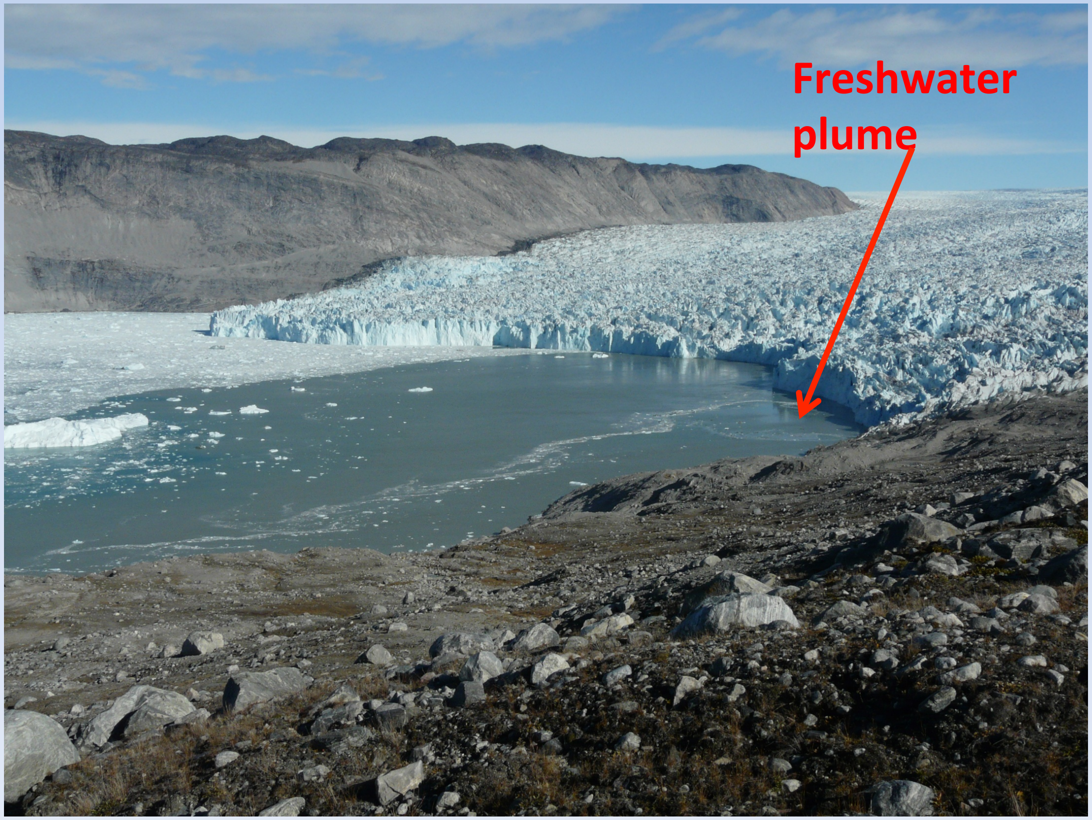
GLACIERS GROUP

Submarine Melting:
Drivers, Measurement, and Importance

Roman J Motyka , *Prof. of Geophysics, Emeritus*



Kangiata Nunaata Sermia (KNS), early Sept. 2010

- Tidewater glaciers account for ~50 % of ice loss in coastal Alaska and in Greenland.

- Submarine melting has been increasingly implicated as a contributing factor in controlling the stability of outlet tidewater glaciers worldwide, summarized in BAMS article

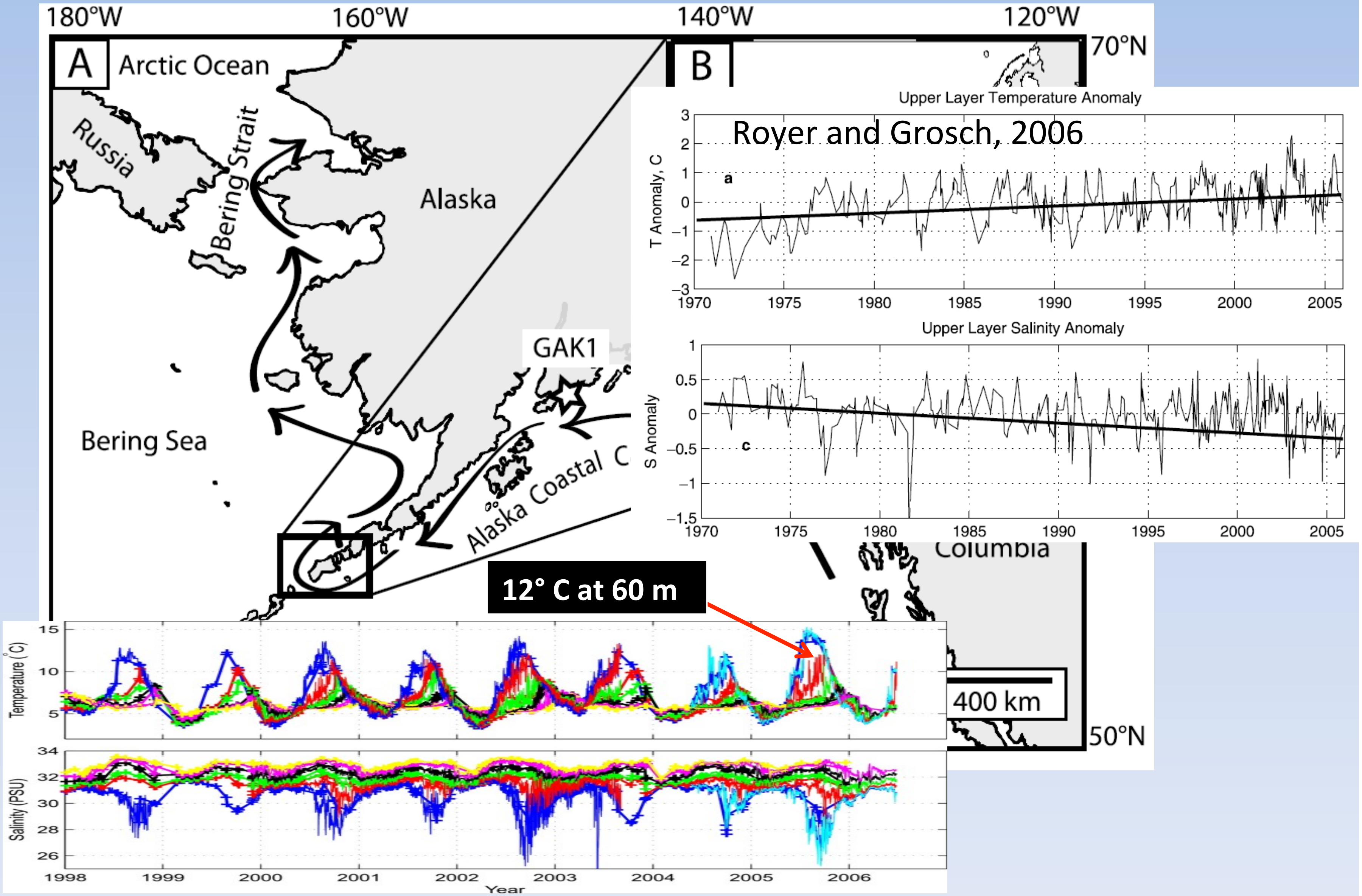
LeConte Glacier, AK 2012

- Just what is the role of submarine melting anyway?

- What do you need to promote submarine melting?

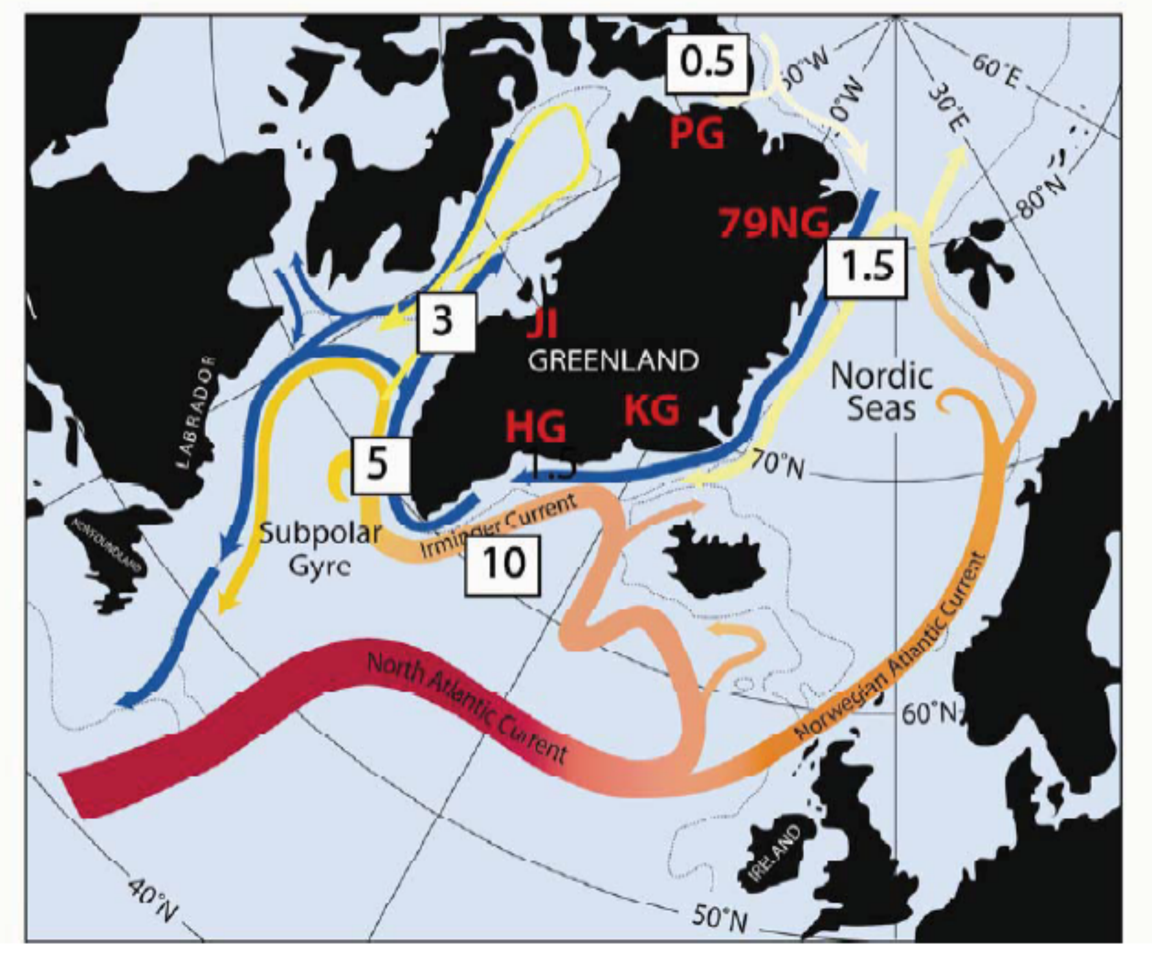
  1. Heat source: oceans and fjords, tremendous reservoirs of thermal energy

  2. A way to get this heat to a marine terminating outlet glacier: convection



Royer and Grosch, 2006

12° C at 60 m

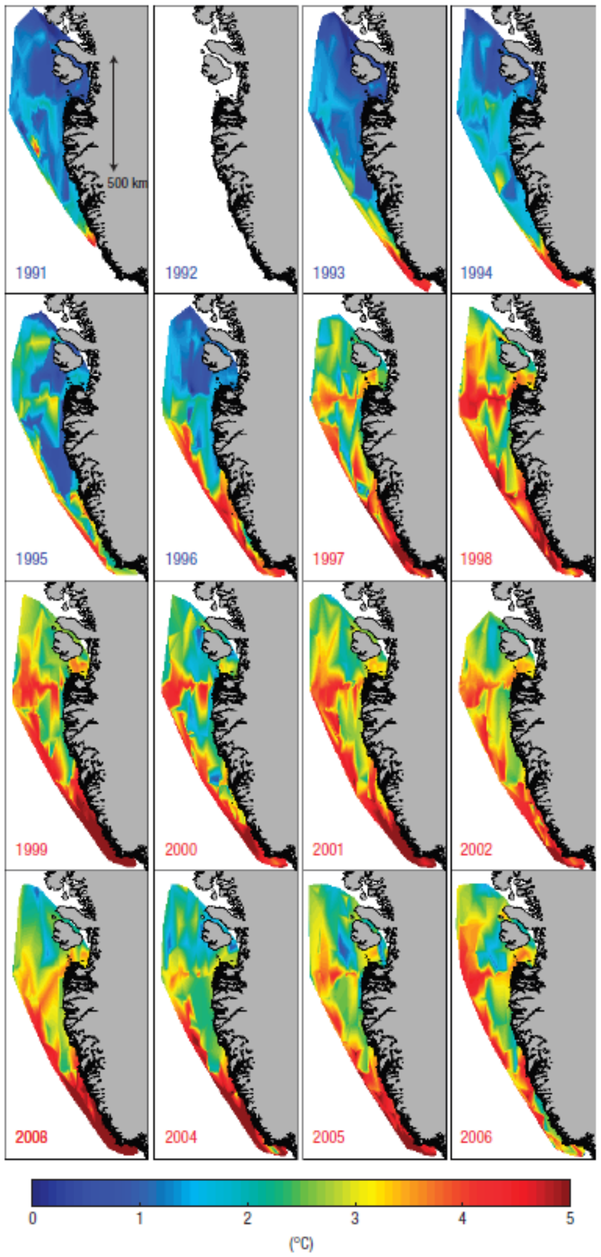


GrIS: 210 marine terminating glaciers

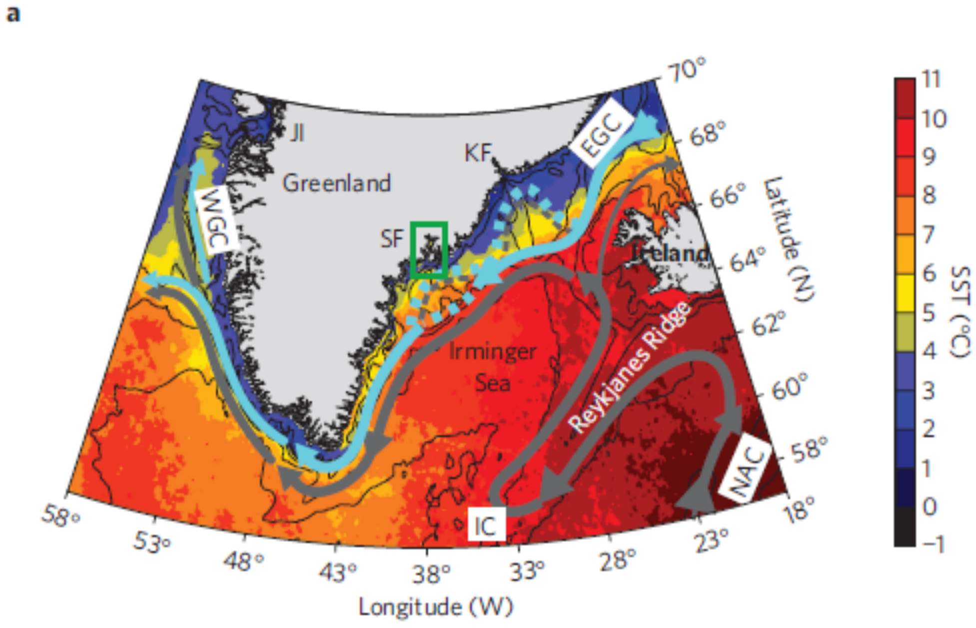
Howat and Eddy, 2011, JG

Numbers indicate the mean temperature of the AW circulating offshore.

Straneo et al, 2012



Holland et al, 2008



Circulation around SE Greenland and Sermilik Fjord (*Straneo et al, 2010*)

GODTHÅBSFJORD:

Deep tide-induced mixing of FW in the outer sill region, a major heat source for the energy balance of the fjord (Mortensen et al. 2011).

Late summer fjord seawater temperatures at ‘grounding line’ depth

Alaska	°C		Greenland	°C
Columbia[1]	**11**		***Helheim***[5]	**4**
Yahtse[2]	**10**		***Godthåbsfjord***[6]	**3.5**
Hubbard[3]	**10**		***Jakobshavn***[5]	**3**
LeConte[4]	**7**		***Store***[7]	**2.8**
			Petermann[8]	**0.2**
			79 NG[5]	**1**

[1] NOAA, unp. data; [2]Bartholomaus et al., submitted; [3]Motyka and Truffer, 2007; [4]Motyka et al., 2003; [5]Straneo et al., 2012; [6]Mortensen et al., 2011; [7]Xu et al., 2012; [8]Johnson et al., 2011

But you need a way to get this heat to an outlet glacier

What drives currents and convection in fjords?

1. **Winds (katabatic, long-shore, other)**
2. **Tides**
3. **Estuary flow, Fresh water flux**

These can bring warm seawater into a fjord.

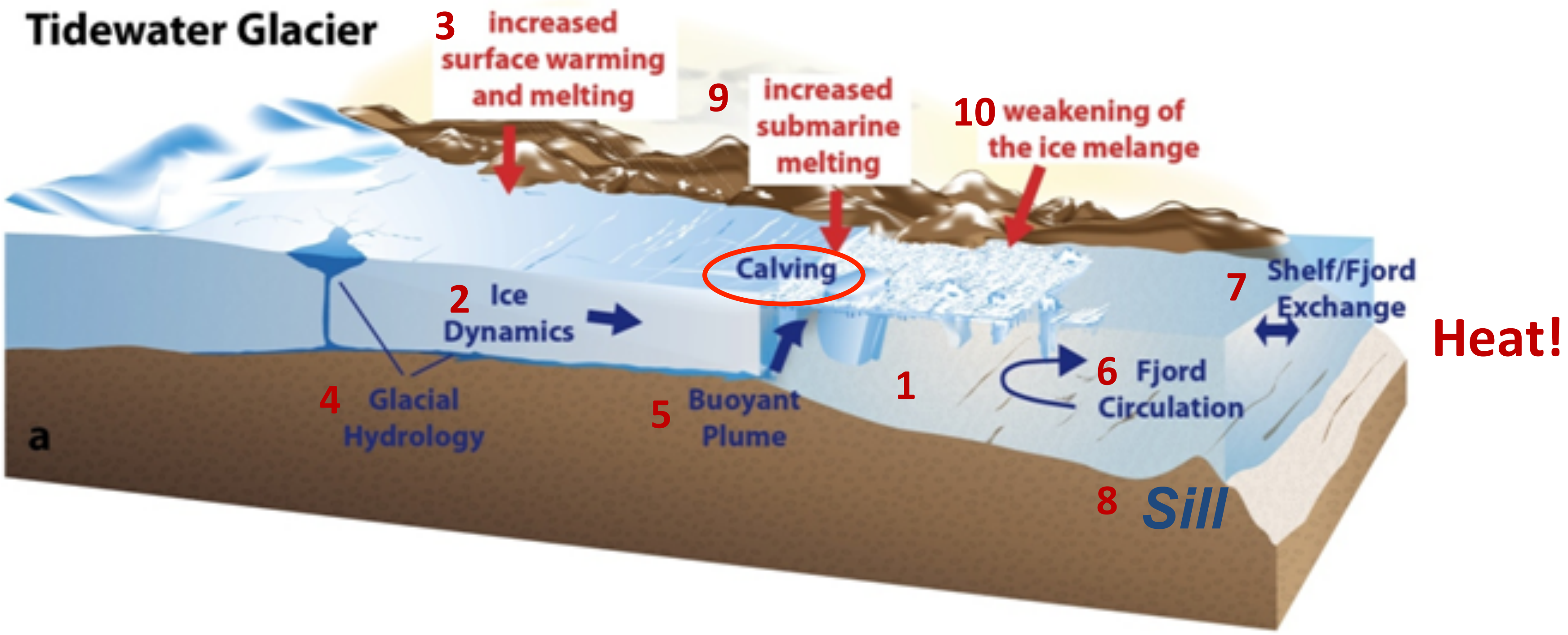
But need to bring thermal energy in contact with glacier tongue or grounded face:

Thermohaline (Antarctica), winter GrIS, maybe northern GrIS

Subglacial discharge

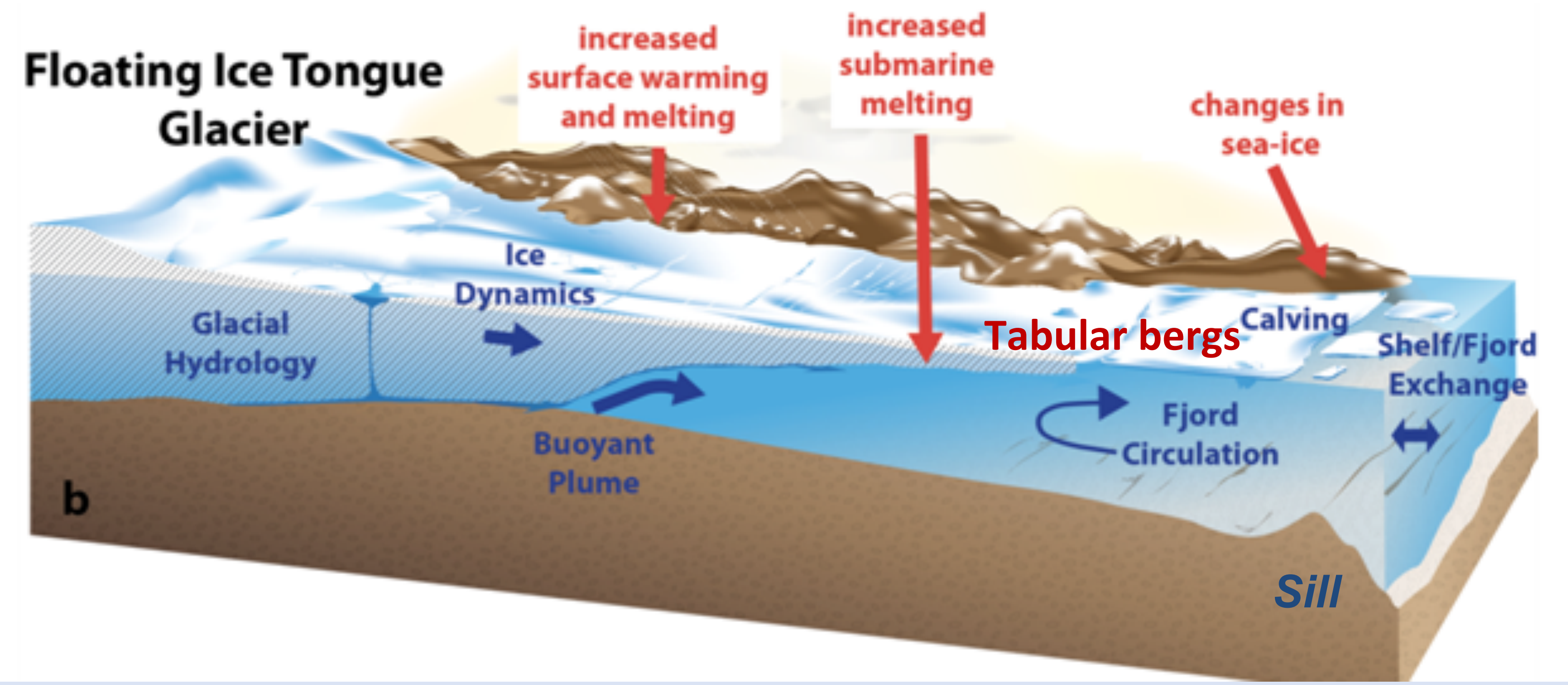
The engine that seasonally drives convection for AK and many GrIS TWGs

AK and many GrIS TWGs



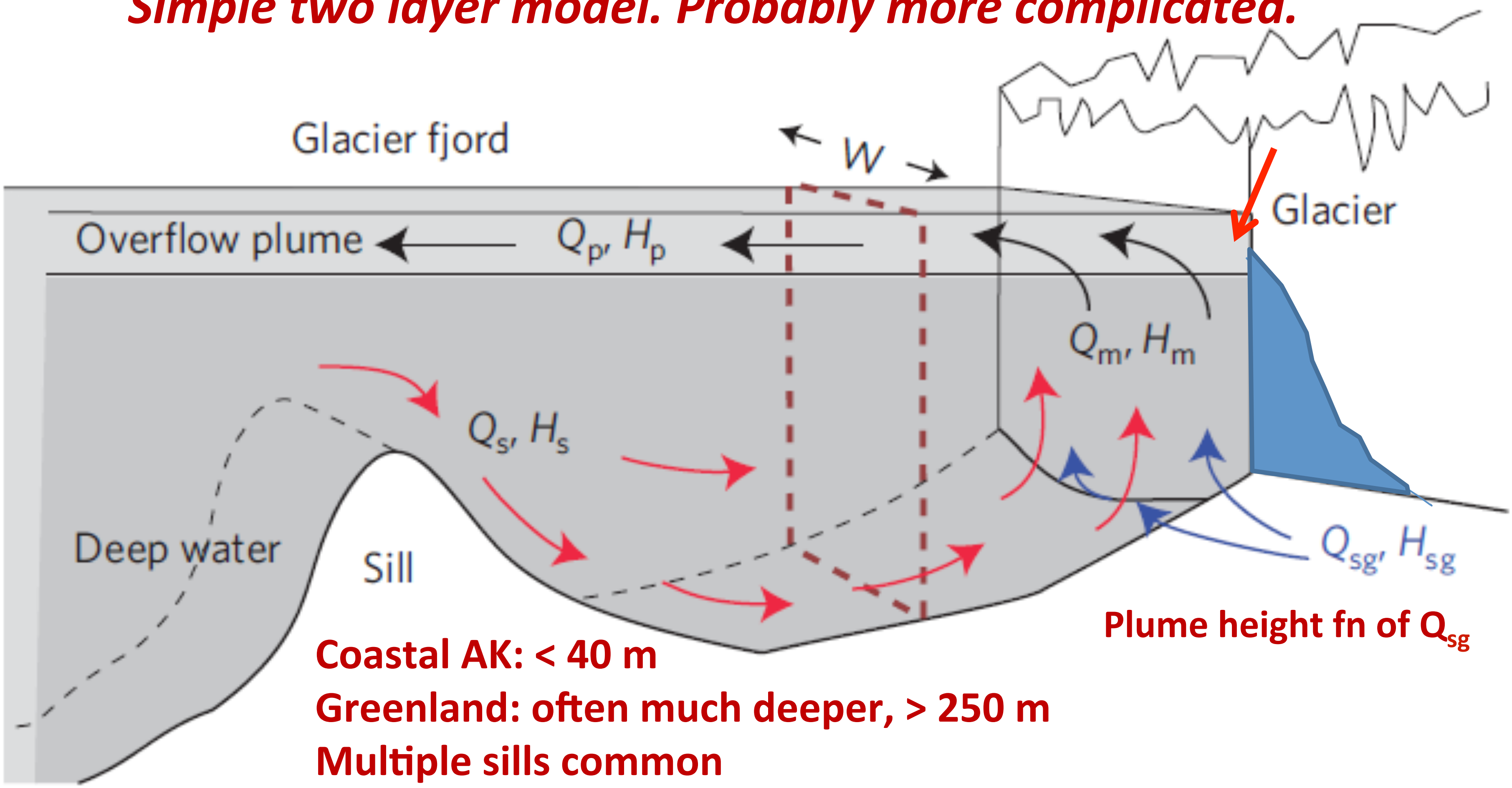
Factors affecting calving and the role of submarine melting

Several major GrIS outlet glaciers



Grounded Glaciers

Simple two layer model. Probably more complicated.



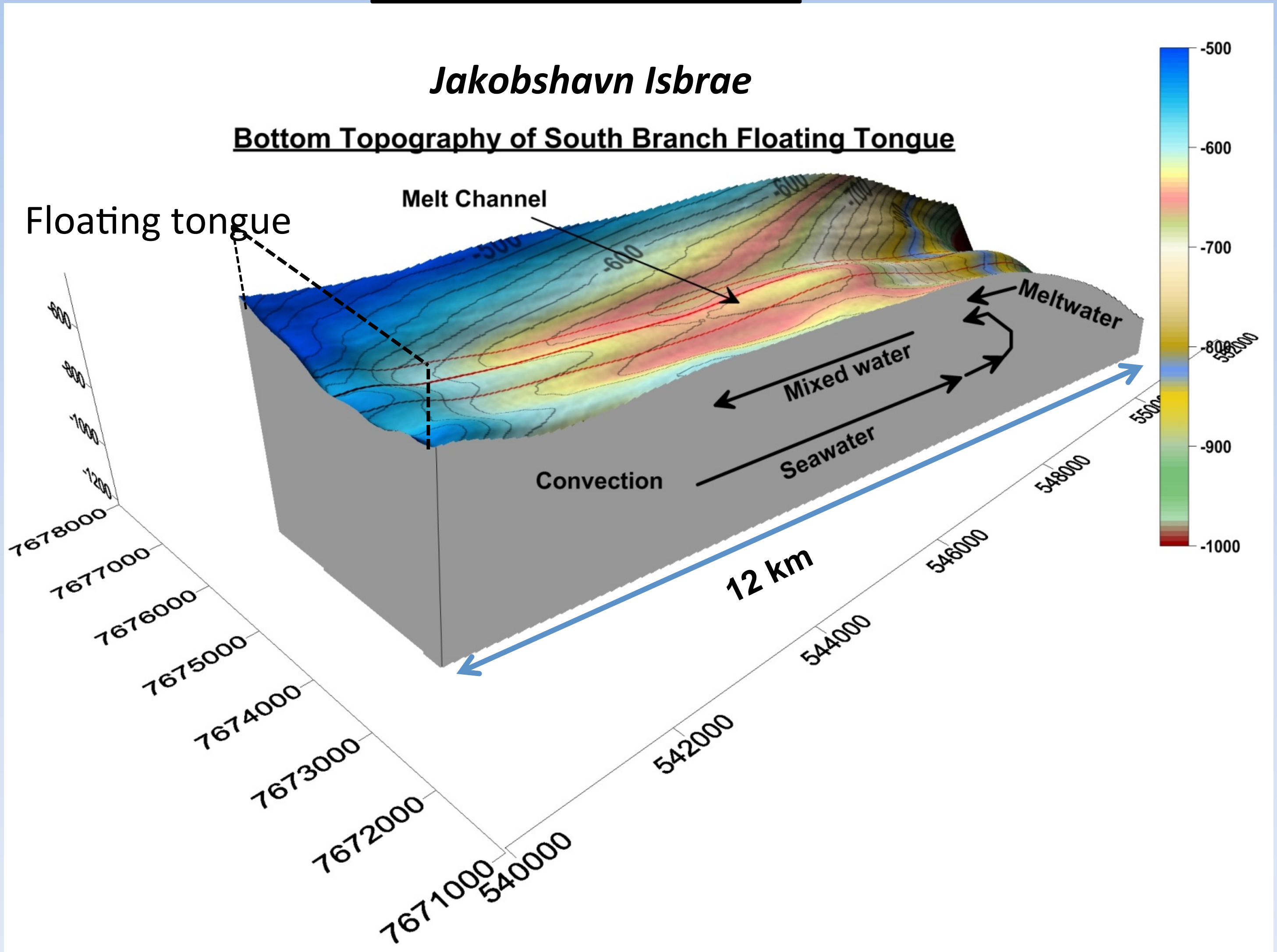
Plume height fn of Q_{sg}

Coastal AK: < 40 m
Greenland: often much deeper, > 250 m
Multiple sills common

Figure 2 | A simplified two-layer model of forced convective flow in a glacier fjord. Deep-water access is guarded by a sill and terminated by a

Rignot et al, 2010

Floating Tongues



Jakobshavn Isbrae

Bottom Topography of South Branch Floating Tongue

Motyka et al., 2011

- **Complications: Proglacial fjord dynamics are a complex function of freshwater influx, fjord geometry, Coriolis effects, calving, and ice mélanges.**

1. **Sills: barriers to flow or at least modulate flow and affects access to 'warm' ocean water.**
2. **Ice mélanges: how do they affect convection?**
3. **Deep iceberg keels sets up tortuosity; melting cools waters?**

How do you measure it?

- Obtaining accurate measurements of proglacial fjord properties, much less submarine melting, is notoriously difficult given the usually hostile environments and remote regions where such measurements need to be made.

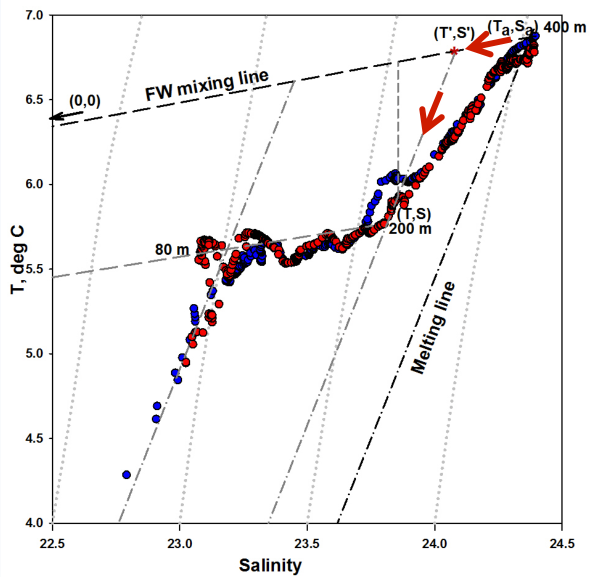
- Several tactics have been employed and/or proposed for deriving estimates of submarine melting.

Gade melt line and T & S analysis

- The first studies on glacier melt: Matthews and Quinlin (1975), Griesman (1979): Muir Glacier, Glacier Bay, AK

- Melt line analysis,Gade (1979), Jenkins (1999): Gade slope, and T & S diagrams. Used extensively in recent literature to interpret water column characteristics, meltwater content, and water types in TWG fjords

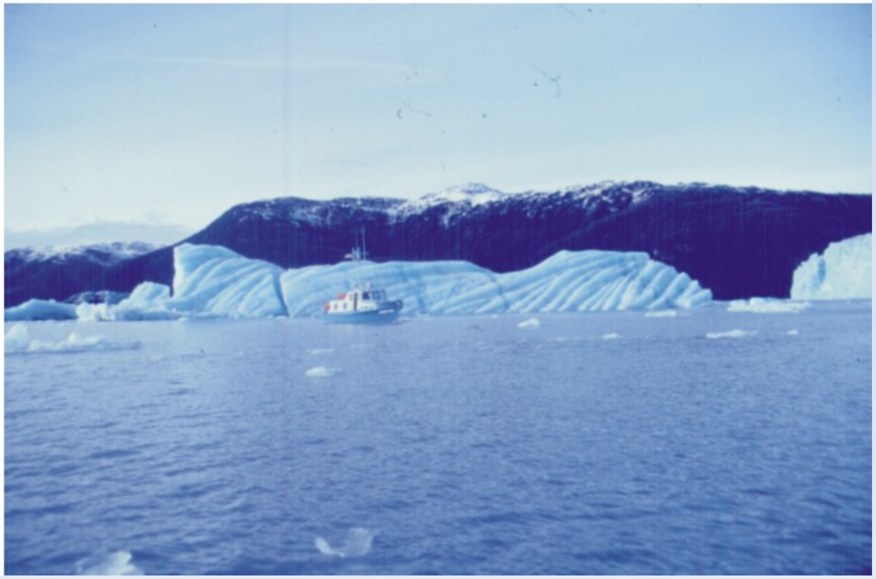
- Limitations of this approach: no information on fluxes or melting rates.



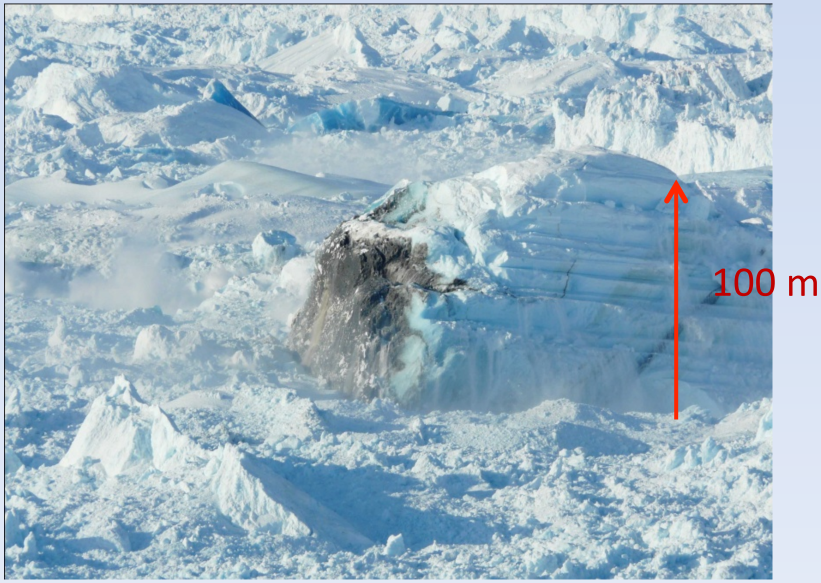
Columbia

Qualitative observations, melting important at least seasonally:

- **Iceberg volume, Warren et al (1995) Glaciar San Rafael, Chile; Motyka et al (2003) LeConte Glacier, AK.**
- **Flutes on calved icebergs**



LeConte Glacier



Jakobshavn Isbrae

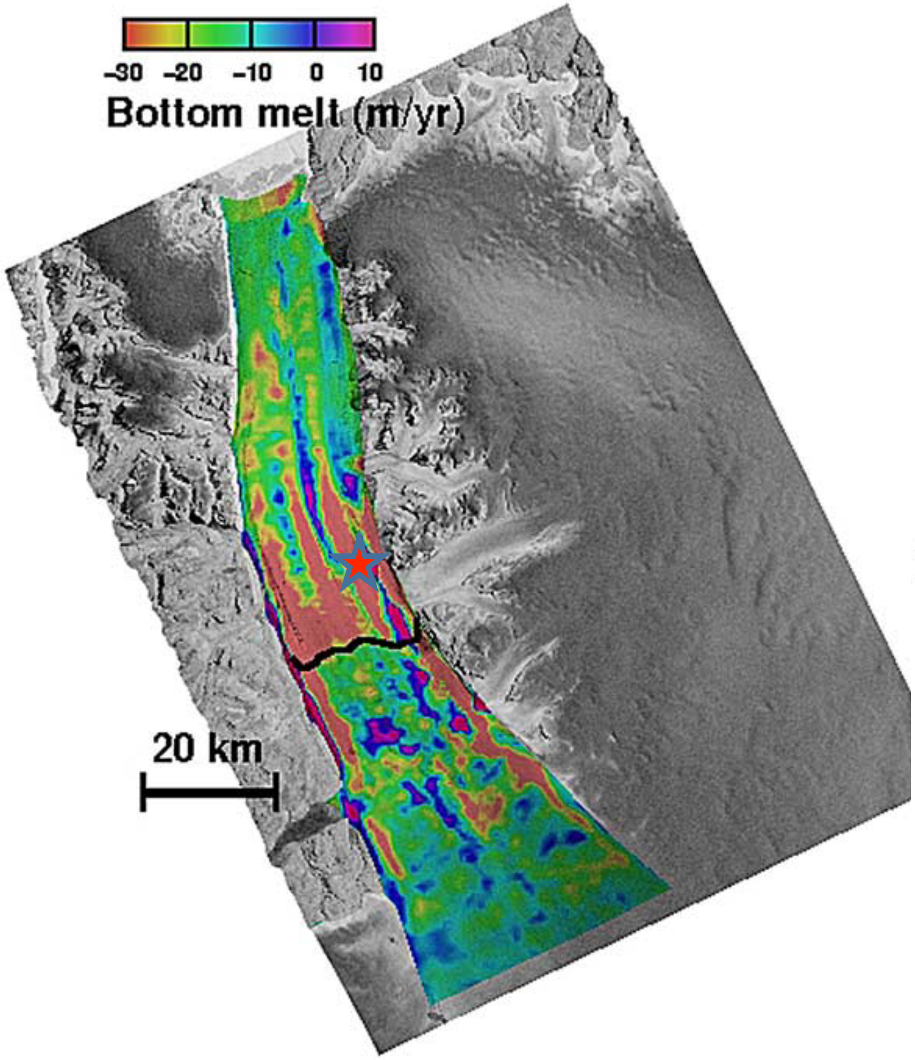
For outlet glaciers with floating tongues methods include:

1. **Flux divergence and thinning of a floating tongue: analysis of high quality DEMs and/or ATM data, velocity fields of a floating tongue** *(e.g., Petermann (Rignot and Steffan (2008), Jakobshavn (Motyka et al, 2011), GrIS (Enderlin and Howat, 2013).*

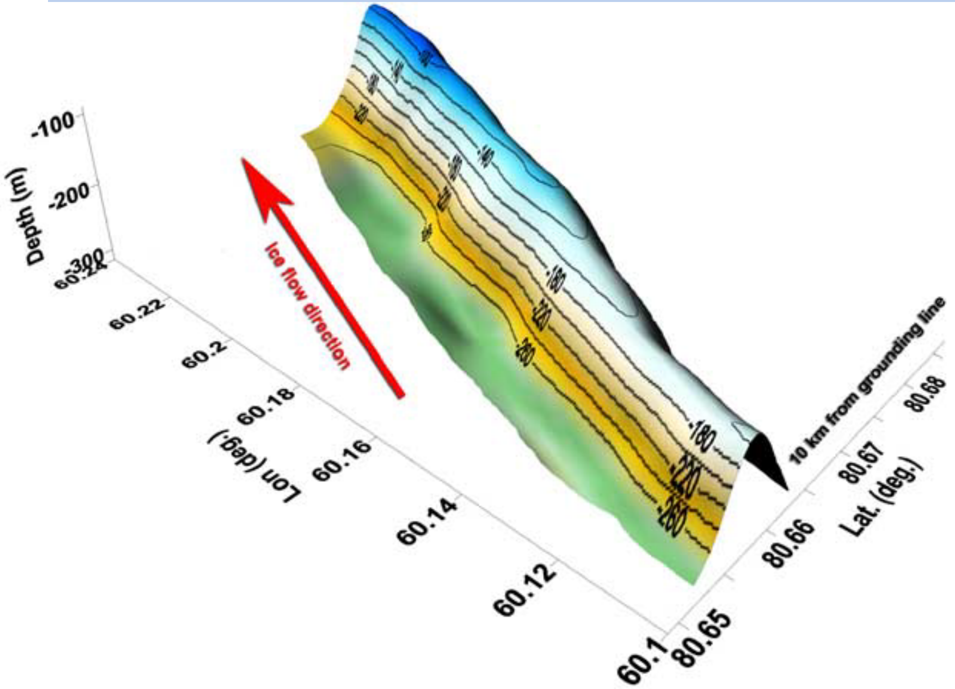
2. **Radio echo sounding techniques for bottom topography** *(e.g., Petermann Glacier)***.**

3. **Instrumenting boreholes drilled through a floating tongue** *(PIG, other examples?).*

4. **Deployment of autonomous survey vehicles** (e.g. *Pine Isl., Jenkins et al., 2010)*



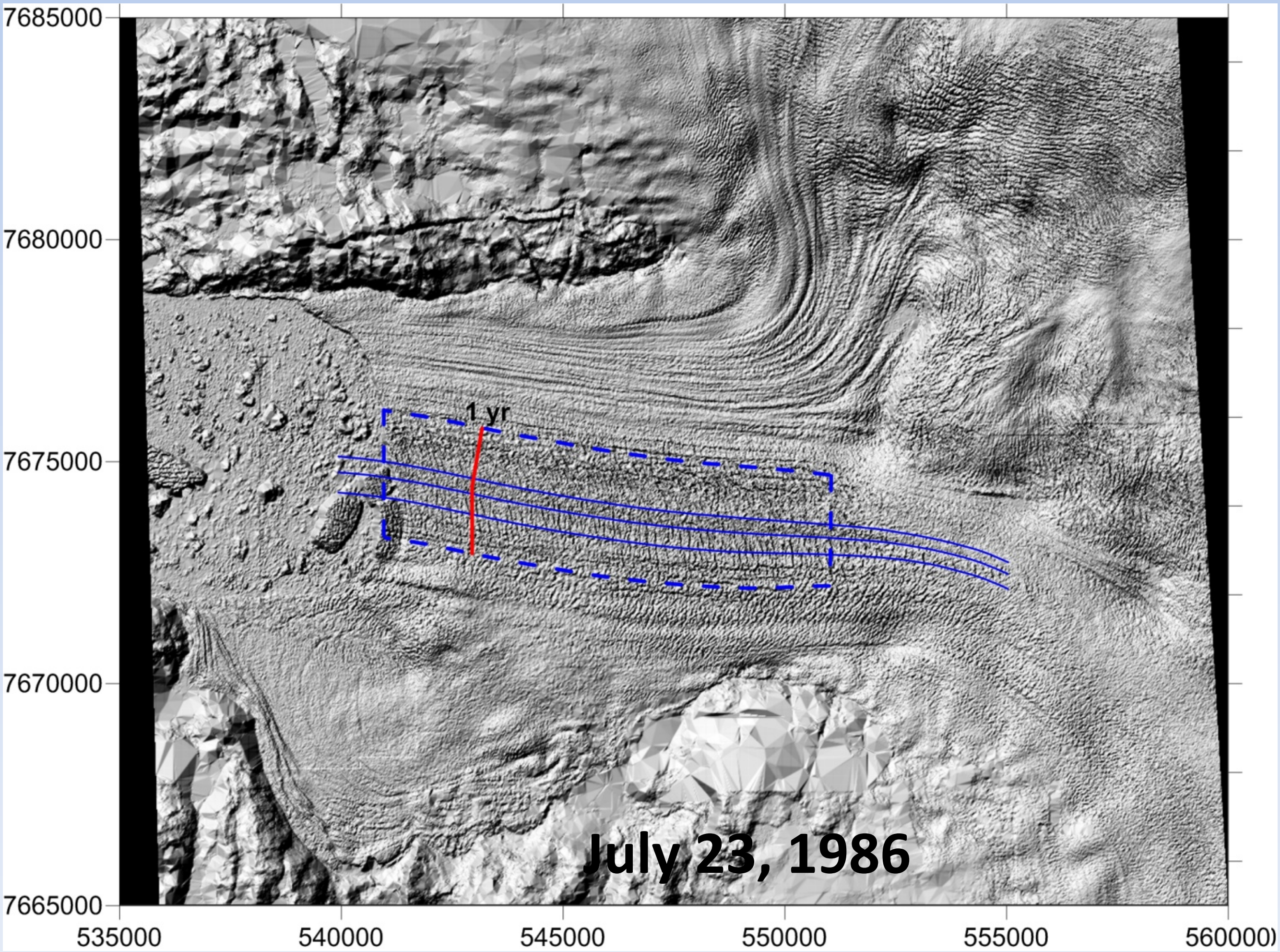
Petermann Glacier steady-state bottom melt rate in m/yr calculated on a 600-m grid from the divergence in ice flux. (Rignot & Steffan, 2008)



Three-dimensional view of the sub-ice-shelf melt channel

$$\langle \dot{m} \rangle = \frac{1}{T}\left(h_{gz} - h(x) - \int_0^x \left(h\,(\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy})/u \right) dx \right)$$

Ave melt rate = change in thickness - divergence



July 23, 1986

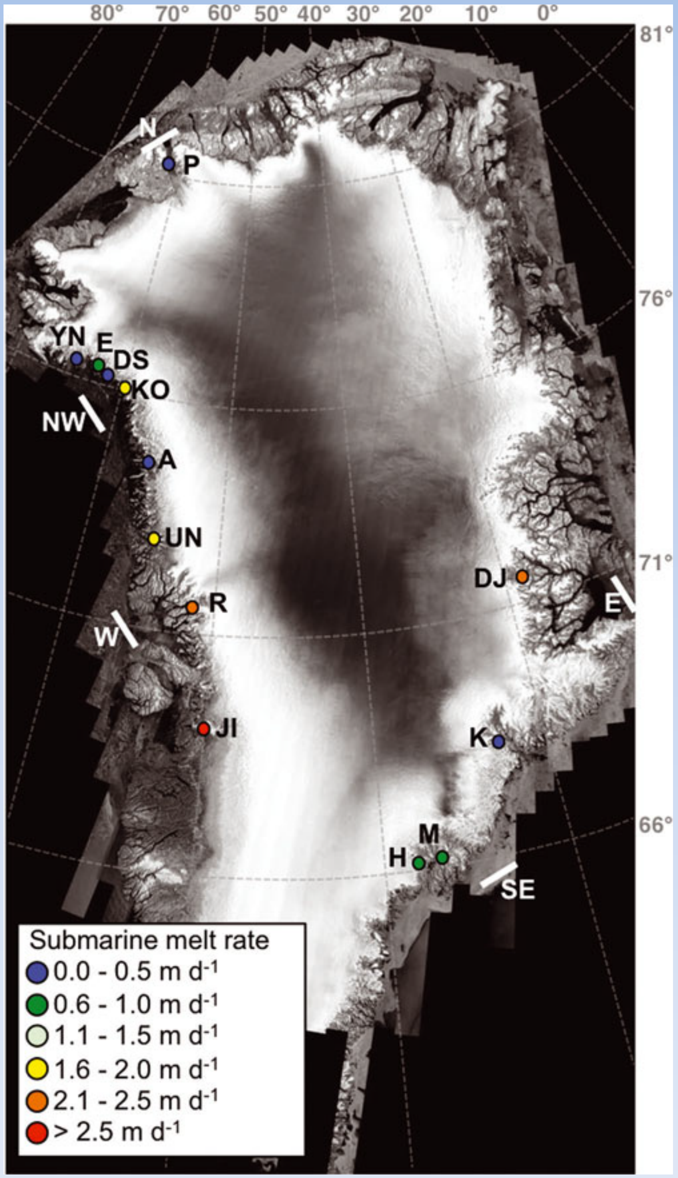
Jakobshavn Isbrae
Annual melt rate for 24-July-1985 to 23-Jul-1986

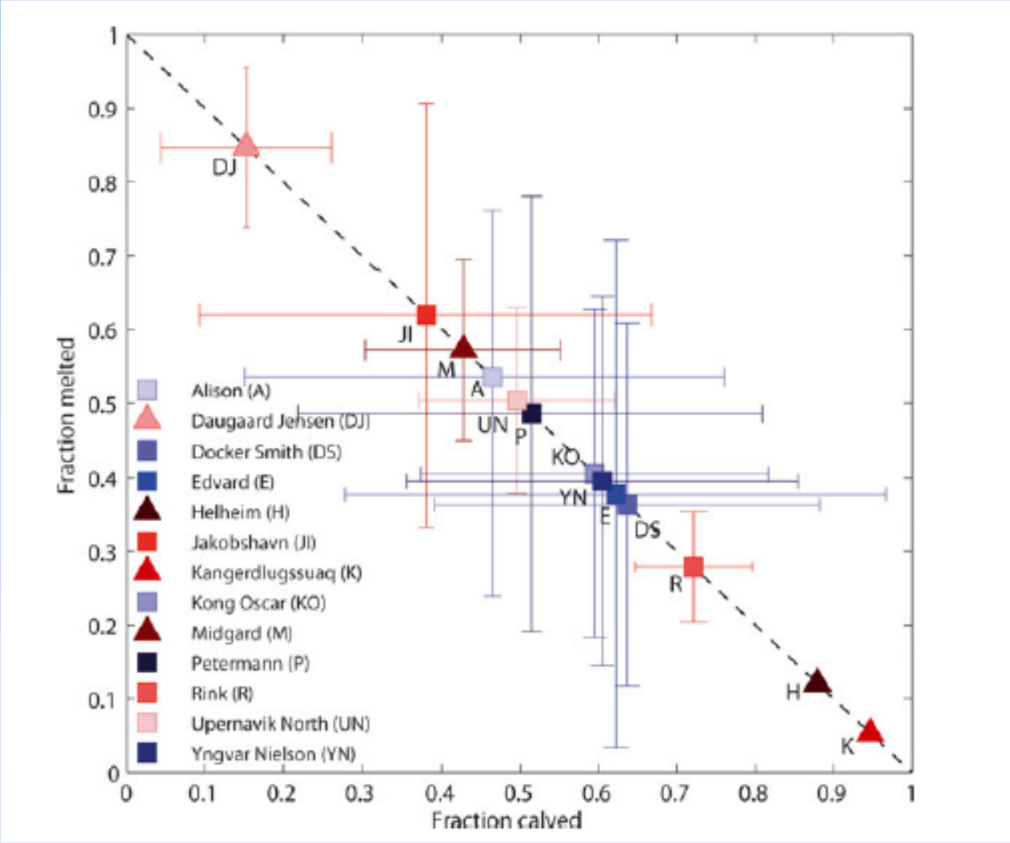
	“South Branch”
Average melt rate, m a^{-1}	**233 ± 22**
Ablation, m a^{-1}	**4.0 ± 0.4**
Submarine melt rate, m a^{-1}	**229 ± 22**
Average melt rate, m d^{-1}	**0.63 ± 0.06**

Integrates spatial and temporal variations

Floating tongue ice loss %

Calving	**70**
Submarine melting	**29**
Surface ablation	**1**





ENDERLIN & HOWAT, 2013

Grounded Tidewater Glaciers

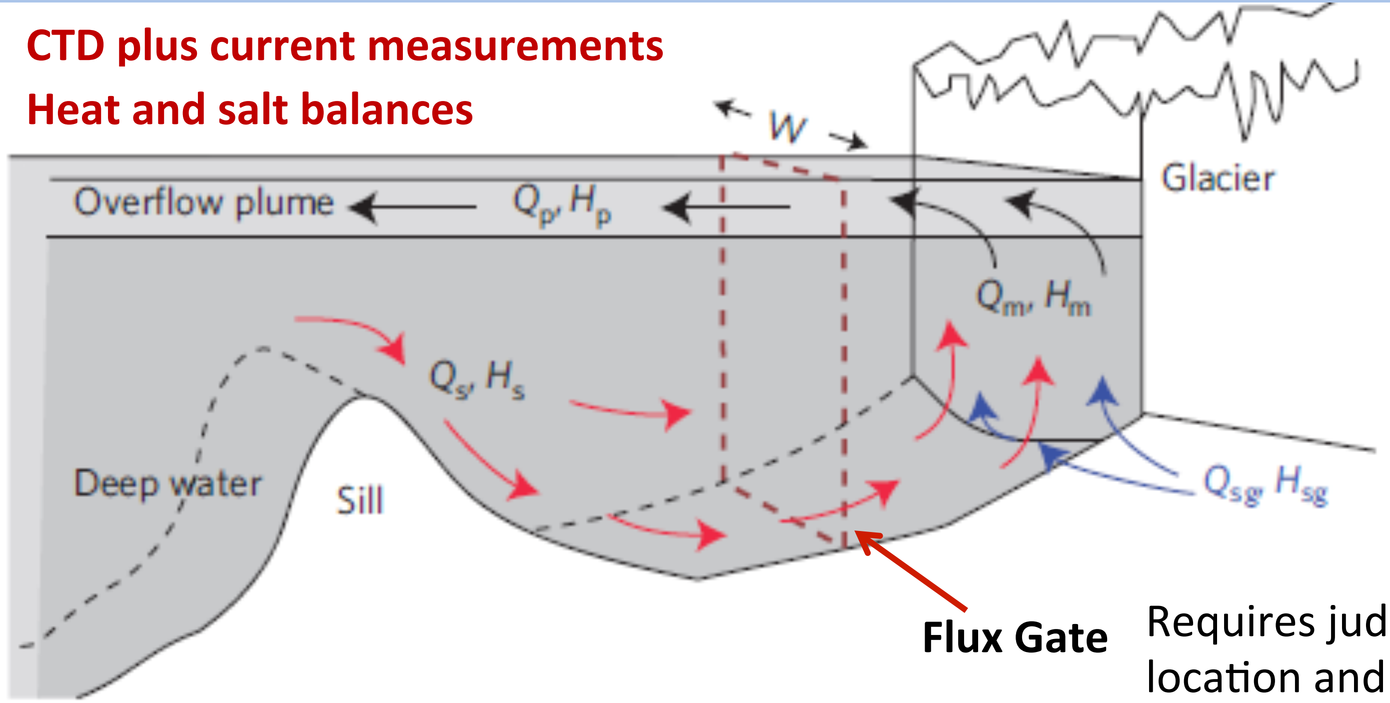
- **Measurements are sparse and have been mainly derived from detailed but short-term hydrographic surveys over a "fluxgate" near calving termini** *(e.g., Columbia and LeConte Glaciers in Alaska; Eqip Sermia, Kangilerngata Sermia, and Sermeq Kujatdleq in central West Greenland), Store Gl W GrIS, Helheim Glacier, Semilik Fjord SE GrIS)*.

- **Because of the brevity and timing of these studies, they only provide snapshots that capture seasonal effects late in the melt season.**

- **Multibeam bathymetry?**

- **So far, no seasonal or annual observations near calving termini, although several have been proposed.**

CTD plus current measurements
Heat and salt balances



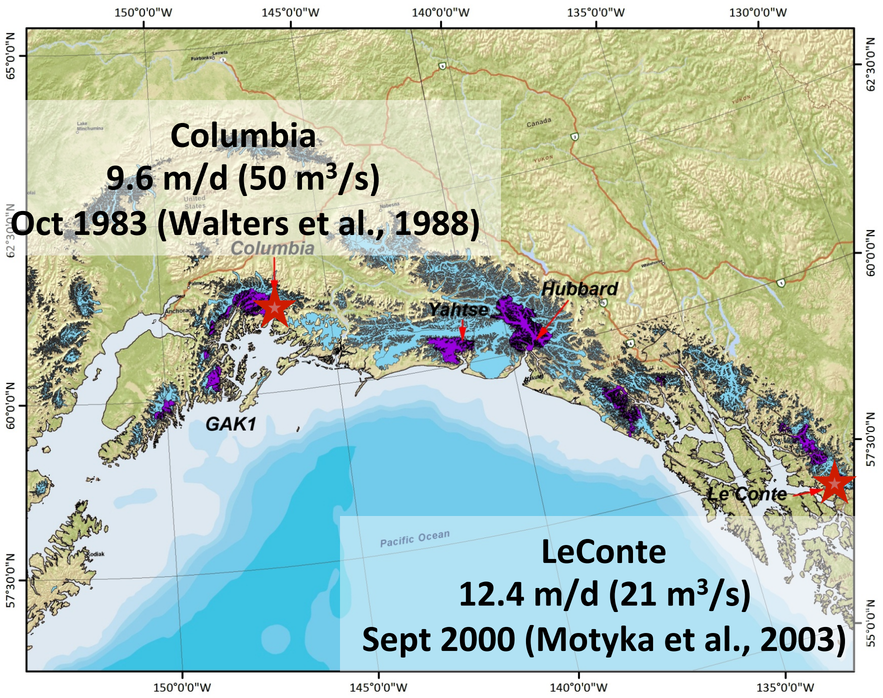
Flux Gate

Requires judicious location and sampling interval

$$H_m = \Delta H = H_s - H_p$$

$$Q_m = H_m/L$$

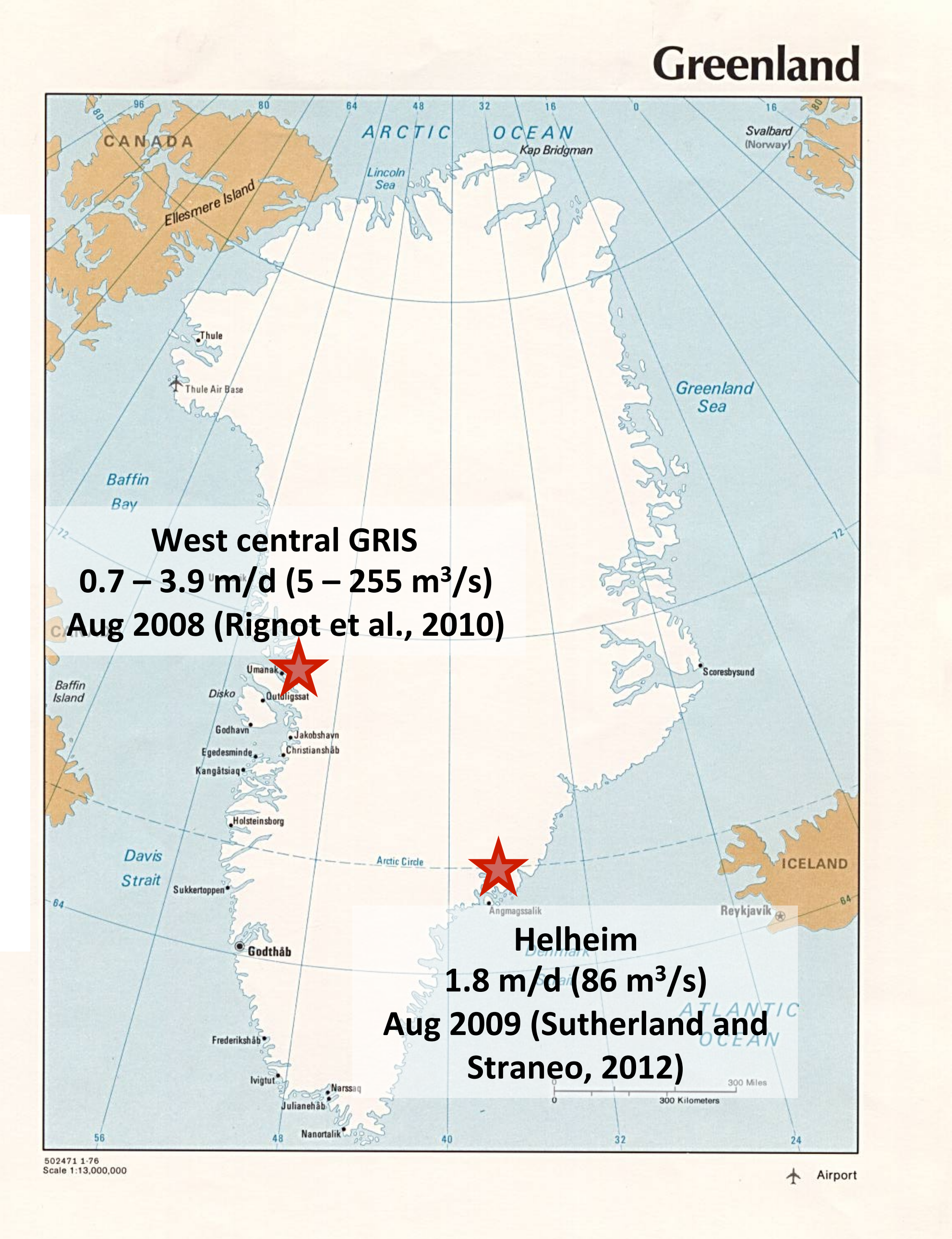
$$H_s = \rho_s Q_s C_s T_s \qquad X_{sp} = S_p/S_s$$



Columbia
9.6 m/d (50 m³/s)
Oct 1983 (Walters et al., 1988)

LeConte
12.4 m/d (21 m³/s)
Sept 2000 (Motyka et al., 2003)

Coastal Alaska



West central GRIS
0.7 – 3.9 m/d (5 – 255 m³/s)
Aug 2008 (Rignot et al., 2010)

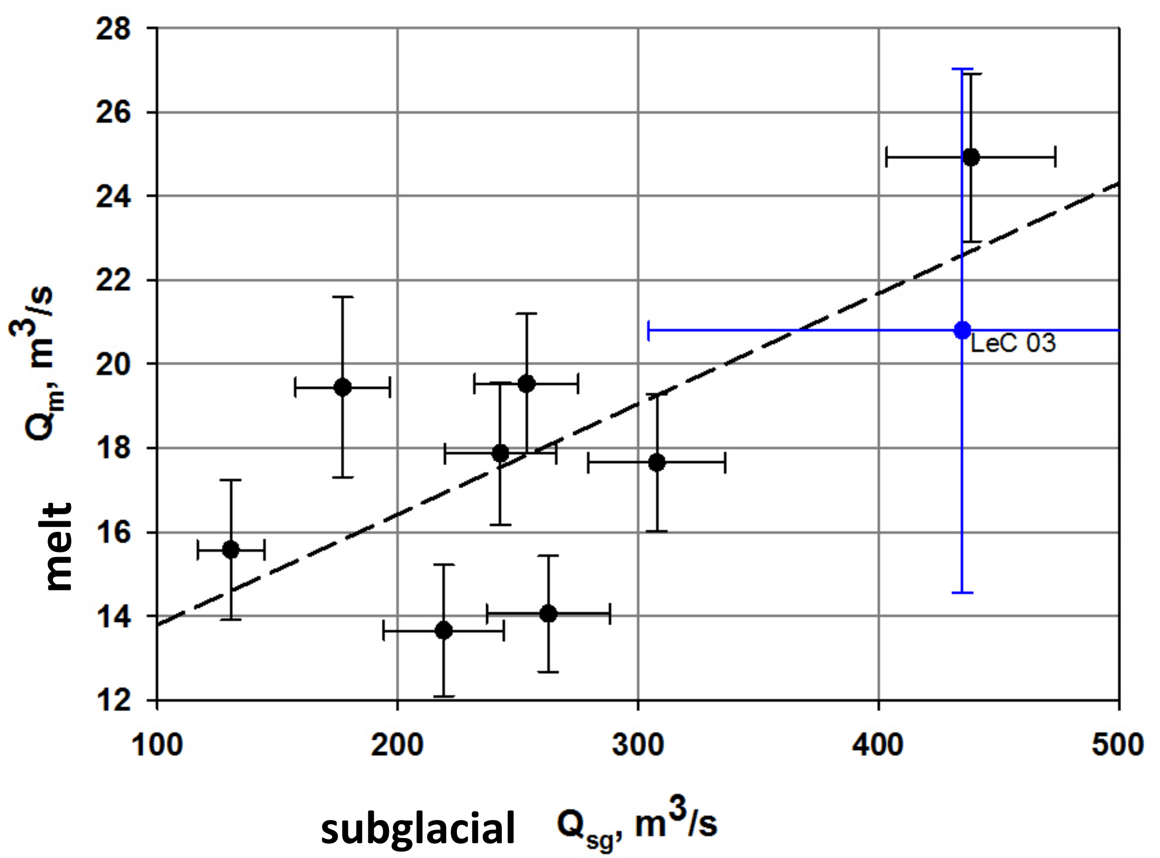
Helheim
1.8 m/d (86 m³/s)
Aug 2009 (Sutherland and Straneo, 2012)

Frontal ablation: ~ 50% melting

LeConte Glacier Sept. 2012

Q_m= submarine melting, m^3/s.

Transect ID, date, time	Q_m, m^3/s	m/d, i. e.	% unc
T3, 9/7,14	15.6	11.3	10.7
T5, 9/8, 9	13.7	9.1	11.4
T6, 9/8, 11	17.6	11.9	9.3
T7, 9/8, 12.5	14.1	9.5	9.8
T8, 9/8, 14.5	19.5	14.1	8.5
T9, 9/9, 9	19.4	13.2	11.0
T10, 9/9, 11.5	17.9	12.5	9.5
T11, 9/10, 13	24.9	16.8	8.0


28
26
24
22
20
18
16
14
12
100
200
300
400
500
LeC 03
melt
Q_m, m^3/s
subglacial
Q_{sg}, m^3/s

Modeling

Thermal forcing & subglacial discharge vs. melt rates

Adrian Jenkins, 2011, Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers, *J. Phys. Oceanography* 10.1175/JPO-D-11-03.1

Yun Xu et al., 2012, Numerical experiments on subaqueous melting of Greenland tidewater glaciers in response to ocean warming and enhanced subglacial runoff, *Annals of Glaciology*, 53(60) 2012 doi: 10.3189/2012AoG60A139**.**

Lastly, just how important is submarine melting anyway?

I guess that's for us to figure out!

1. Floating tongue: important for mass balance of glacier and has the potential for destabilizing glacier terminus
   a. if thermal forcing increases
   b. and/or subglacial drainage increases.

2. Grounded glaciers: at least seasonally important for mass balance and for controlling location of terminus position. Does it lead to destabilization? Probably part of a complex series of mechanisms.

3. For either grounded or floating tongue glaciers, a warming climate will increase surface ablation, thereby increasing subglacial discharge and submarine melting, even if ocean T stays same.

Floating Tongues

Jakobshavn Isbræ

Echelmeyer, 1986

15 km retreat: 1998 - 2007

Fahnestock, 2007

Thomas et al., 2003
Thomas, 2004
Holland et al., 2008
Motyka et al., 2011
Enderlin and Howat, 2013

Grounded Glaciers

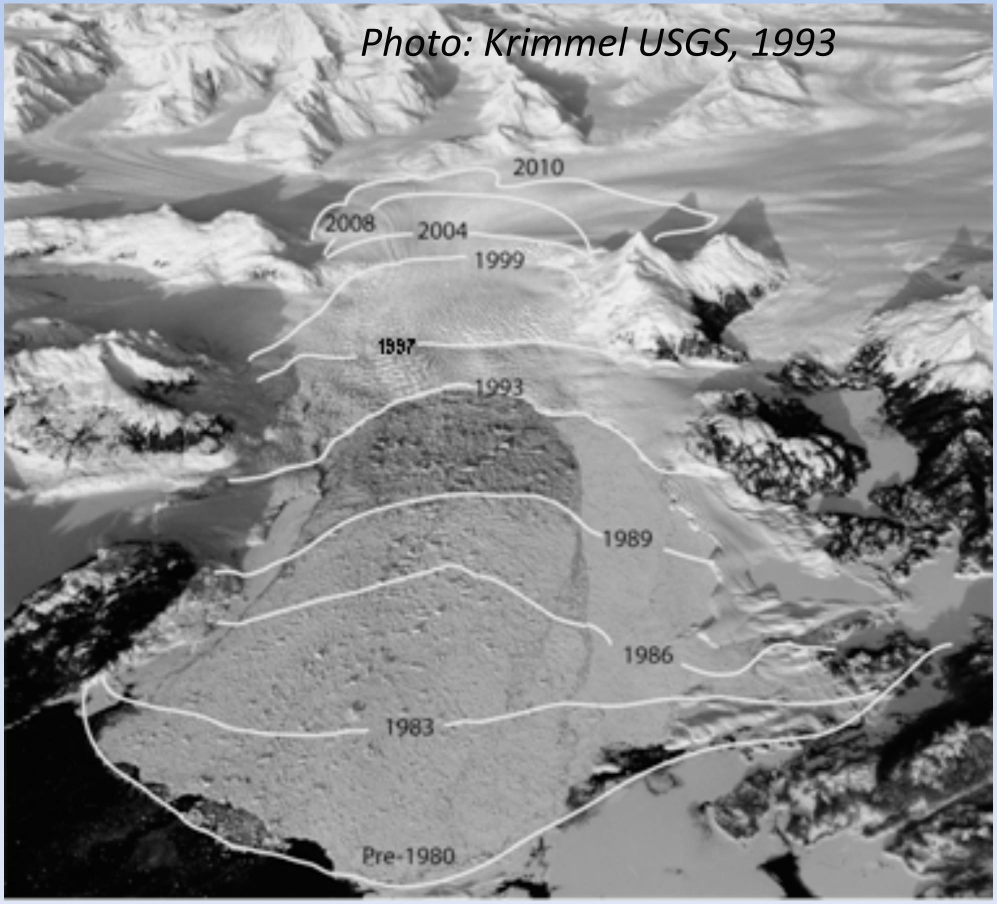


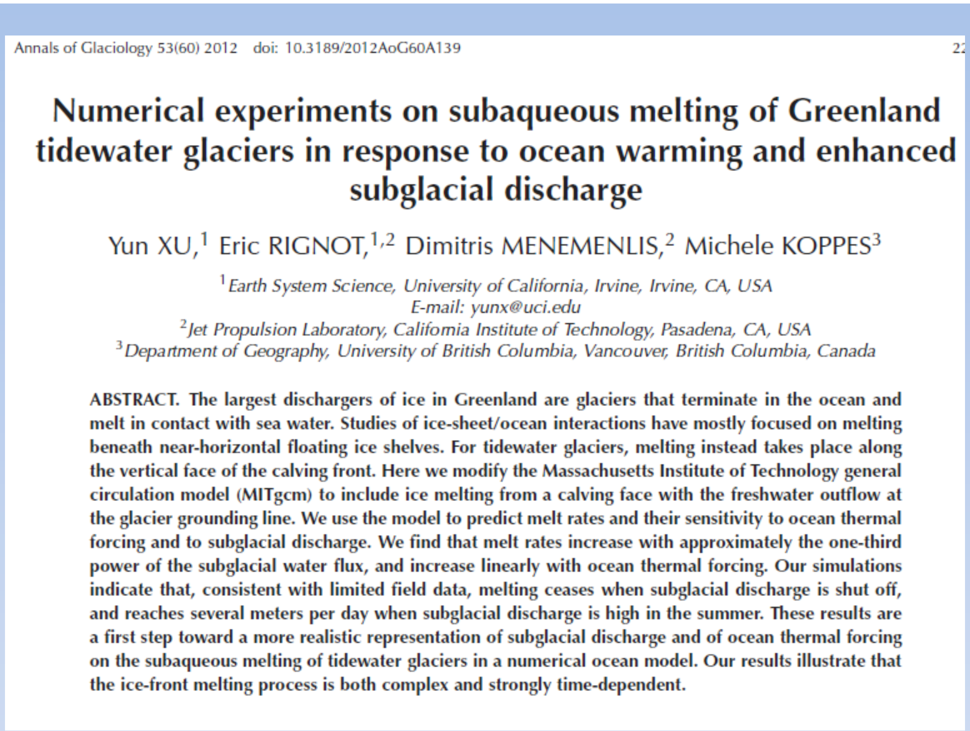
Photo: Krimmel USGS, 1993

Columbia Glacier
20 km retreat 1980 - 2010

Walters et al., 1988
Motyka et al., 2003
Rignot et al., 2010
Motyka et al., 2013

Thanks!

Photo: David Podrasky



Annals of Glaciology 53(60) 2012 doi: 10.3189/2012AoG60A139

Numerical experiments on subaqueous melting of Greenland tidewater glaciers in response to ocean warming and enhanced subglacial discharge

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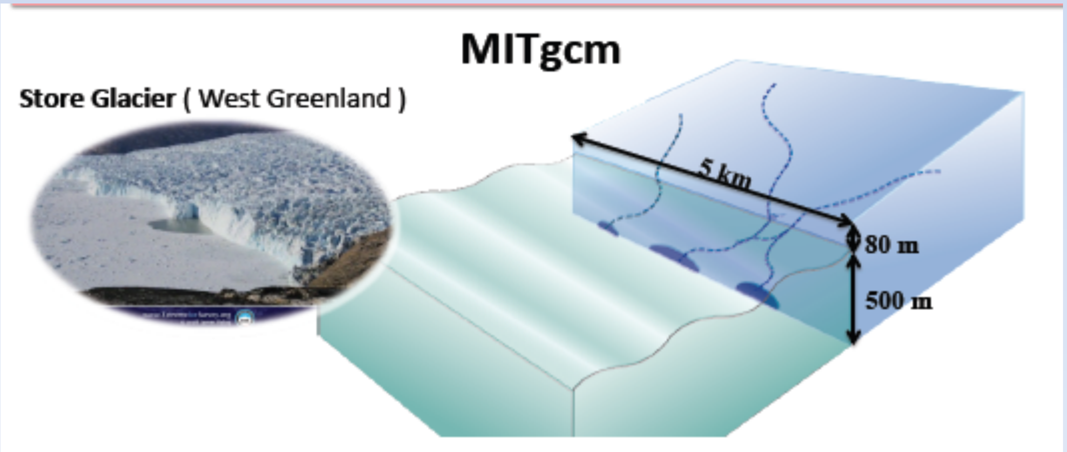
ABSTRACT. The largest dischargers of ice in Greenland are glaciers that terminate in the ocean and melt in contact with sea water. Studies of ice-sheet/ocean interactions have mostly focused on melting beneath near-horizontal floating ice shelves. For tidewater glaciers, melting instead takes place along the vertical face of the calving front. Here we modify the Massachusetts Institute of Technology general circulation model (MITgcm) to include ice melting from a calving face with the freshwater outflow at the glacier grounding line. We use the model to predict melt rates and their sensitivity to ocean thermal forcing and to subglacial discharge. We find that melt rates increase with approximately the one-third power of the subglacial water flux, and increase linearly with ocean thermal forcing. Our simulations indicate that, consistent with limited field data, melting ceases when subglacial discharge is shut off, and reaches several meters per day when subglacial discharge is high in the summer. These results are a first step toward a more realistic representation of subglacial discharge and of ocean thermal forcing on the subaqueous melting of tidewater glaciers in a numerical ocean model. Our results illustrate that the ice-front melting process is both complex and strongly time-dependent.

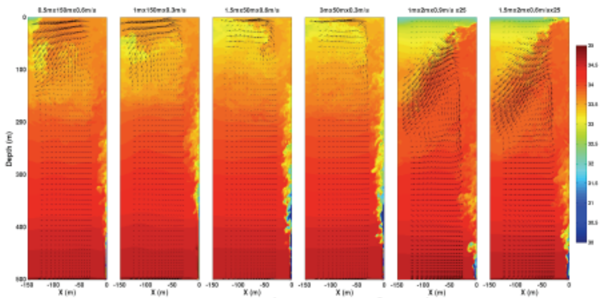


MITgcm

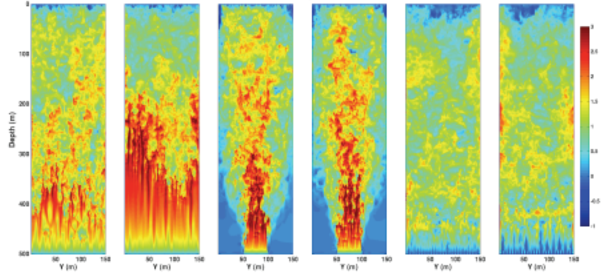
Store Glacier (West Greenland)

3-D Numerical Results

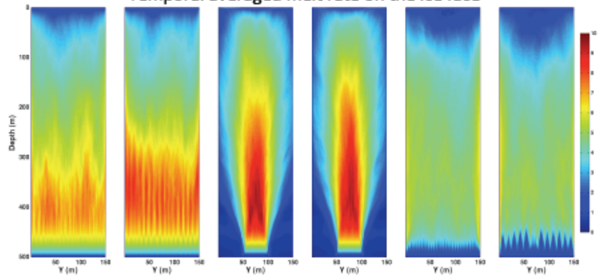
Instantaneous salinity – view from the side



Instantaneous velocity – view from the ice

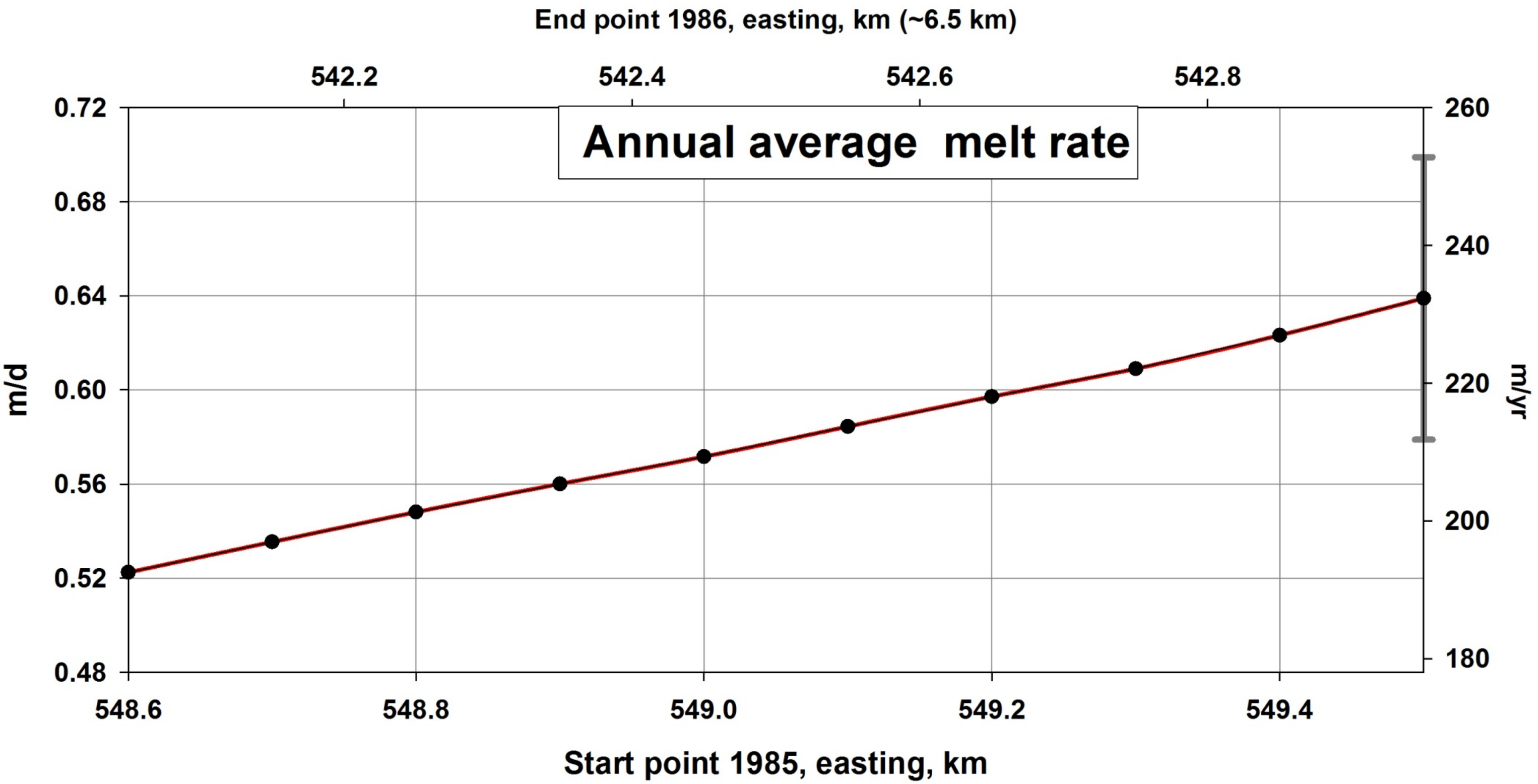


Temporal averaged melt rate on the ice face

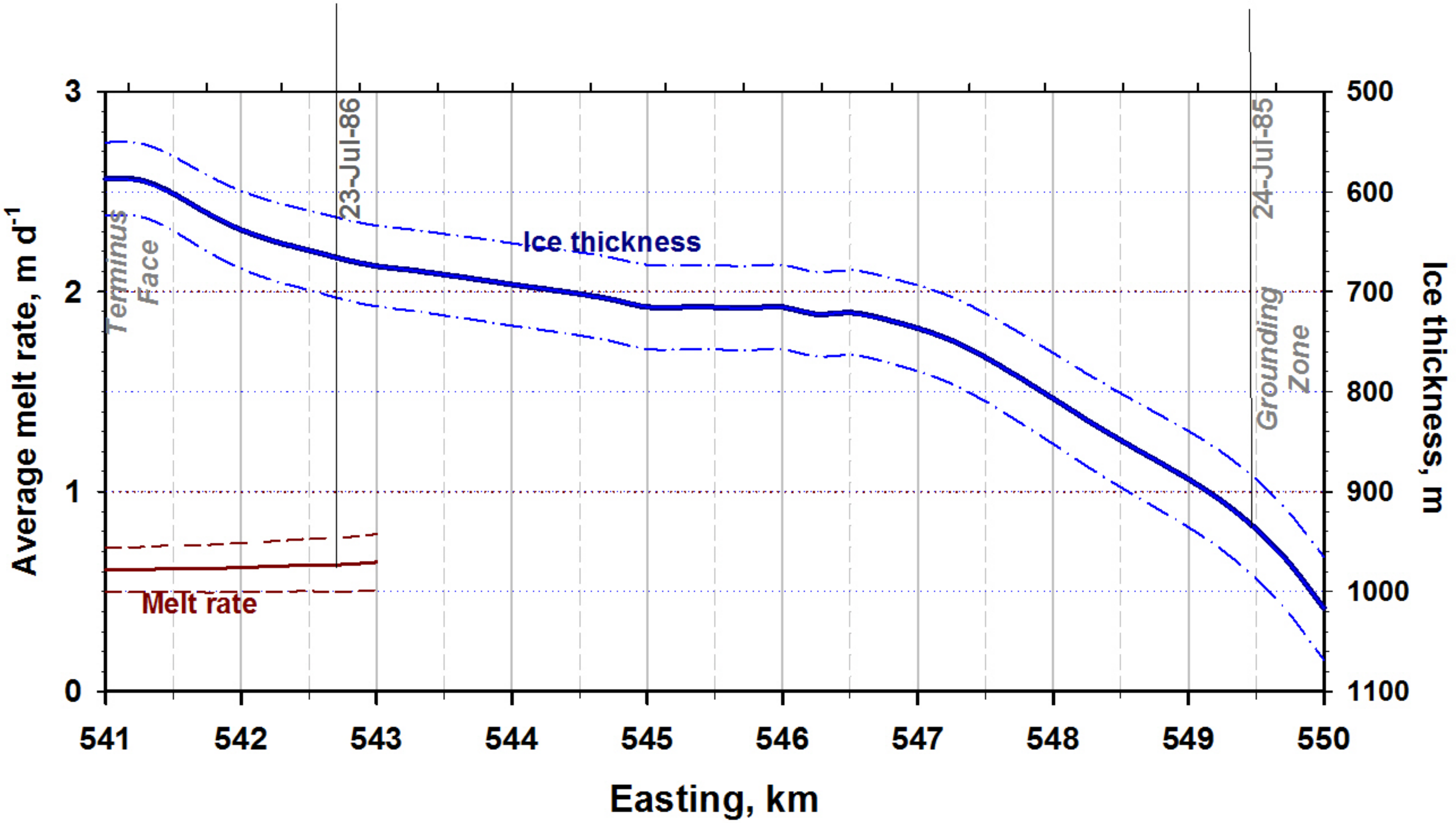


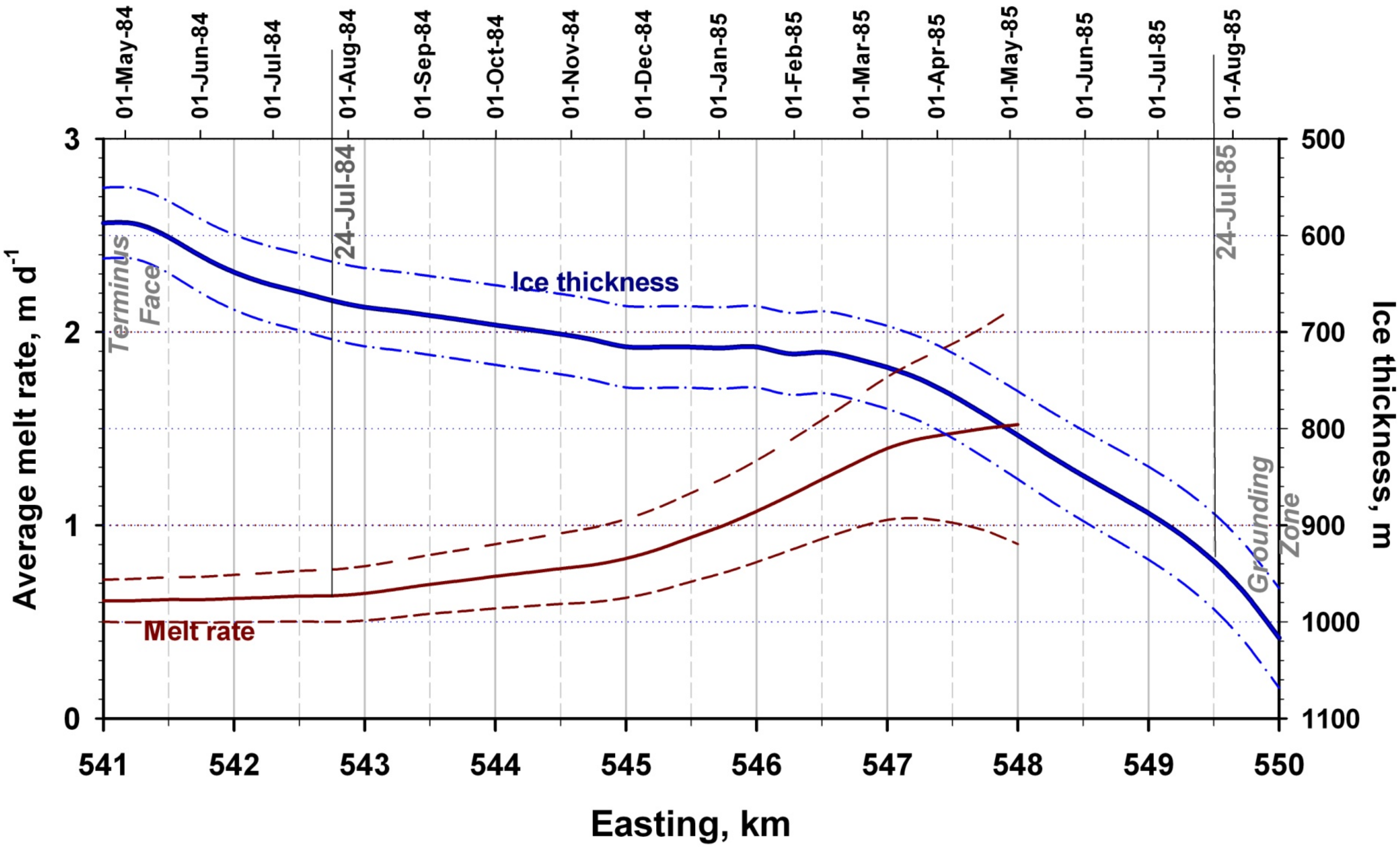
Averaged T, S, V & Melt Rate on the ice face

	0.5mx150m x0.6m/s	1mx150m x0.3m/s	1.5mx50m x0.6m/s	3mx50m x0.3m/s	1mx2m x25 x0.9m/s	1.5mx2m x25 x0.6m/s
T(°C)	1.98	1.89	2.00	1.99	2.26	2.24
S	31.9	31.6	32.4	32.4	33.1	33.1
W (m/s)	1.35	1.47	1.11	1.11	0.94	0.92
Melt Rate (m/d)	5.0	5.4	4.2	4.1	4.0	3.9



Integrates spatial and temporal variations


Average melt rate, m d^{-1}
Ice thickness, m
Easting, km
0
1
2
3
500
600
700
800
900
1000
1100
541
542
543
544
545
546
547
548
549
550
Terminus Face
23-Jul-86
24-Jul-85
Grounding Zone
Ice thickness
Melt rate


01-May-84
01-Jun-84
01-Jul-84
01-Aug-84
01-Sep-84
01-Oct-84
01-Nov-84
01-Dec-84
01-Jan-85
01-Feb-85
01-Mar-85
01-Apr-85
01-May-85
01-Jun-85
01-Jul-85
01-Aug-85
24-Jul-84
24-Jul-85
Terminus Face
Grounding Zone
Ice thickness
Melt rate
Average melt rate, m d^{-1}
Ice thickness, m
Easting, km
0
1
2
3
500
600
700
800
900
1000
1100
541
542
543
544
545
546
547
548
549
550