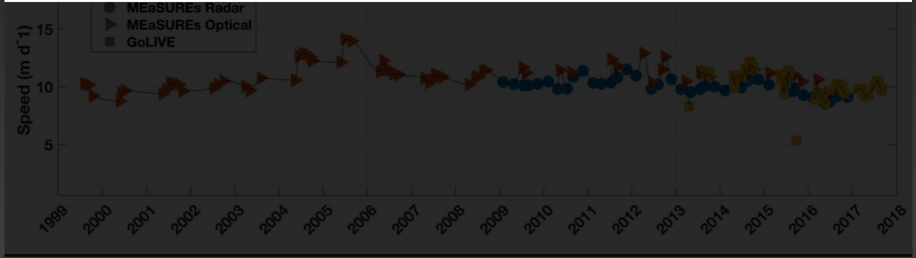
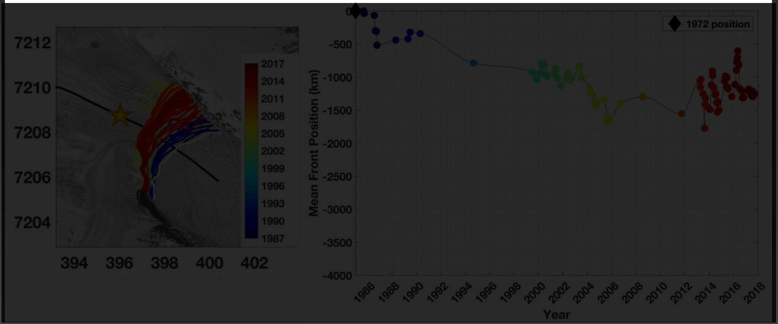
Multi-year variability

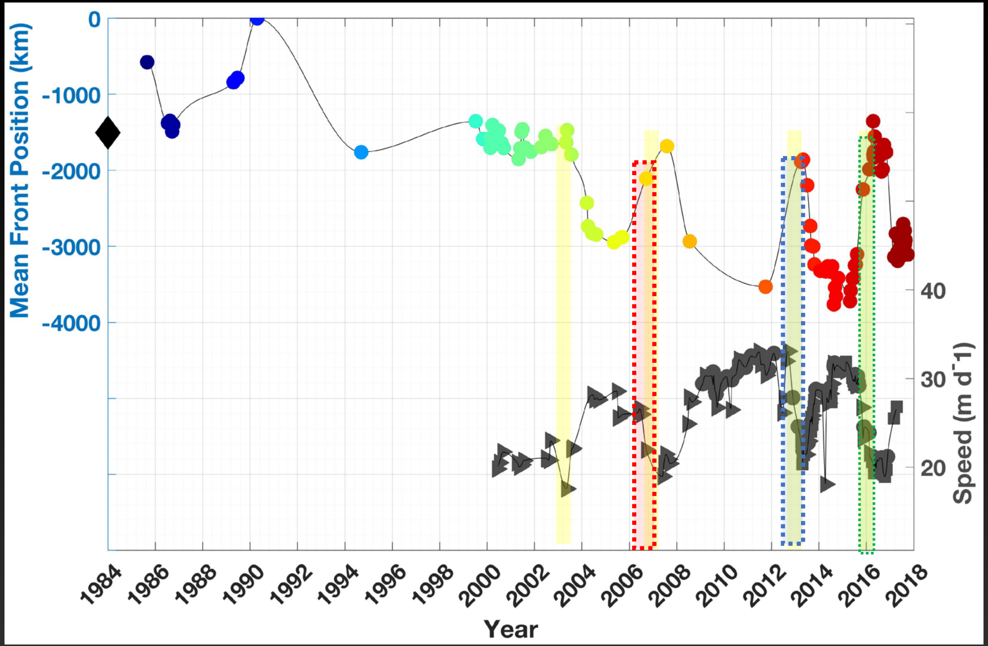
- ***Prolonged increase in speed followed by rapid slow down***
- ***Slowdowns initiate in summer and occur over 6-9 months***
- ***2002 and 2012 slowdowns coincide with peak melt years (Steffen et al, 2004; Nghiem et al, 2012)***

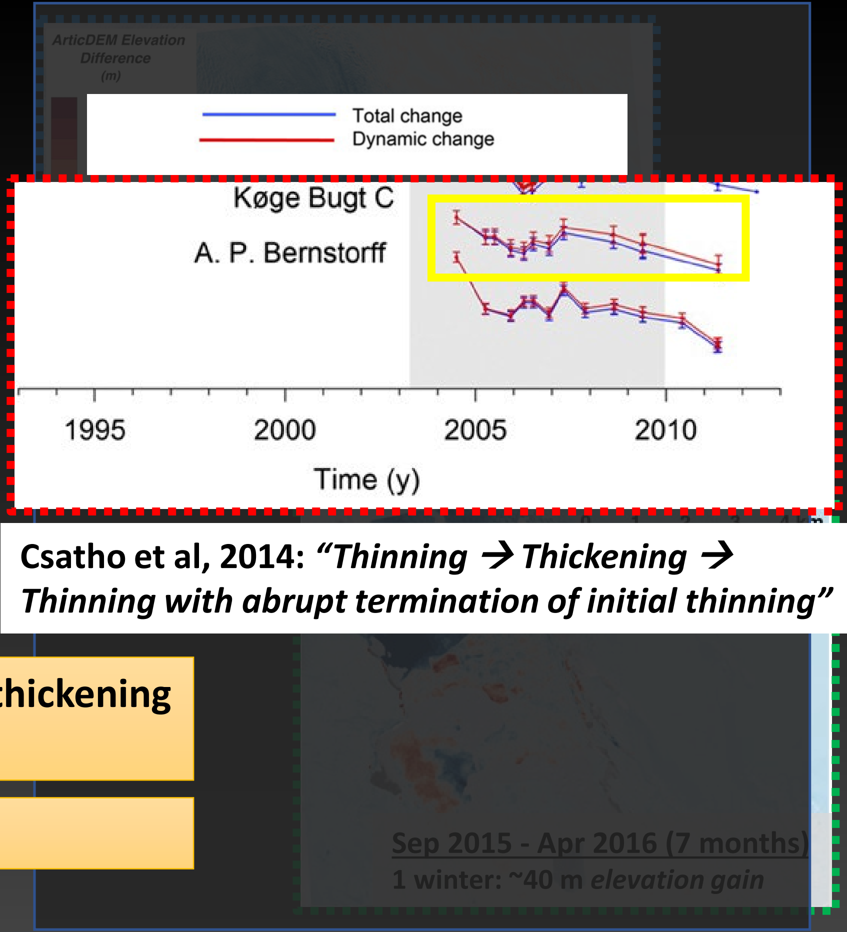










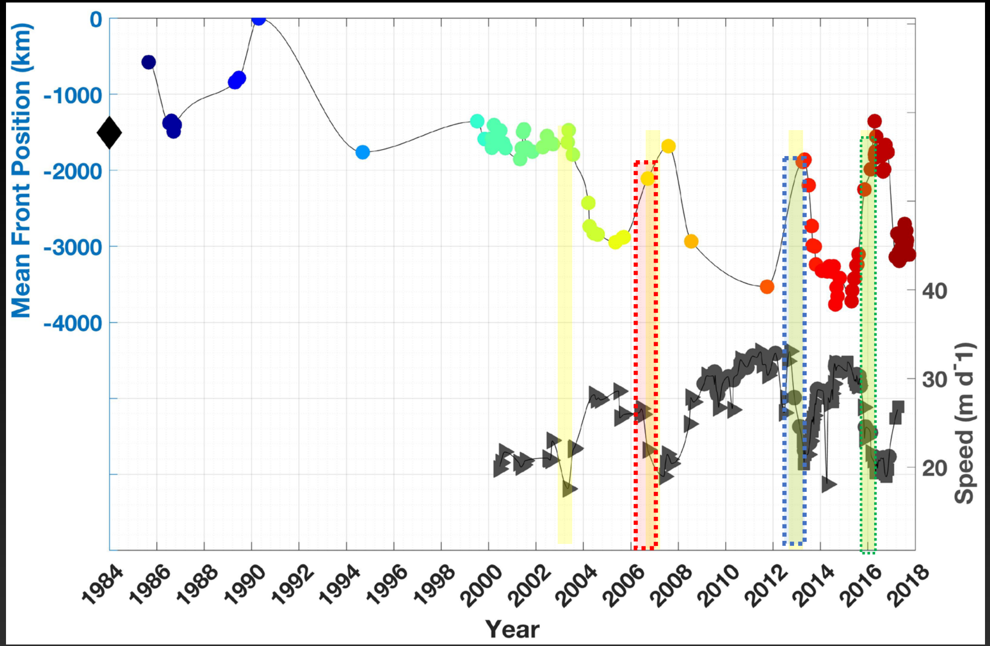


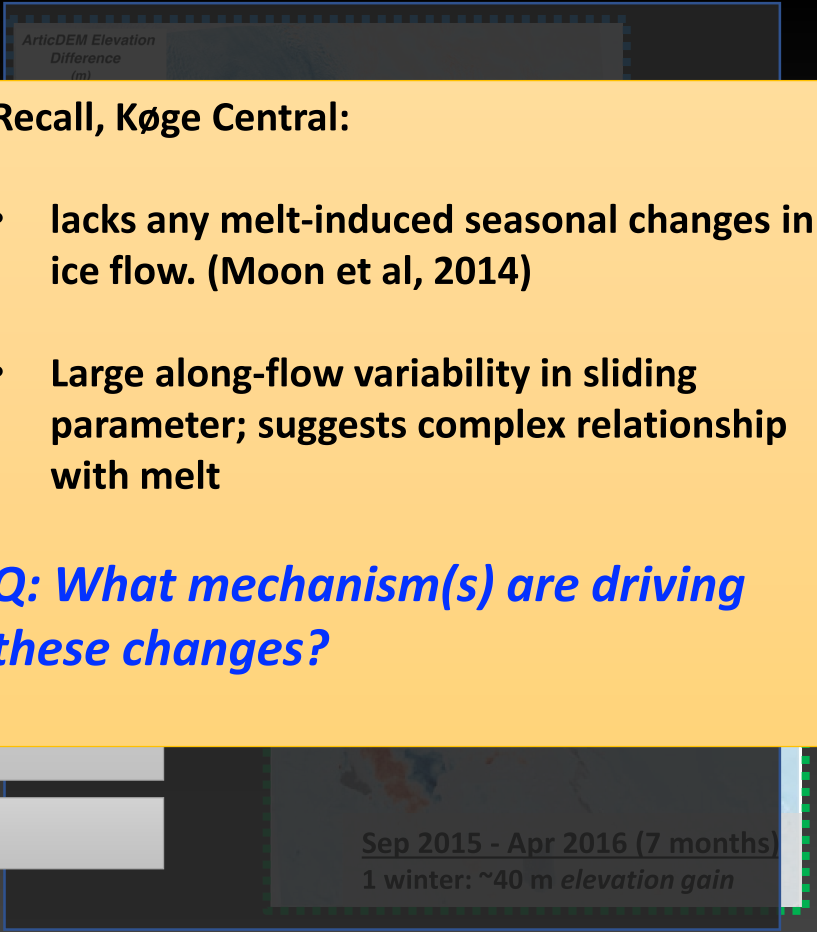
Csatho et al, 2014: *"Thinning → Thickening → Thinning with abrupt termination of initial thinning"*

Coincident speed reductions, terminus advance & ice thickening

- **2003, 2007, 2013, 2016**

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?

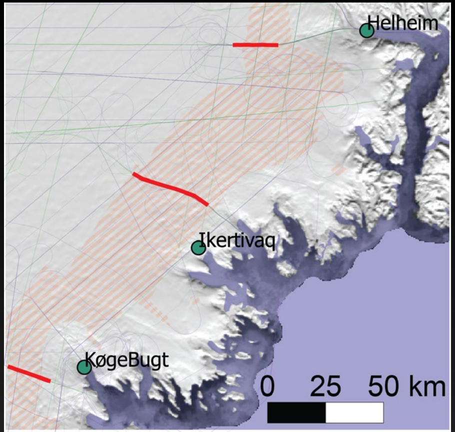
Coincident speed reductions, terminus advance & ice t

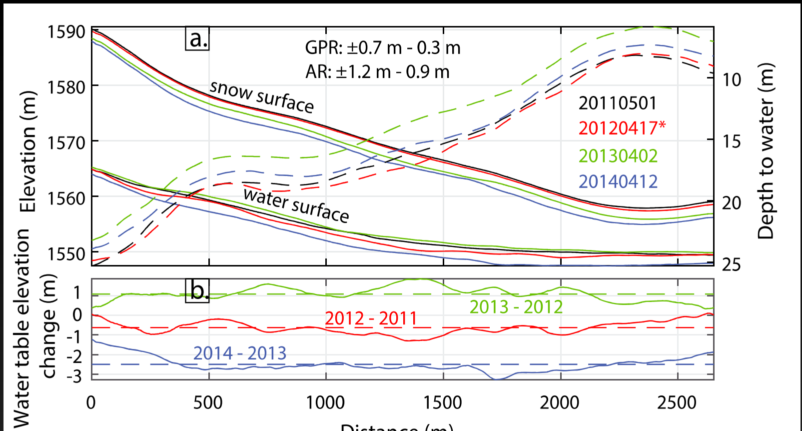
- 2003, 2007, 2013, 2016

Large scale dynamic thickening events

Firn Aquifer Driver?

- **Perennial firn aquifer ~30 km upglacier (Forster et al, 2013)**
- **2013**
  - **Water table increased 2 m**
  - **4 km inland expansion**



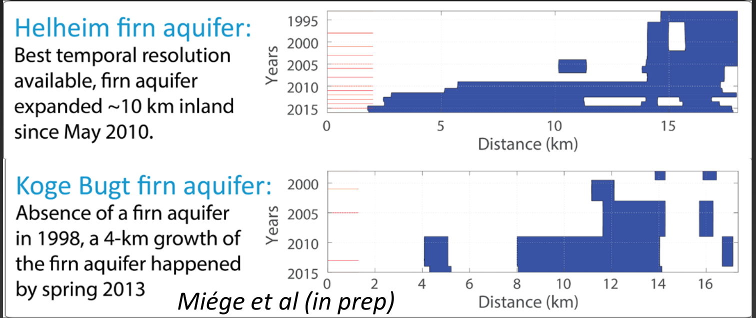


Miege et al, 2016

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

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

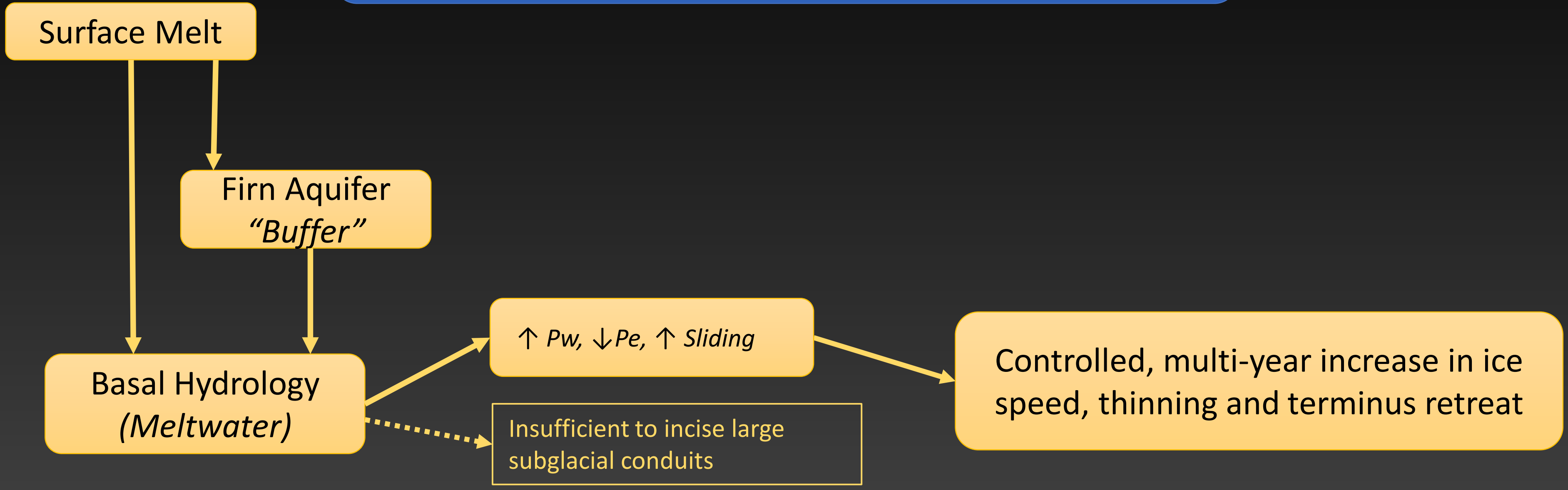
2014: FA again lower (draining) → glacier again accelerating, thinning, and retreating.



Miége et al (in prep)

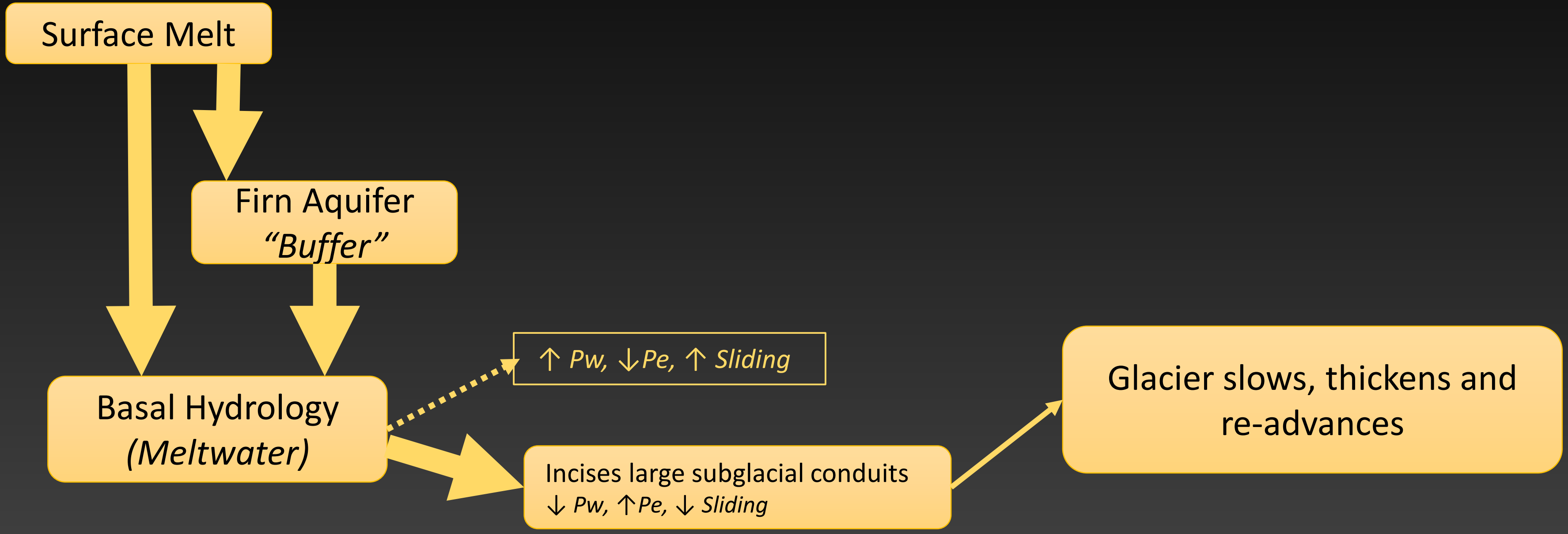
Conceptual Model: Firn aquifer mechanism for ice dynamics

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



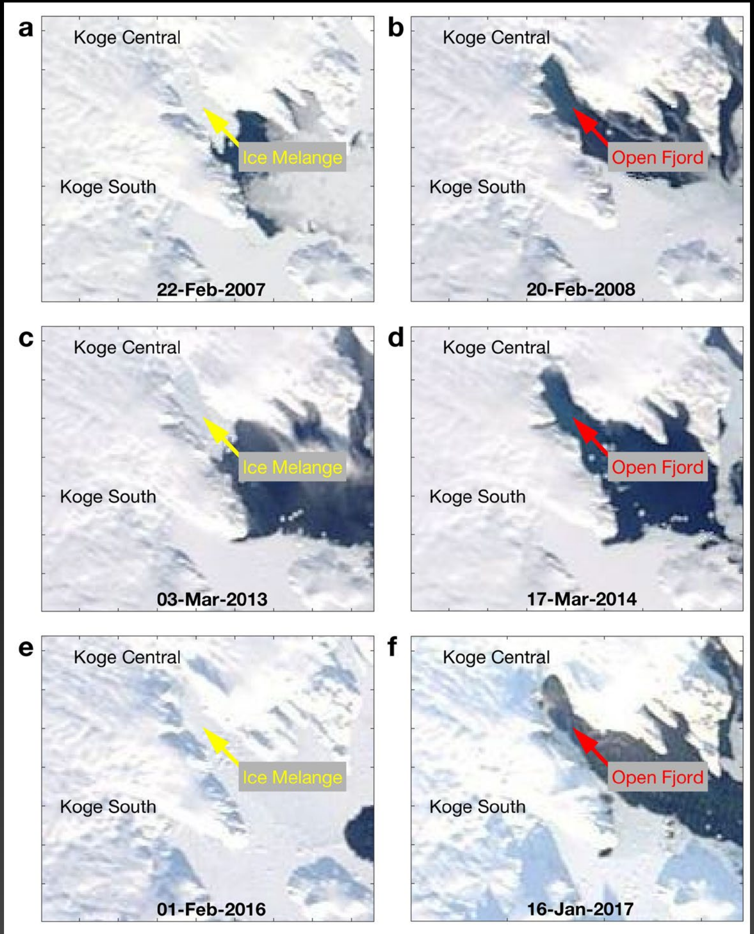
Conceptual Model: Firn aquifer mechanism for ice dynamics

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

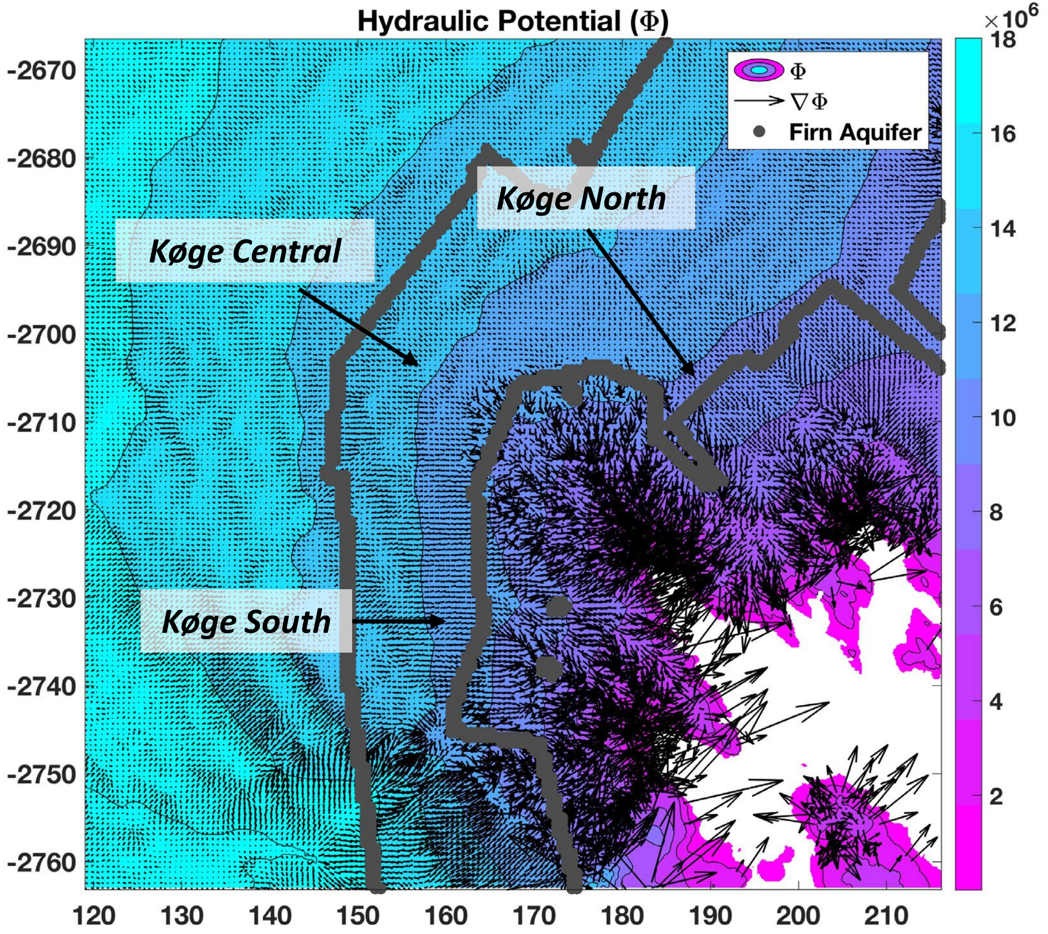
- Daily MODIS 250-m images
- Proglacial fjord typically ice free Jan – Mar
- *EXCEPTIONS:* 2007, 2013 & 2016 (years with a slower, thickening, and advancing terminus)
- This might suggest:
  - 1) an ice mélange influence
  - 2) low subglacial discharge (FA not draining?)



Additional Evidence

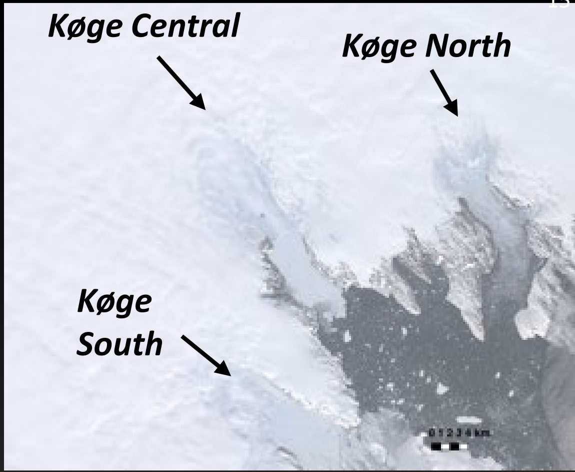
Hydraulic Potential

- $\Phi = \rho_w g Z_b + \rho_i g H k_p$



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 mélange 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 mélange proxy)
- Investigate plume detection methods

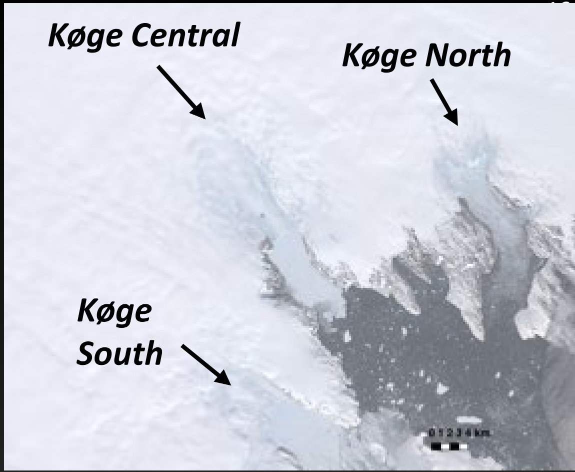
Summary

- 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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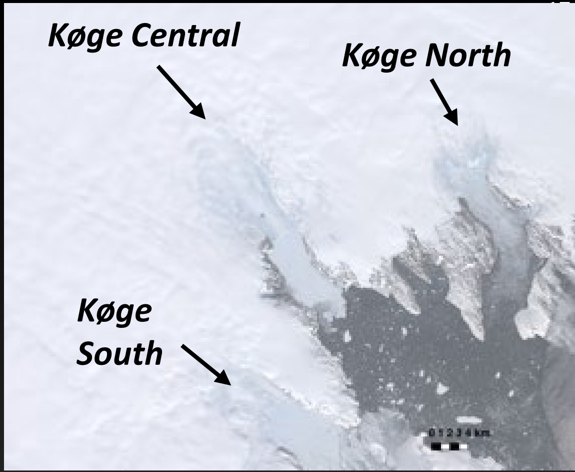


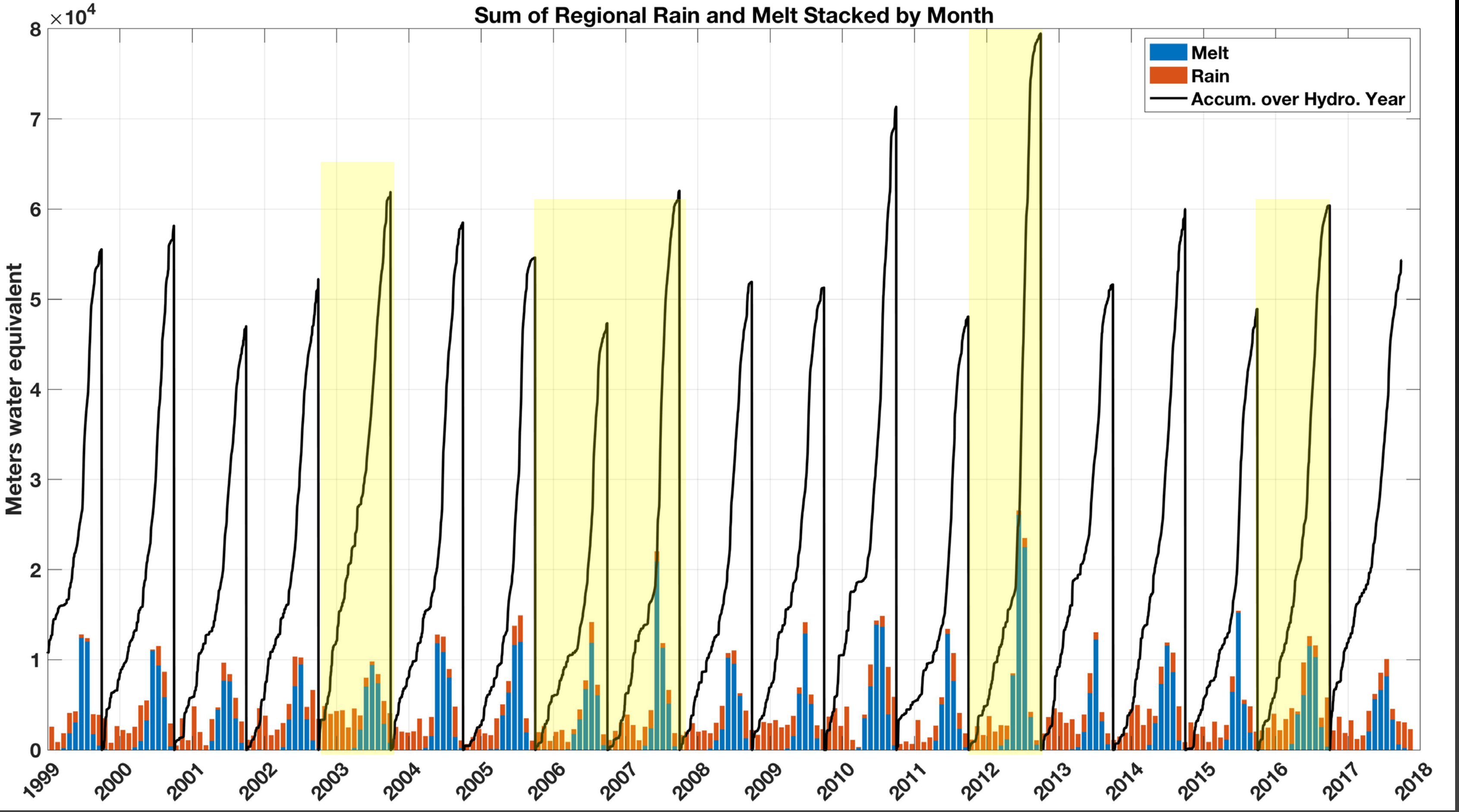
- ***Køge Central changes coincide with variations in the firn aquifer, first known evidence of firn aquifer influence on TWG dynamics***

- ***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


Sum of Regional Rain and Melt Stacked by Month
Meters water equivalent
×10^4
0
1
2
3
4
5
6
7
8
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
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2011
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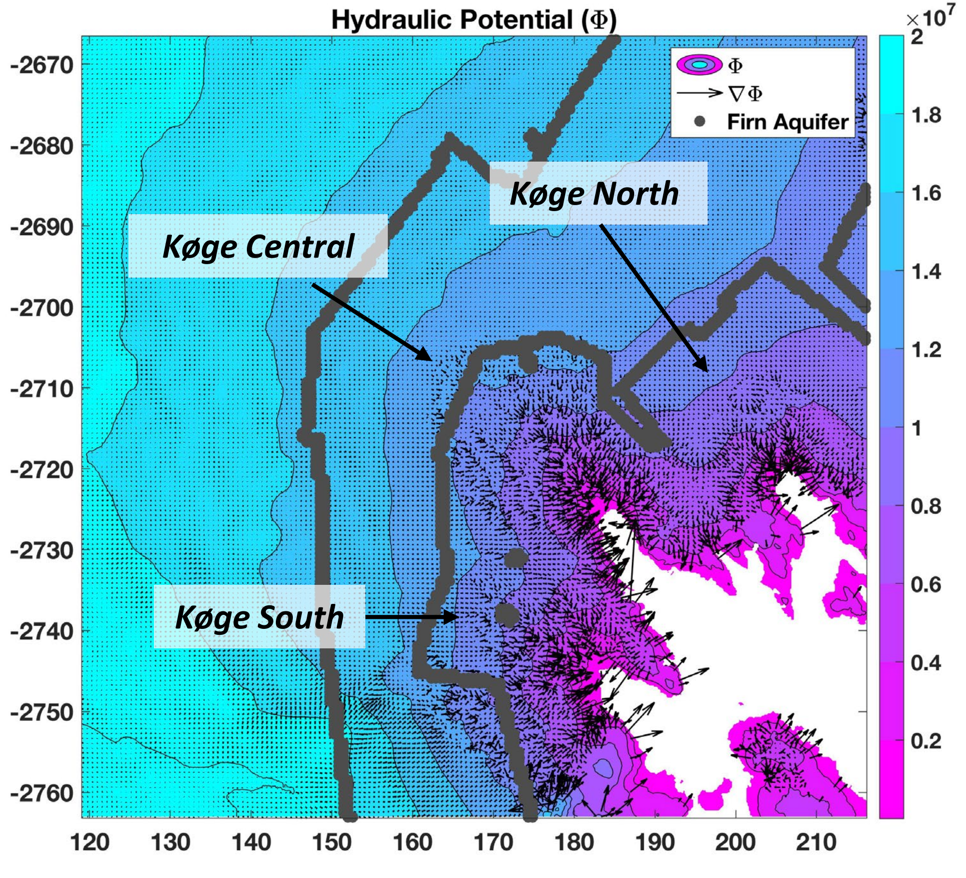
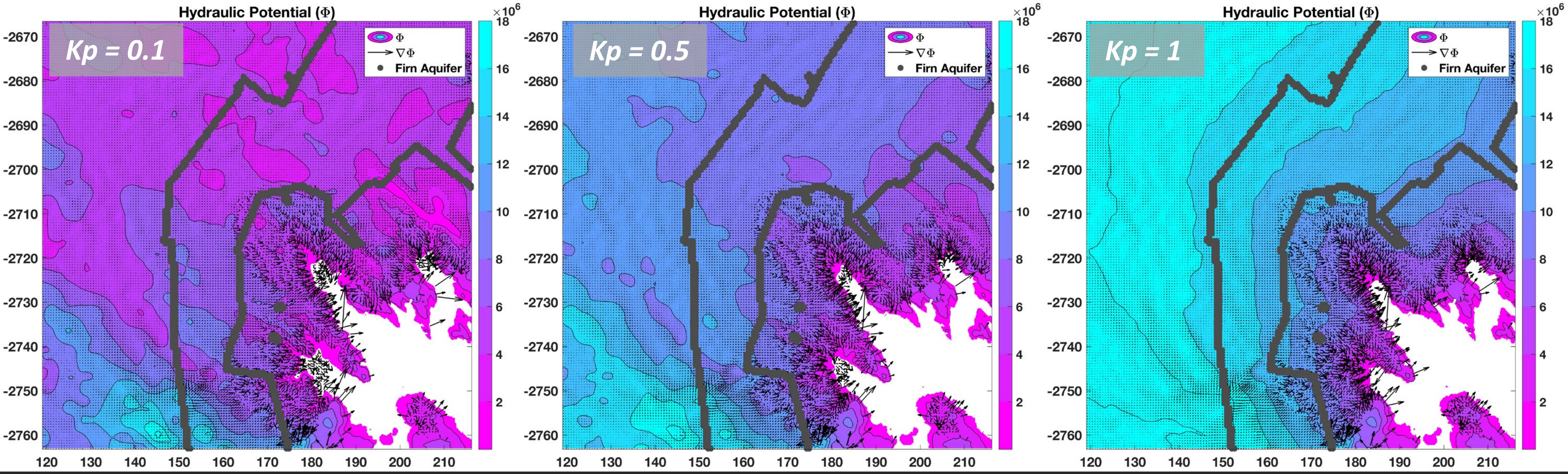
2018
Melt
Rain
Accum. over Hydro. Year



- $\Phi = \rho_w g Z_b + \rho_i g H k_p$



Hydraulic Potential

- $\Phi = \rho_w g Z_b + \rho_i g H k_p$

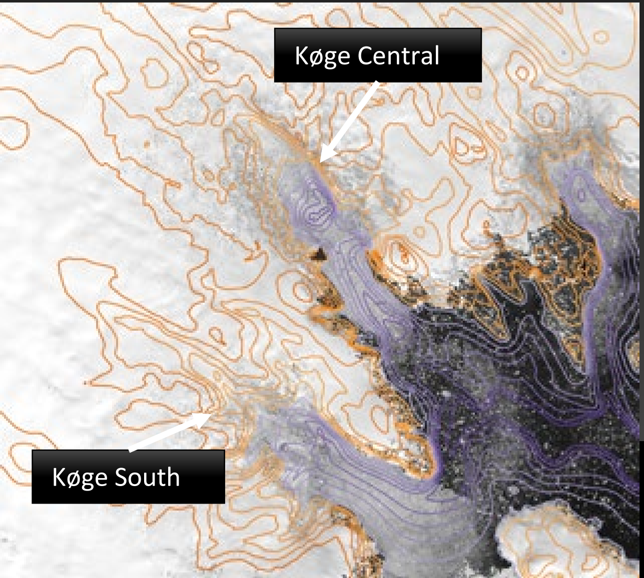
Bed Geometries

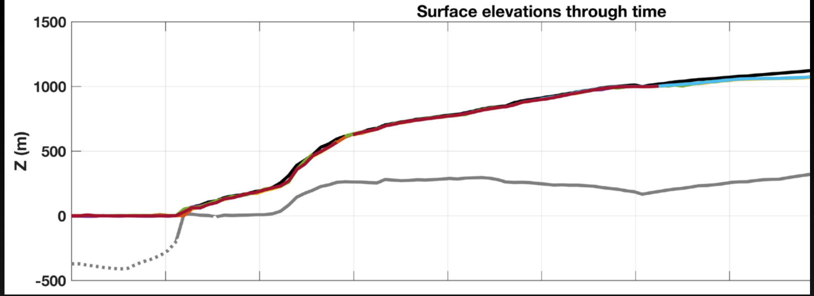
Similar bed profiles along lower 22 km:

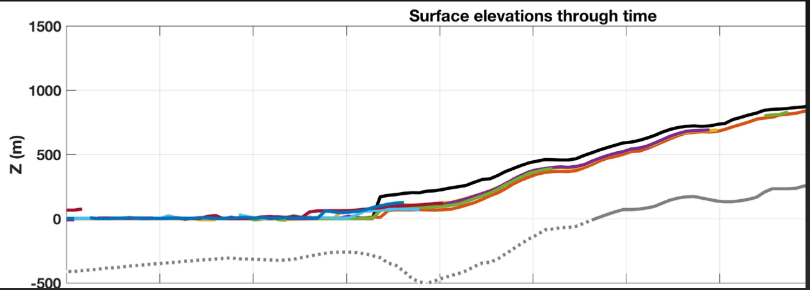
- 22 km (behind calving front): ~400 m ASL
- 3 km: at sea level
- 0 – 3 km: below sea level

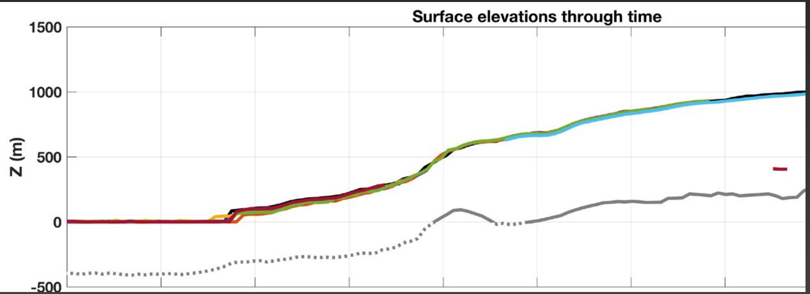
Major Difference:

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



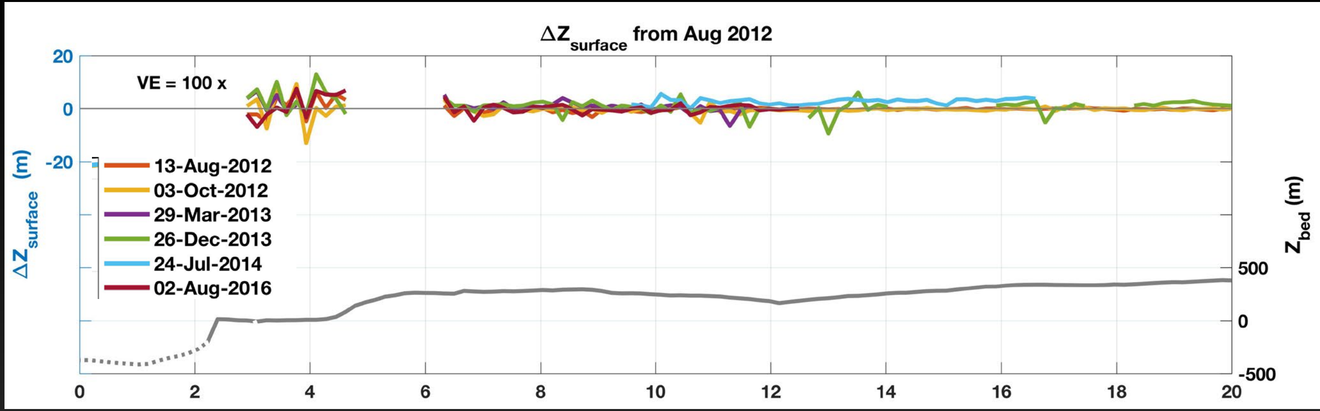






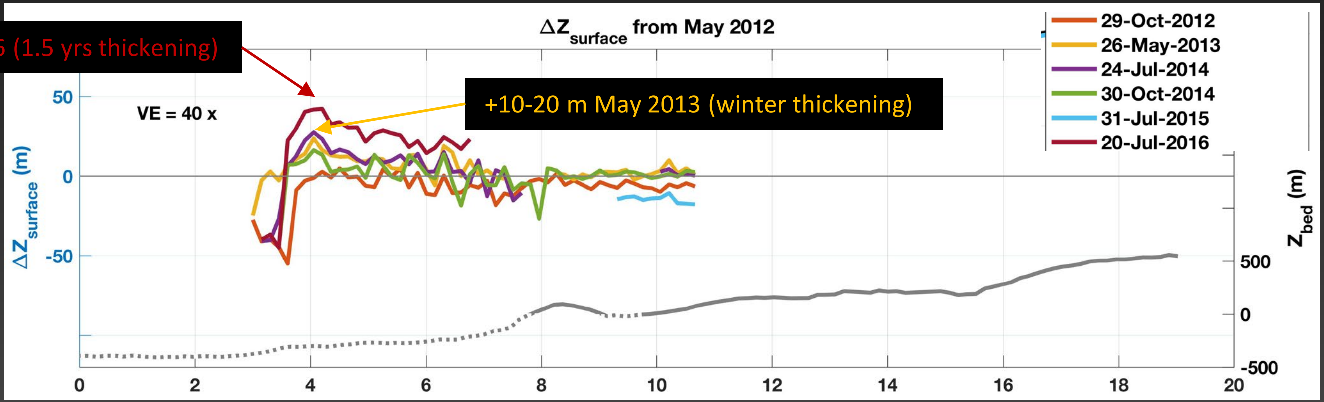
Køge North

- Negligible change in surface elevation

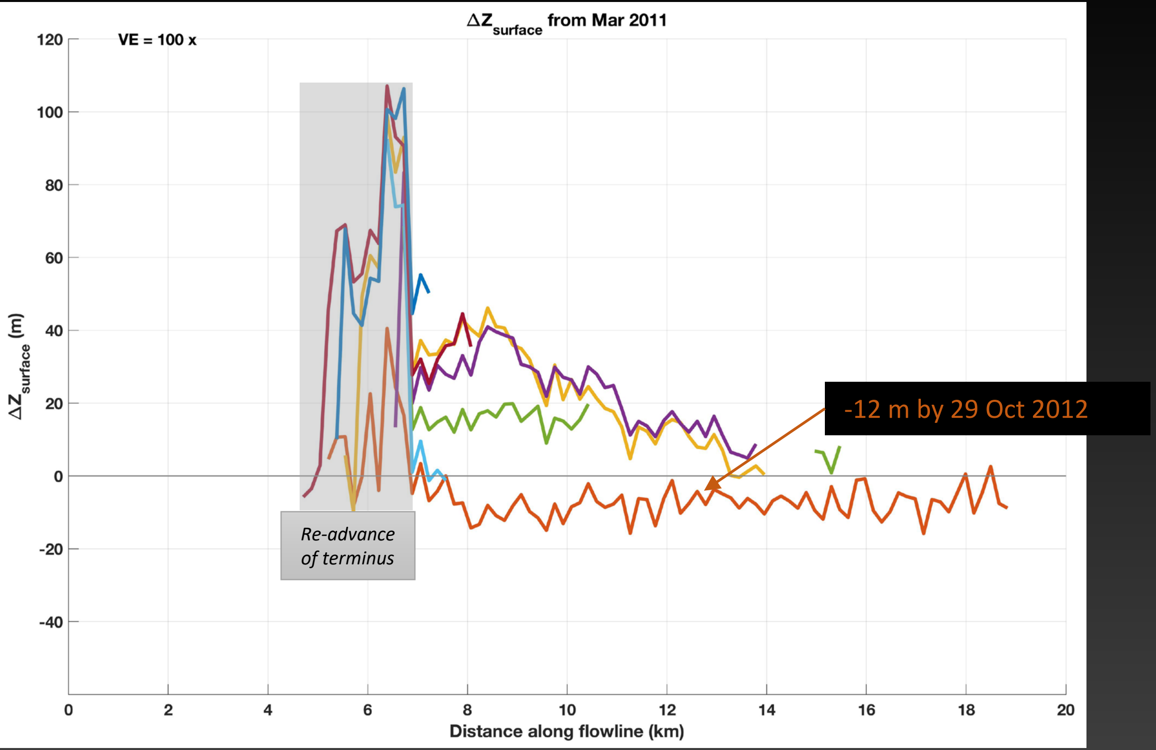


Køge South

- Some dynamic changes
- Smaller in magnitude
- Perhaps seasonal



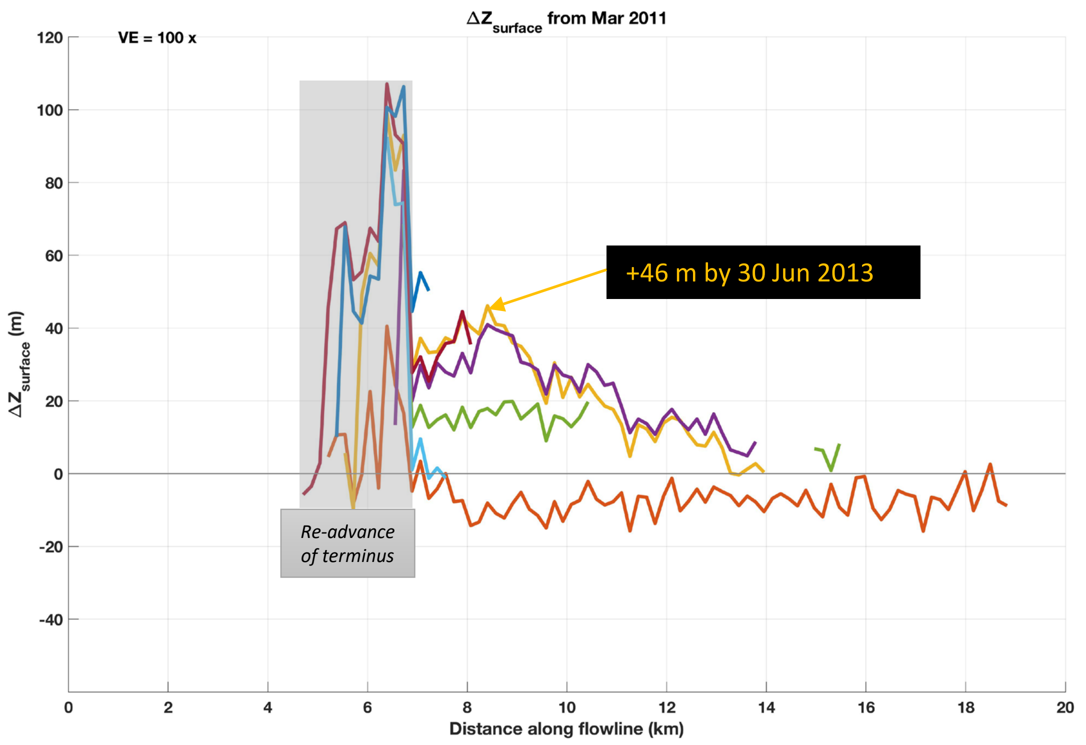
Surface Elevations Over Time



Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012

Surface Elevations Over Time

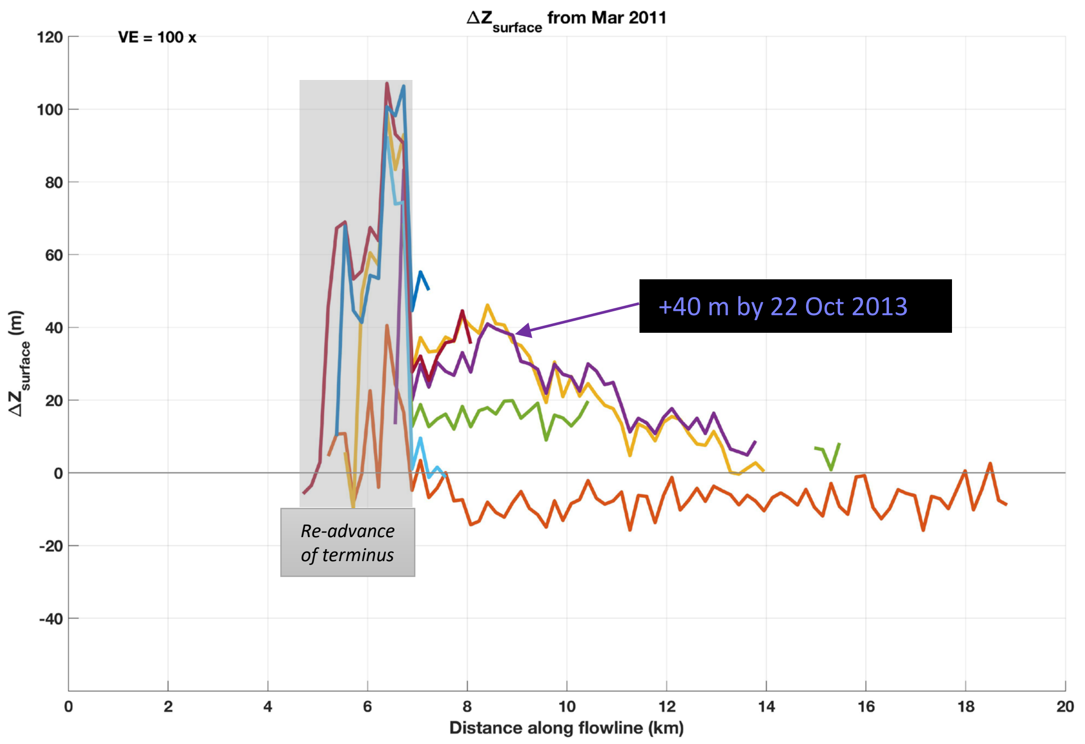


Surface elevation change from Mar 2011

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

Winter Thickening

Surface Elevations Over Time



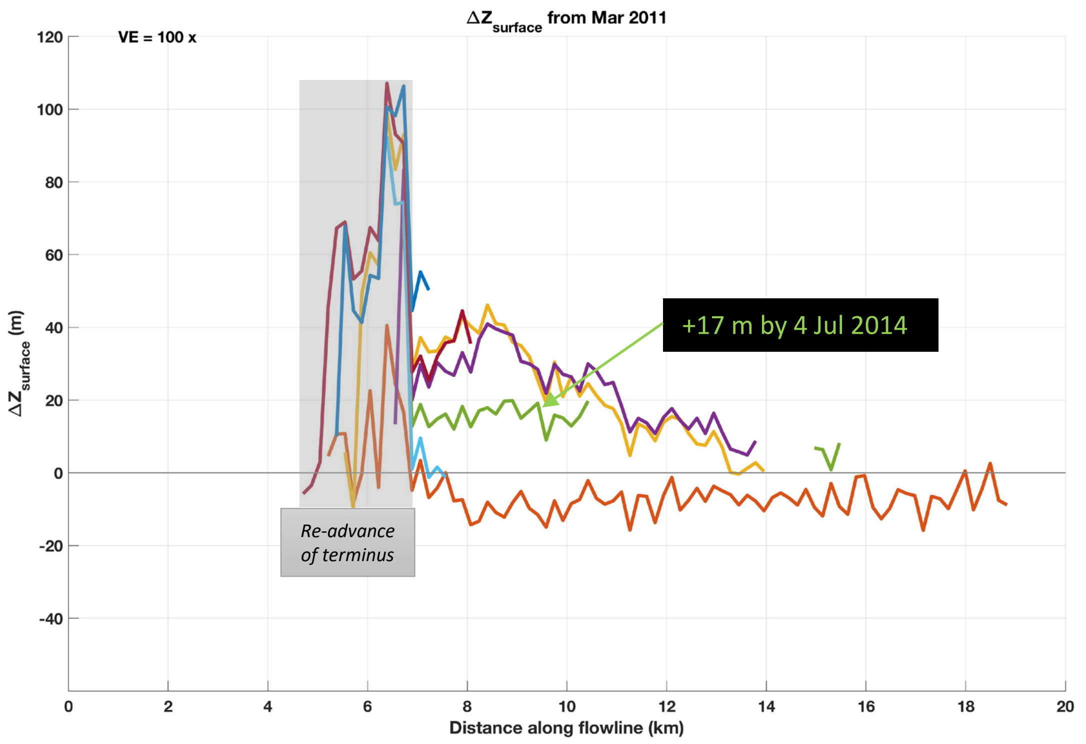
Surface elevation change from Mar 2011

- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013

Winter Thickening

Summer Thinning

Surface Elevations Over Time



Surface elevation change from Mar 2011

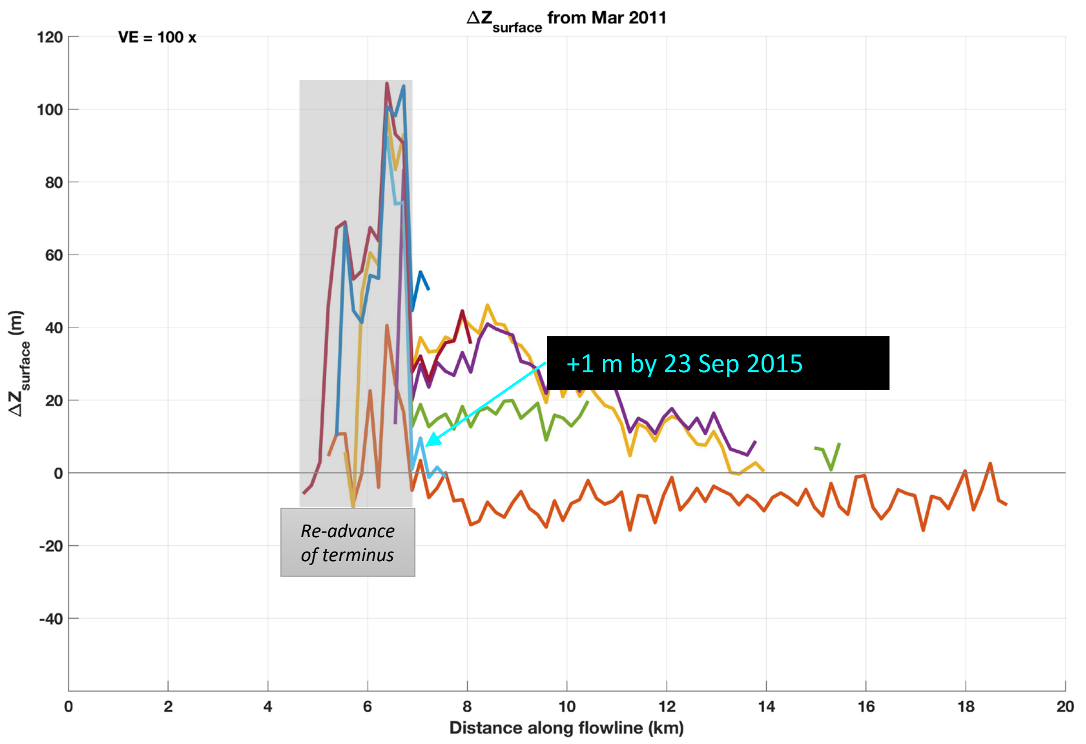
- 1.6 yrs: -12 m 29 Oct 2012
- 2.2 yrs: +46 m 30 June 2013
- 2.6 yrs: +40 m 22 Oct 2013
- 3.3 yrs: +17 m 4 Jul 2014

Winter Thickening

Summer Thinning

Winter Thinning

Surface Elevations Over Time



Surface elevation change from Mar 2011

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- 4.5 yrs: +1 m 23 Sep 2015

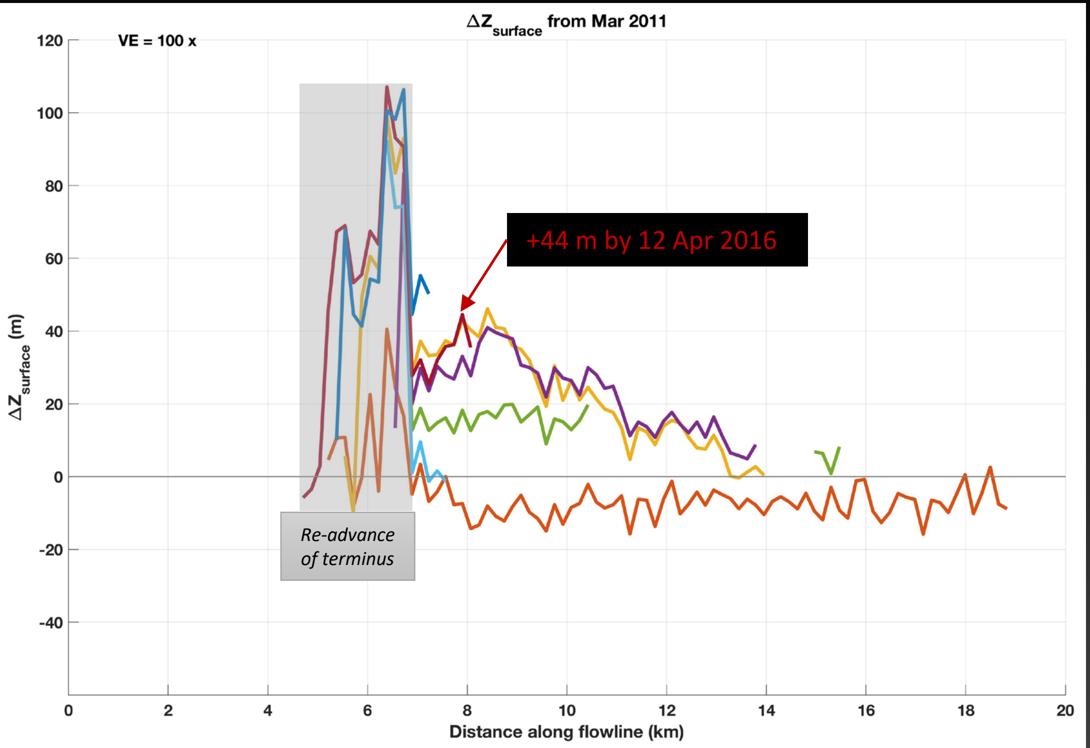
Winter Thickening

Summer Thinning

Winter *Thinning*

Multi-year Thinning

Surface Elevations Over Time



Surface elevation change from Mar 2011

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- 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

Winter Thickening

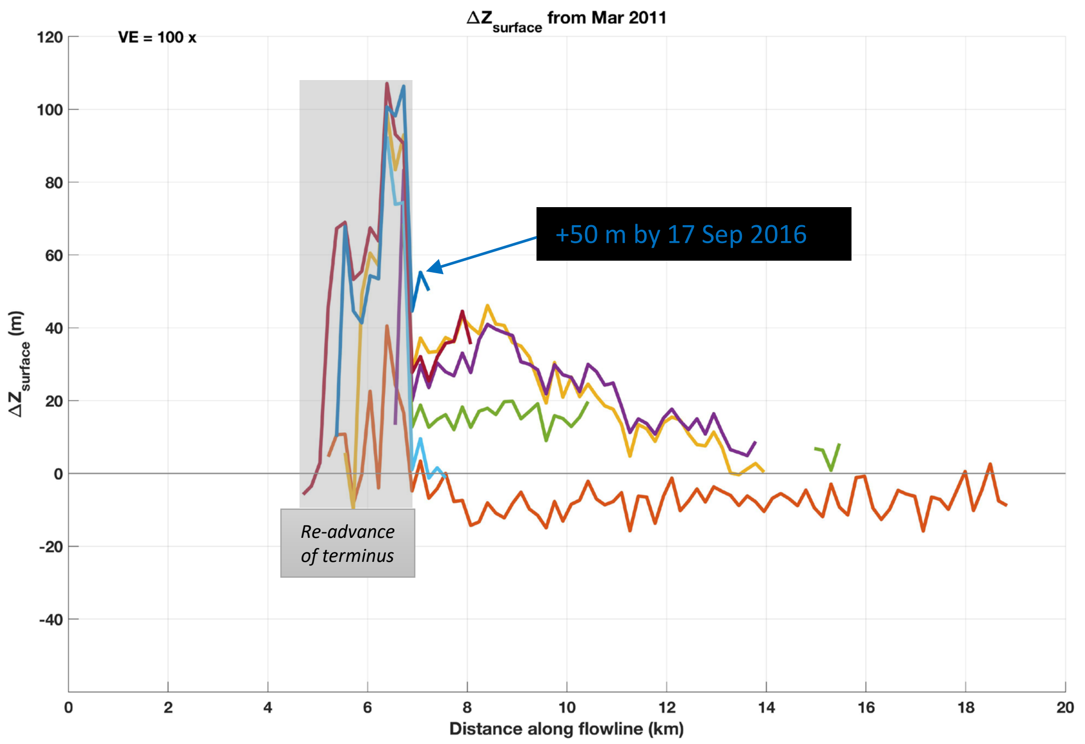
Summer Thinning

Winter *Thinning*

Multi-year Thinning

Winter Thickening

Surface Elevations Over Time



- Multiple large-scale thickening events: Winters 2012 & 2016
- Thinning *winter* 2014
- Thickening summer 2016

Surface elevation change from Mar 2011

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- 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

Winter Thickening
Summer Thinning
Winter *Thinning*
Multi-year Thinning
Winter Thickening
Summer *Thickening*