Ocean-glacier interactions in Greenland

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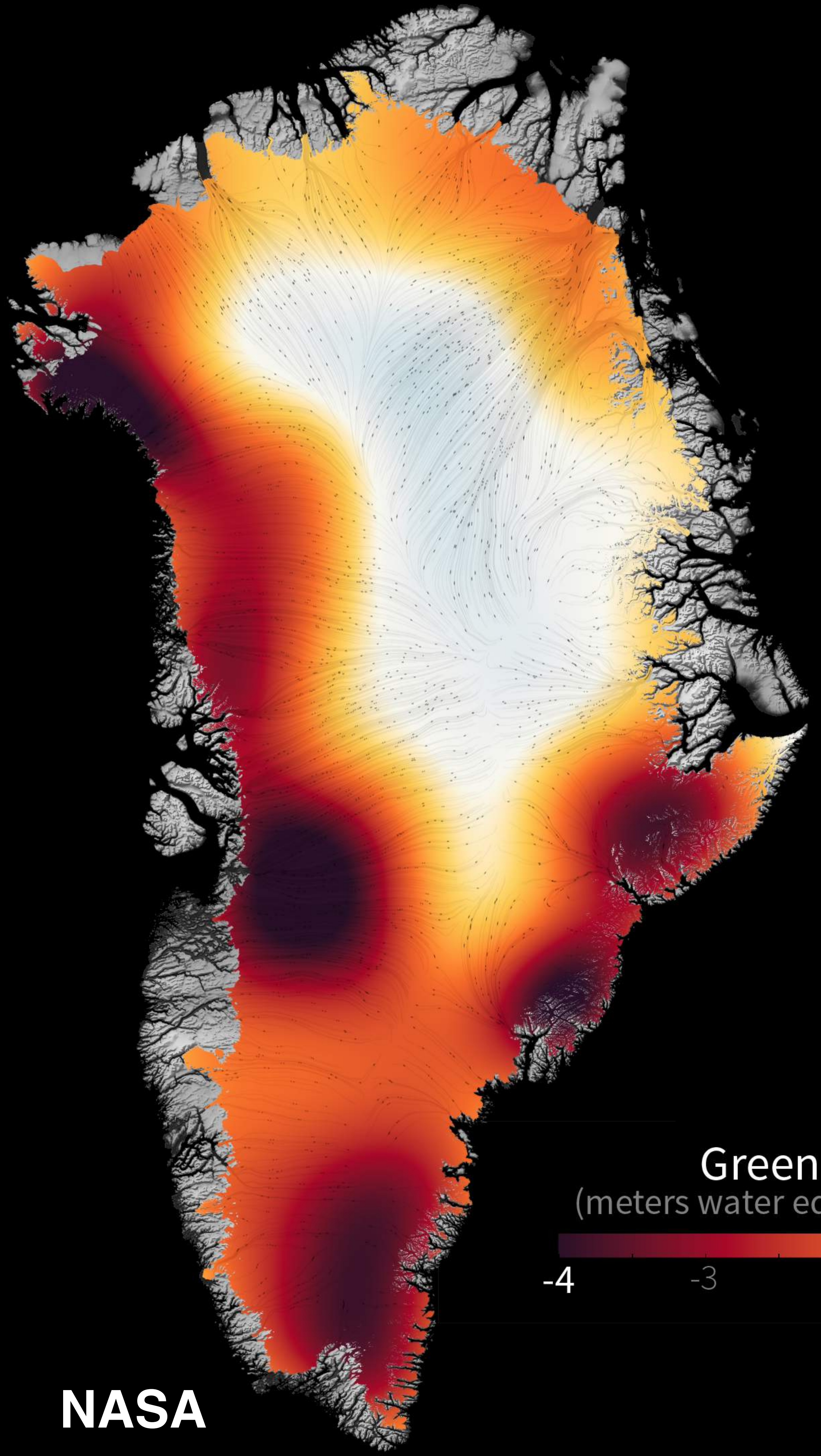
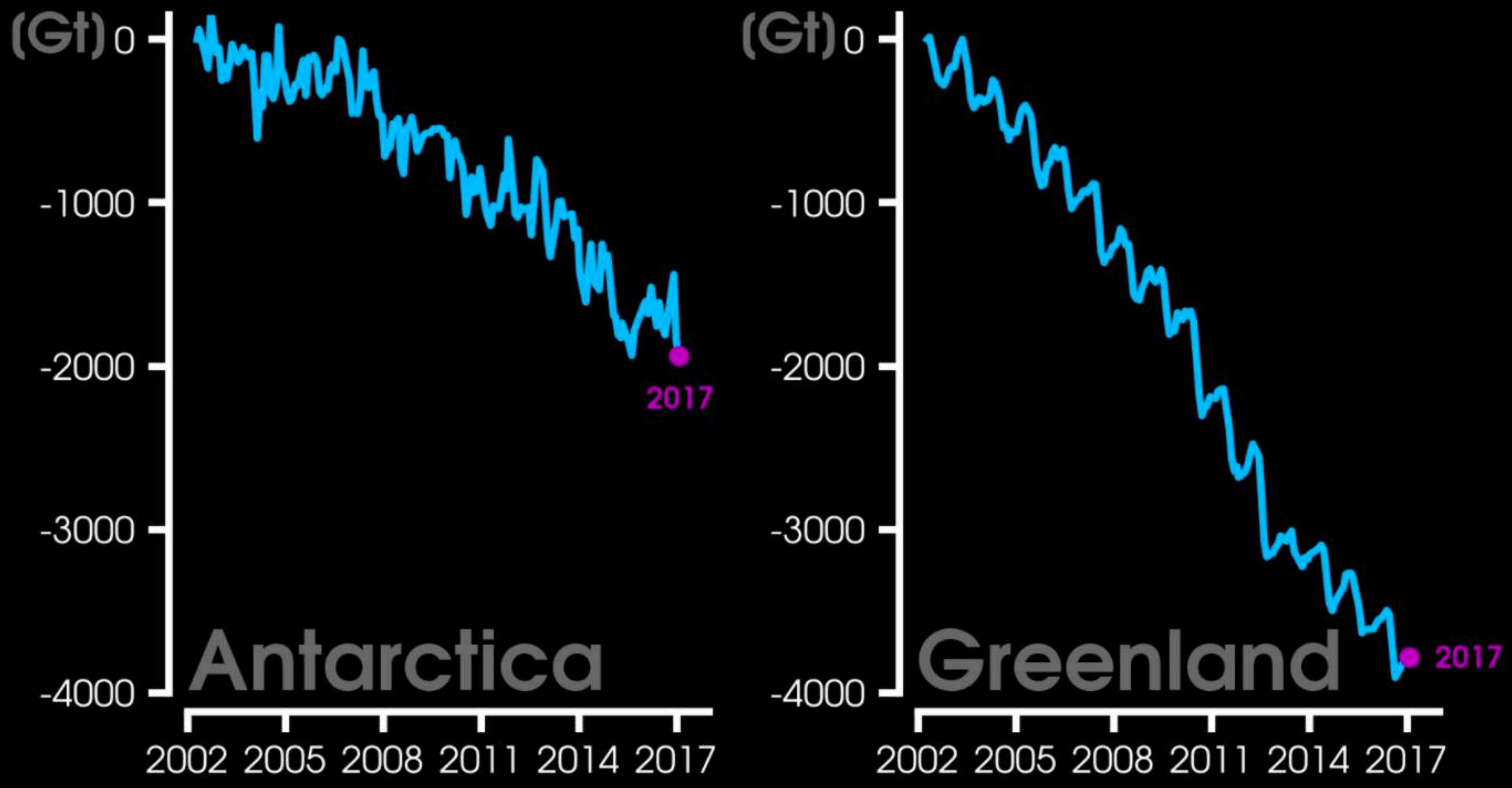
NASA

Mass loss from glaciers & ice sheet → sea level rise



NASA

GRACE observations of ice mass changes

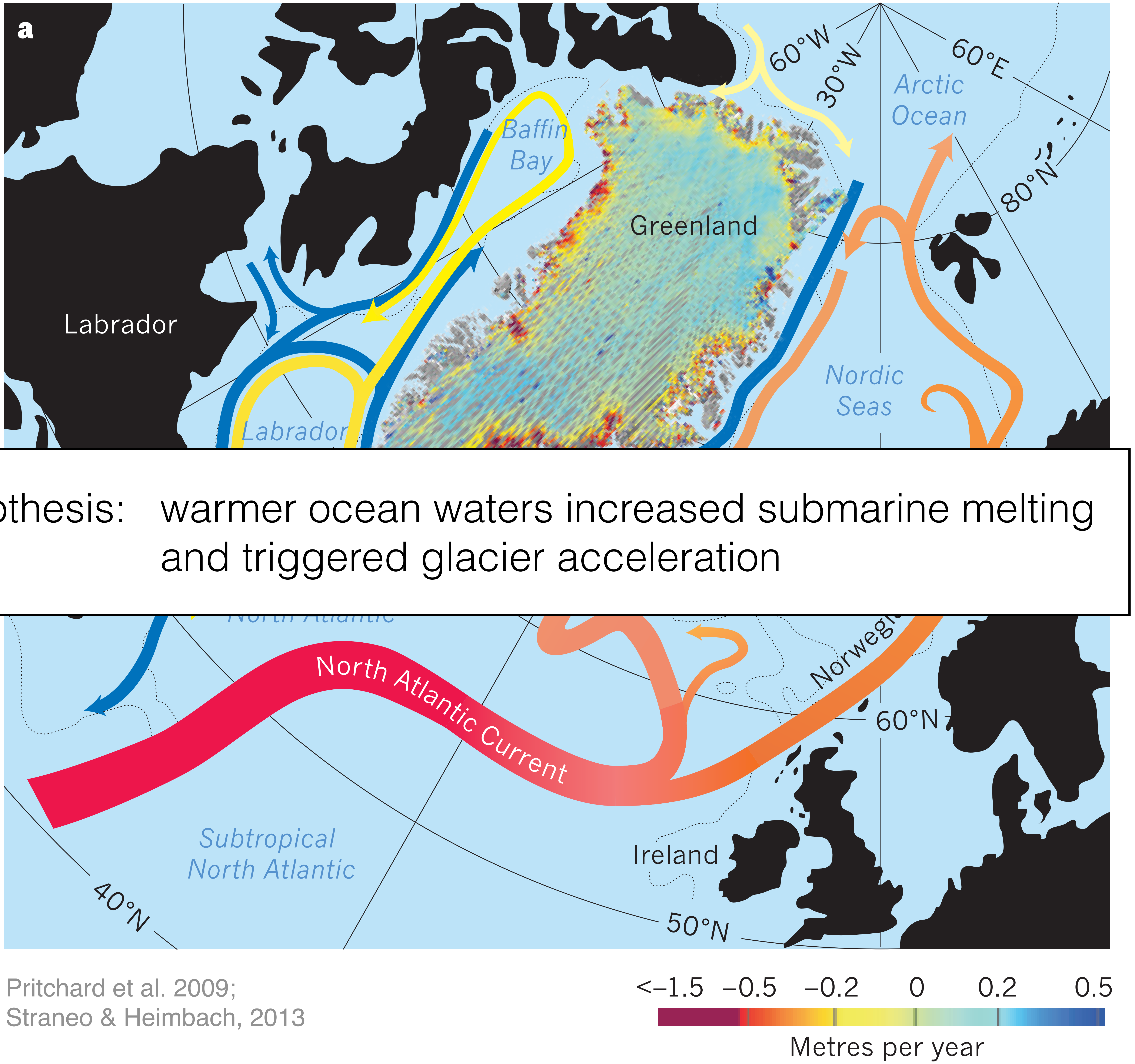


Sea level rise from Greenland:

= 0.8 mm/yr

→ contributing ~¼ of global rate

Dynamic mass loss concentrated at marine margins

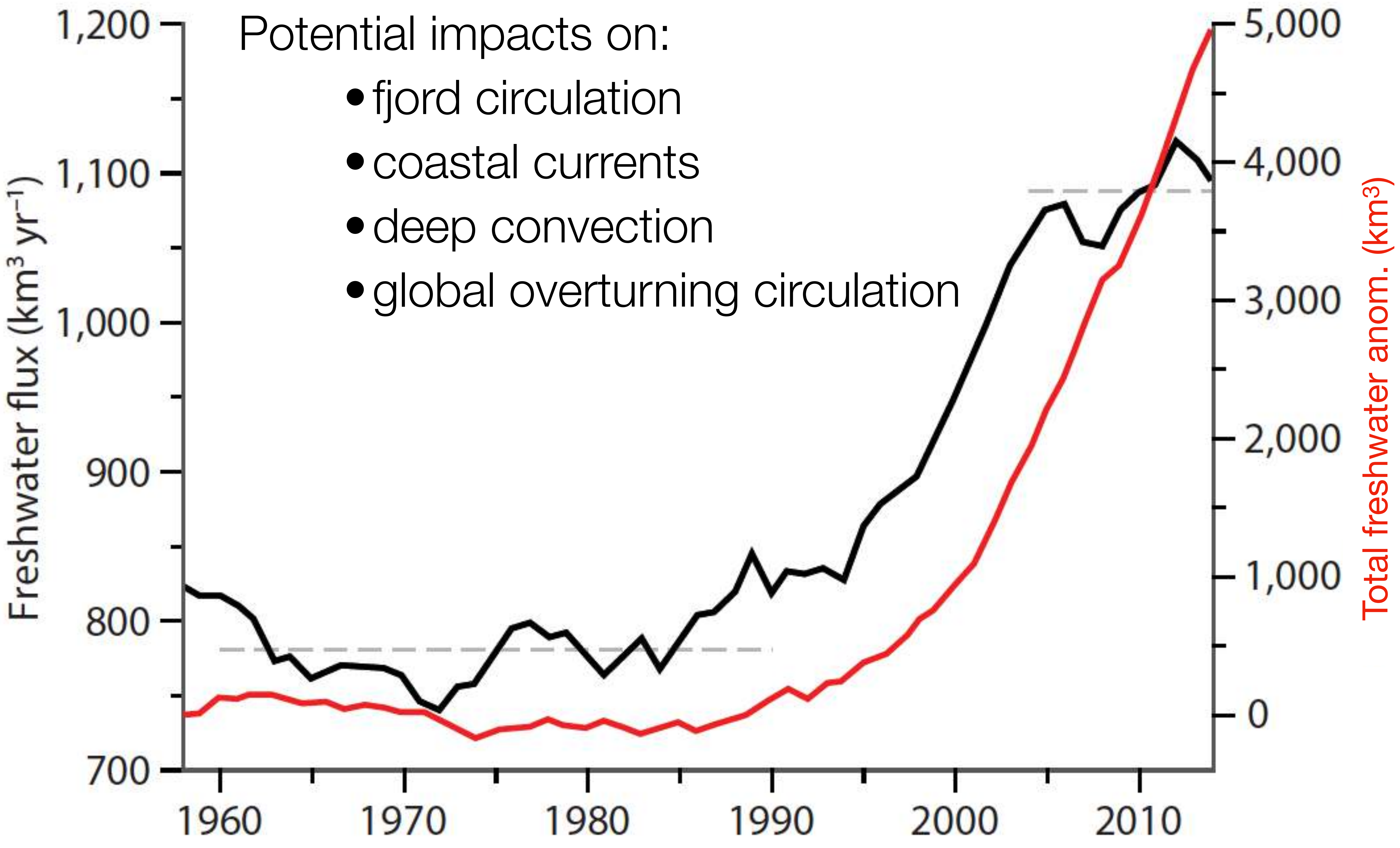


Pritchard et al. 2009;
Straneo & Heimbach, 2013

Hypothesis: warmer ocean waters increased submarine melting and triggered glacier acceleration

(e.g. Thomas 2004;
Holland et al. 2008;
Nick et al. 2009;
Vieli & Nick, 2011;
Straneo & Heimbach 2013)

Increasing freshwater into ocean from Greenland

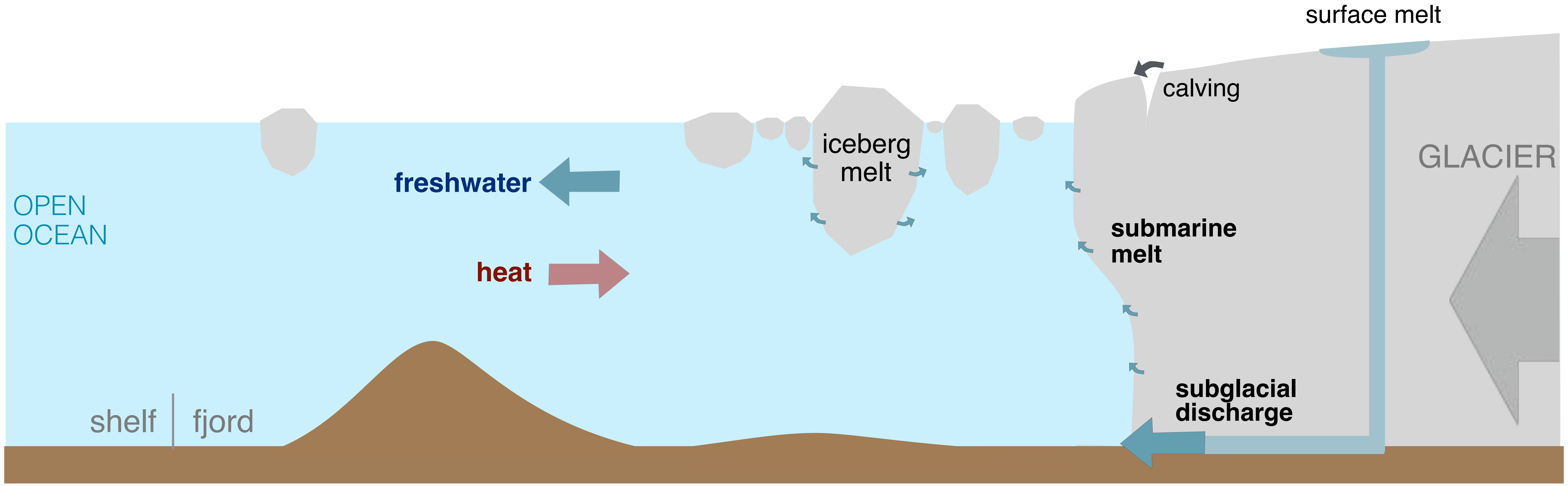


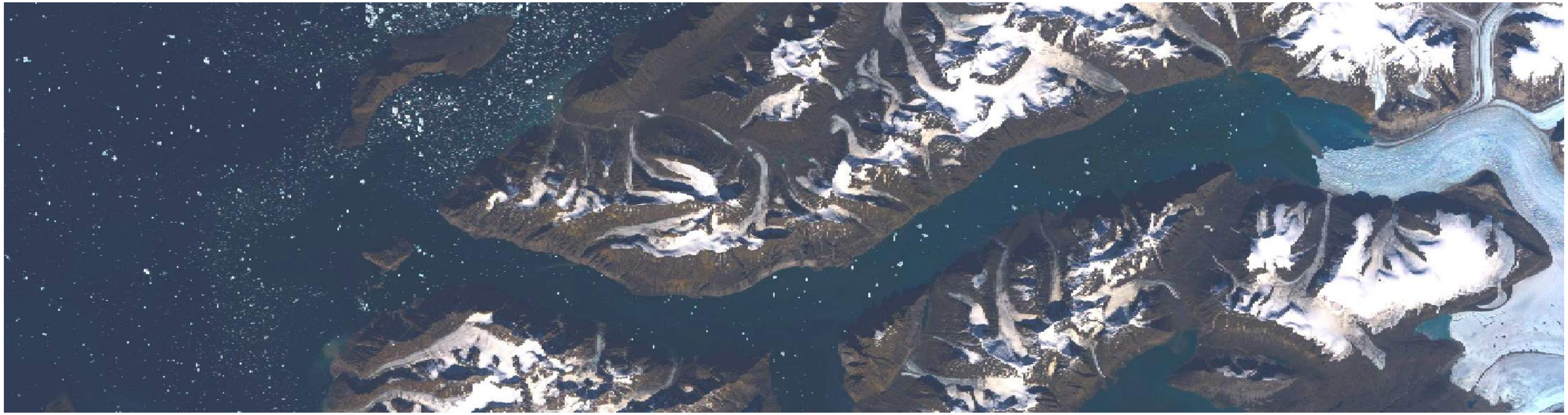
Potential impacts on:

- fjord circulation
- coastal currents
- deep convection
- global overturning circulation

Frajka-Williams et al., 2016

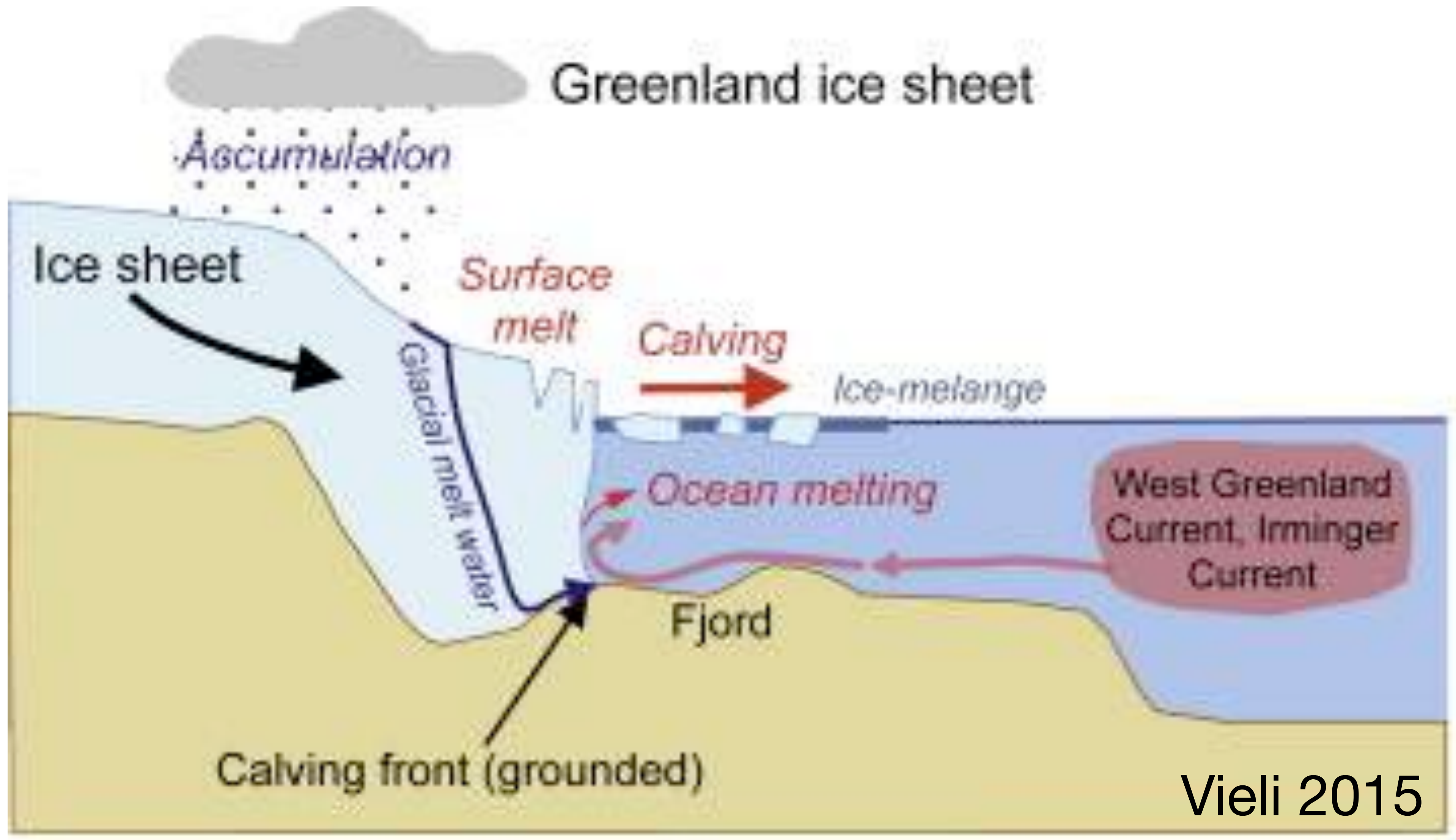
Heat & freshwater exchanges





tidewater glaciers vs. ice shelves

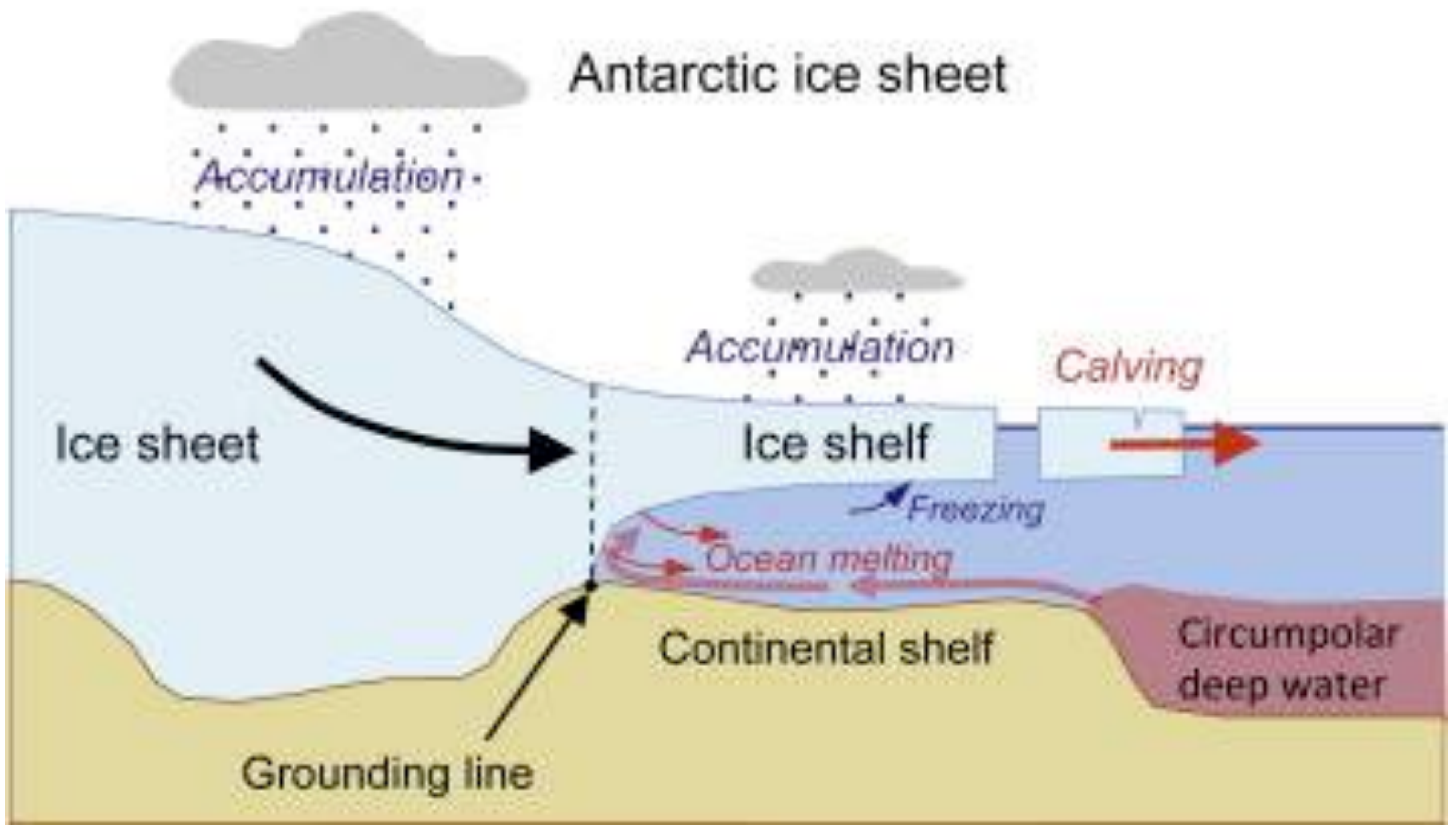
(common in Greenland)



Vieli 2015

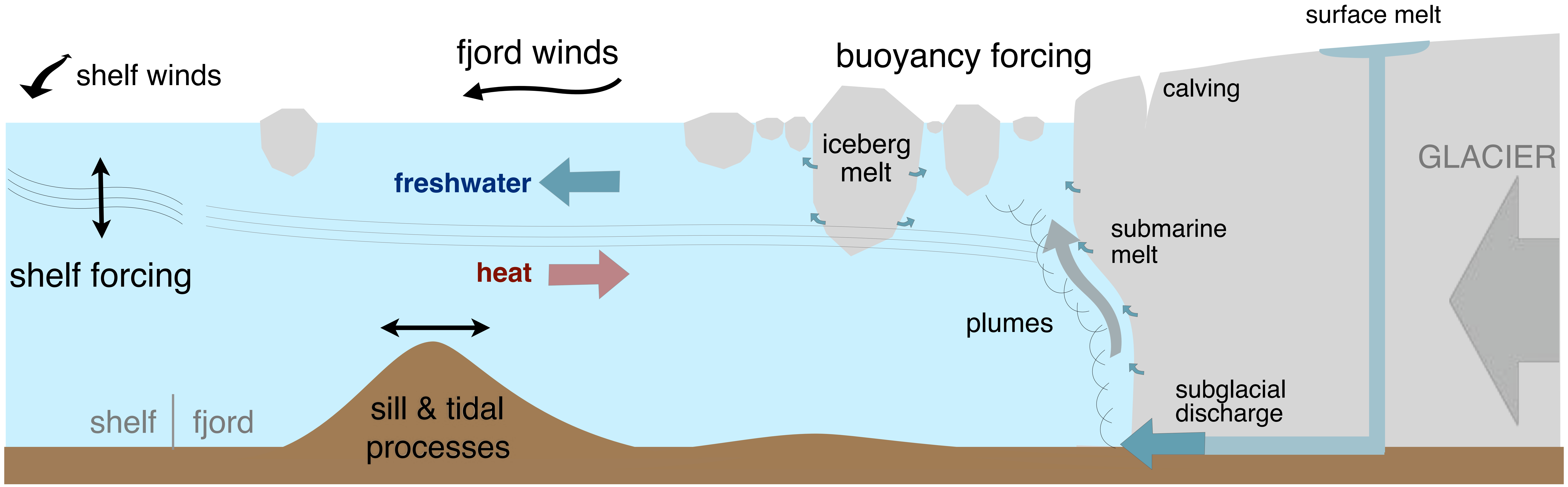
- **near-vertical** ice face with **calving** & submarine **melt**
- large freshwater flux of **subglacial discharge**
- **freshwater fluxes very poorly constrained**
  - submarine melting: almost no direct obs.
  - subglacial discharge: estimated with atm. models
- relatively **small scales** → hard to resolve in models
  - fjord: 5 x 80 km || ice-ocean interface: 5 km x 500 m

(common in Antarctica)

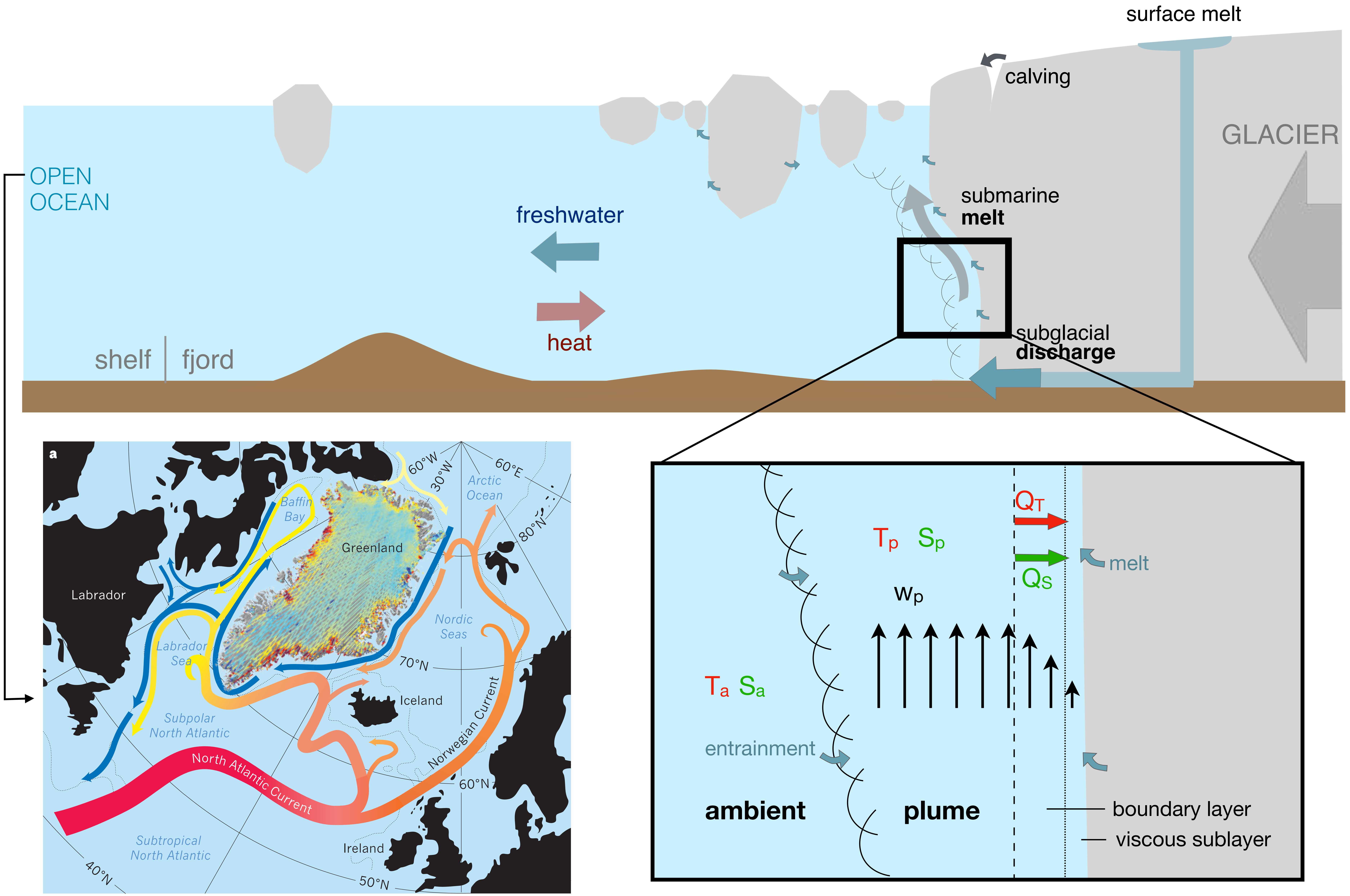


- **near-horizontal** ice face; **melt** often dominant
- no or little subglacial discharge
- **submarine melt rates are better constrained**
  - with satellite data (assuming floatation) and drilling through ice shelves
- **larger scales**
  - ice shelf cavity: 100 x 100 km or more!

Drivers of circulation & heat/freshwater transport

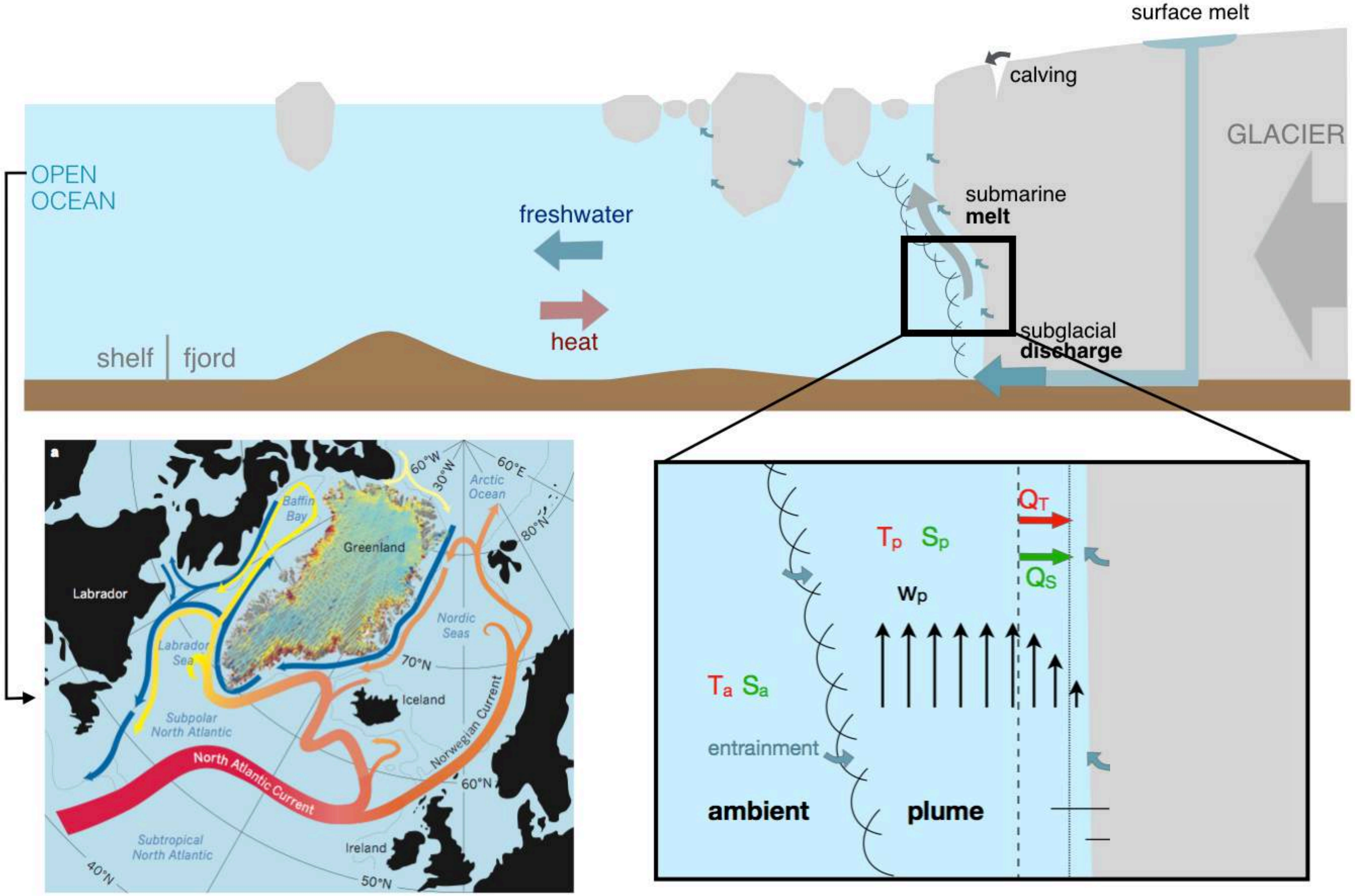


Scales: from subpolar gyre to ocean-ice boundary



Outline

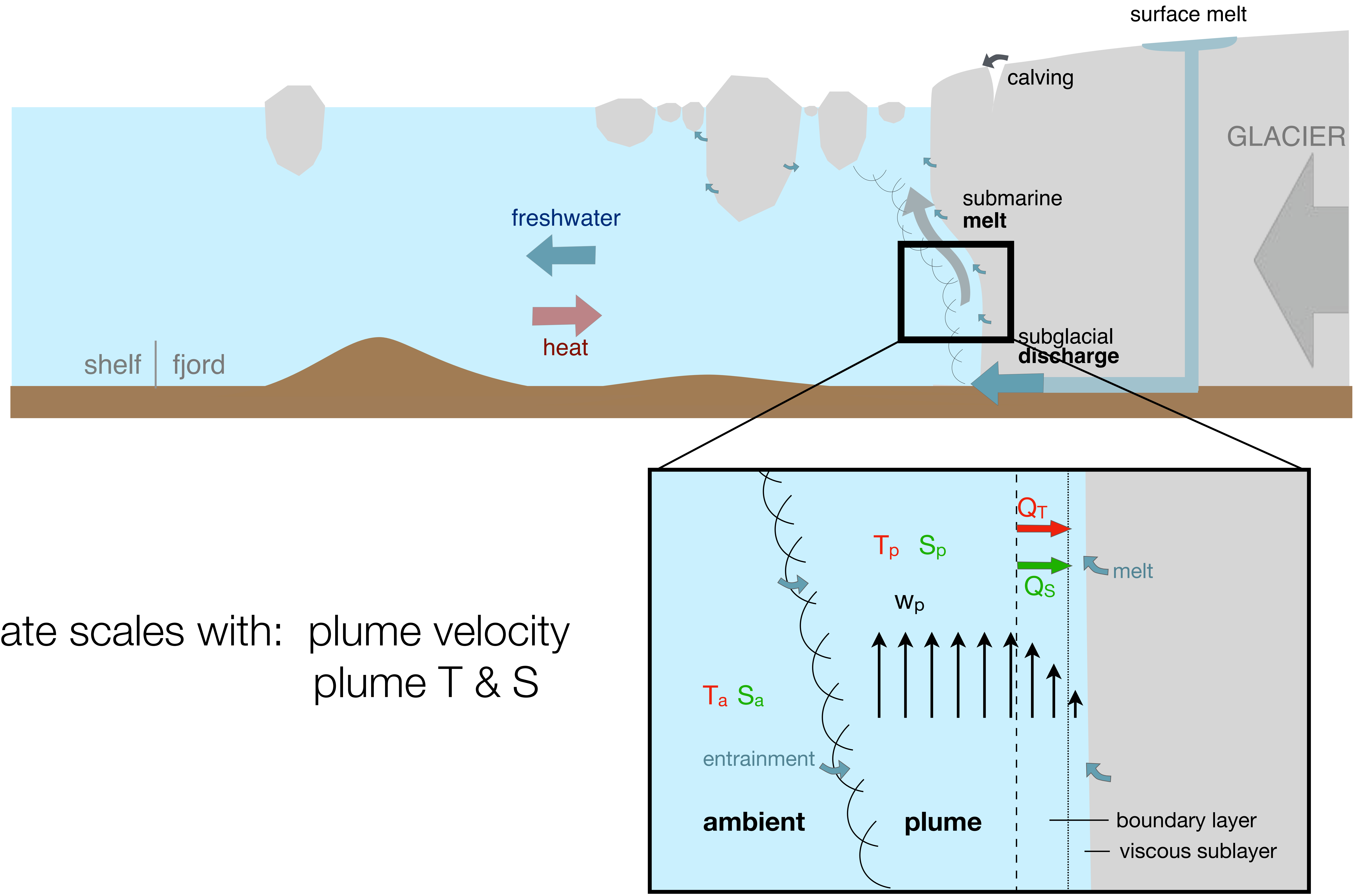
- **near-glacier plumes**: melting & mixing
    - theory & models
    - testing with observations
- **fjord circulation**
- **measuring freshwater fluxes**
    - fjord budgets
    - noble gases
    - multibeam surveys
- connection to **shelf & subpolar gyre**
    - glacier→ocean: ecosystems, convection
    - ocean→glacier: water mass origin & variability



Plumes, melting & mixing

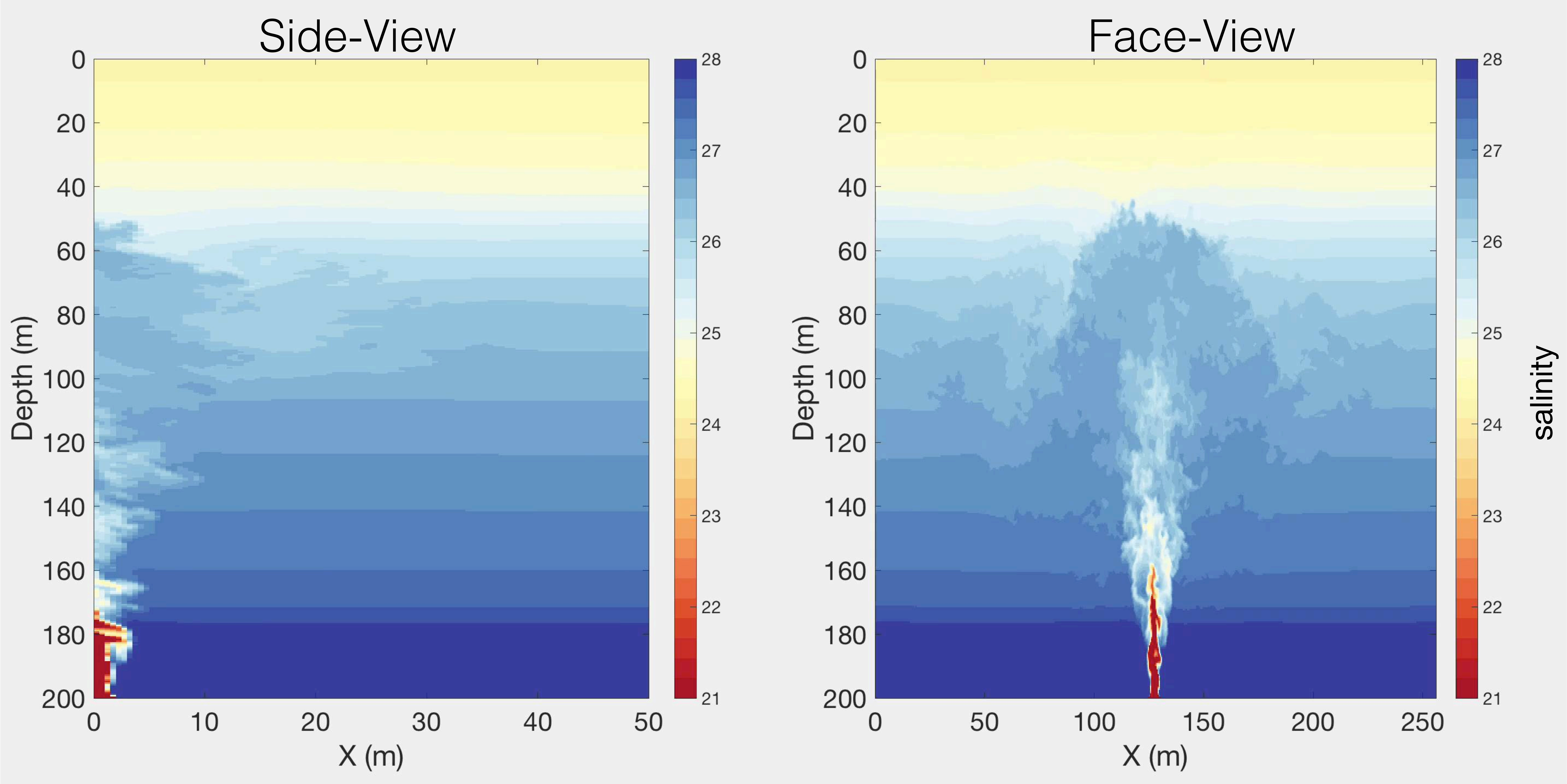
Theory & Models

Plumes drive mixing & melting at glacier terminus



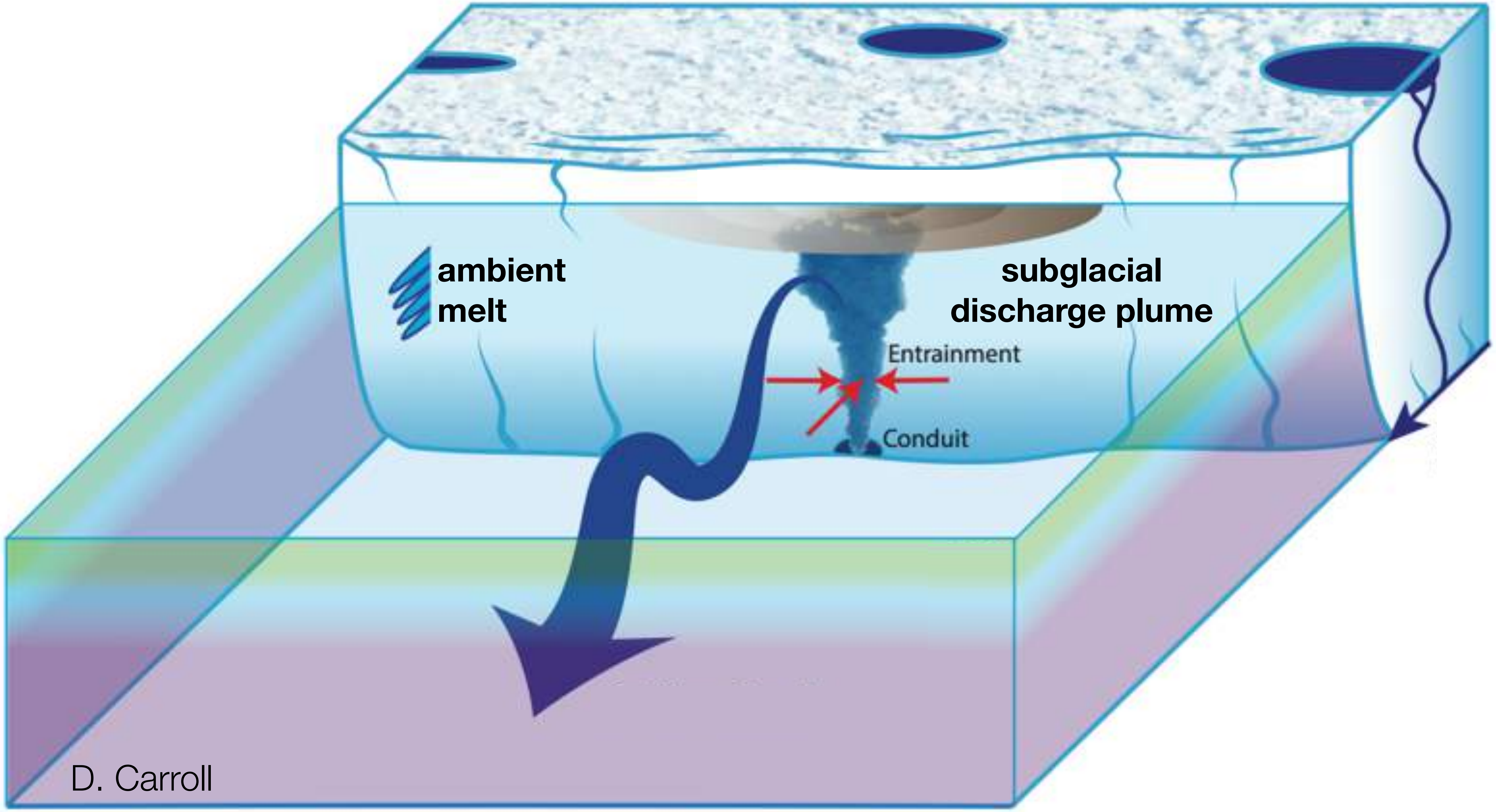
melt rate scales with: plume velocity
plume T & S

LES model of a discharge plume



Large Eddy Simulation, Eric Skyllingstad

Plumes from subglacial discharge & ambient melt

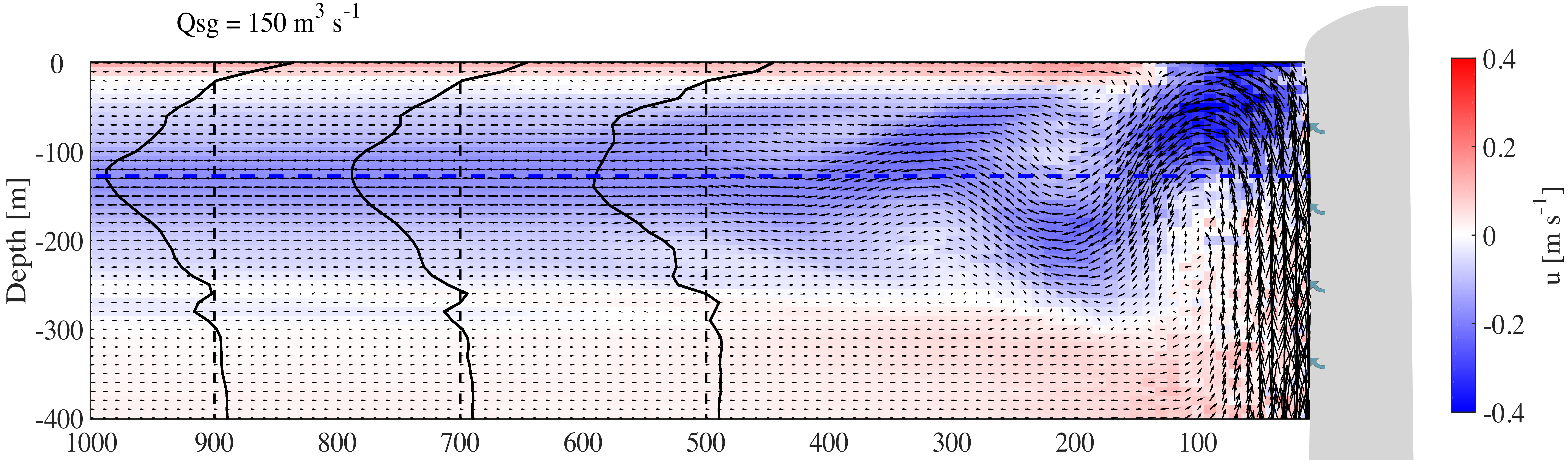


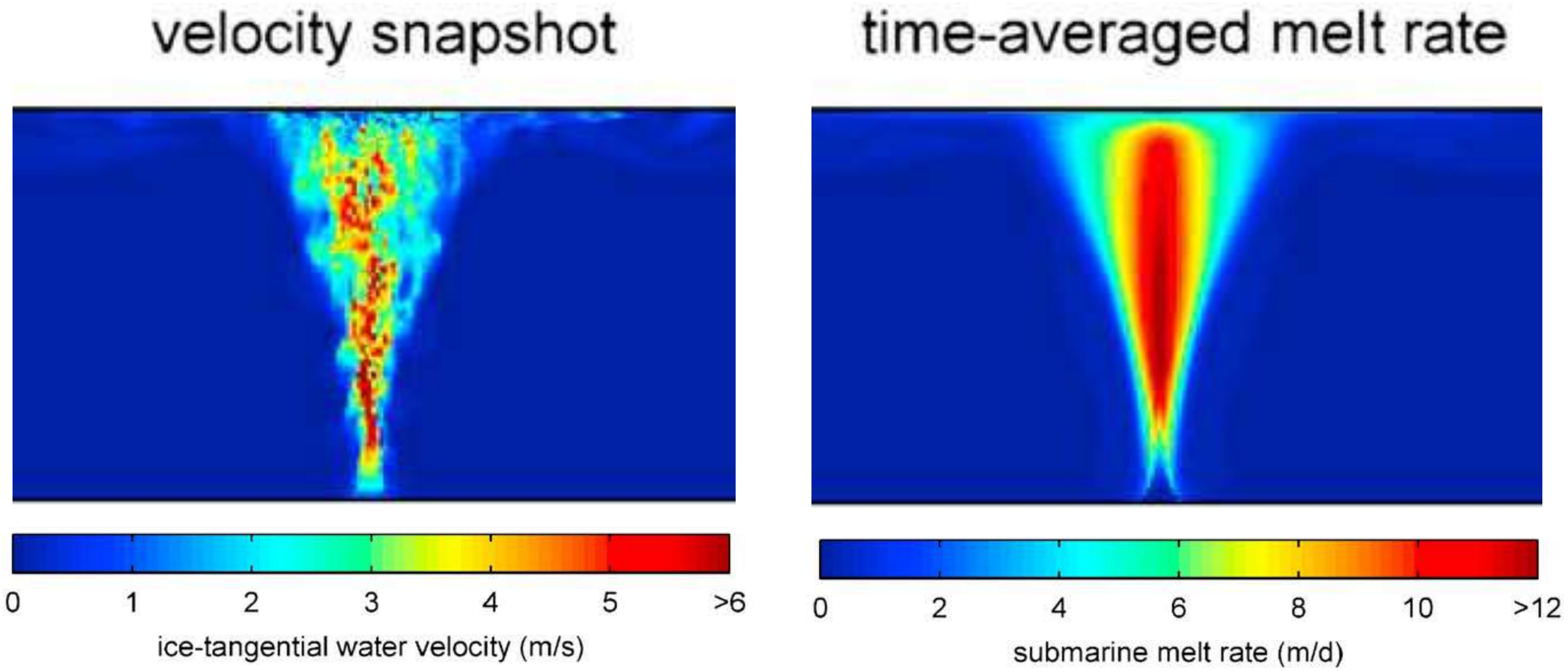
Existing near-glacier observations:

- downstream or at surface (almost none in upwelling region)
- limited velocity measurements
- <10% freshwater in plume after upwelling

Motyka et al 2013
Xu et al 2013
Bendtsen et al 2015
Beaird et al 2015
Mankoff et al 2016
Stevens et al 2016
Jackson et al 2017
Everett et al 2018

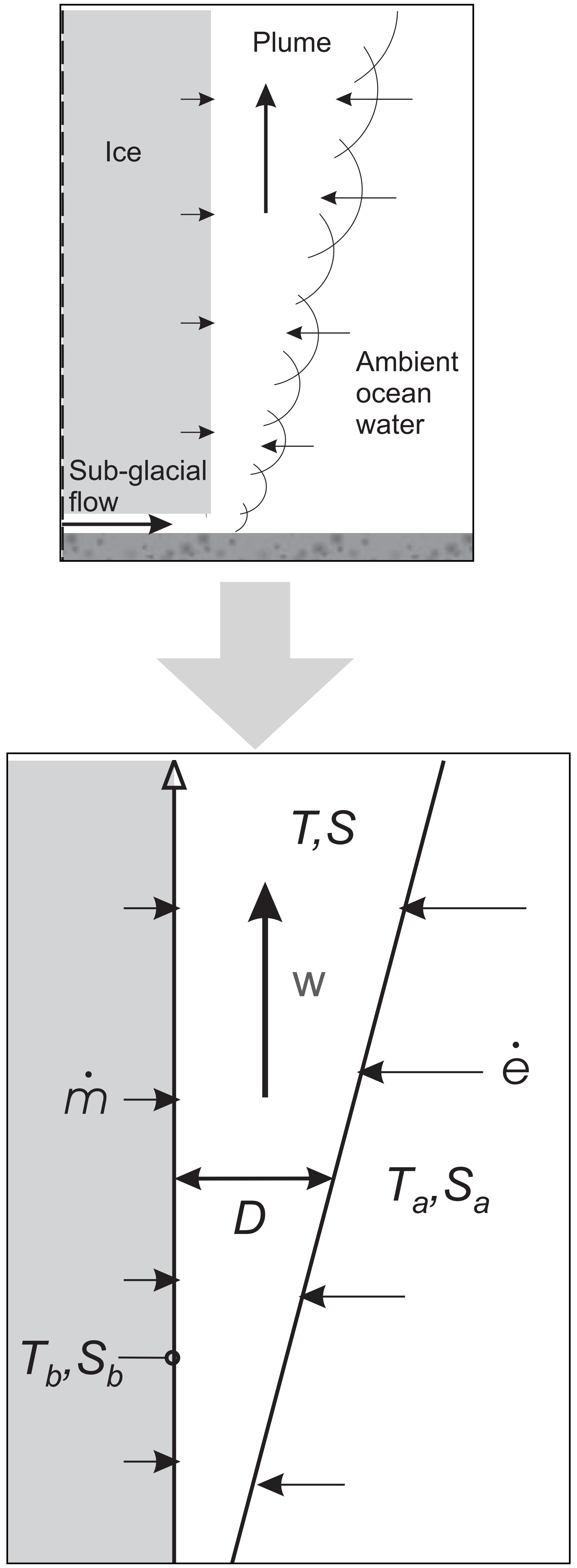
Numerical modeling of glacial plumes & melting





Slater et al 2015

Buoyant plume theory (BPT) for glacial plumes



Conservation equations [Morton et al. 1956; Ellison & Turner, 1959; etc]

Mass $$\frac{d}{dz}(wD) = \dot{e} + \dot{m}$$

Momentum $$\frac{d}{dz}\left(w^2D\right) = D\left(\frac{\rho_a - \rho}{\rho_0}\right)g - C_d w^2$$

Heat $$\frac{d}{dz}(TwD) = \dot{e}T_a + \dot{m}T_b - C_d^{1/2}\Gamma_T w(T - T_b)$$

Salt $$\frac{d}{dz}(SwD) = \dot{e}S_a + \dot{m}S_b - C_d^{1/2}\Gamma_S w(S - S_b)$$

Entrainment parametrization [Morton, 1959; van Reeuwijk & Craske, 2015; etc.]

$$\dot{e} = \alpha w \quad \alpha \simeq 0.1$$

Melt parametrization [Holland & Jenkins, 1999; Jenkins, 2011; etc.]

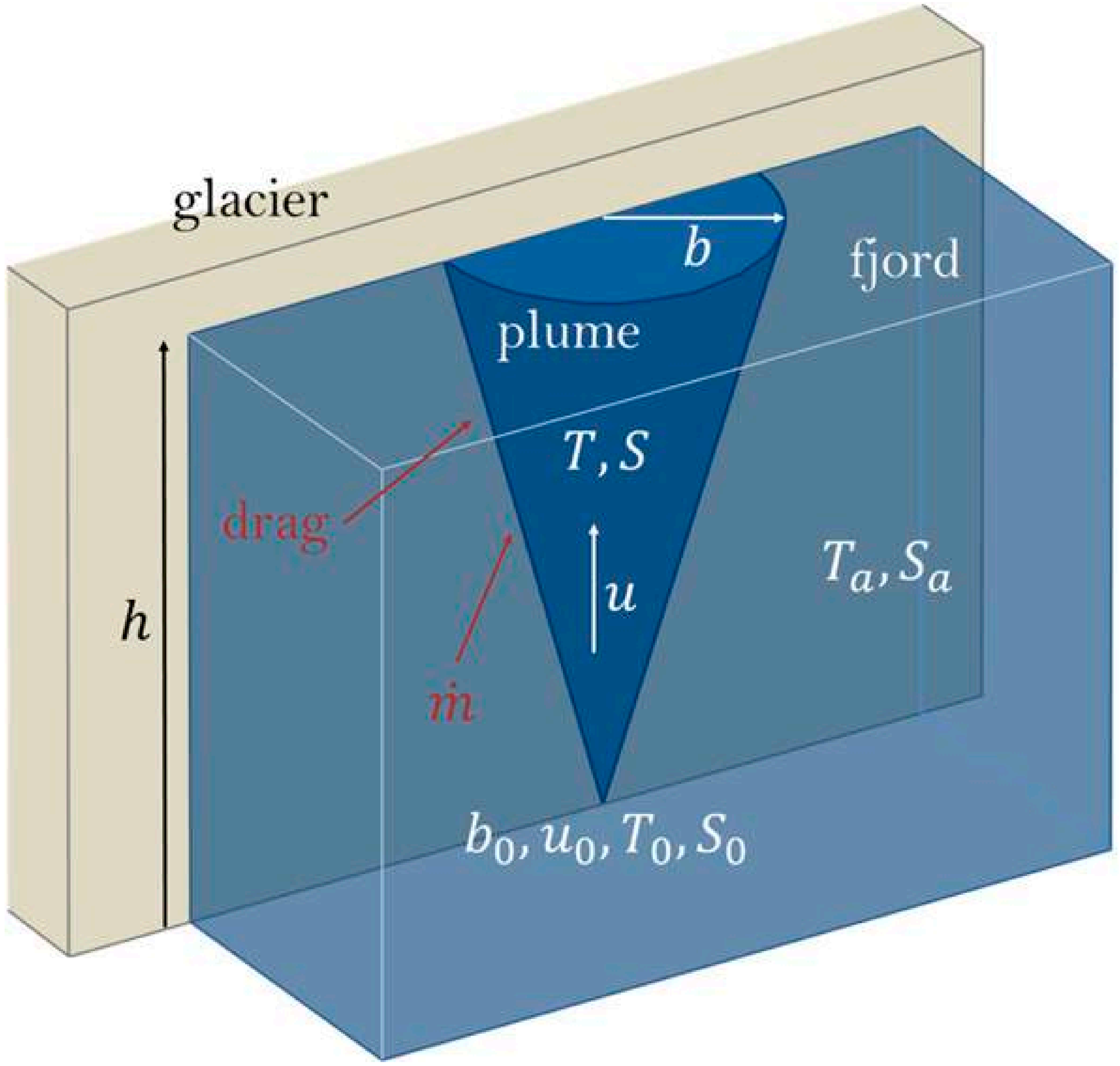
$$\dot{m}\left(c_i(T_b - T_{ice}) + L\right) = \Gamma_T C_d^{1/2} c_\rho w(T - T_b)$$

$$\dot{m}S_b = \Gamma_S C_d^{1/2} w(S - S_b)$$

$$T_b = \lambda_1 S_b + \lambda_2 + \lambda_3 z$$

C_D = drag coefficient
Γ_S, Γ_T = transfer coefficients

Buoyant plume theory (BPT) used to represent plumes & mixing in ocean-glacier models

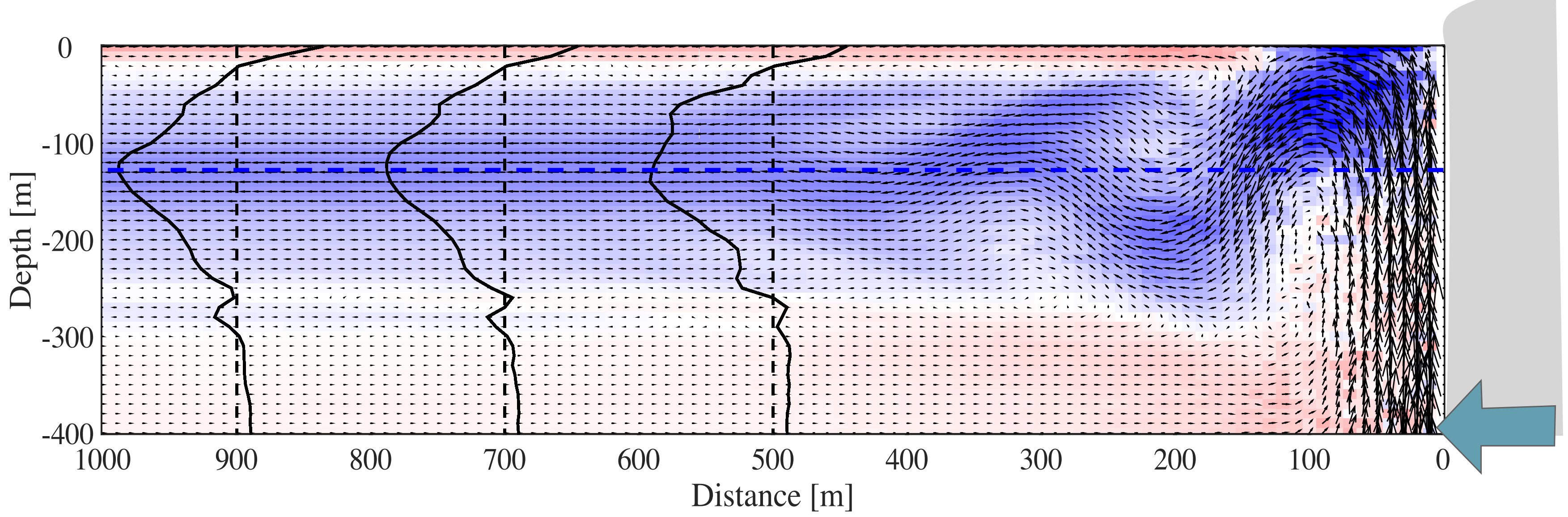


Morton et al. 1956; Ellison & Turner 1959
MacAyeal 1985; Jenkins, 2011

- BPT on its own

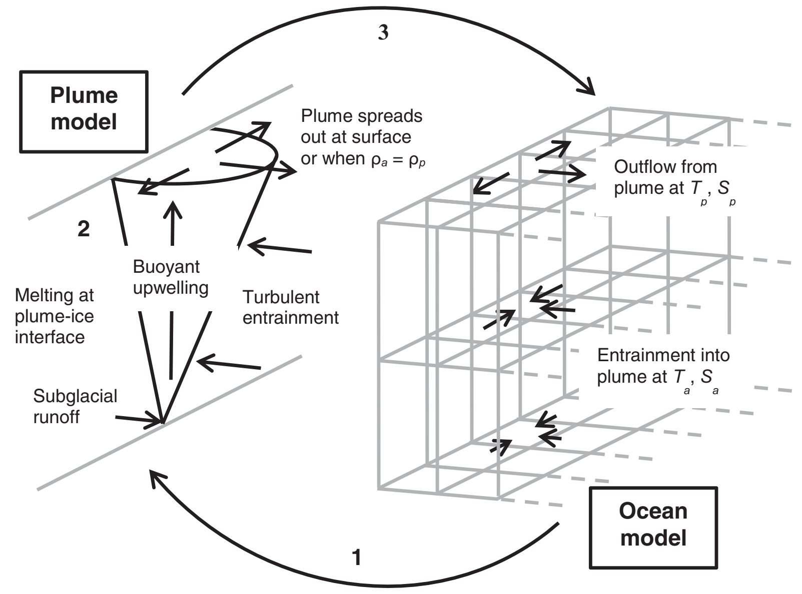
Carroll et al 2016; Bartholomaus et al 2016;
Mankoff et al. 2016; Slater et al, 2016;
Slater et al 2017, Beckmann et al 2017…

- ocean models with mixing tuned to BPT



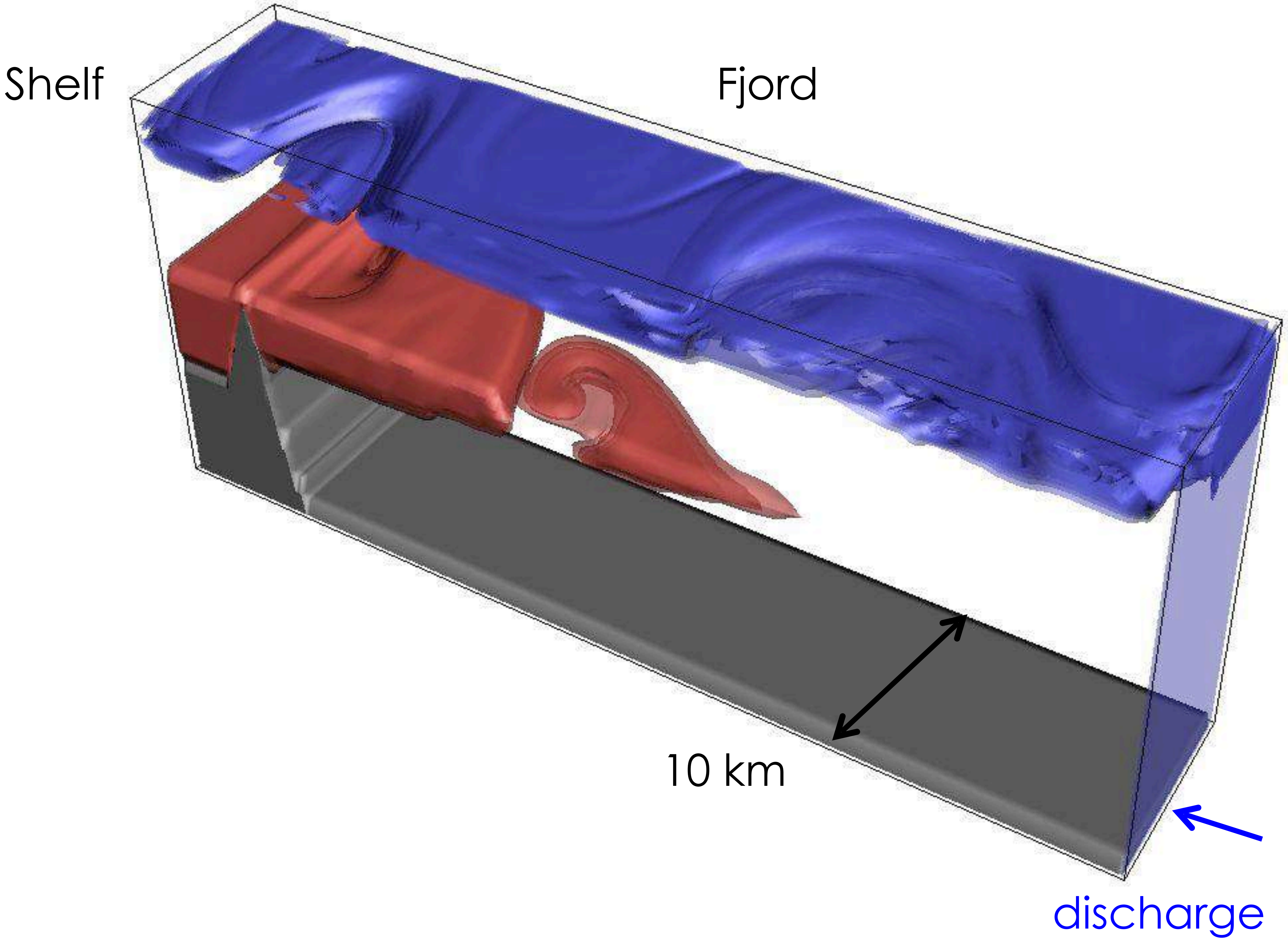
Sciascia et al, 2013; Kimura et al, 2014;
Carroll et al, 2015; Gladish et al, 2015;
Slater et al, 2015; Slater et al, 2017….

- coupling BPT with ocean or glacier model



Cowton et al, 2015;
Slater et al, 2016;
Cowton et al, 2016;
Carroll et al, 2017;
Amundson & Carroll, 2018

Models forced by buoyant plume theory (BPT): pro & cons



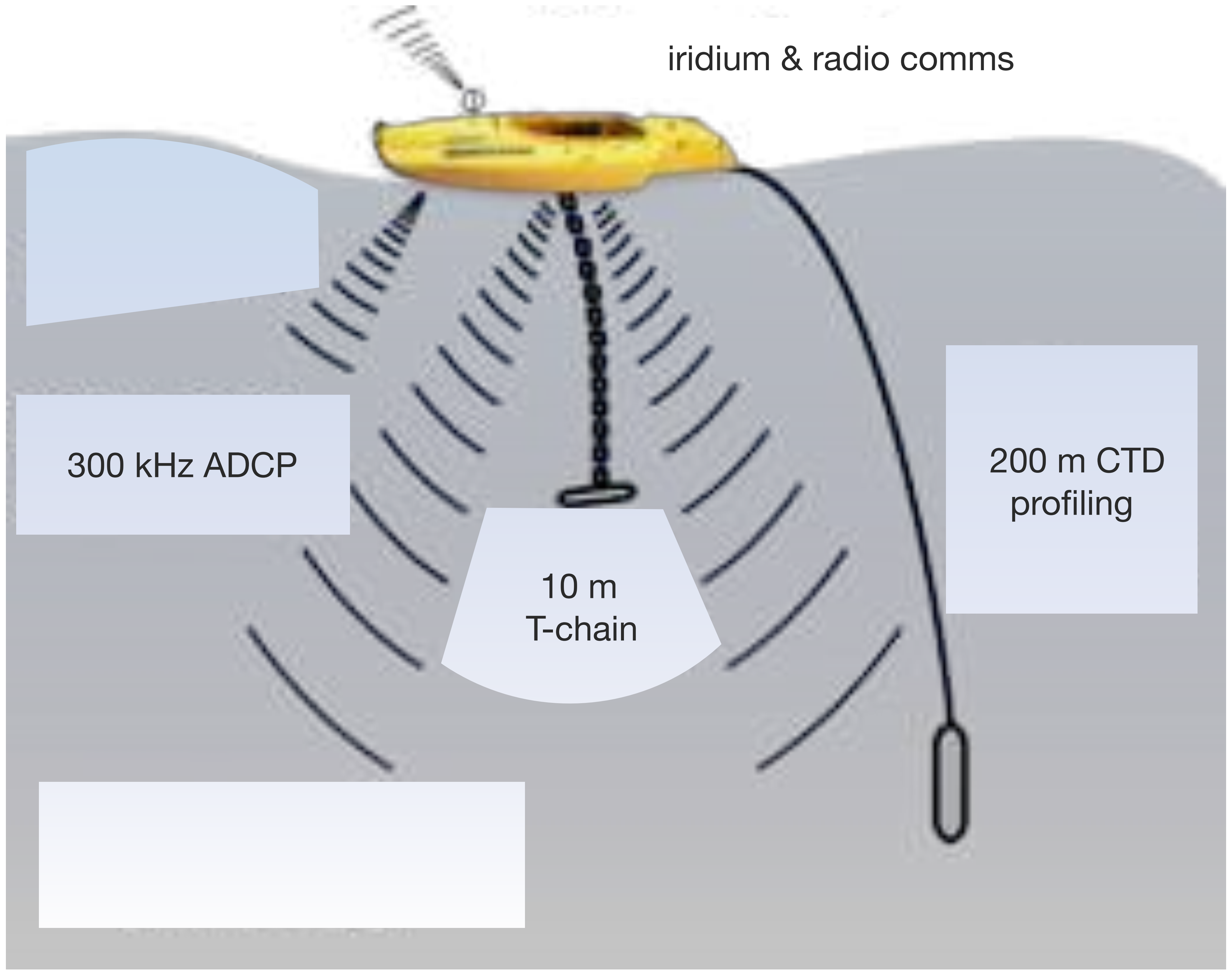
Carrol et al 2017

- BPT is practical
  - deals with non-hydrostatic processes offline
  - only need near-glacier T, S and discharge to represent plume & melt
- BPT gets some basics right
  - diluted, subsurface input of freshwater
  - ***way*** better than just dumping freshwater in at the surface
- **BUT**, not validated with observations! Important b/c BPT sets the nature of ocean-glacier interactions in many models…

Plumes, melting & mixing

Testing theory & models with observations

Autonomous kayaks to measure plumes & melting

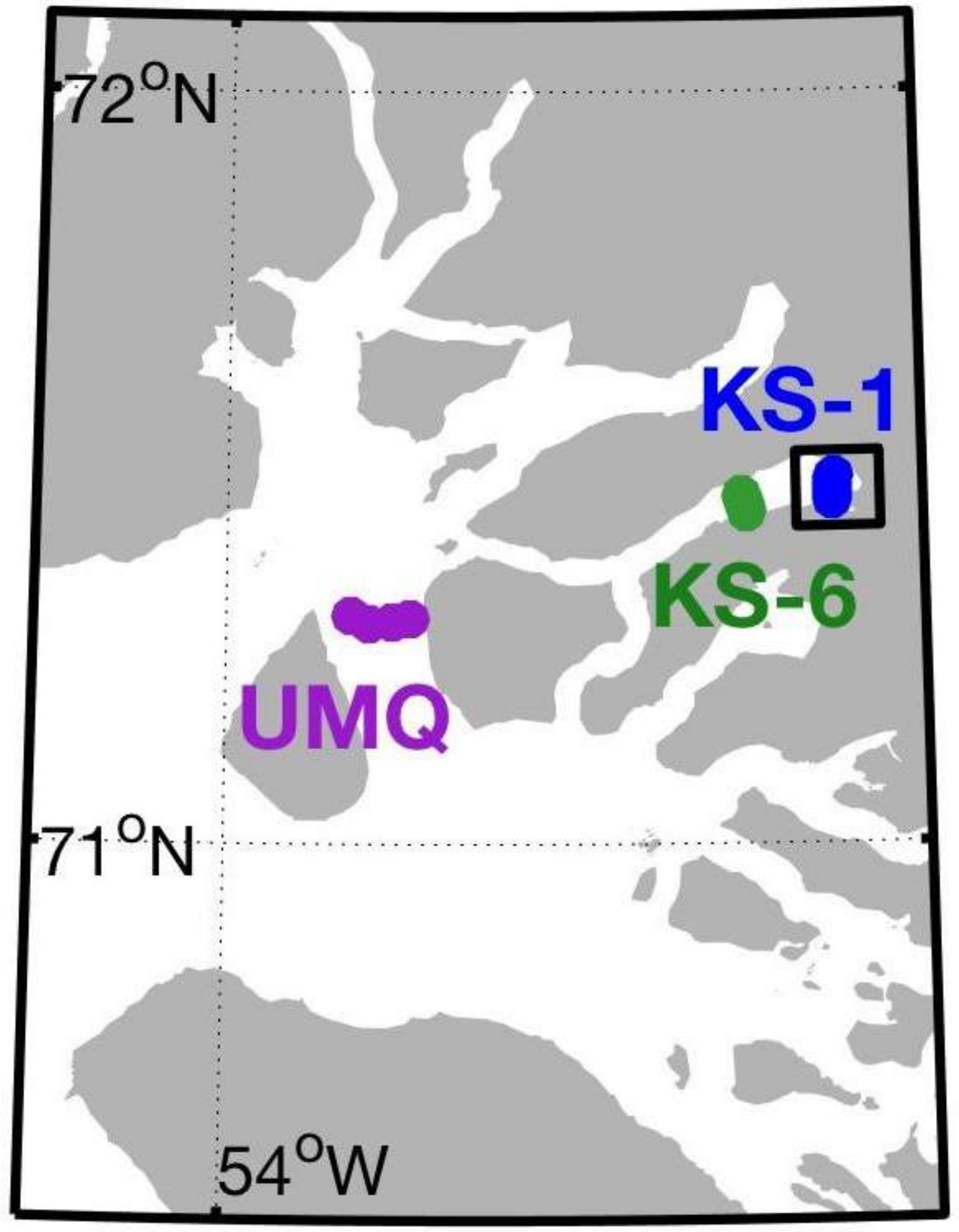


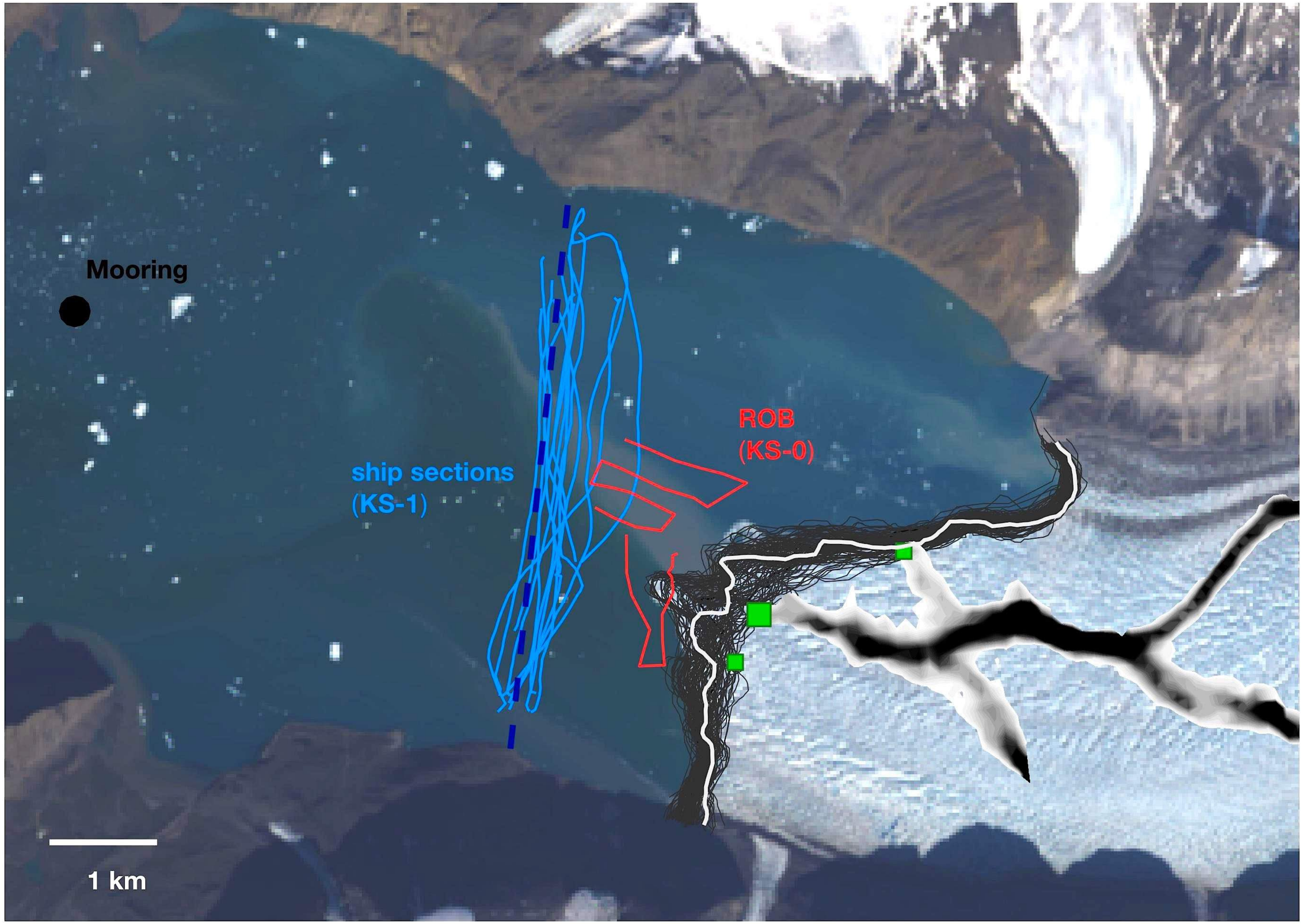
ROB/**ROSS** developed by J. Nash &
Oregon State Robotics Team

sped up 2x

(drone footage from D. Sutherland)

Near-glacier surveying with ship & autonomous kayak

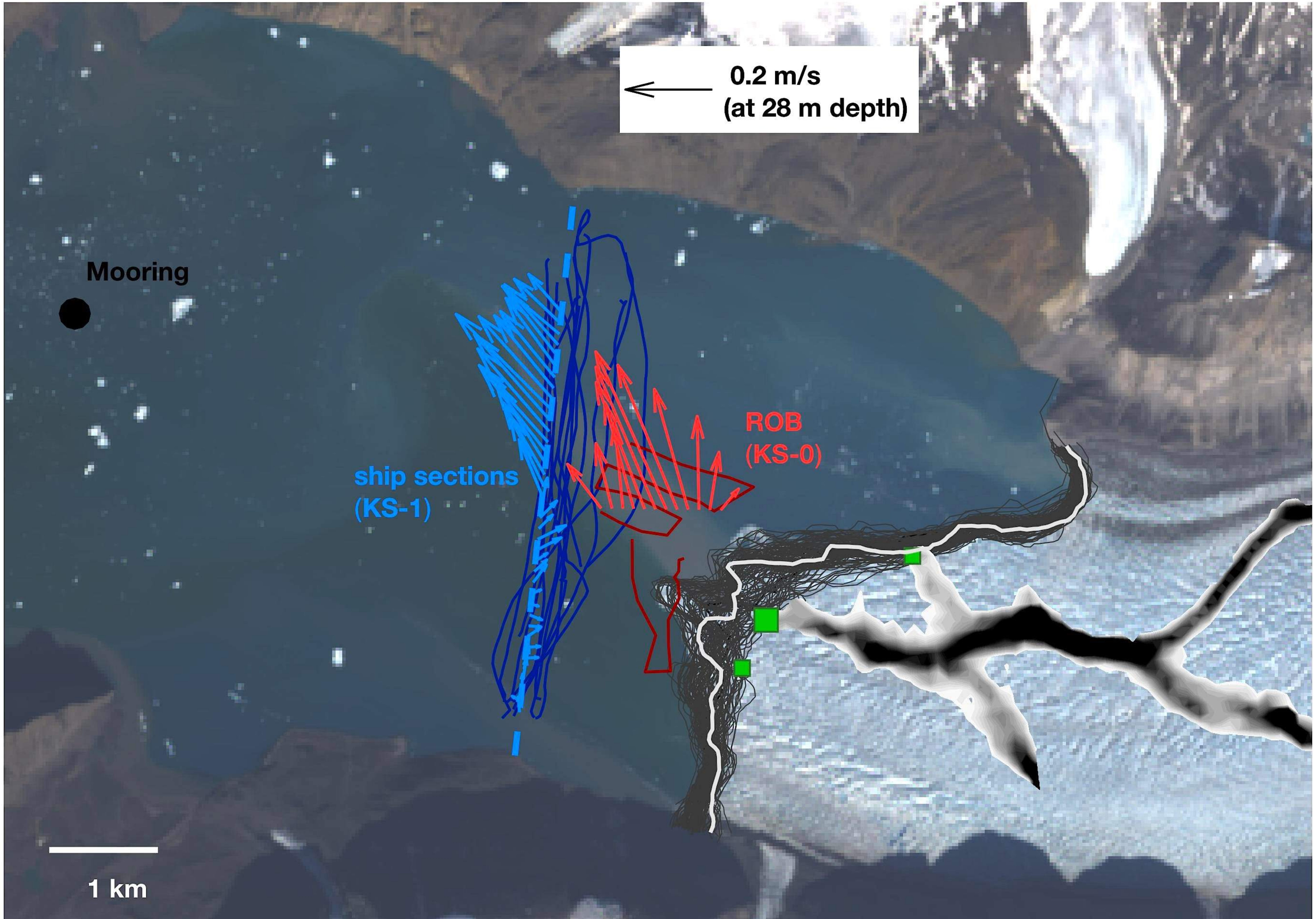




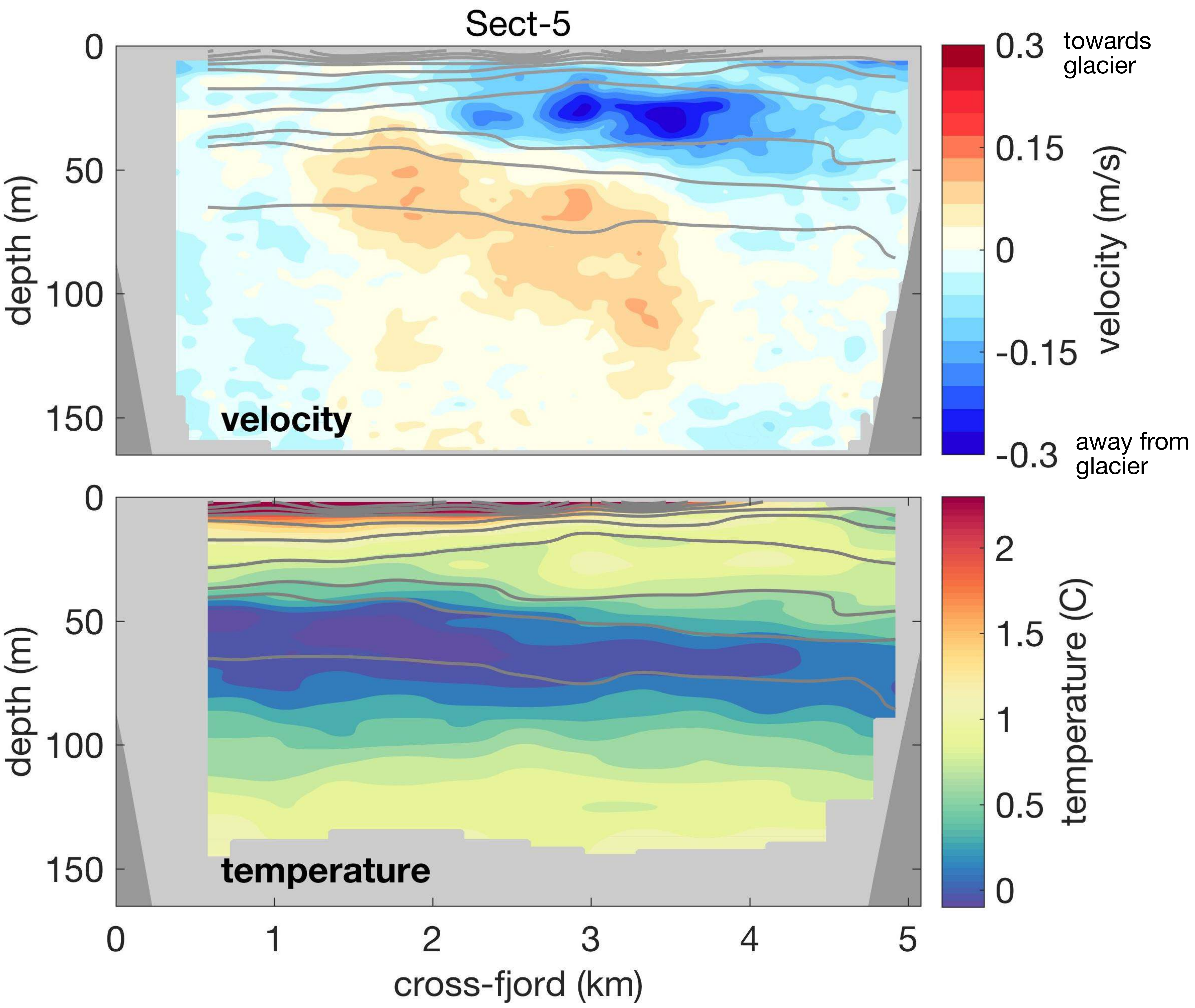
- ship & kayak (ROB) surveying: velocity & water properties
- moorings, surface drifters, time-lapse camera, etc.

Jackson et al, GRL (2017)

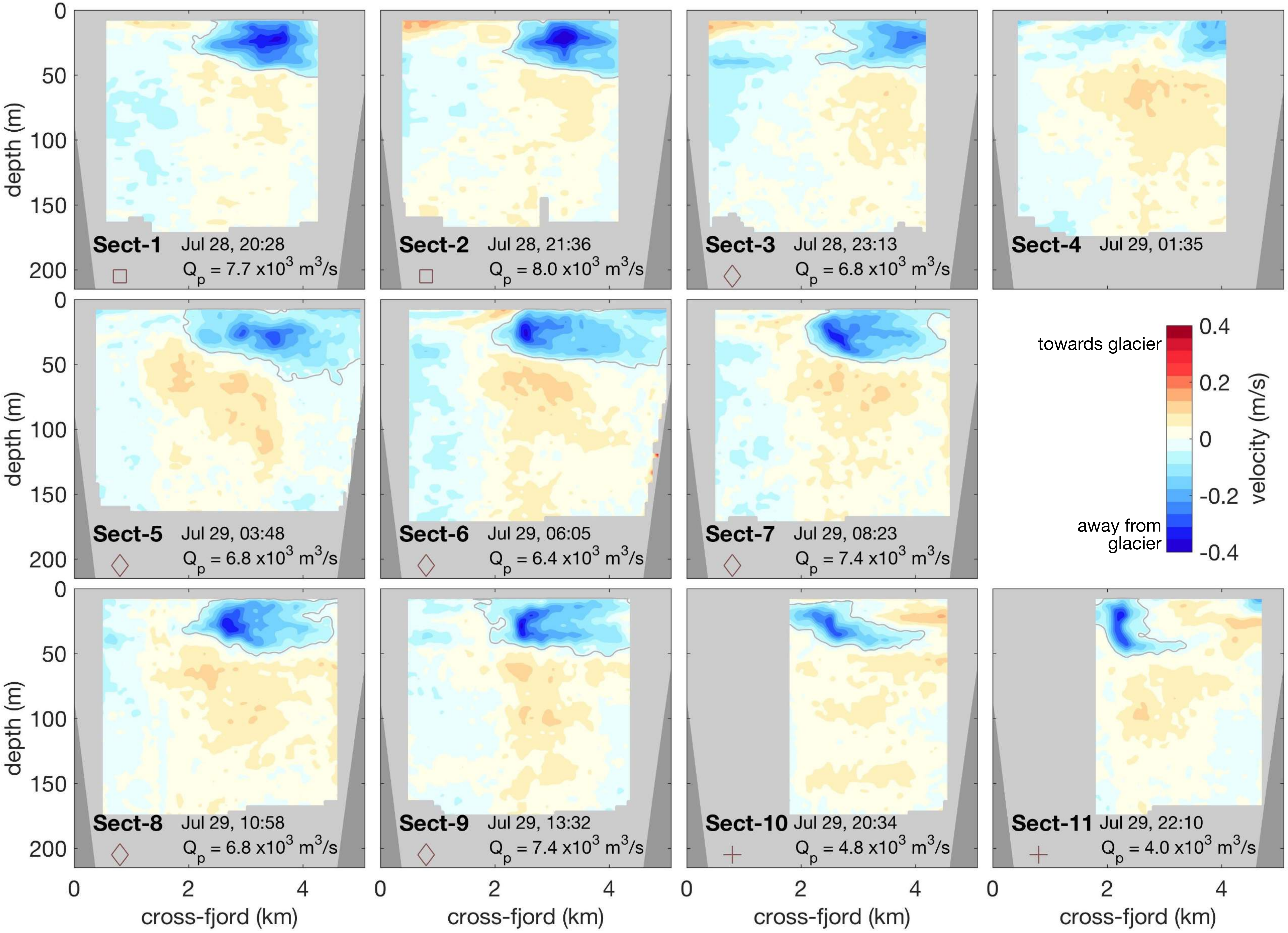
Outflowing discharge plume originating at prow of glacier



Outflowing plume is subsurface intensified



11 repeat sections over 26 hours

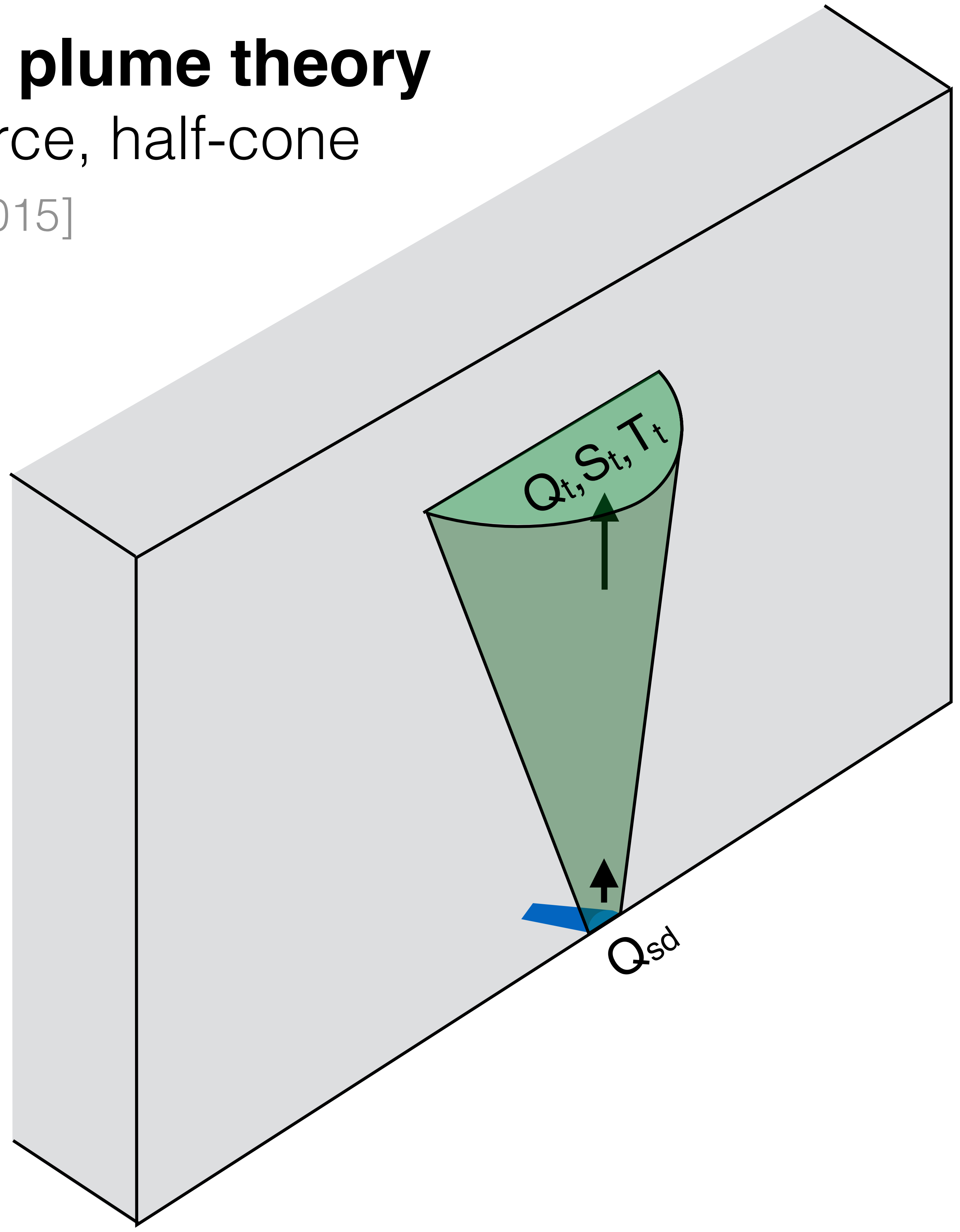


Two versions of buoyant plume theory (BPT)

axisymmetric plume theory

a.k.a. point source, half-cone

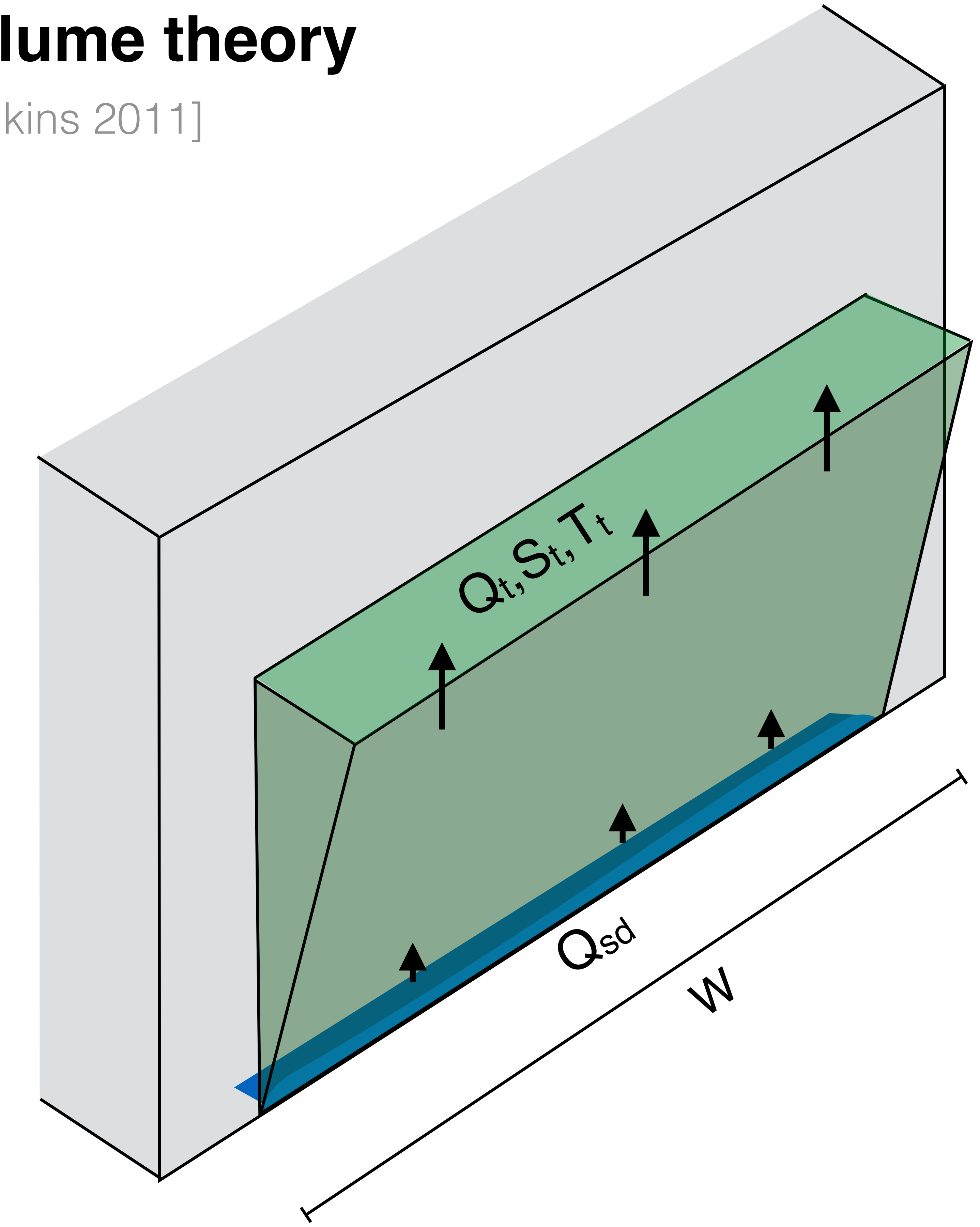
[e.g. Cowton et al. 2015]



- used for discharge plumes in Greenland
- assumes plume spreads radially from small outlet (≤10 m) to radius ~10-30 m

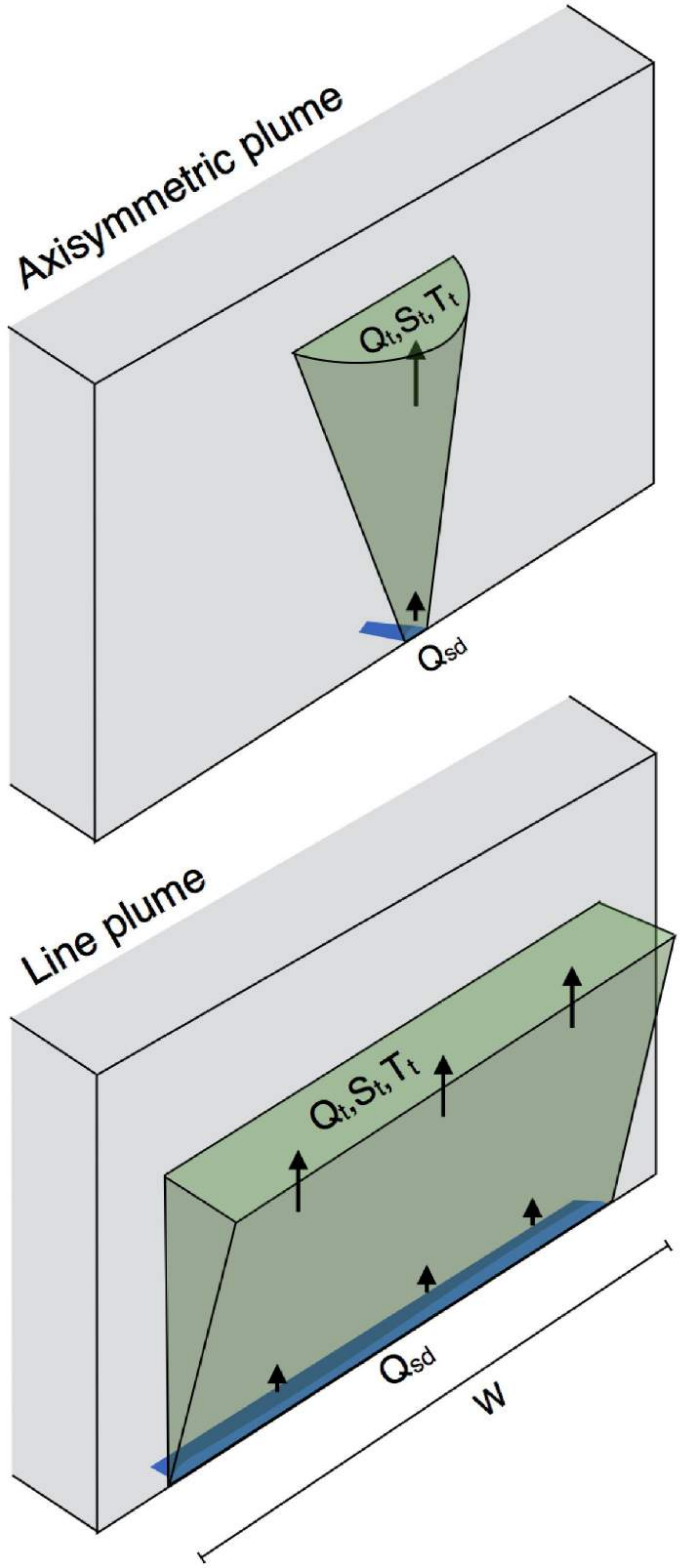
line plume theory

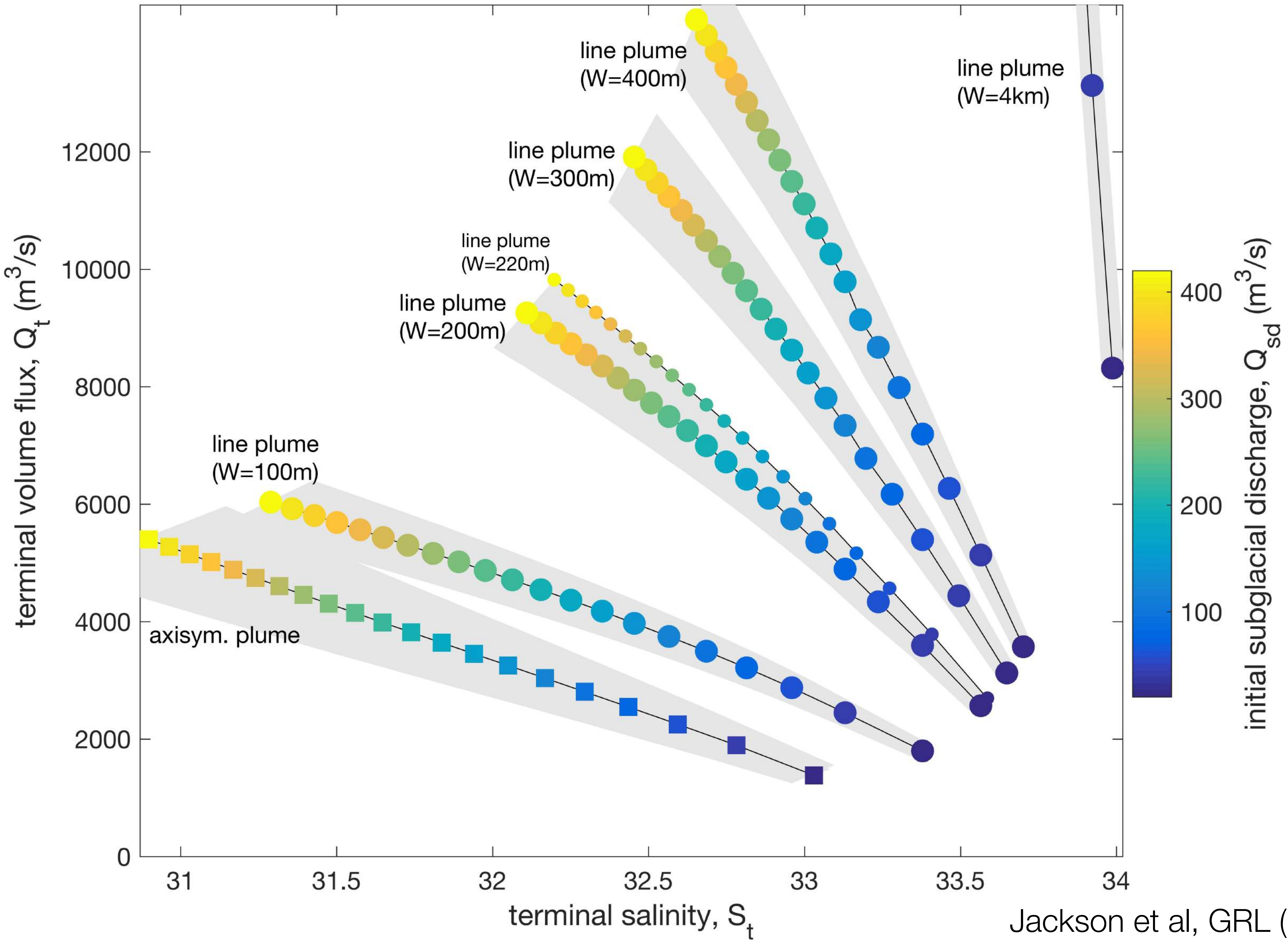
[e.g. Jenkins 2011]



- used for weak distributed discharge across whole terminus, or ambient melt
- assumes plume thickness ≪ width (W)

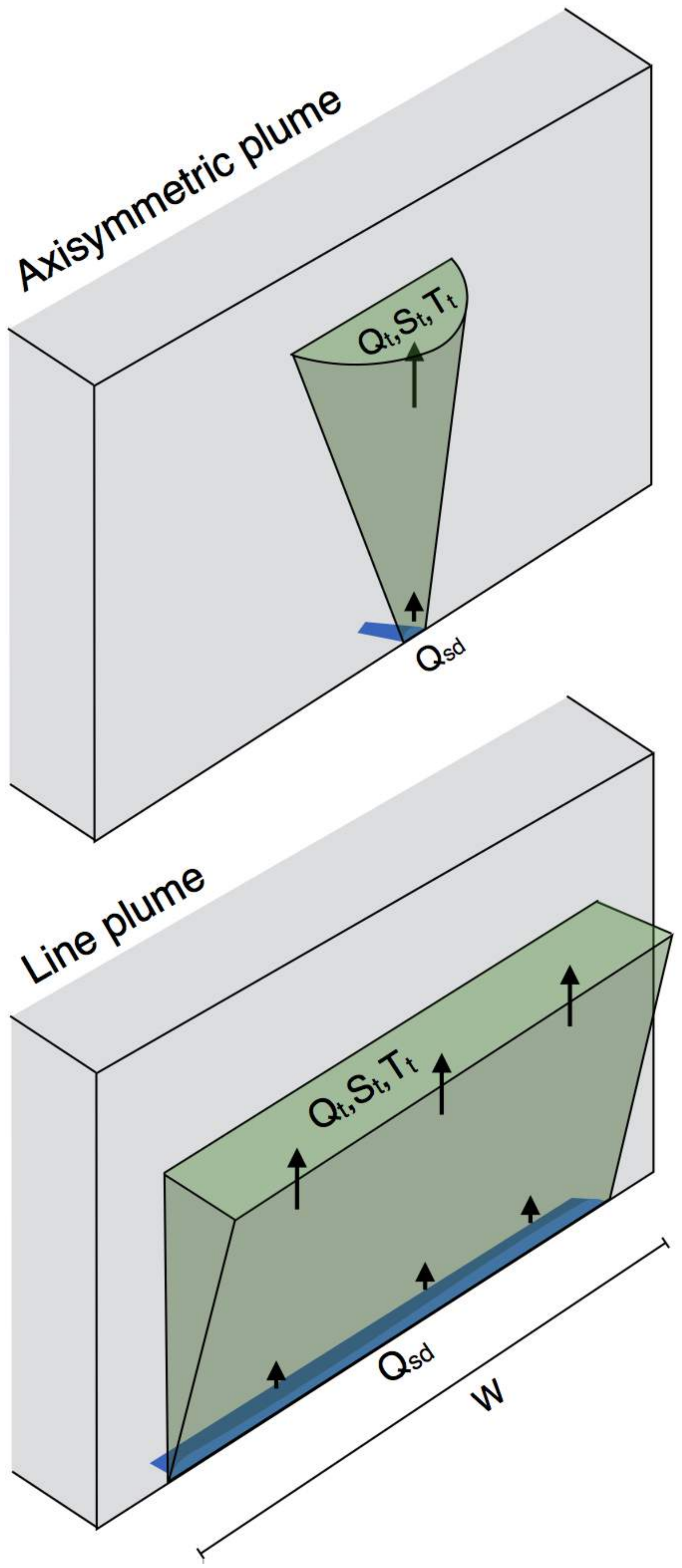
Parameter space of plume volume flux & salinity

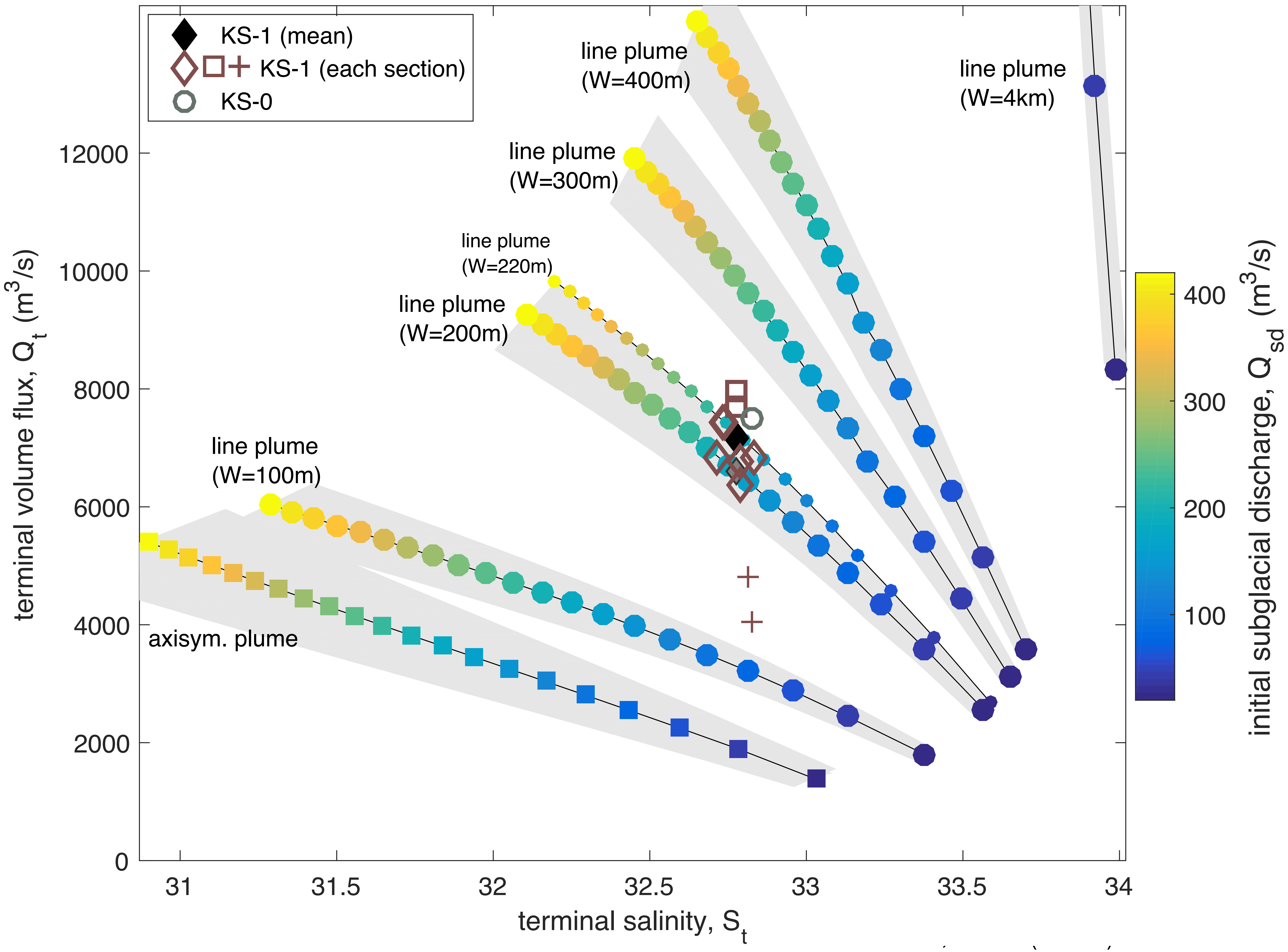




Jackson et al, GRL (2017)

Best fit is ‘truncated’ line plume of 220±20 m width, with 200±40 m^3/s of discharge

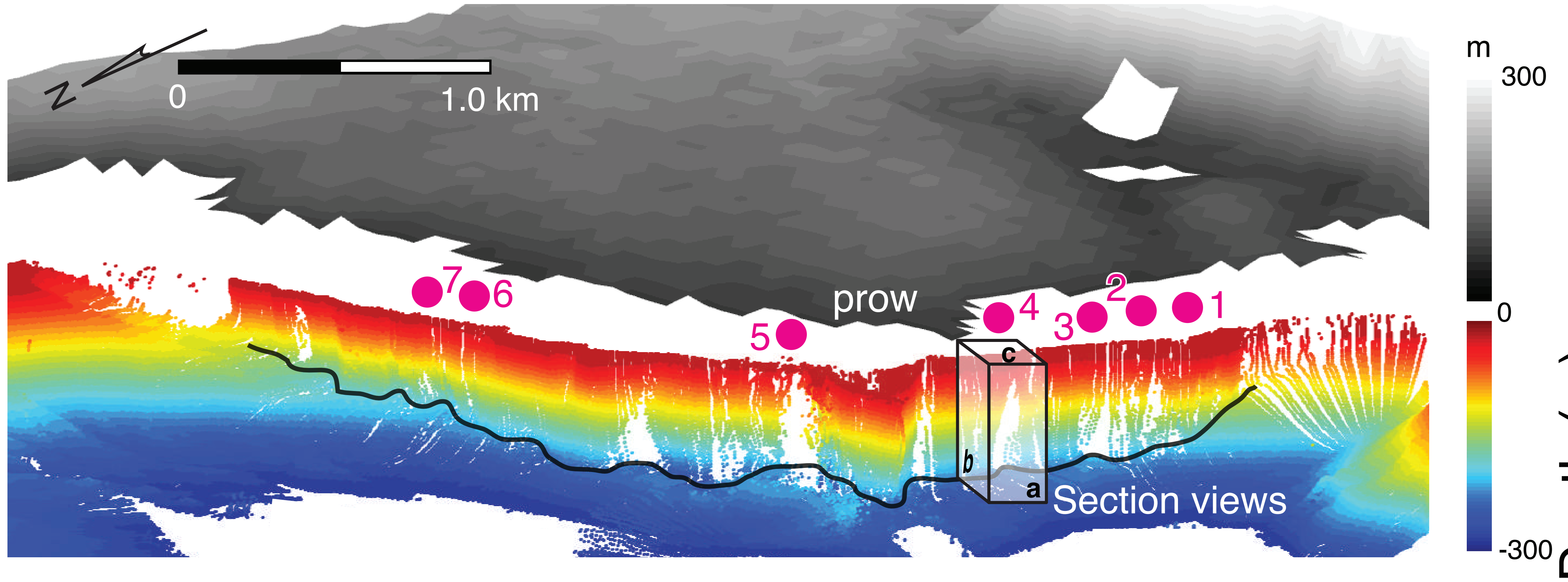


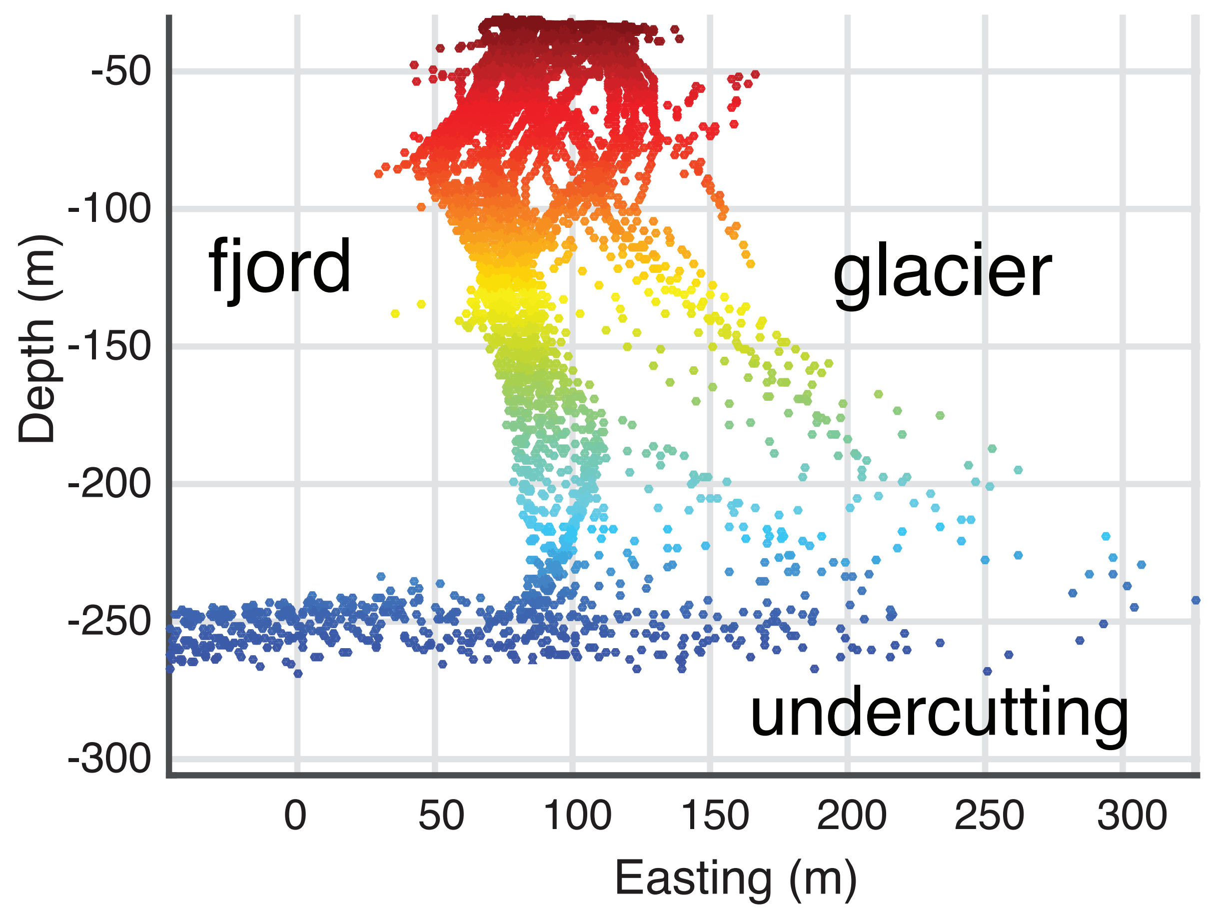


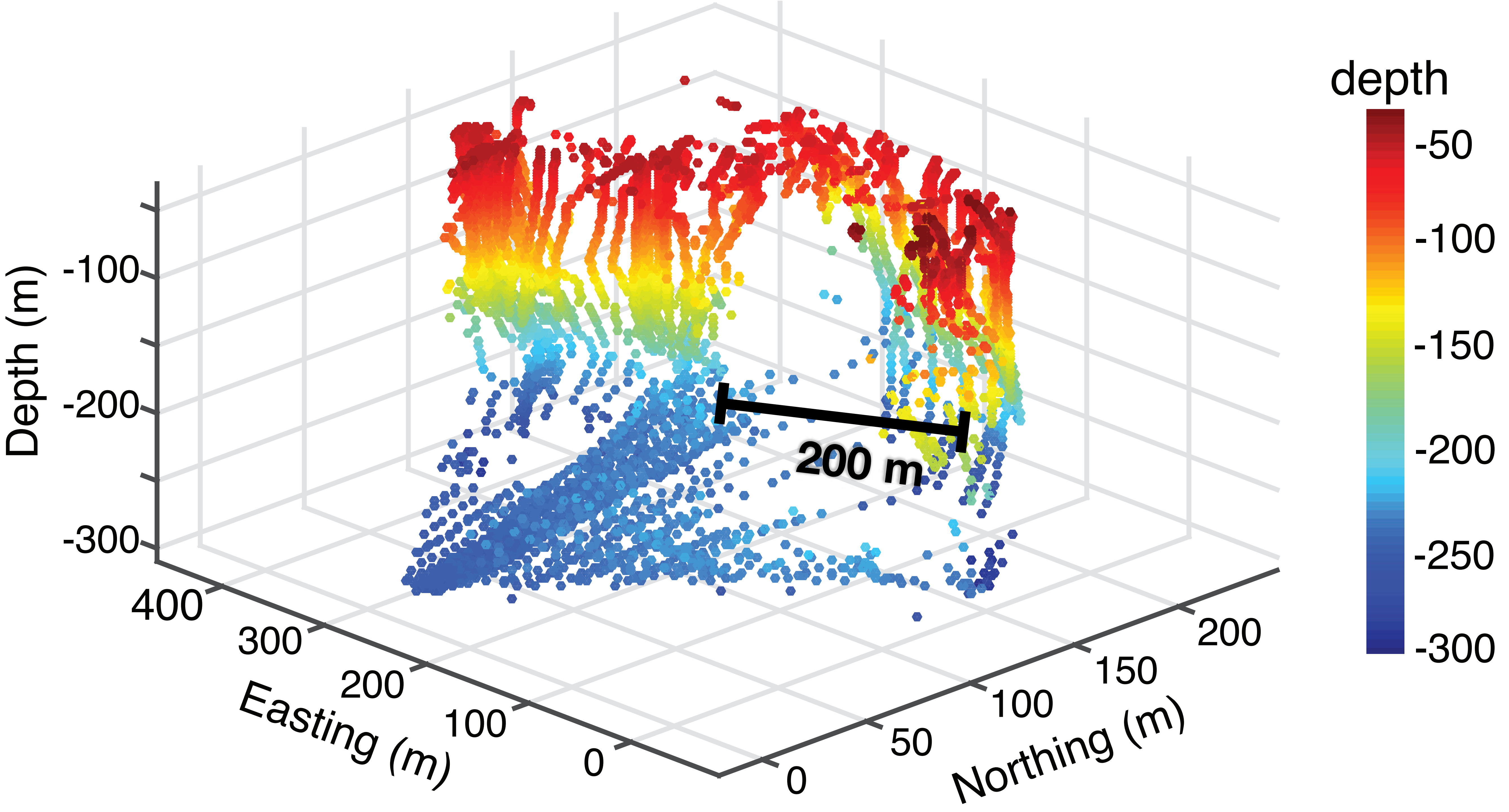
Best fit is ‘truncated’ line plume of 220±20 m width

Compare to:

Multibeam sonar shows ~200 m wide undercut in terminus where plume emerges





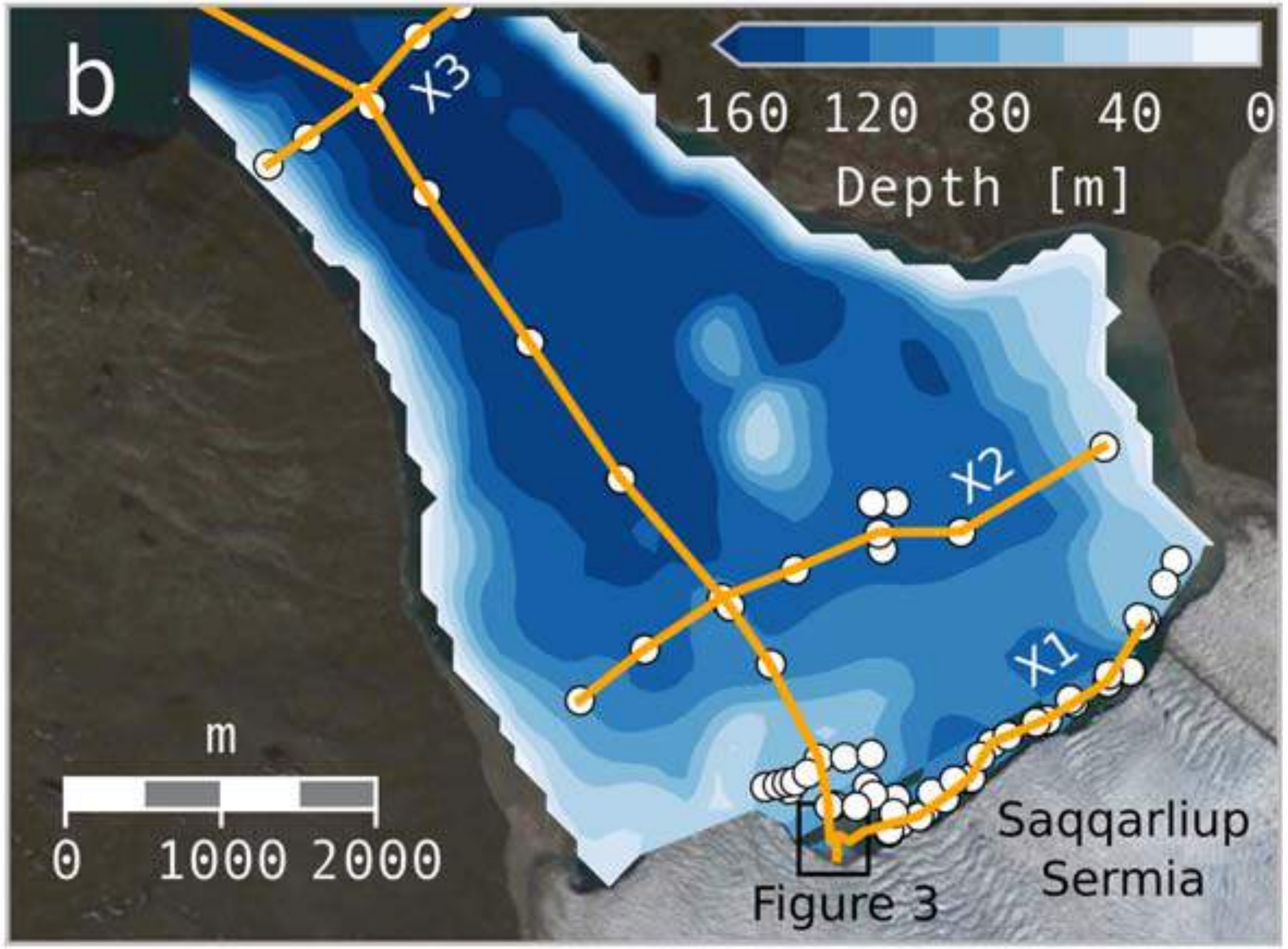


Fried et al 2015

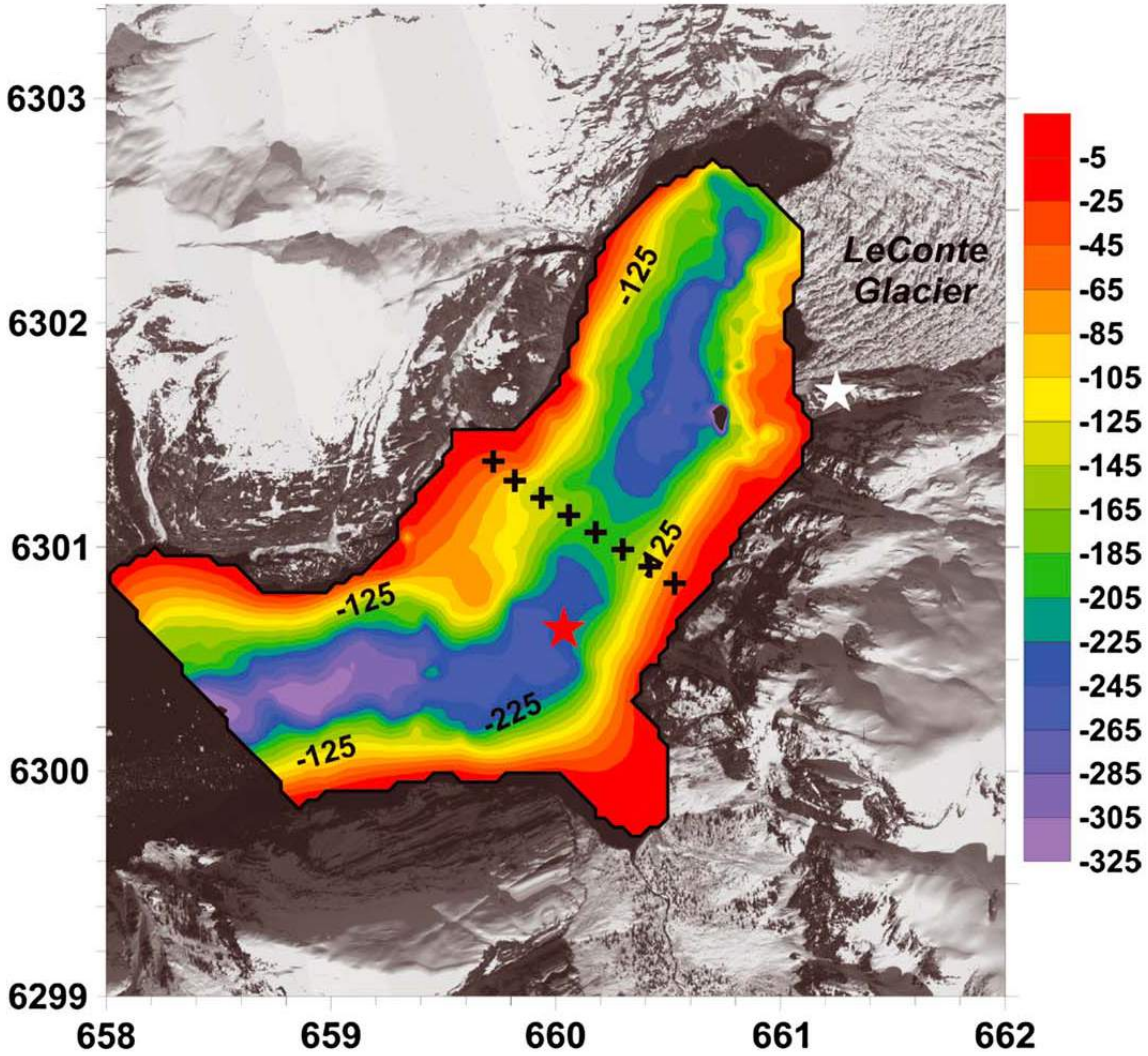
What about other glaciers?

Saqqarliup Sermia, West Greenland

LeConte Glacier, Alaska



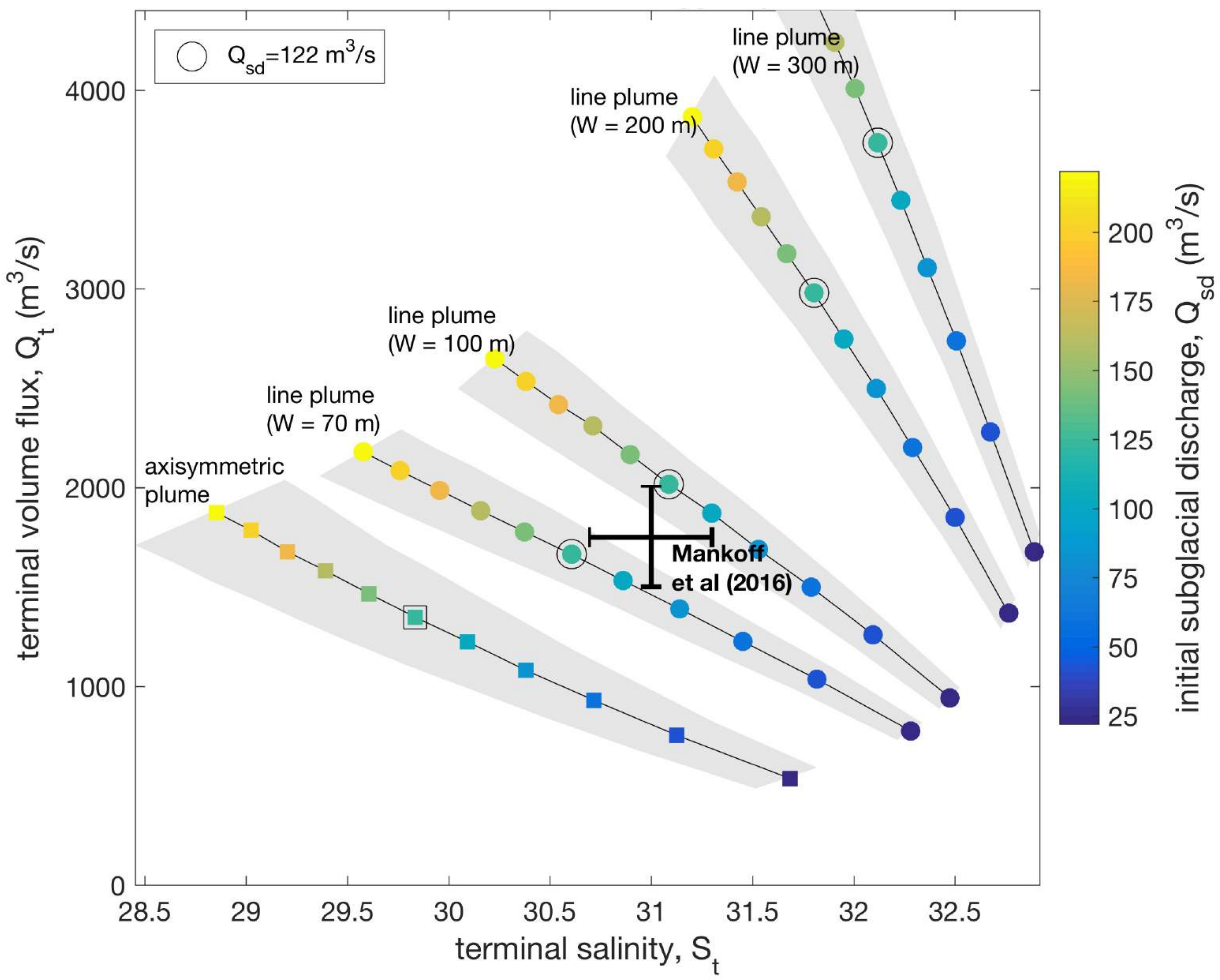
Mankoff et al, 2016



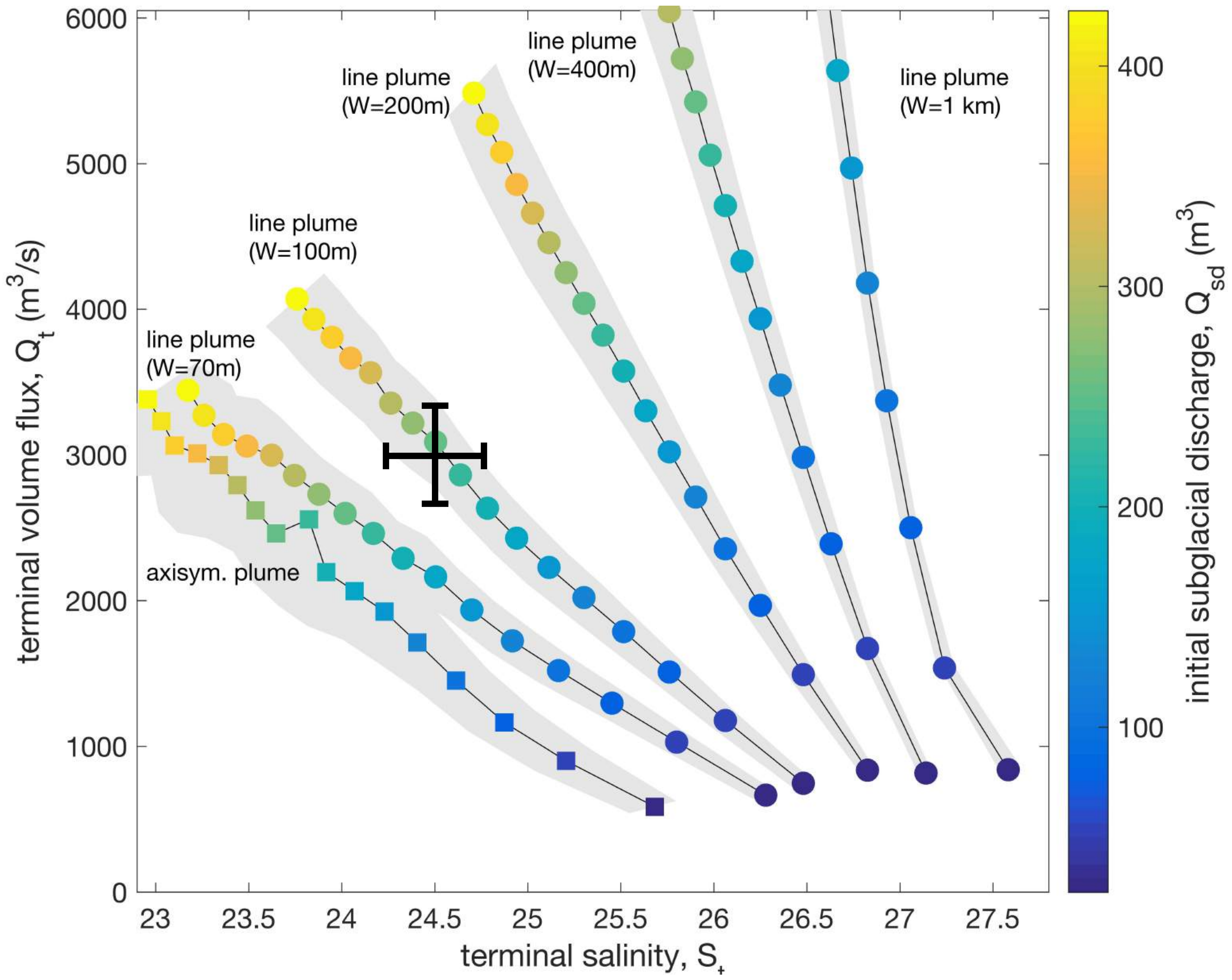
ongoing work (Jackson, Nash, Sutherland, Amundson, Motyka)

These observations also suggest a ‘truncated’ line plume of ~100 m width

Saqqarliup Sermia, West Greenland



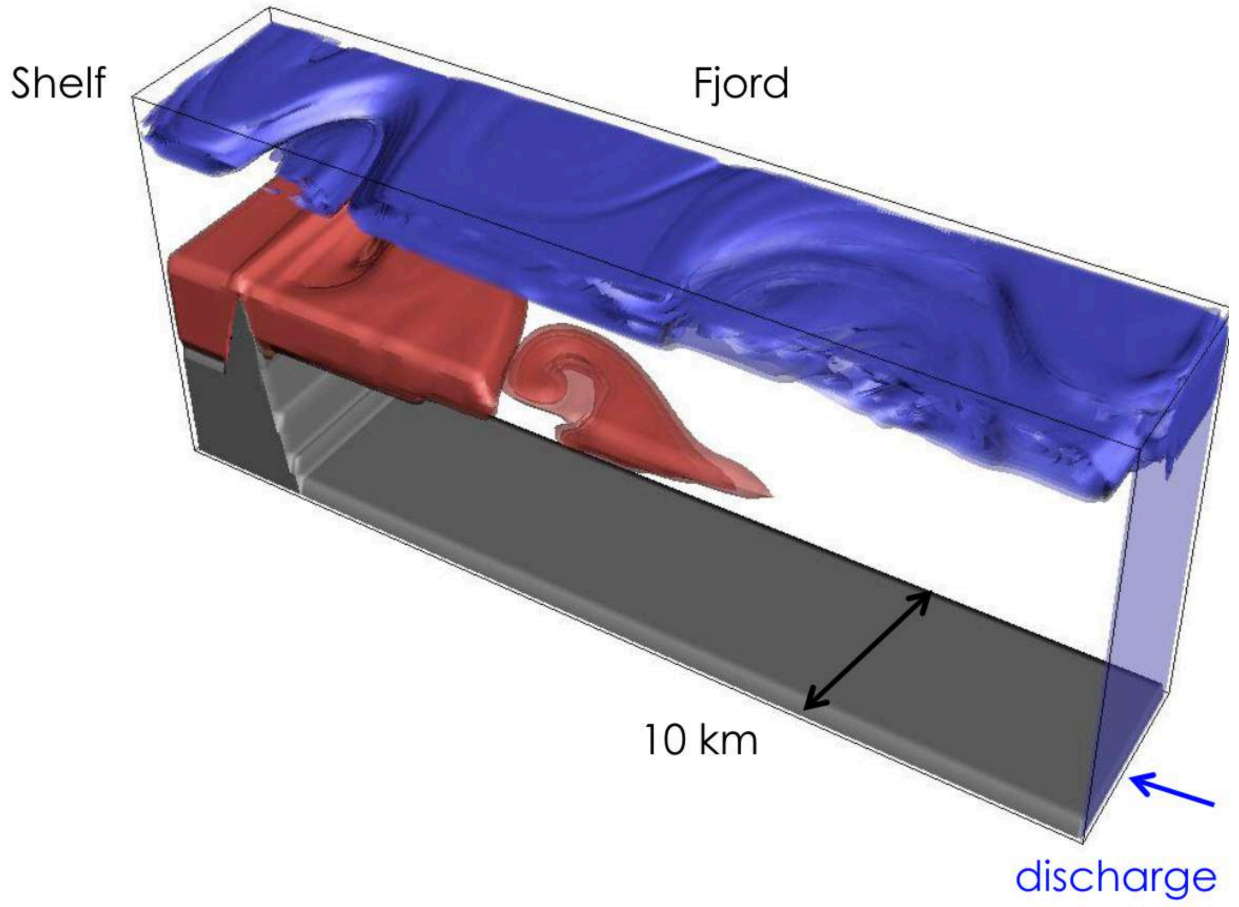
LeConte Glacier, Alaska



→ both suggest much more entrainment than axisymmetric theory can explain

→ best fit are line plumes of W~100 m

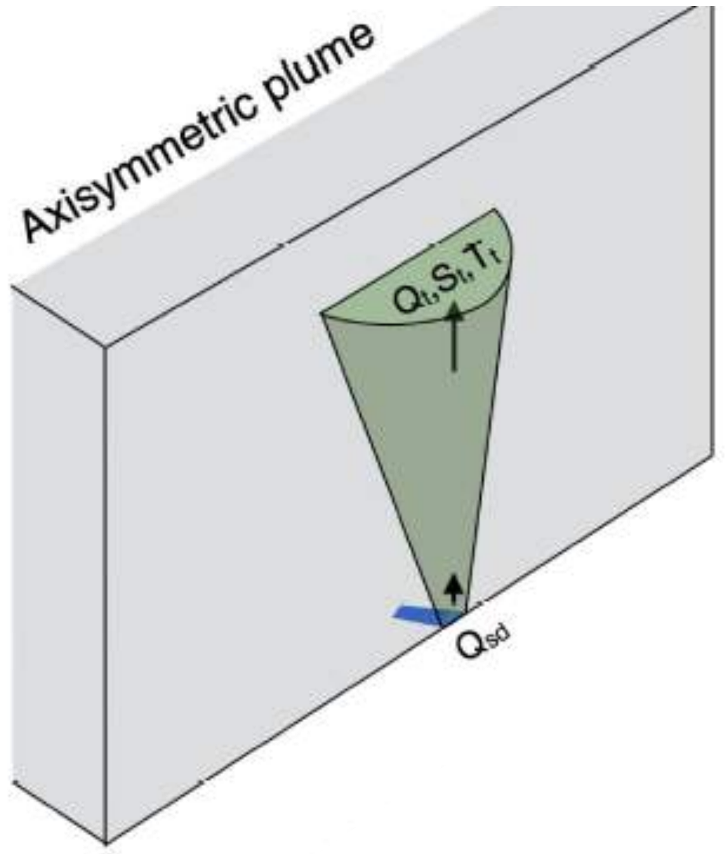
Does this matter for modeling ocean-glacier interactions?

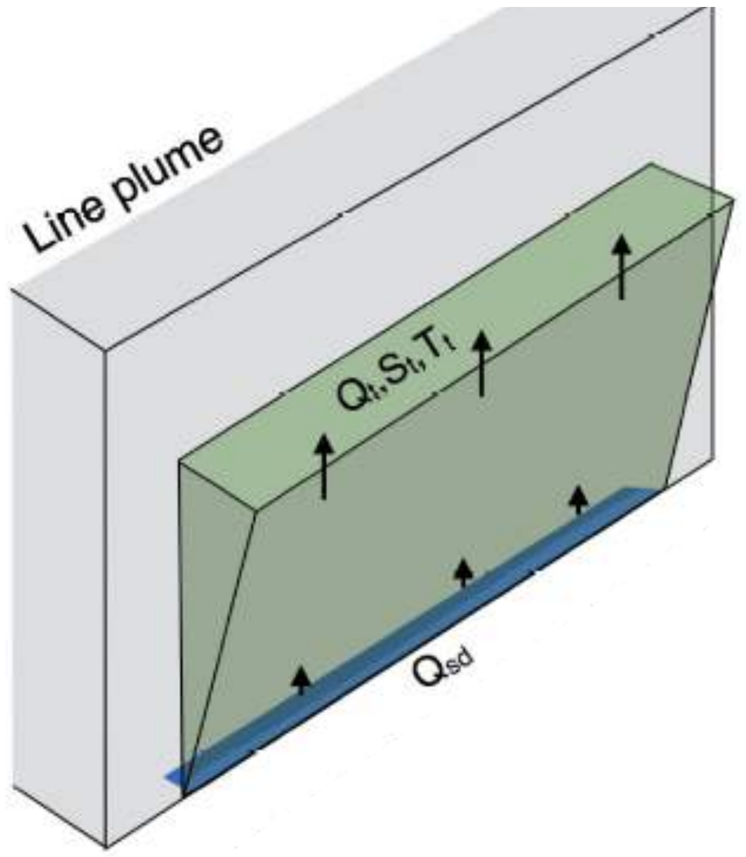


For a given input of subglacial discharge (200 m^3/s) at KS:

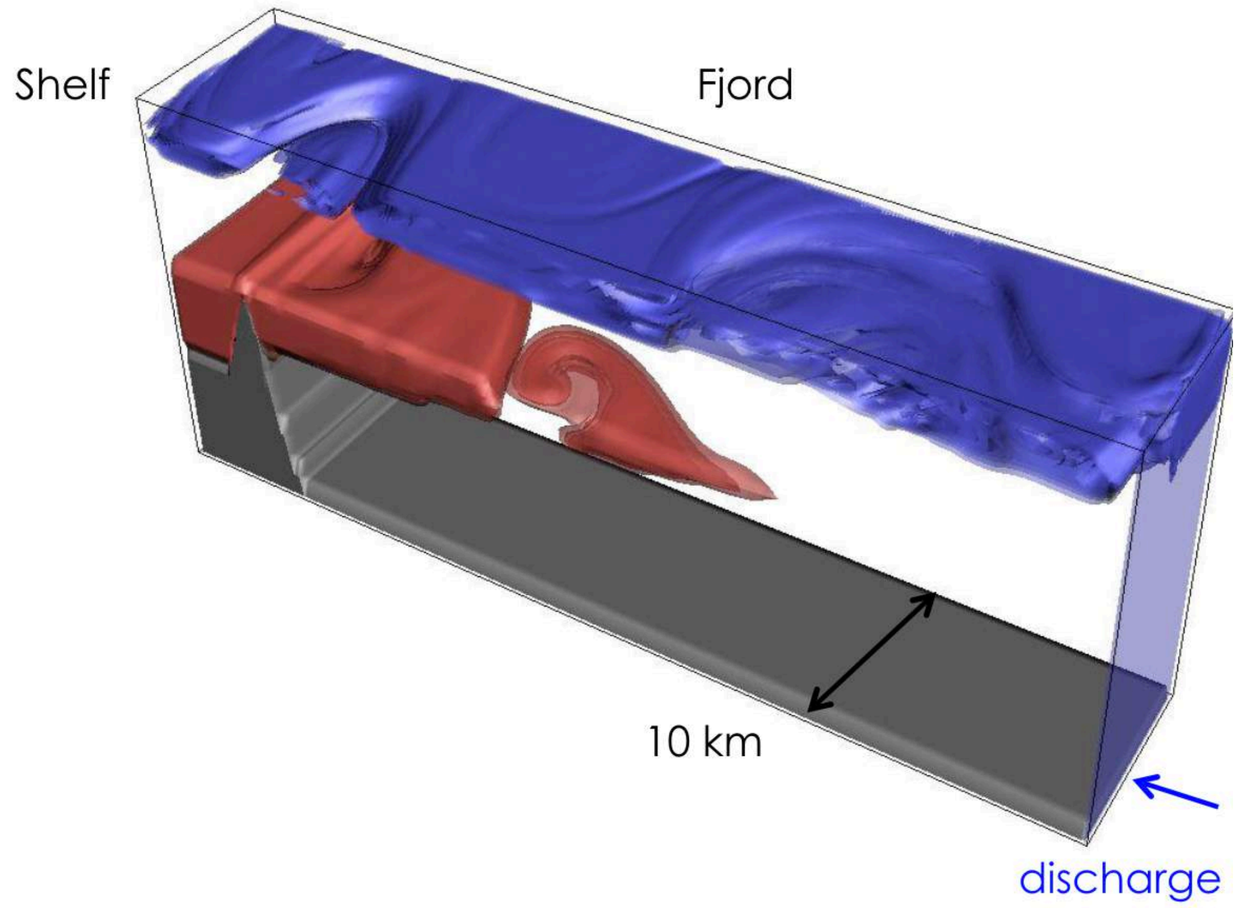
	axisymmetric plume	**'truncated' line plume** (W=220 m)
terminal volume flux	3,600 m^3/s	6,500 m^3/s
freshwater in plume	6%	3%

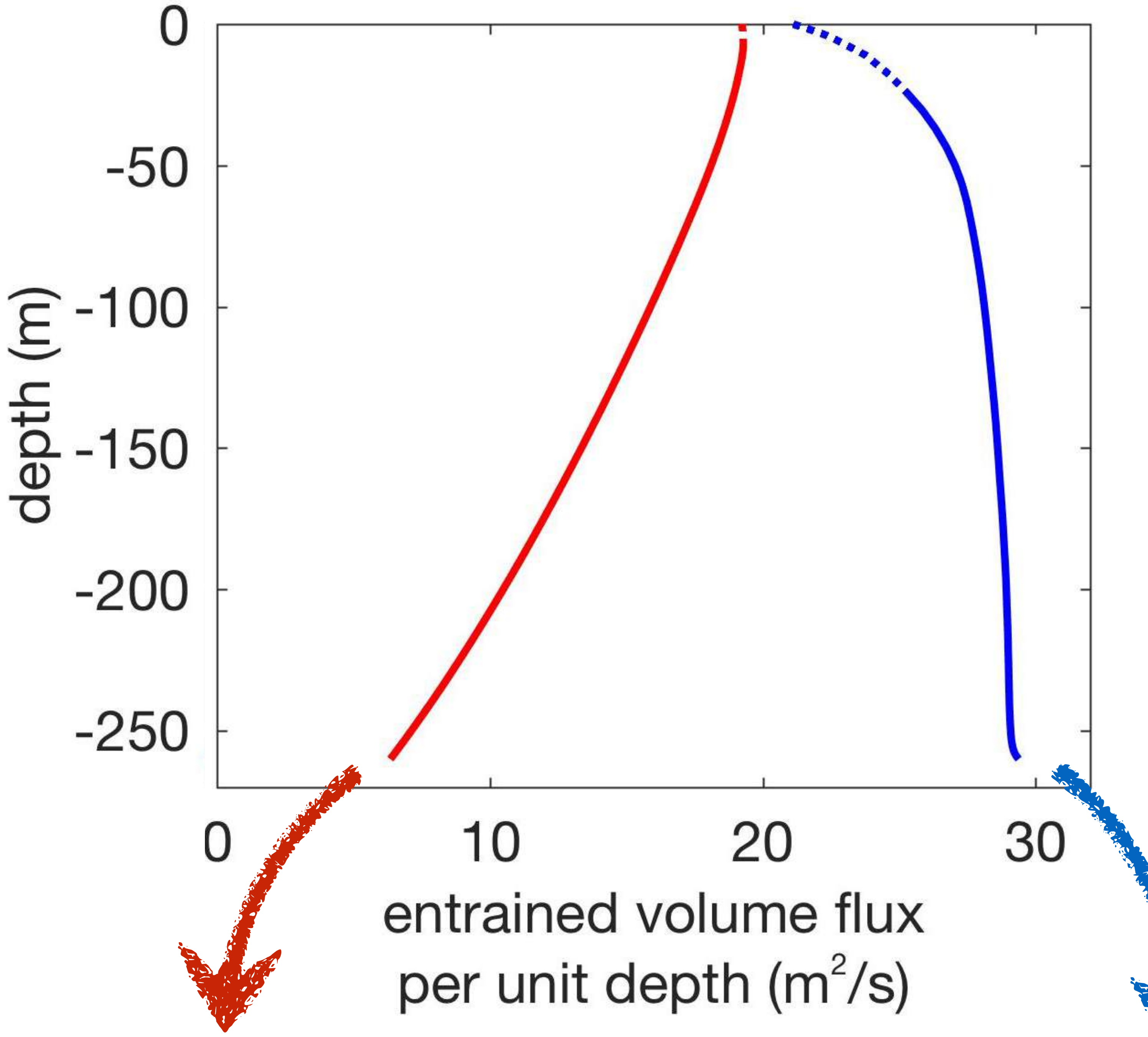
- **2× more vigorous fjord circulation**
- **2× mixing of freshwater**
- **3x more melting**

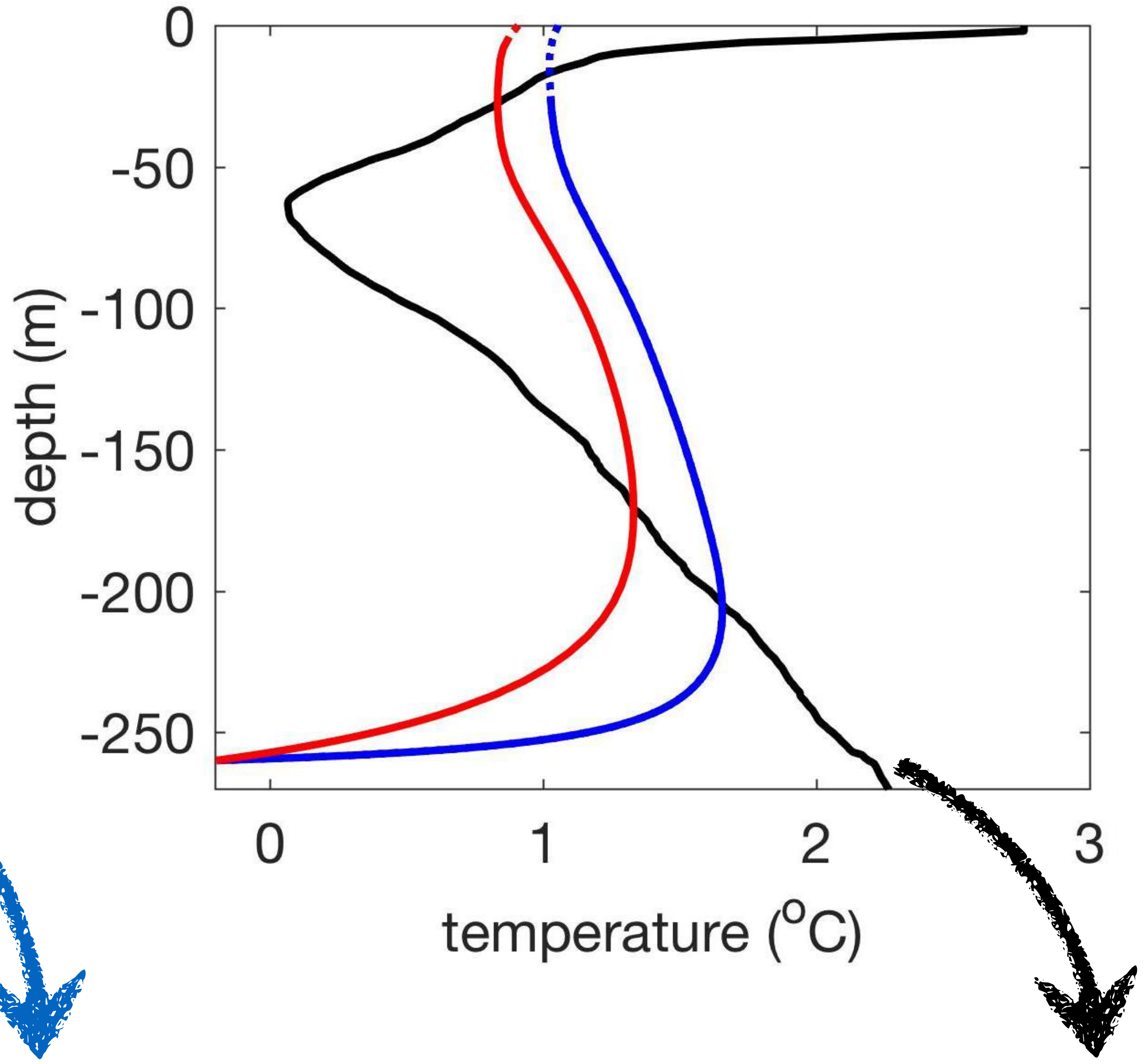




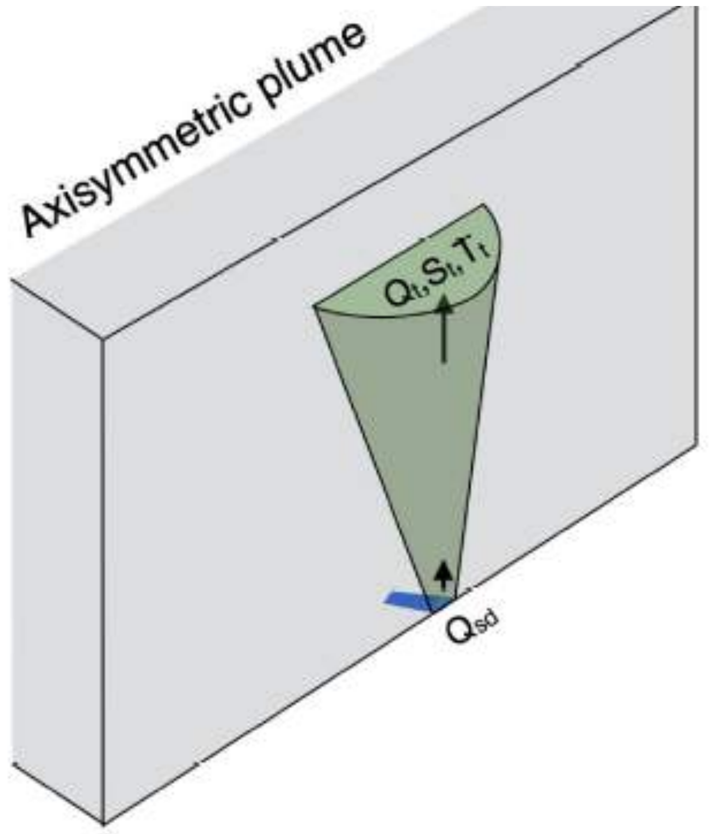
Does this matter for modeling ocean-glacier interactions?

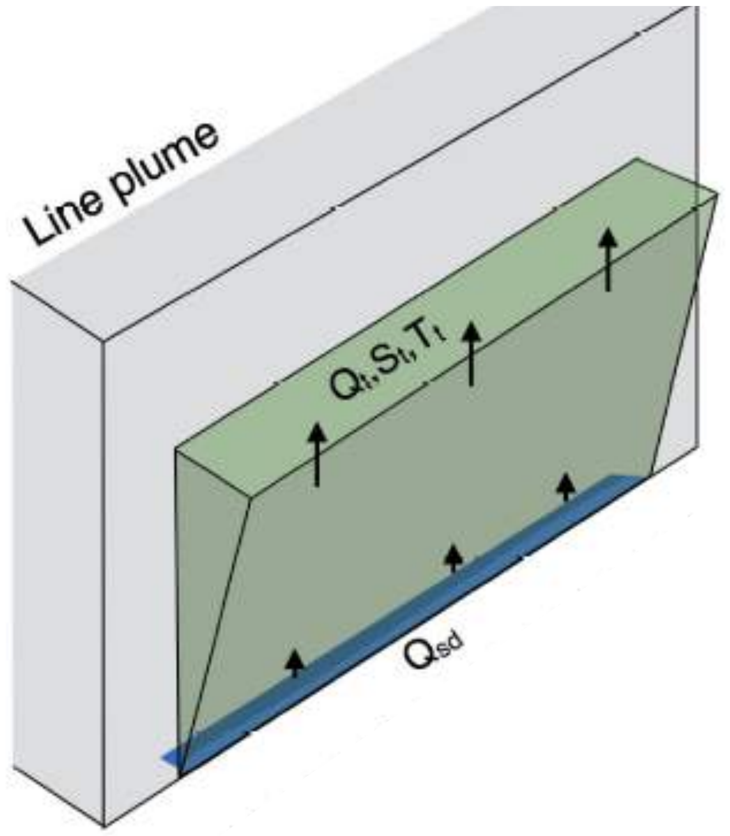






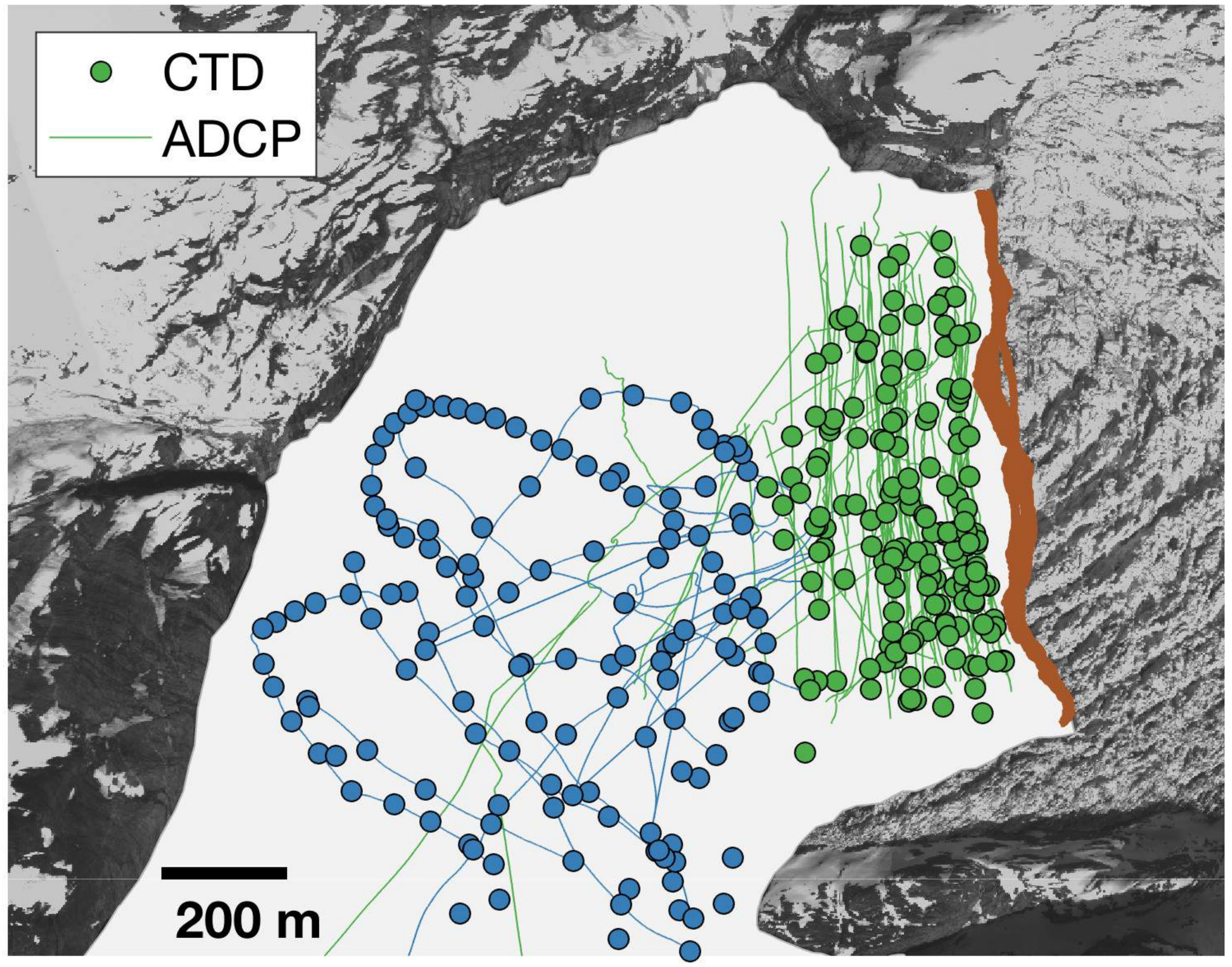
ambient fjord
water

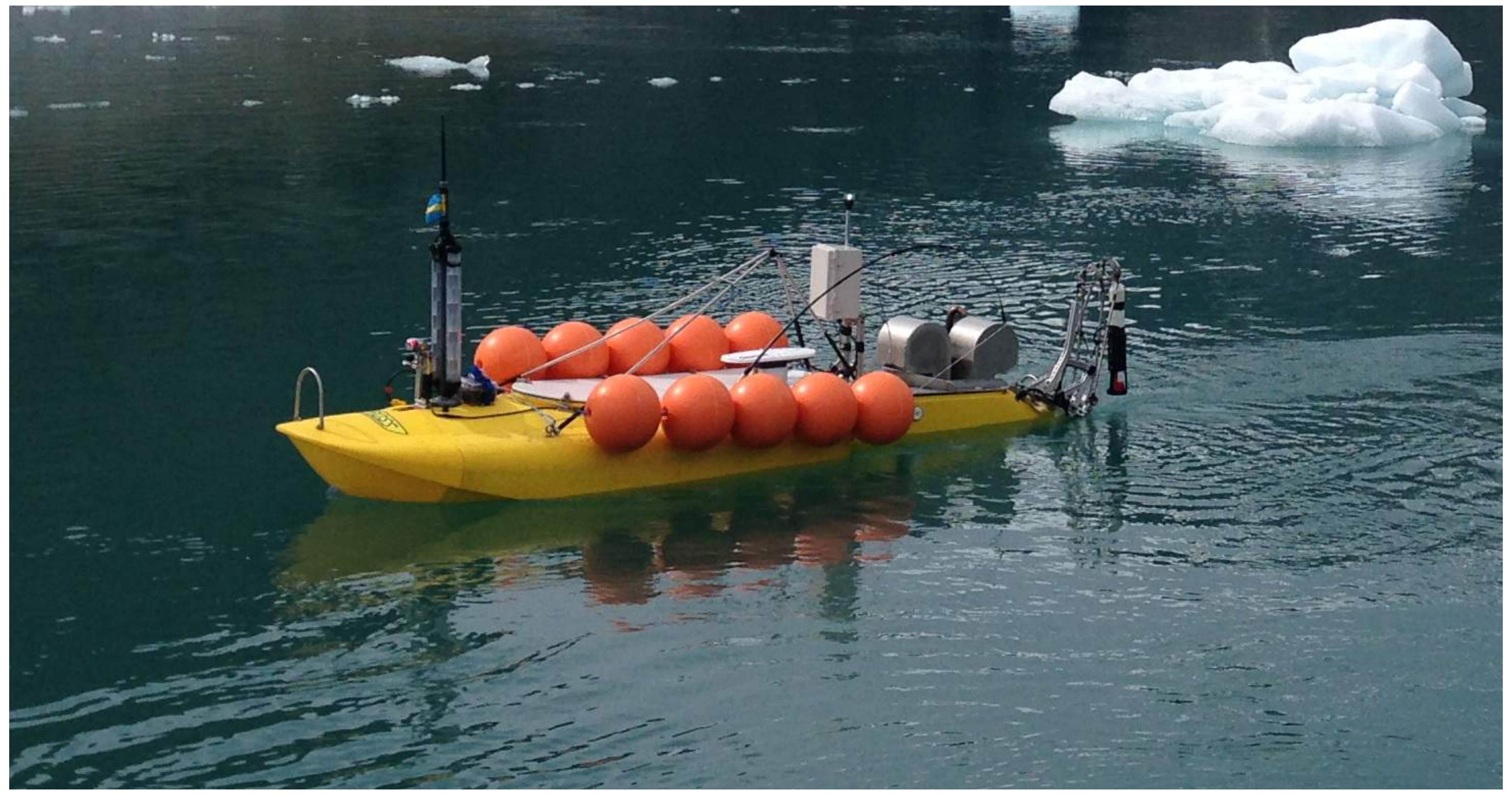




Testing the melt parameterization (used within BPT)

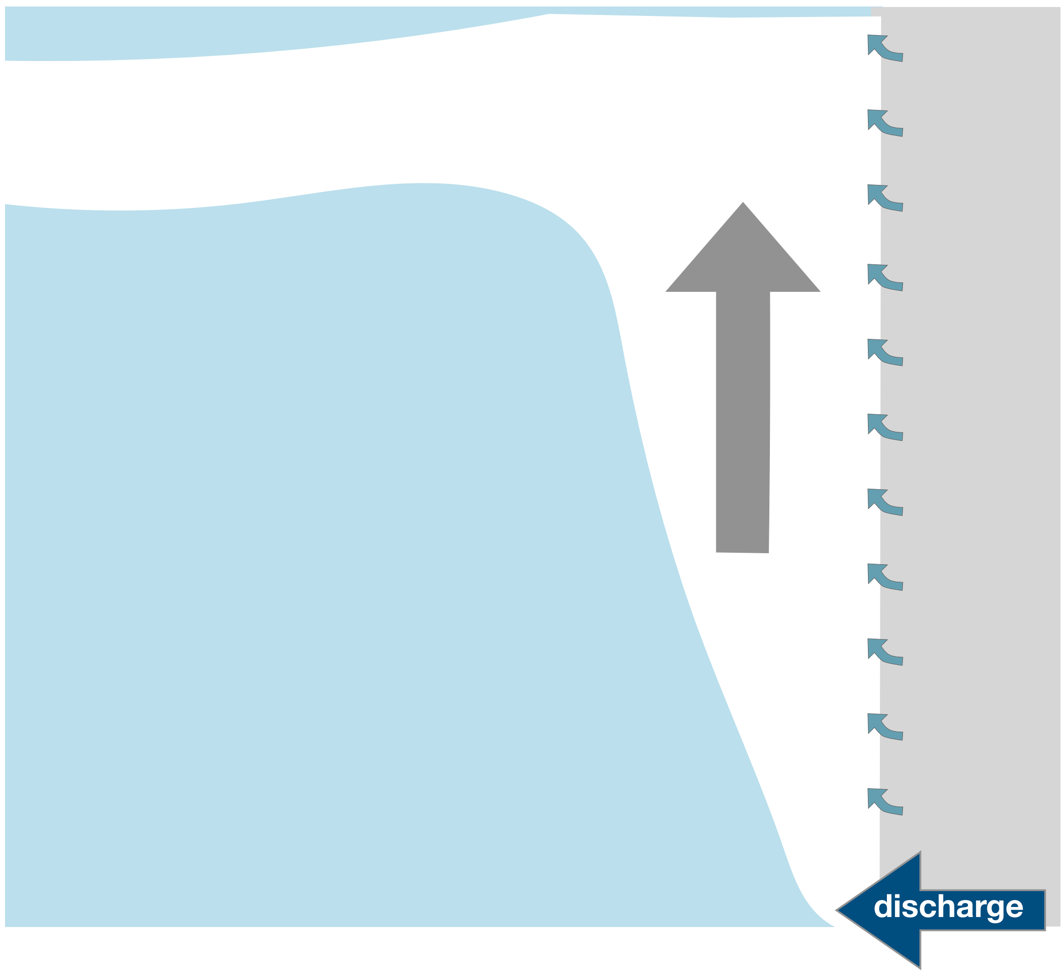
LeConte Glacier, Alaska



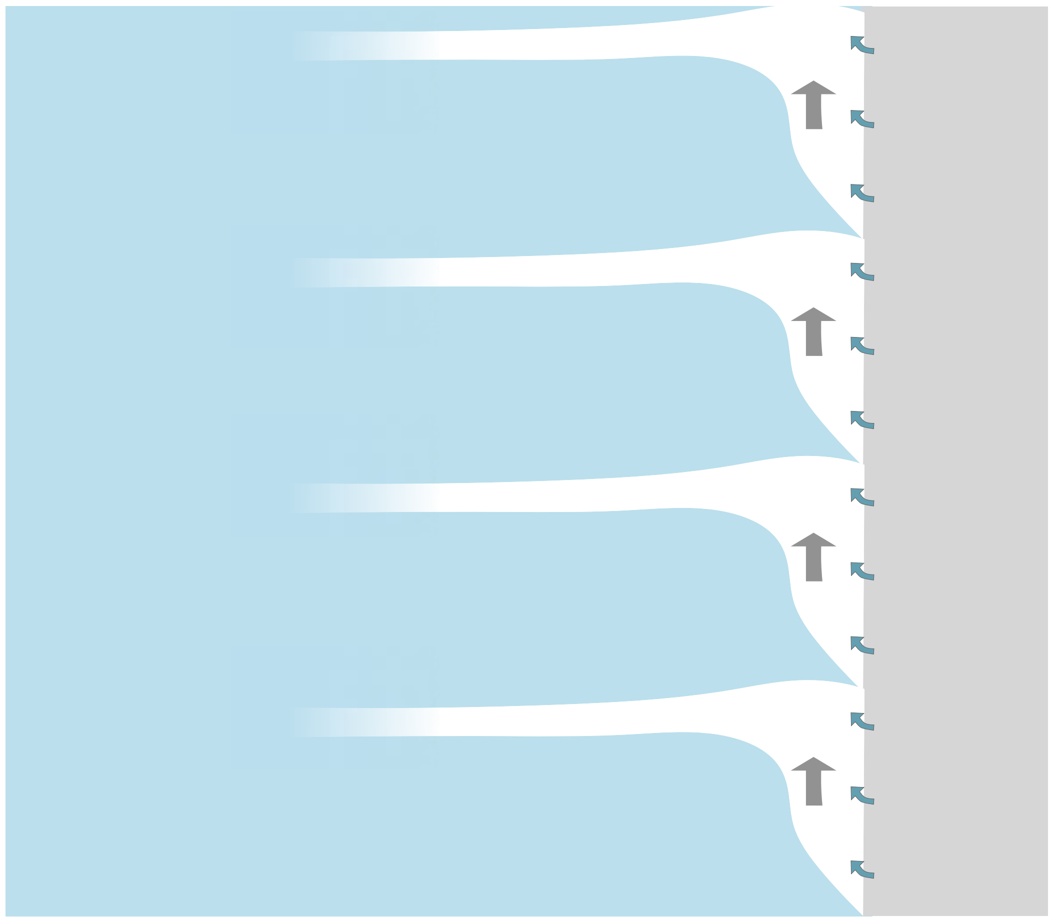


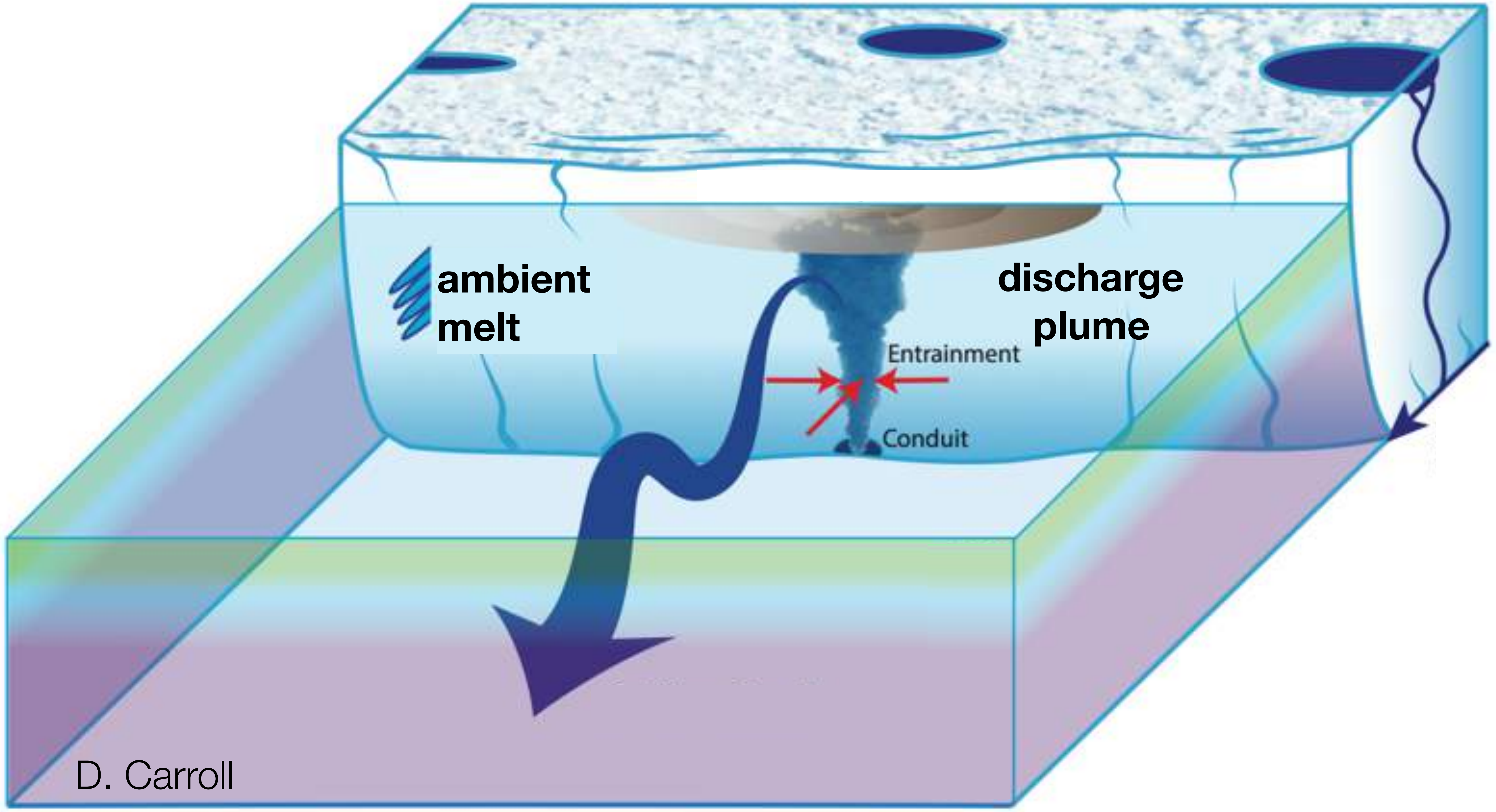
Testing the melt parameterization: **ambient melting**

discharge plume



ambient melt plumes

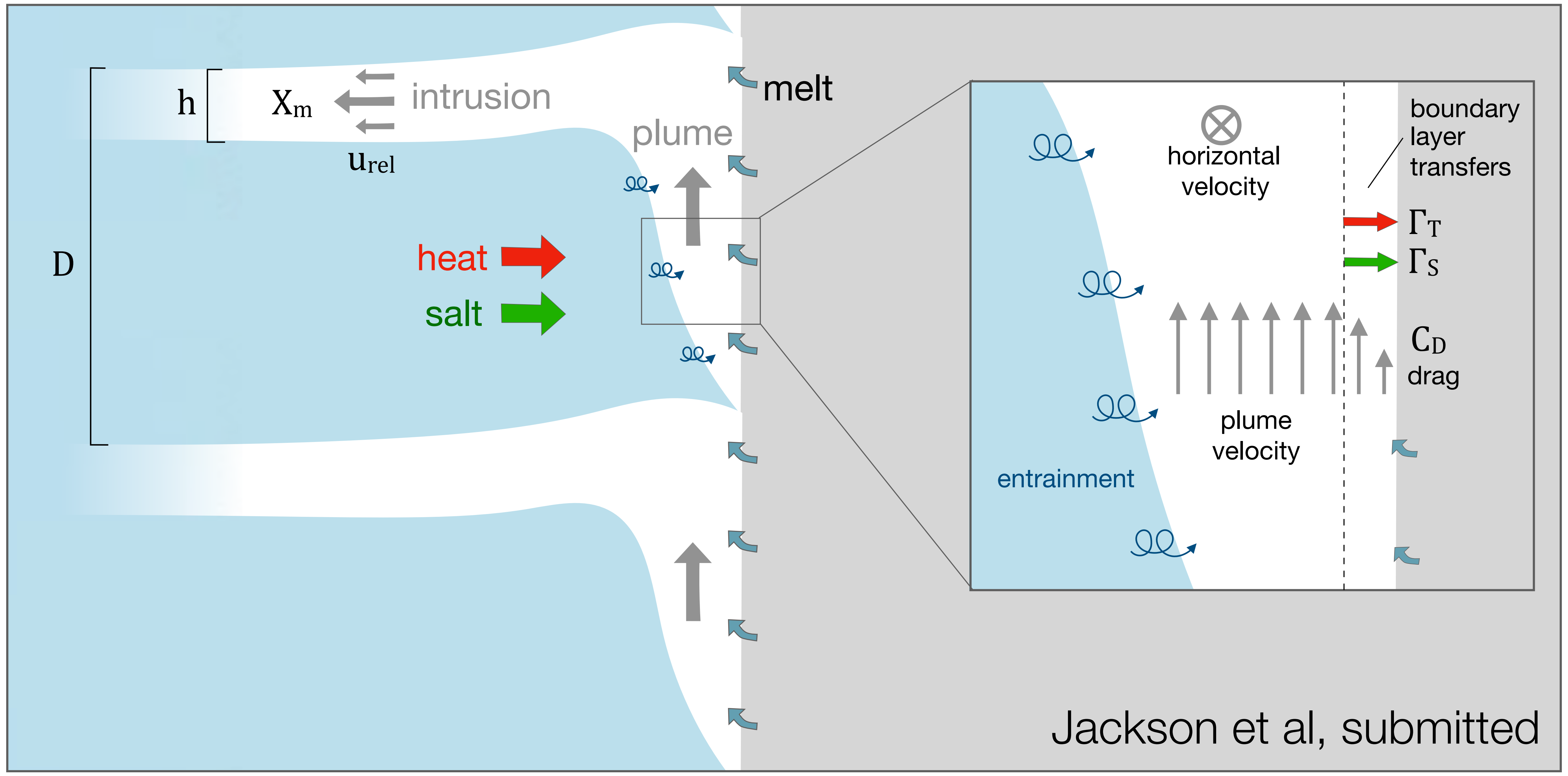




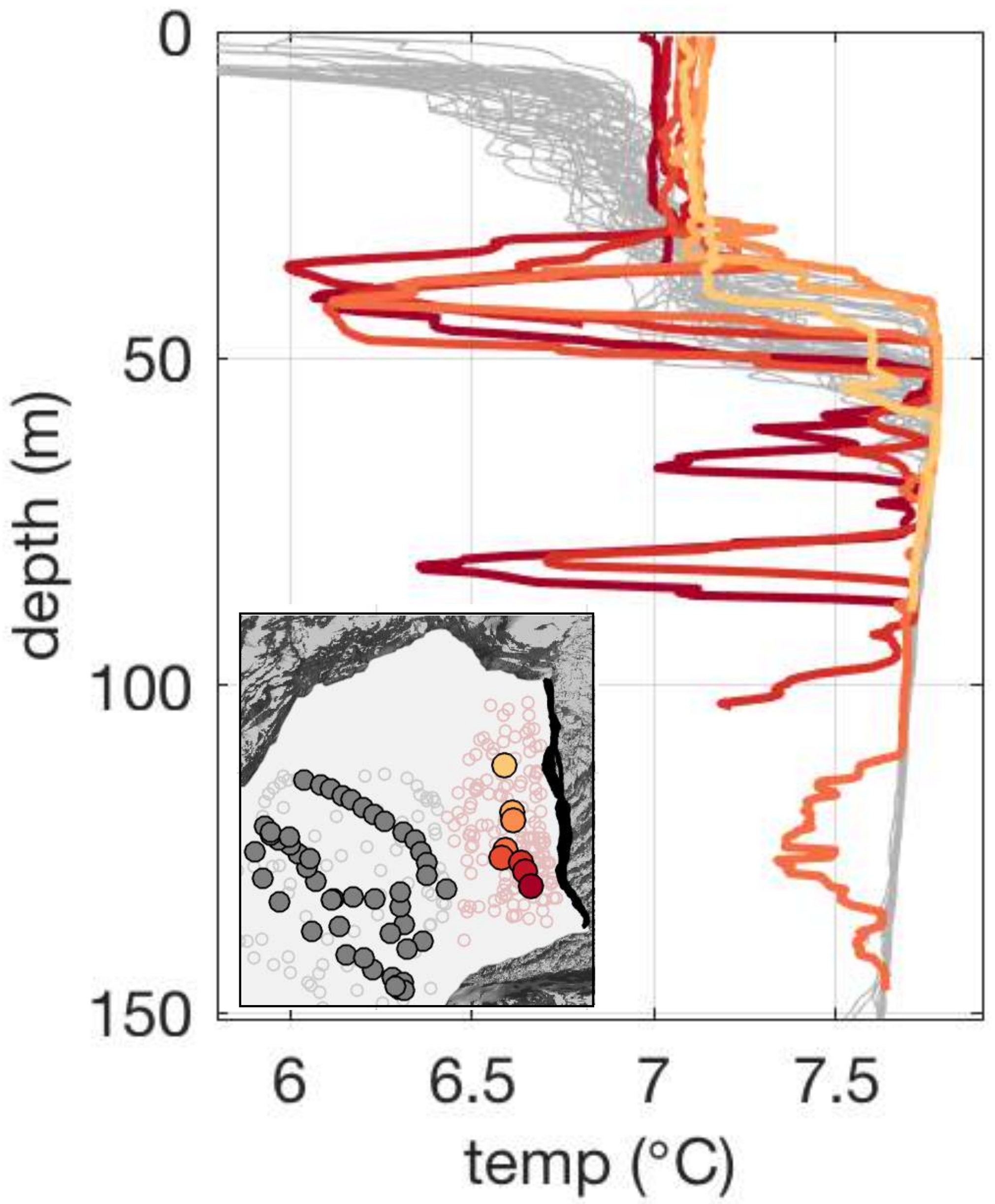
D. Carroll

[plume theory + melt parameterization] often used for both subglacial **discharge plumes** & **ambient melt plumes**

Testing the melt parameterization: **ambient melting**



Jackson et al, submitted



melt rates appear to be **x100 higher** than expected from standard theory

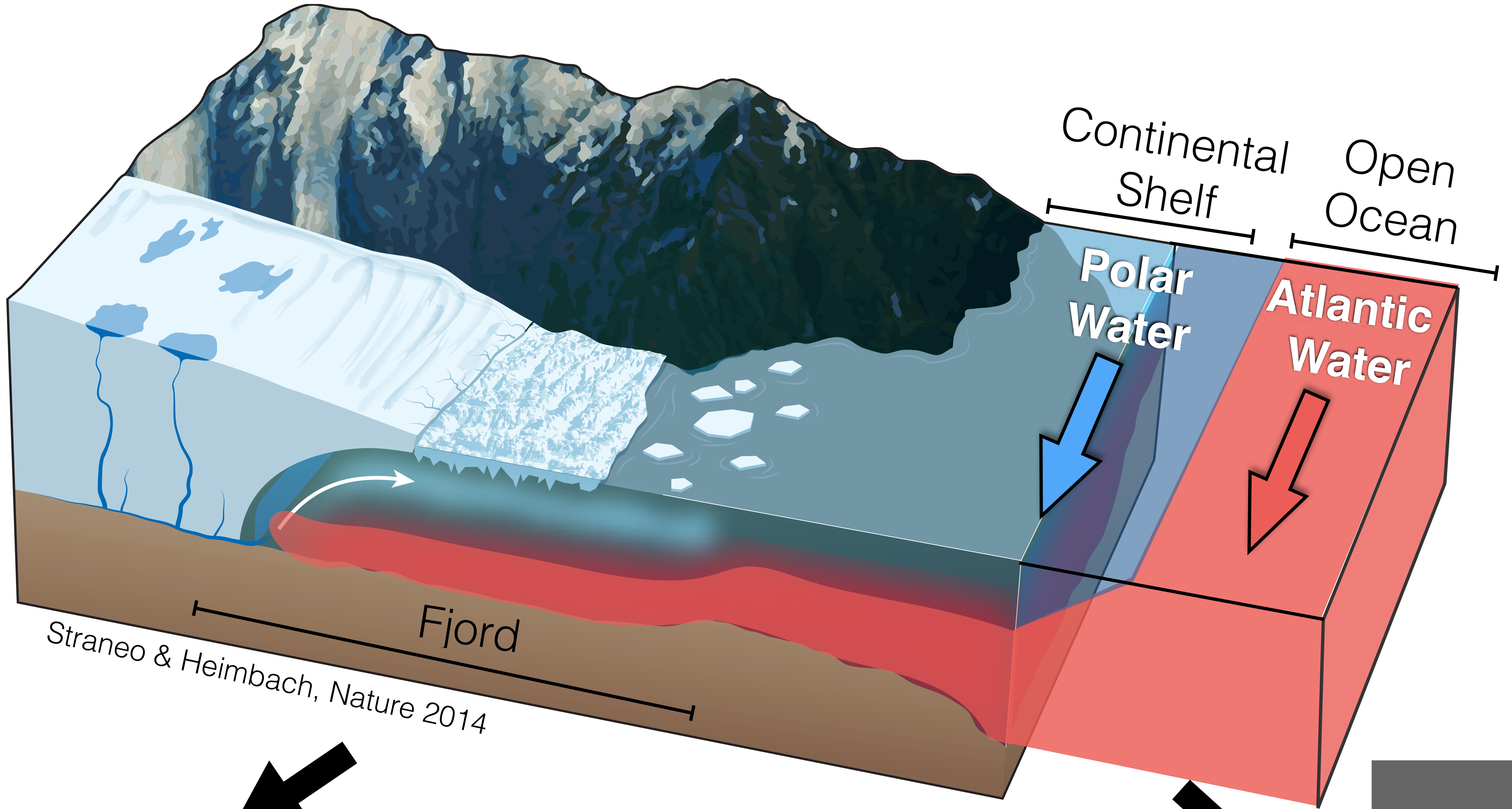
possible adjustments to melt parameterization:

- increase drag coefficient: **C_D** x 175
- increase transfer coefficients: [Γ_S,Γ_T] x 13
- add horizontal velocity….?

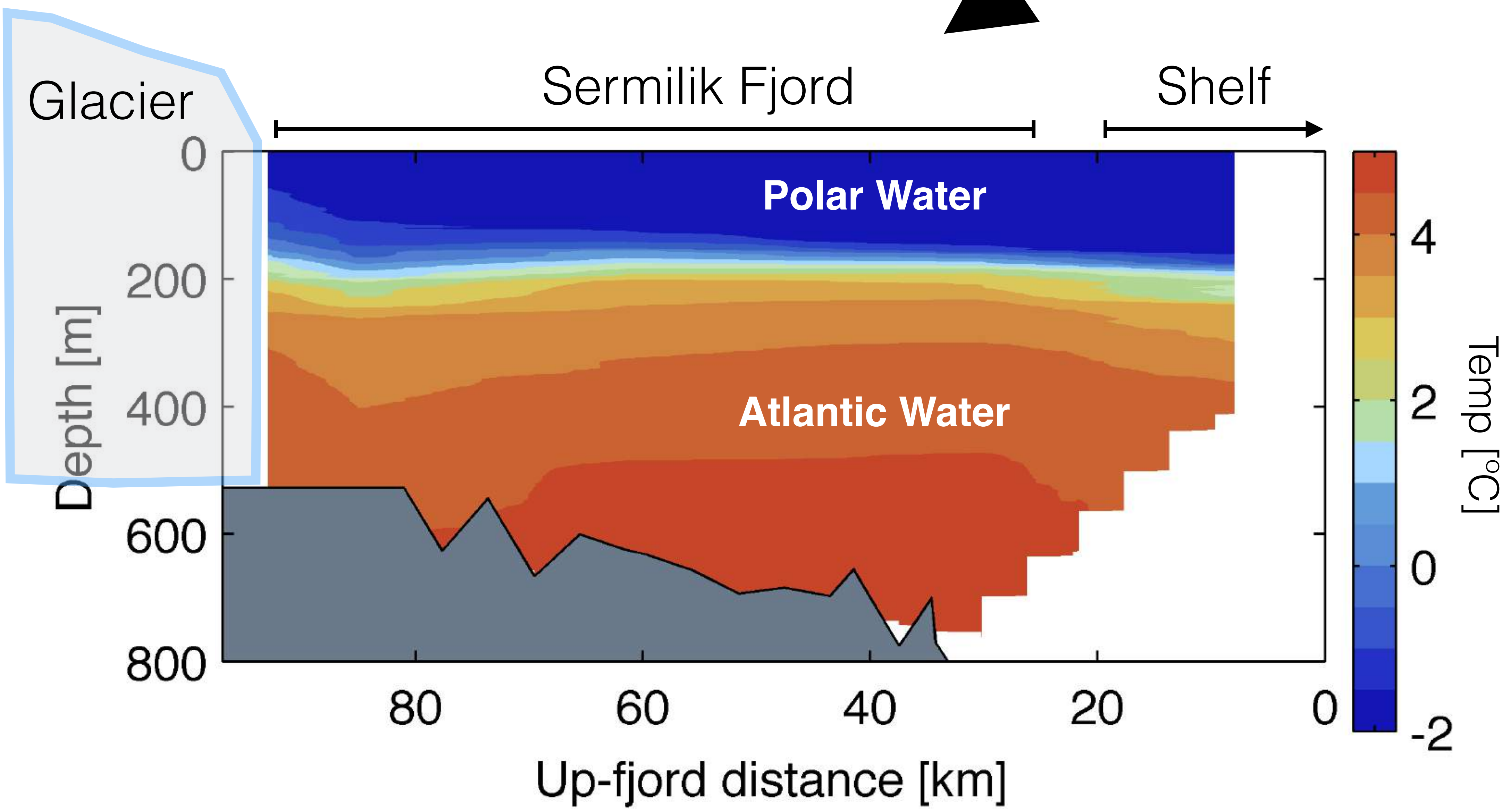
⟹these coefficients are untested for tidewater glaciers but used widely in ocean-glacier studies!

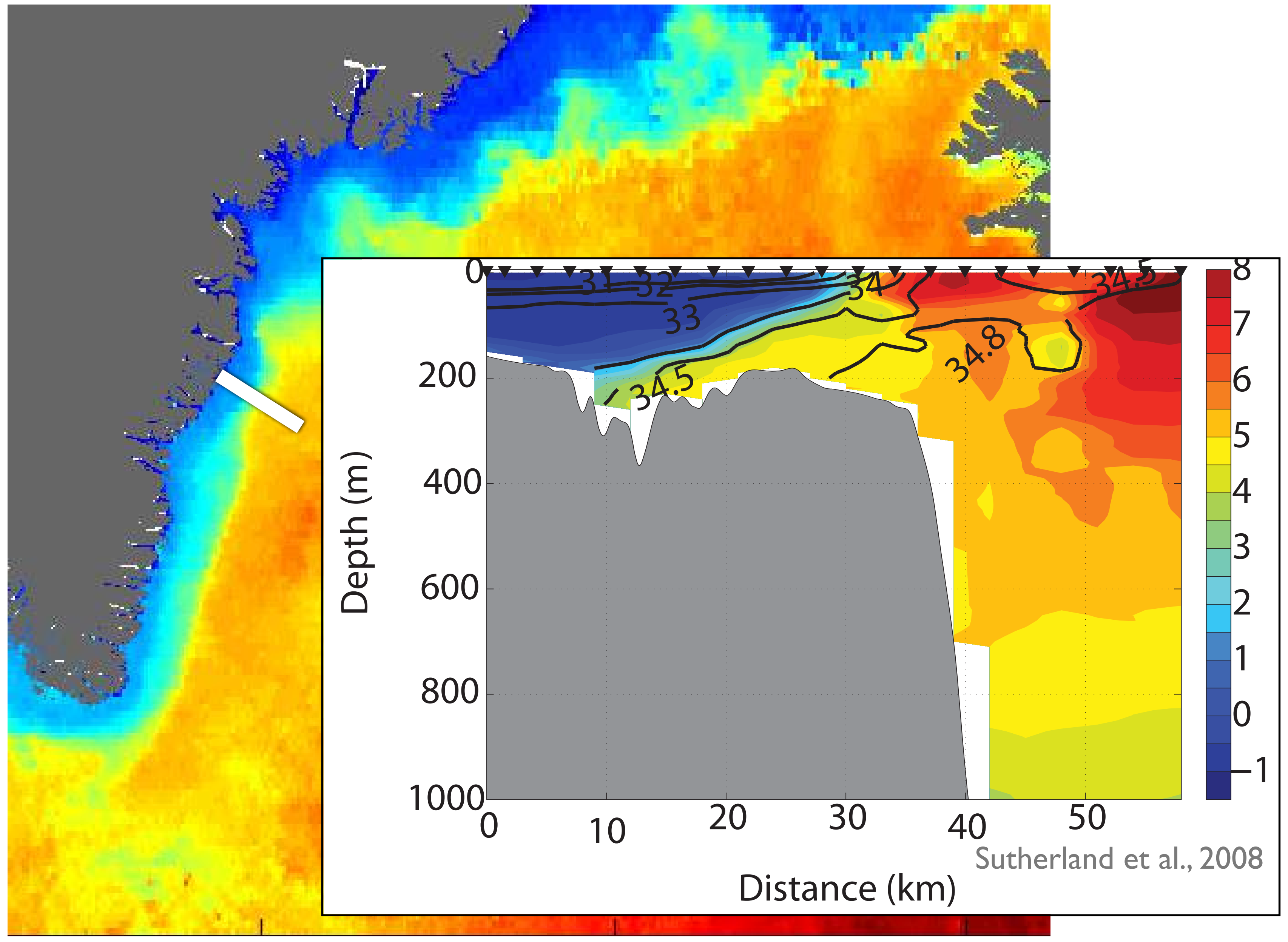
Fjord Circulation

Fjord circulation: connecting glacier to shelf ocean



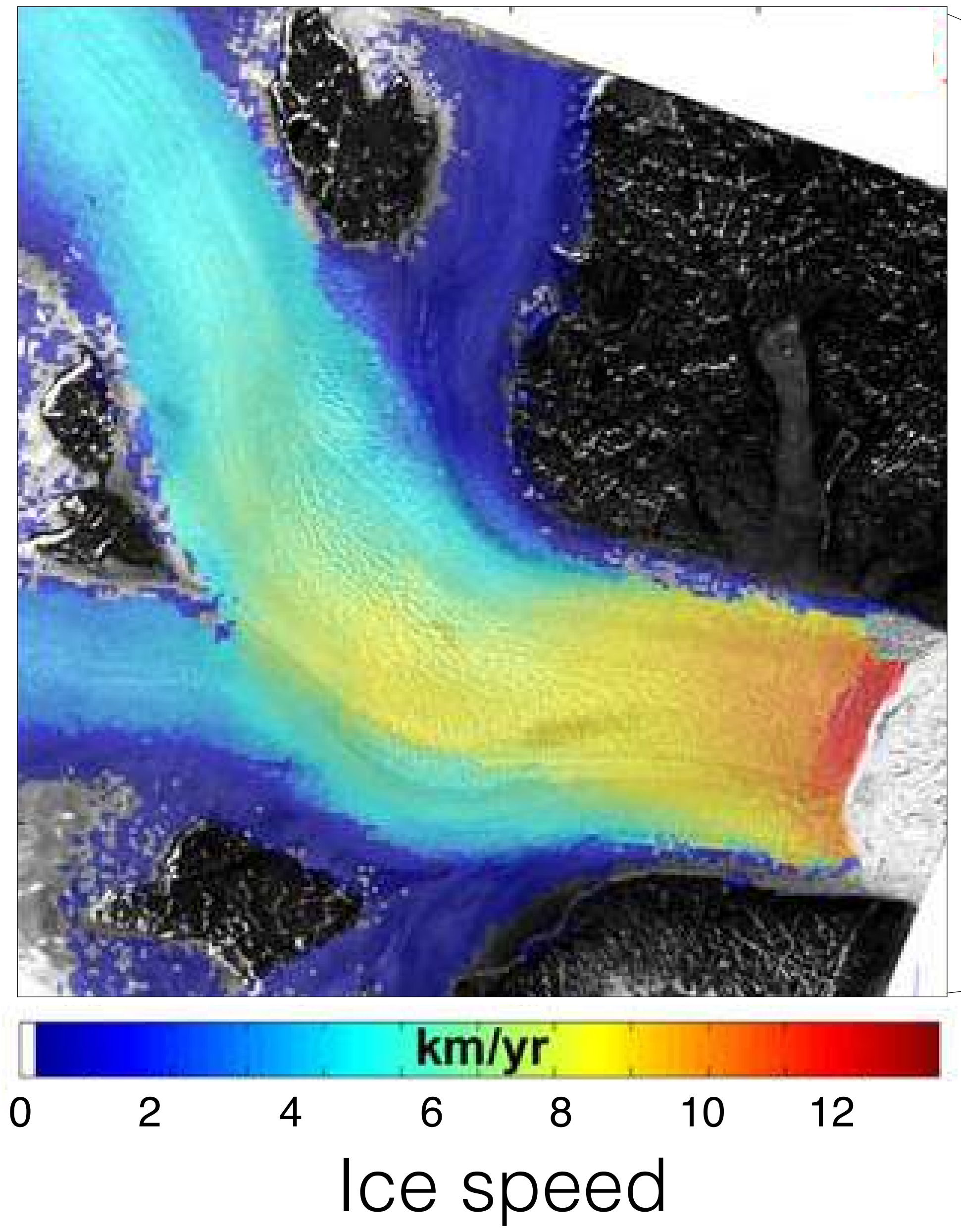
Straneo & Heimbach, Nature 2014

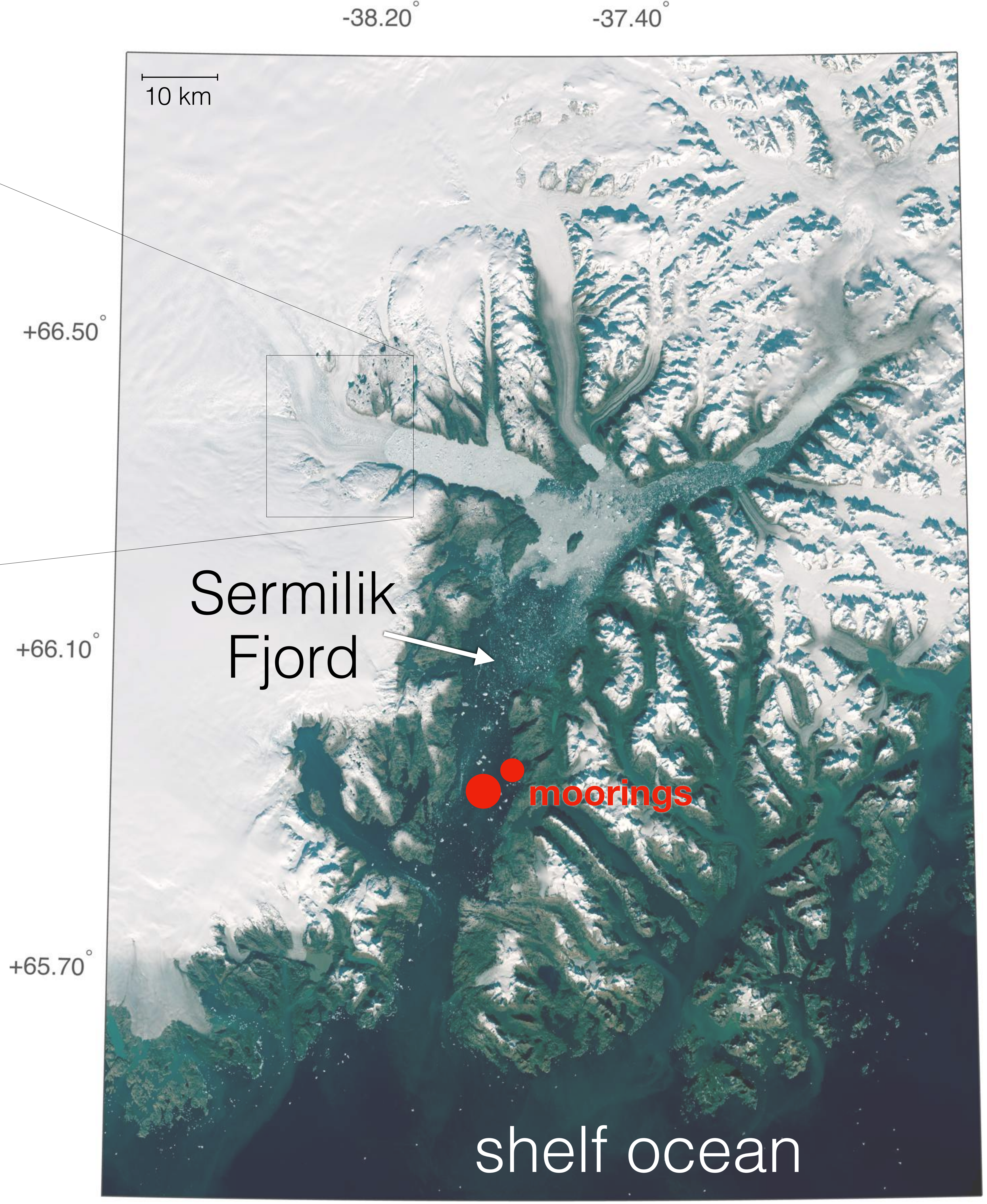




Sutherland et al., 2008

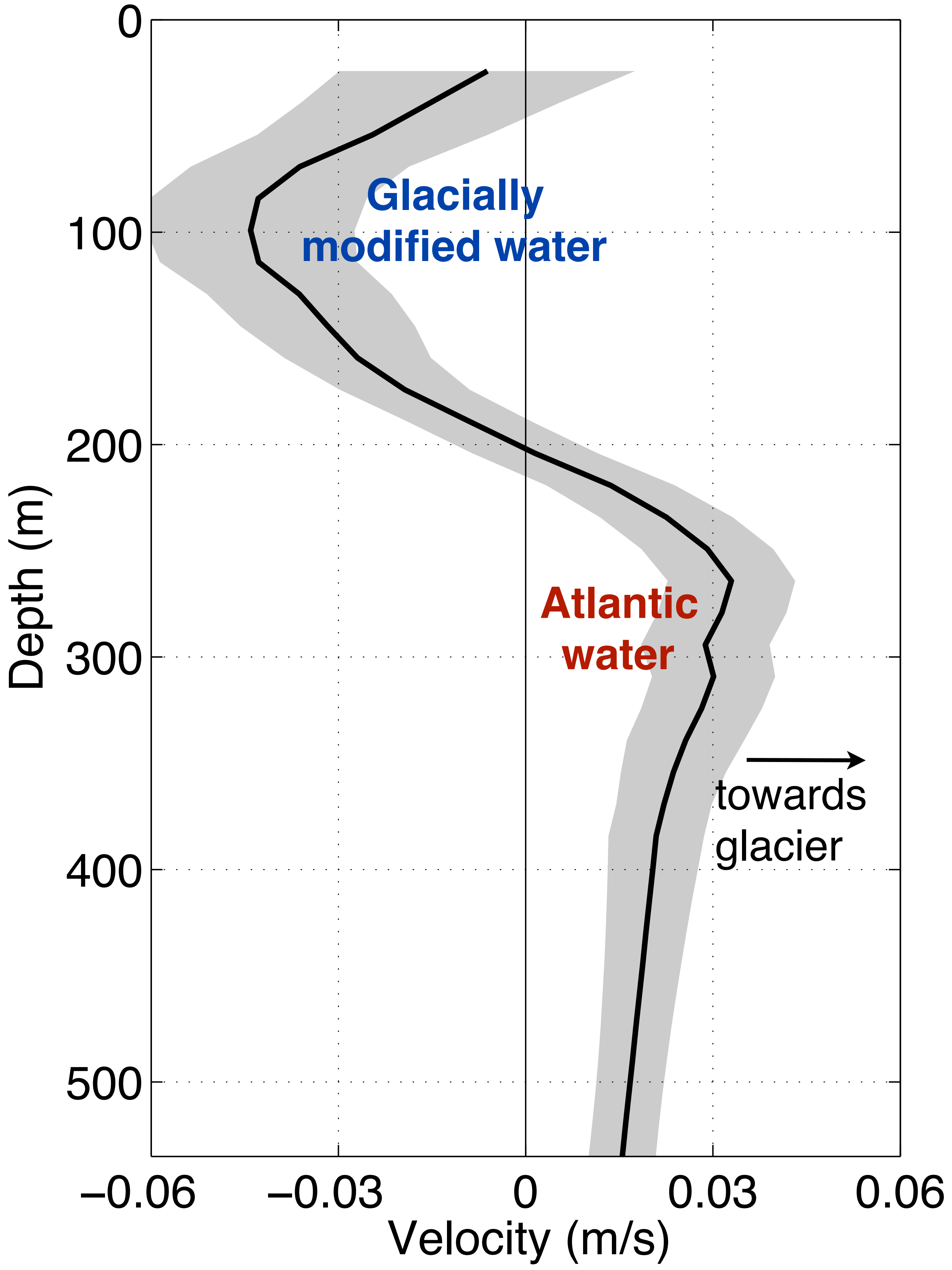
Helheim Glacier



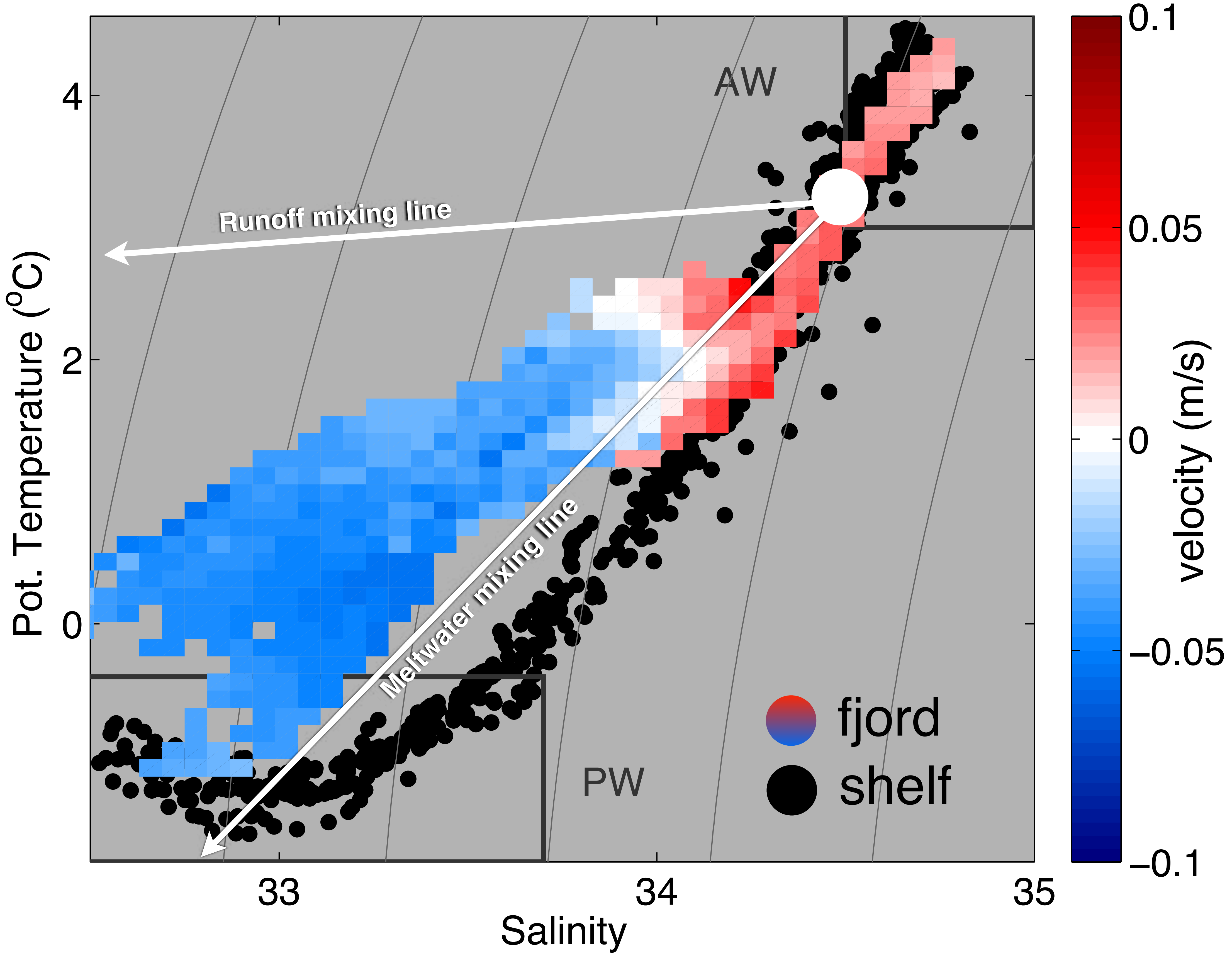


Buoyancy-driven exchange in Sermilik Fjord

Mean velocity profile, u_1
(June-Aug.)



T-S diagram with mean velocity

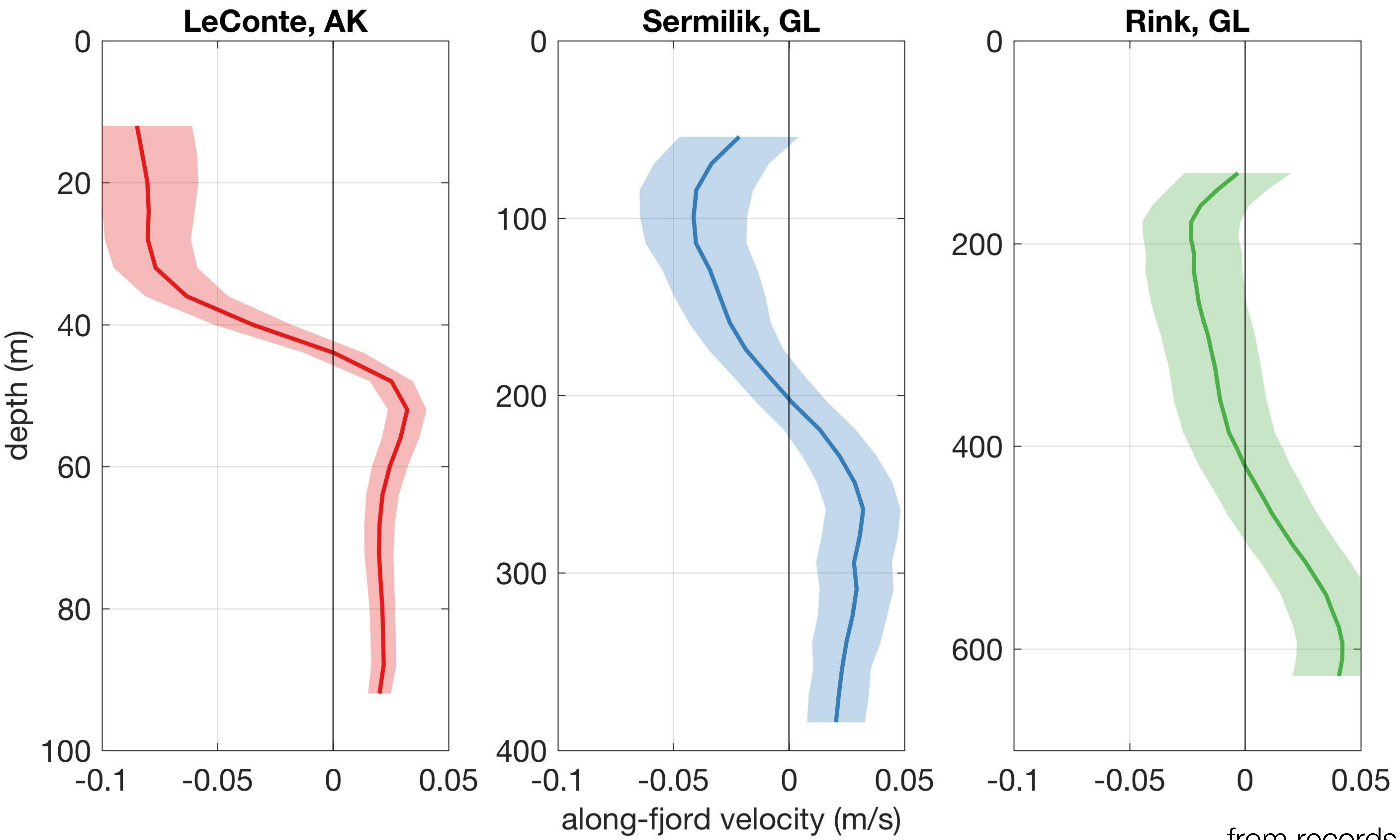


Jackson & Straneo, 2016

Buoyancy-driven exchange flow in other fjords

mean exchange flow

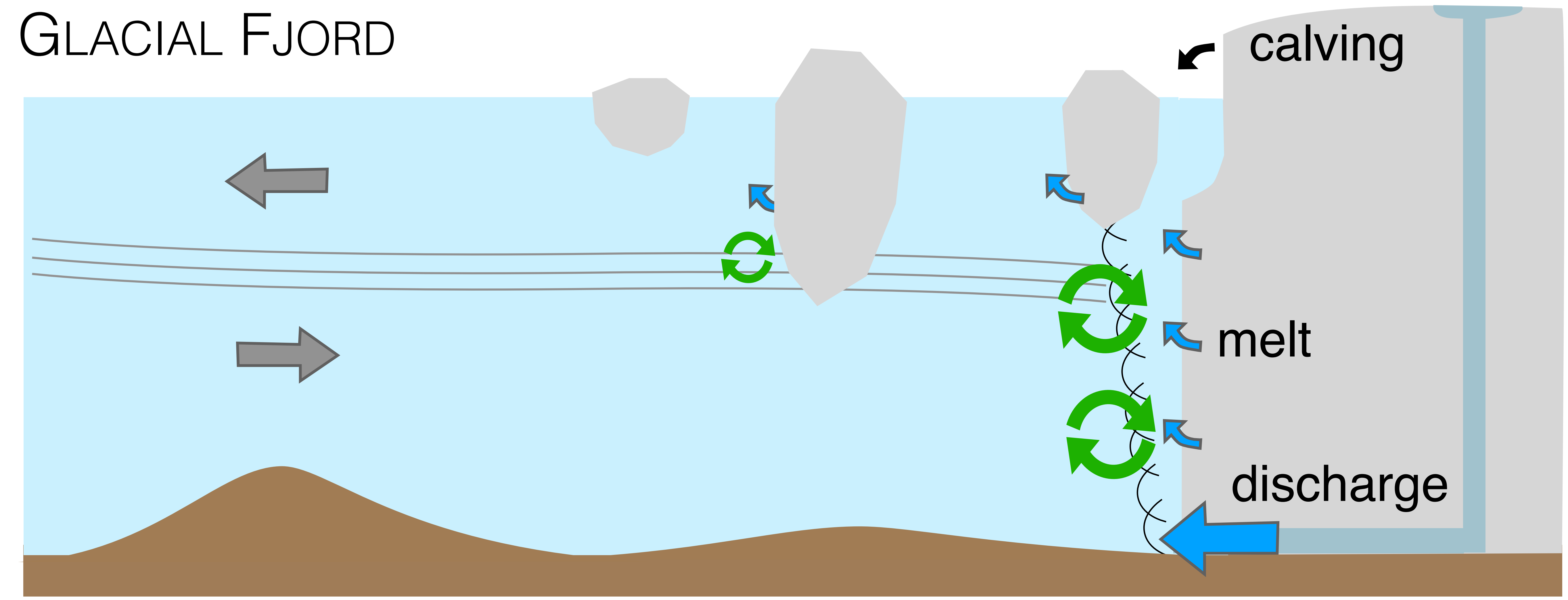
from moorings in glacial fjords

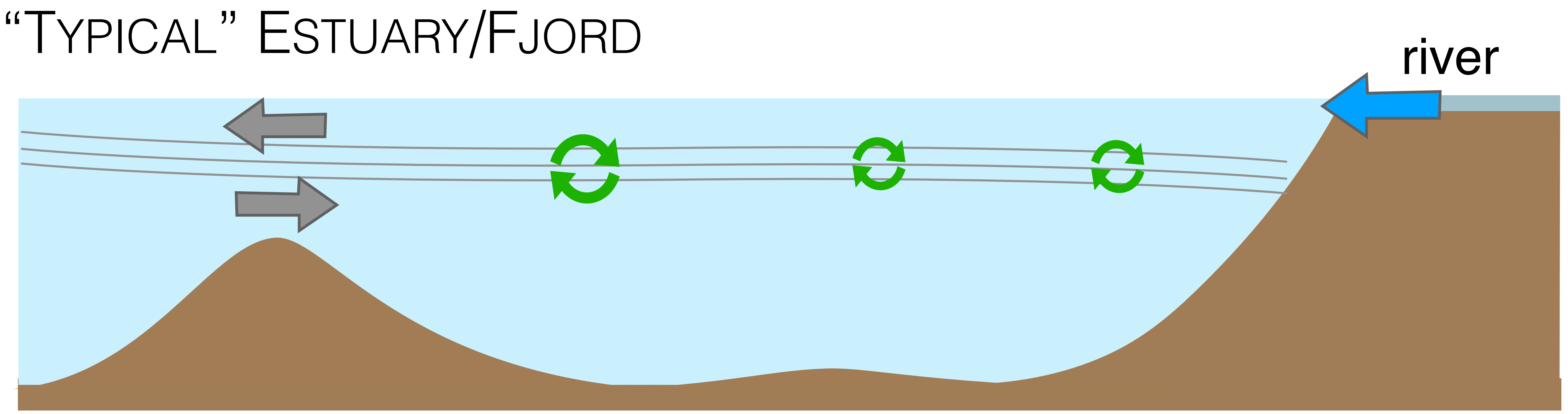


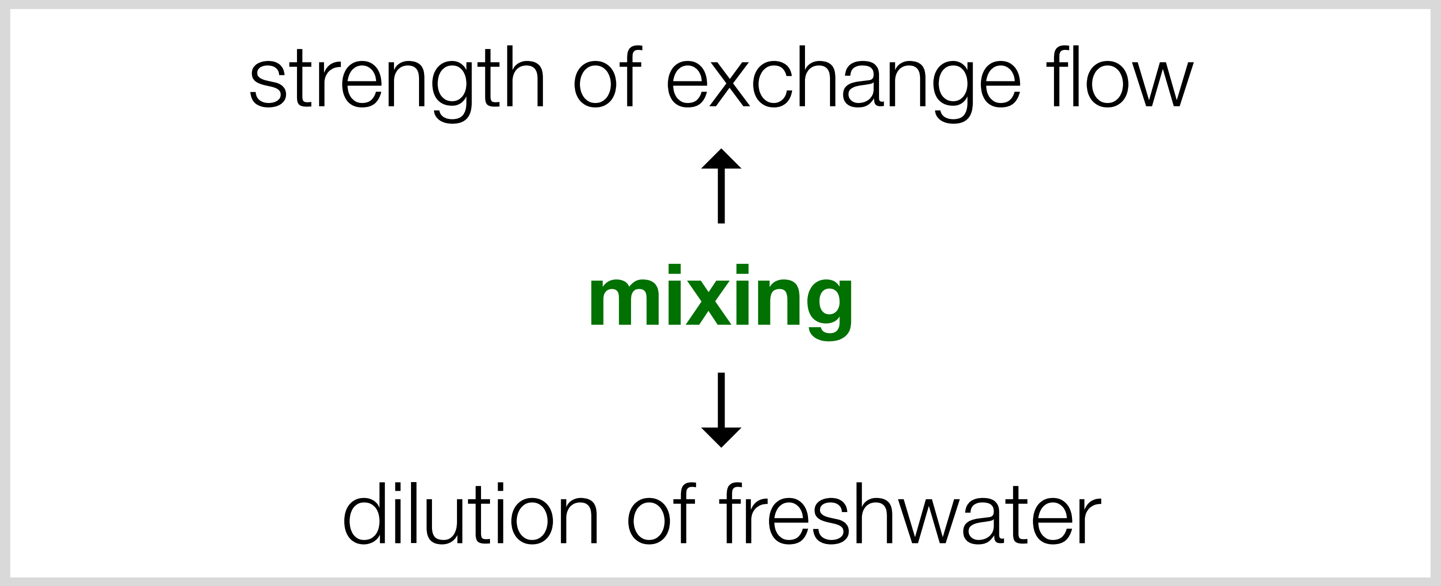
from records in Bartholomaus et al 2016

Jackson & Straneo, 2016

Buoyancy-driven exchange flow: theory?






strength of exchange flow

↑

mixing

↓

dilution of freshwater

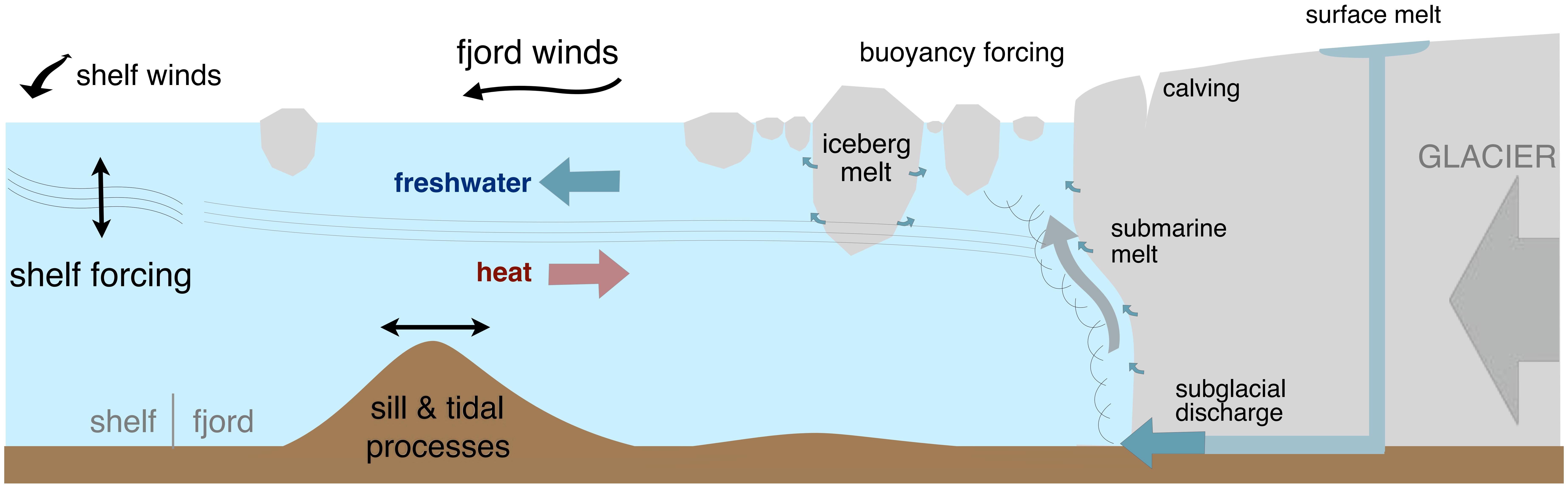
But where does mixing occur in glacial fjords?

all in upwelling plumes or additional modification/mixing elsewhere in fjords?

No existing theory for the dynamics of the exchange flow in glacial fjords

plume theory describes upwelling plumes, but then what?

And other modes of circulation to consider

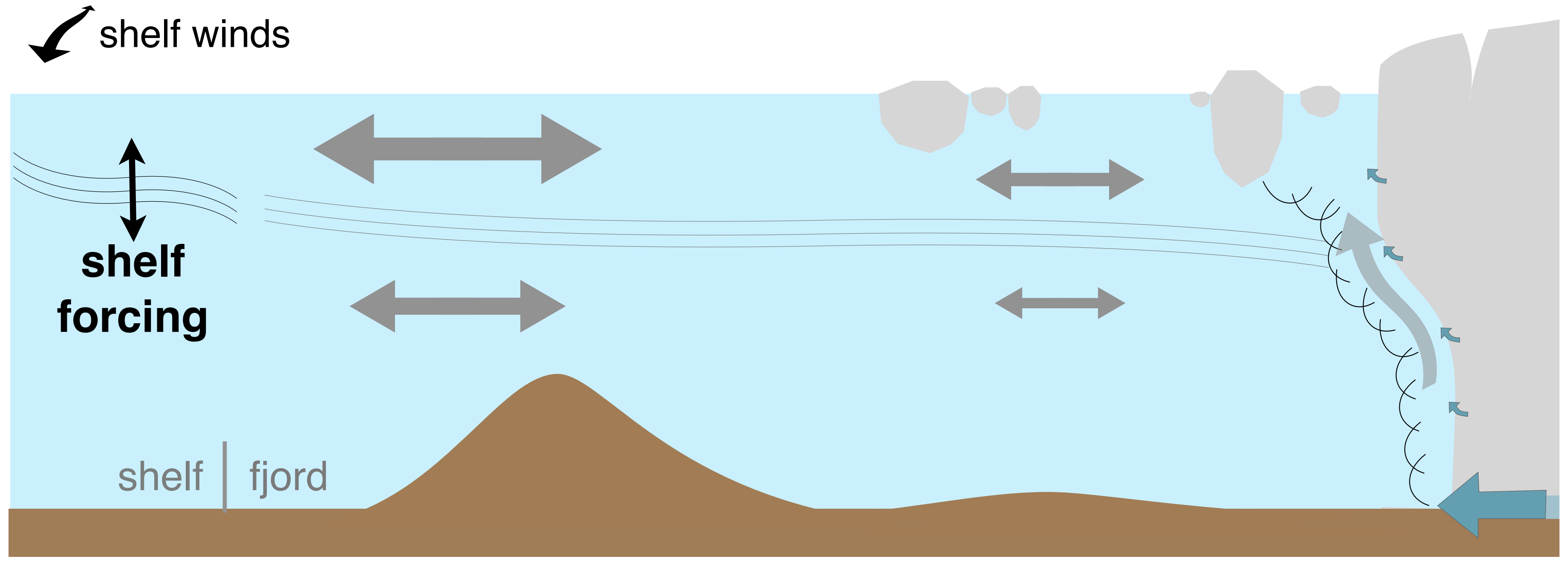


these other drivers can:

- mask the mean exchange flow
- contribute to the mean exchange
- transport heat and salt through eddy fluxes

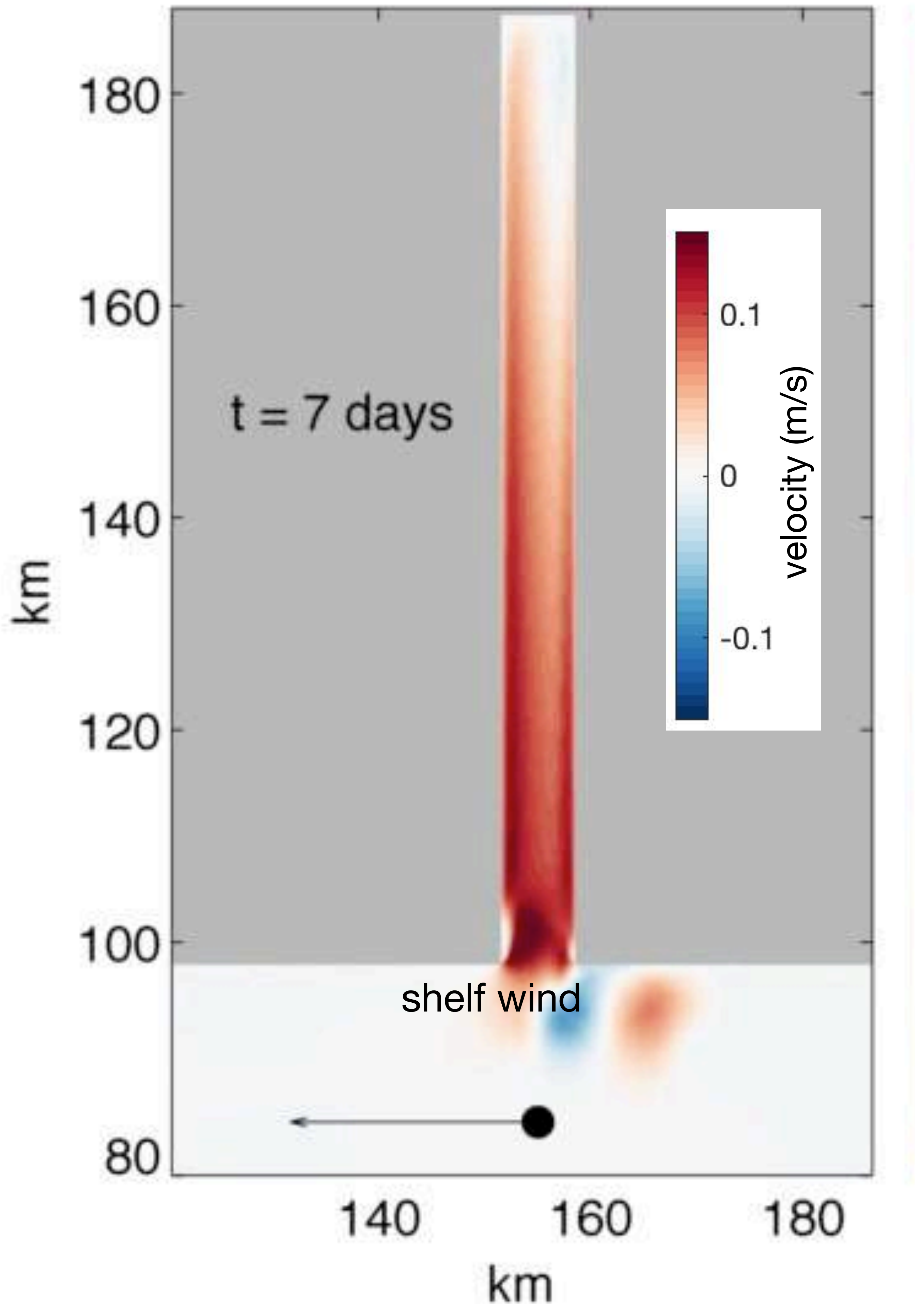
Shelf forcing

a.k.a. intermediary circulation,
baroclinic pumping



model (ROMS)

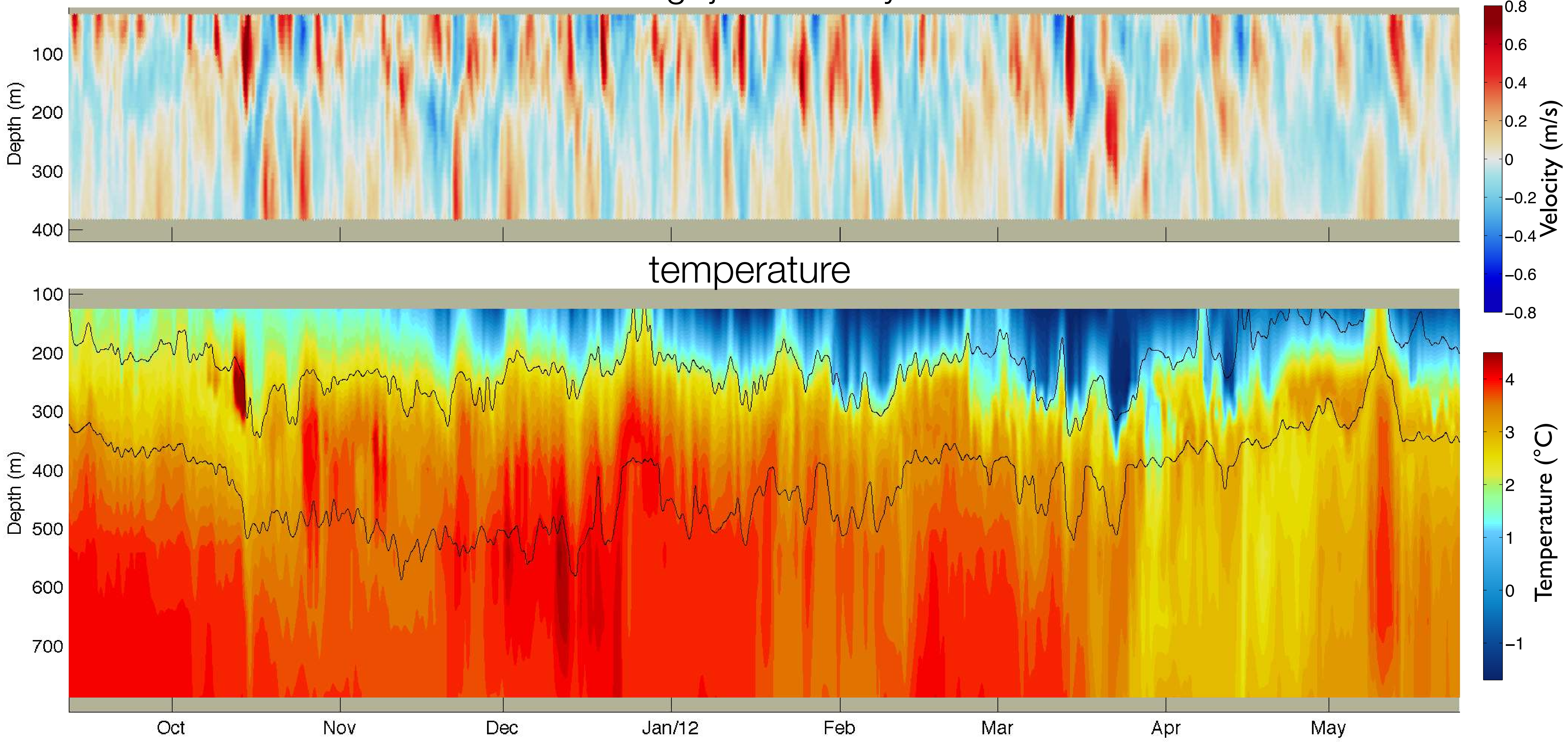
along-fjord velocity



Jackson et al, 2018

moorings from Sermilik Fjord

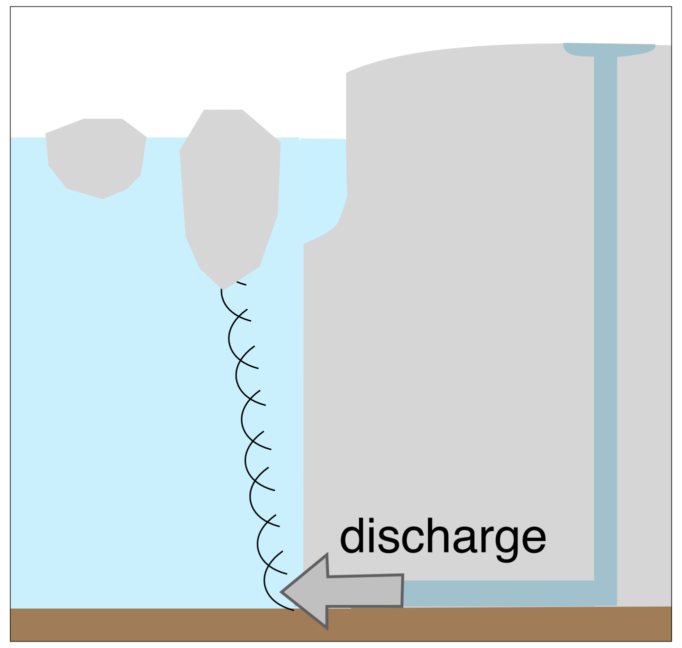
along-fjord velocity



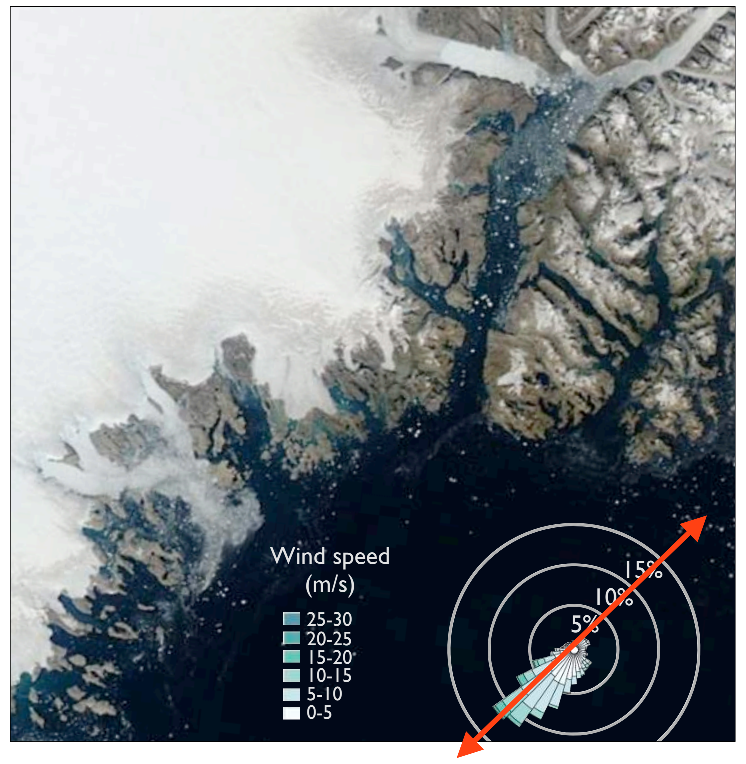
- drives rapid exchange between fjord & shelf

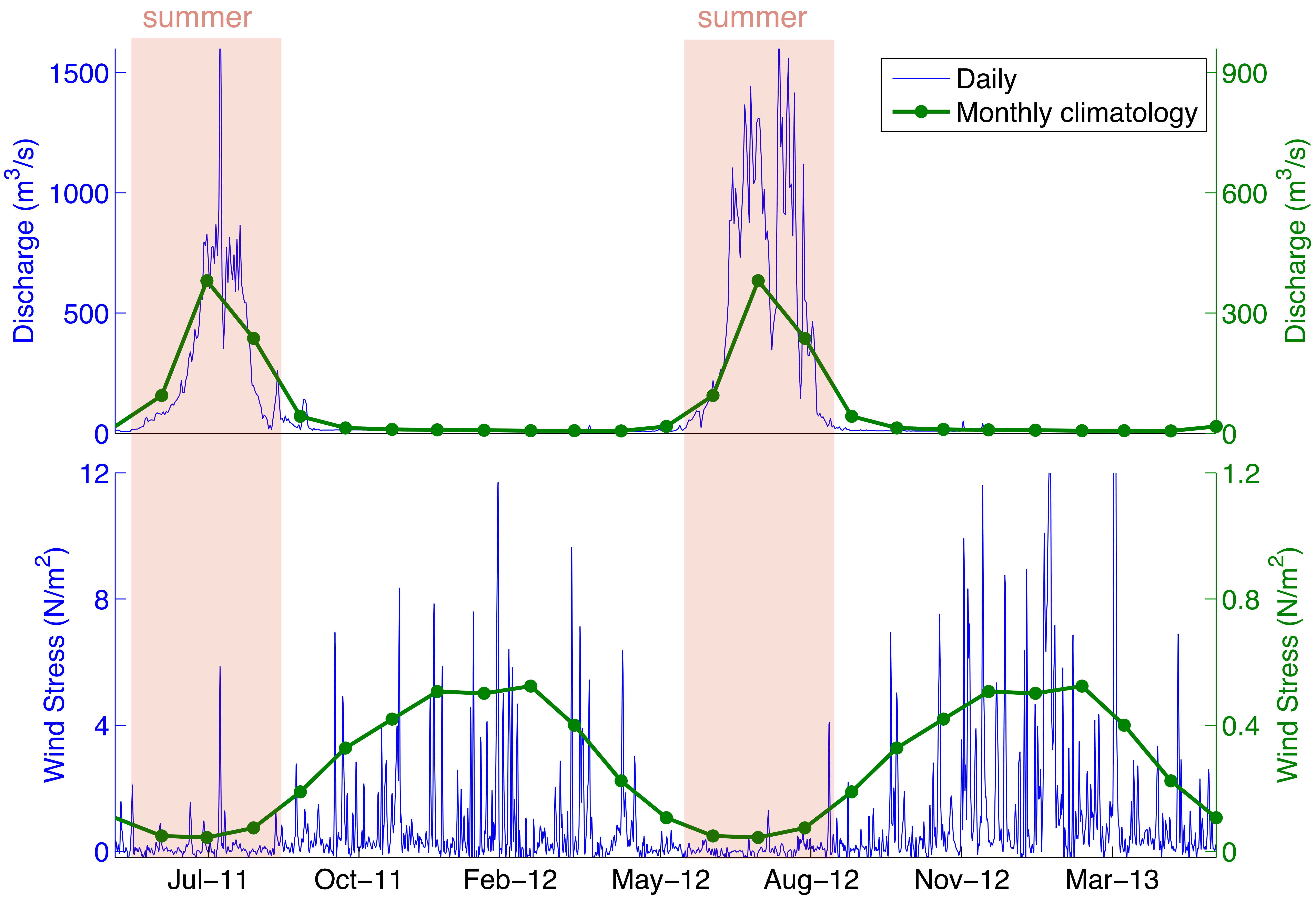
Strong seasonality in fjord drivers & circulation

Subglacial discharge
RACMO2.3 model



Shelf wind stress
ERA-Interim reanalysis

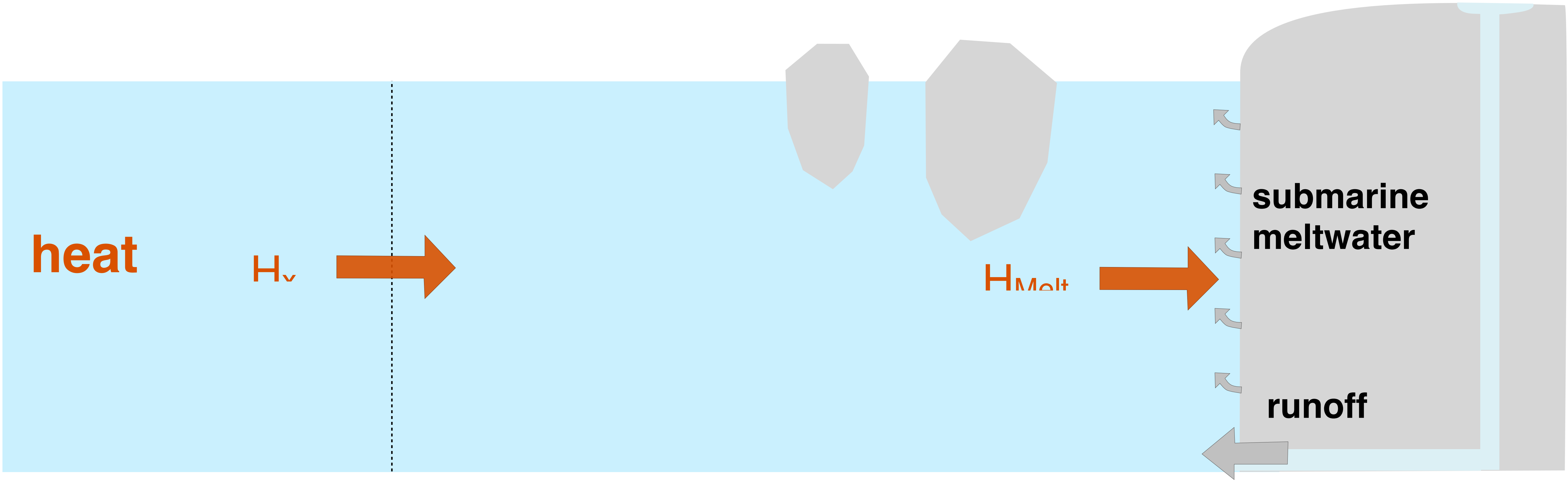




Measuring freshwater fluxes

- fjord budgets
- noble gases
- multibeam sonar

Inferring freshwater fluxes from ocean measurements



Note!
runoff ≈ subglacial discharge

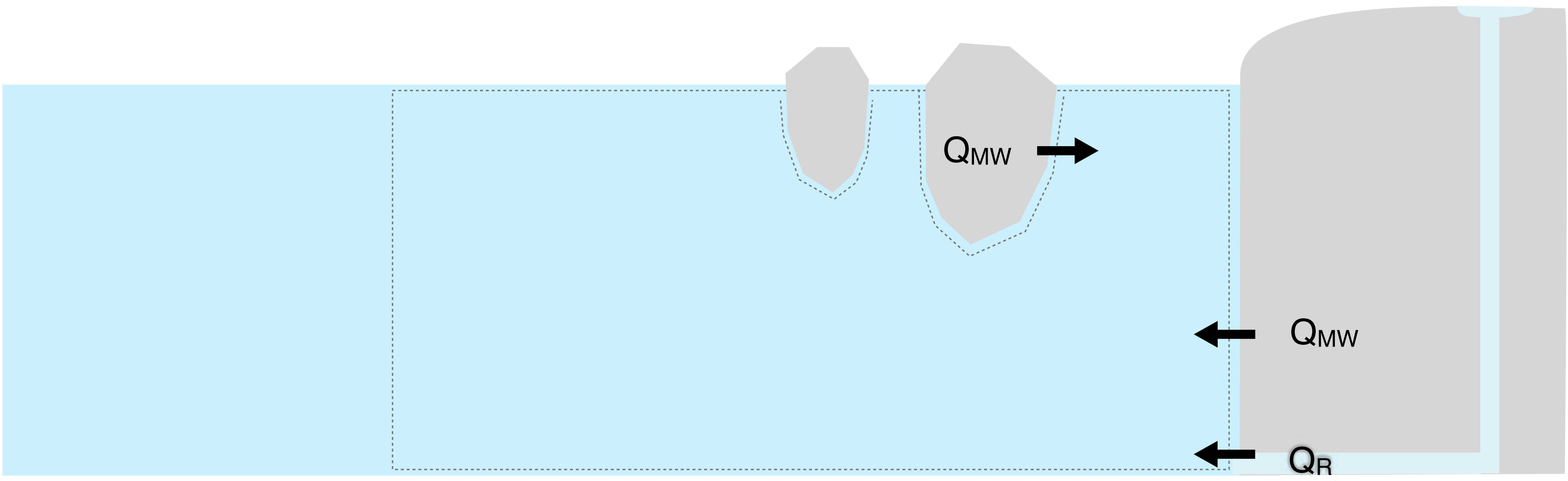
Several variations in literature…
- Motyka et al. 2003
- Rignot et al. 2010
- Johnson et al. 2011
- Christoffersen et al. 2011
- Sutherland & Straneo 2012
- Motyka et al. 2013
- Xu et al. 2013
- Inall et al. 2014
- Mortensen et al. 2014
- Bendtsen el al. 2015
- Jackson & Straneo, 2016

Budgets for glacial fjords

SALT

HEAT

MASS



Q_R = **runoff**

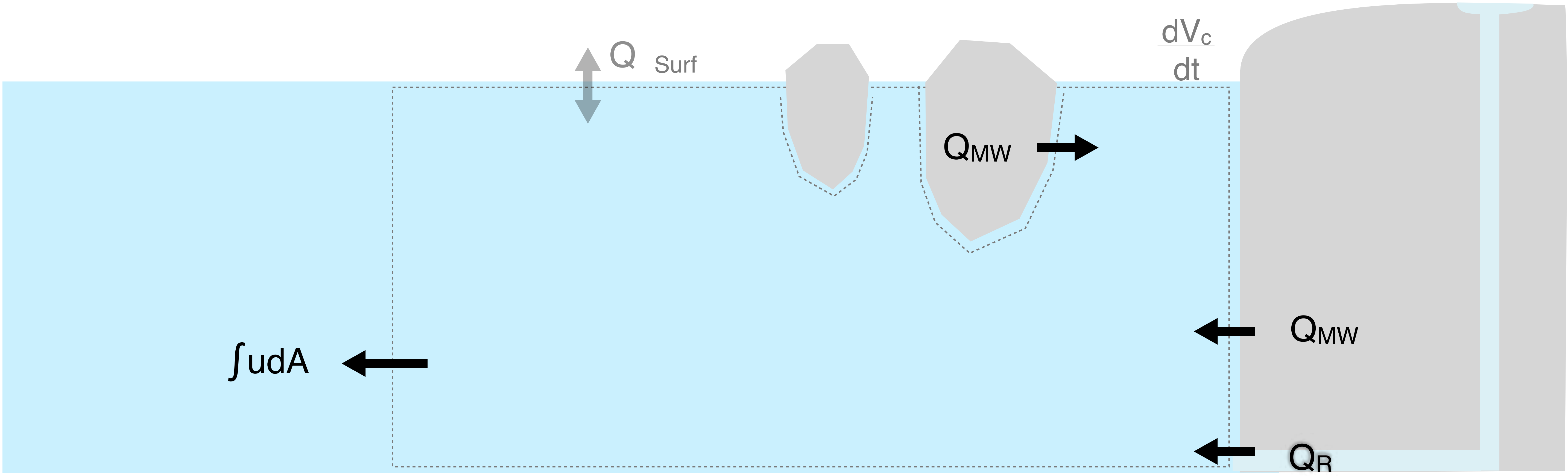
Q_{MW} = **submarine meltwater** of glacier and icebergs

Budgets for glacial fjords

SALT

HEAT

MASS



Q_R = **runoff**

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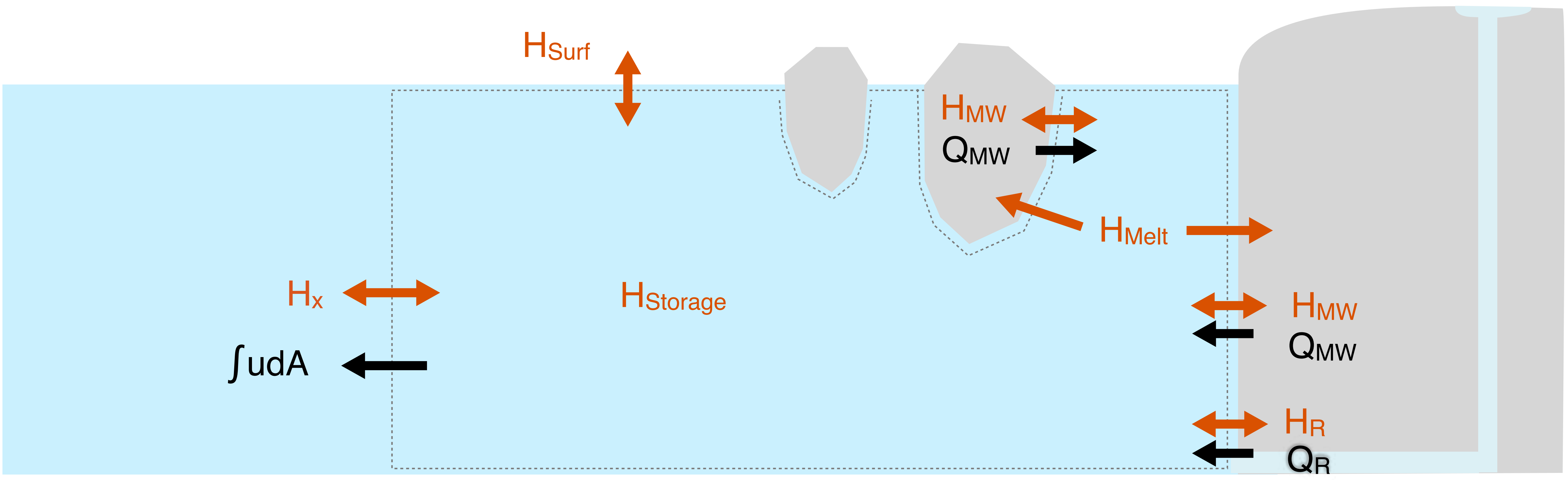
Budgets for glacial fjords

SALT

HEAT

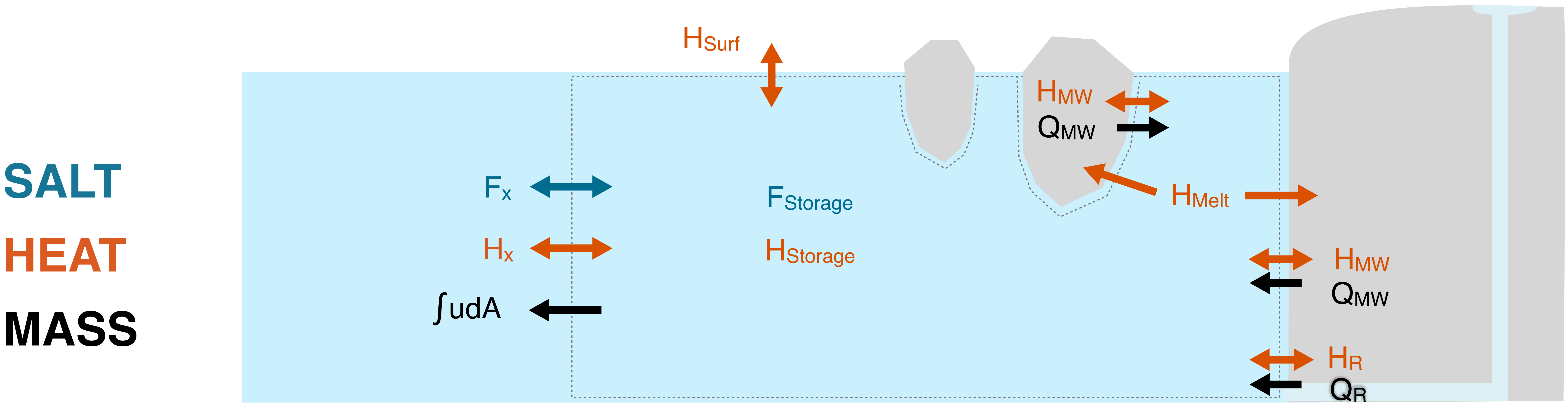
MASS



Q_R = **runoff**

Q_{MW} = **submarine meltwater**
of glacier and icebergs

Budgets for glacial fjords



Q_R = **runoff**

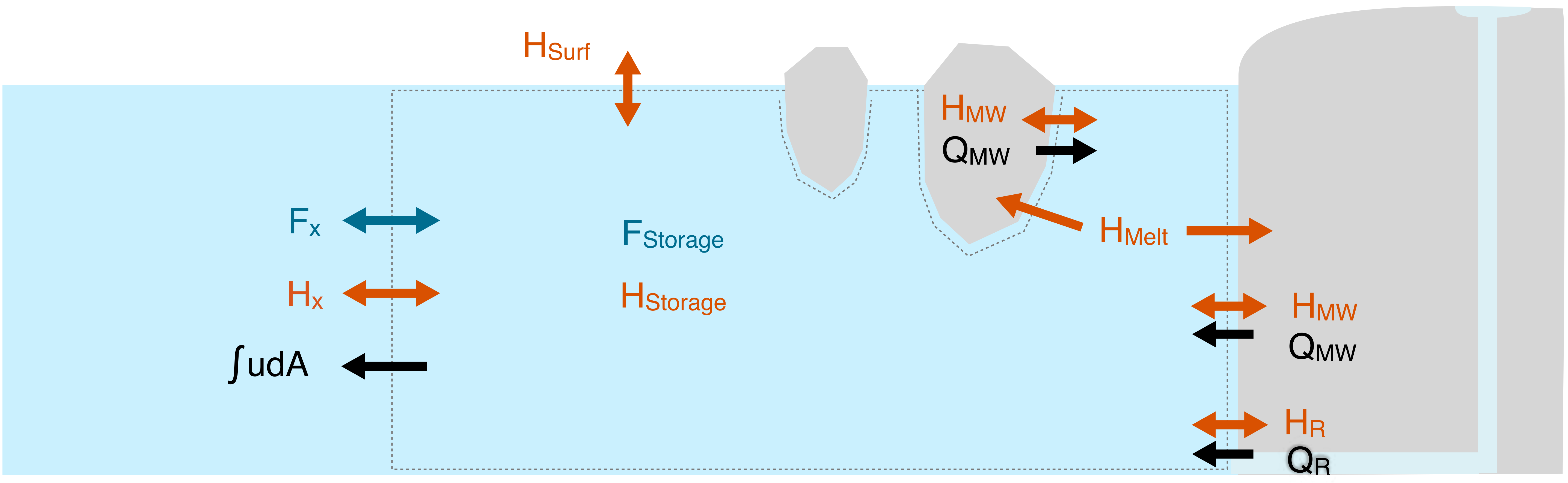
Q_{MW} = **submarine meltwater** of glacier and icebergs

Budgets for glacial fjords

SALT

HEAT

MASS



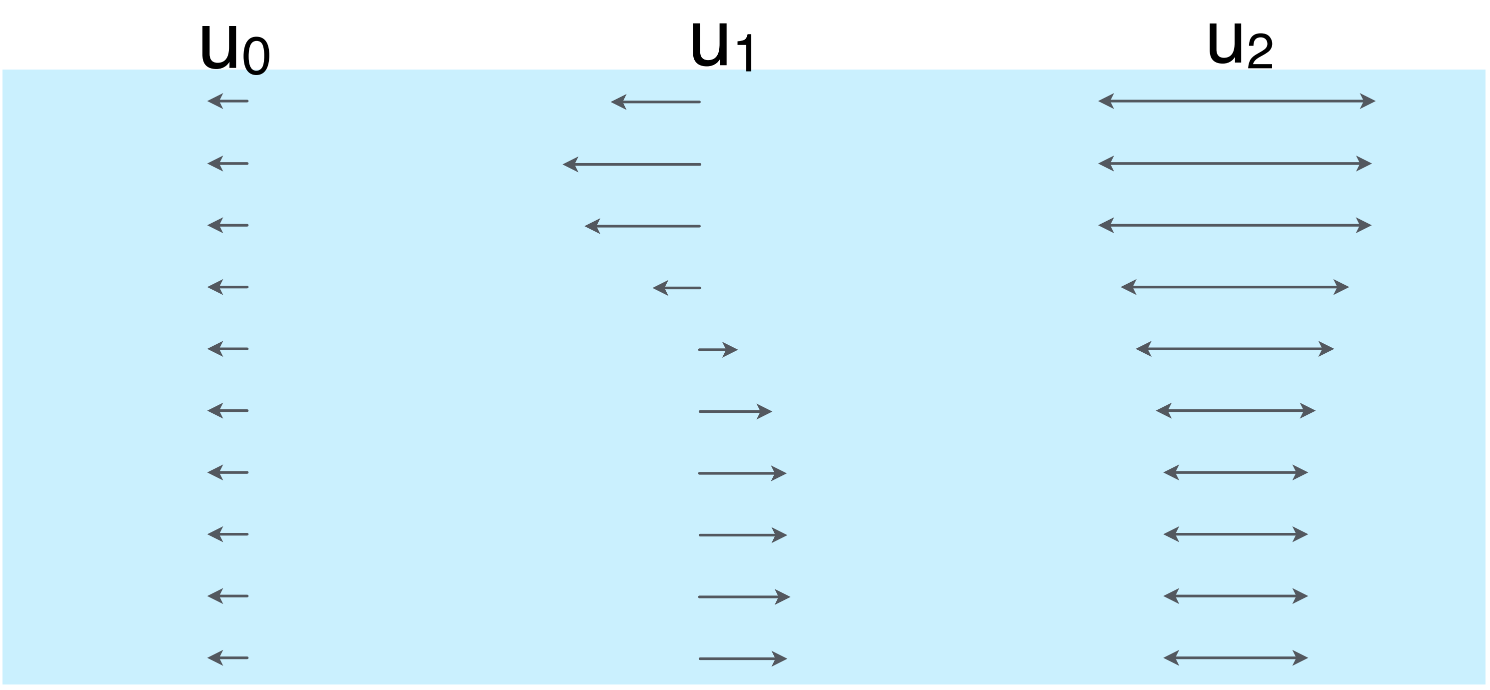
Time-average budgets and decompose cross-section transports into:

(building on estuarine salt budgets studies, e.g. Lerczak et al. 2006; MacCready & Banas 2011)

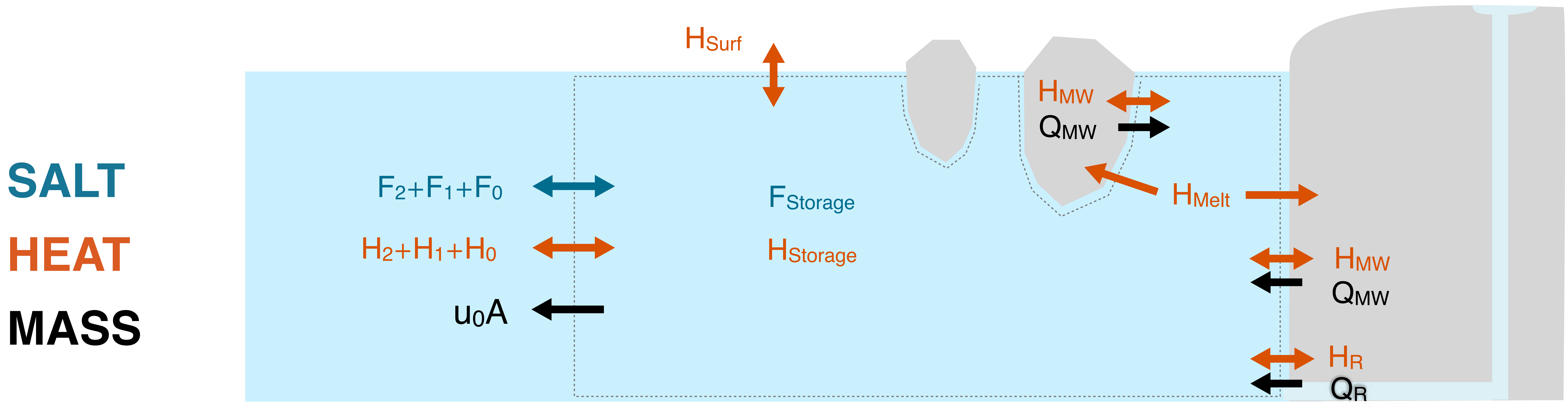
0. Barotropic
depth-average,
time-average

1. Exchange
time-average,
depth-varying

2. Fluctuating
residual



Budgets for glacial fjords



SALT

HEAT

MASS

$F_2+F_1+F_0$

$H_2+H_1+H_0$

u_0A

H_{Surf}

$F_{Storage}$

$H_{Storage}$

H_{MW}

Q_{MW}

H_{Melt}

H_{MW}

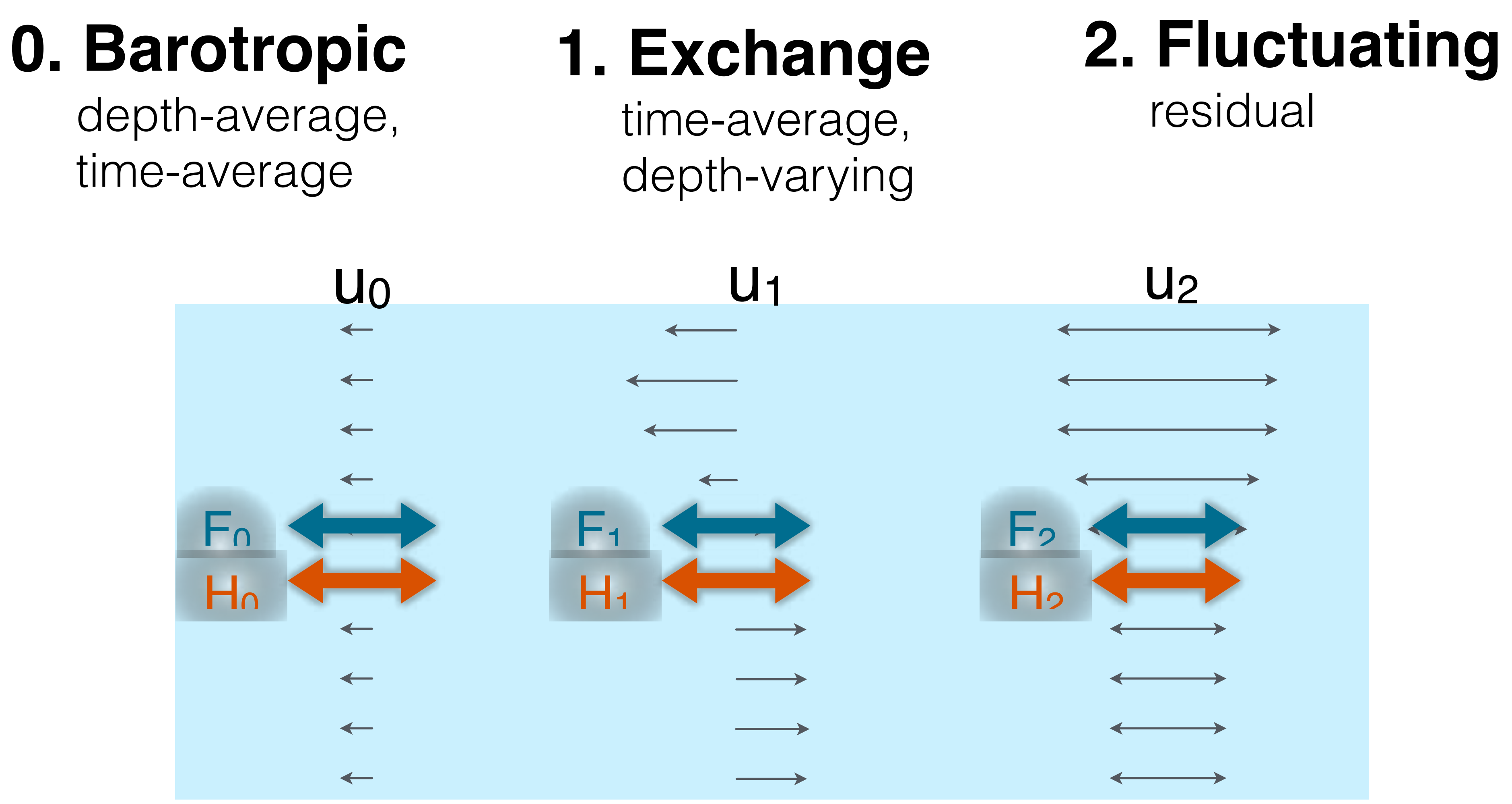
Q_{MW}

H_R

Q_R

Time-average budgets and decompose cross-section transports into:

(building on estuarine salt budgets studies,
e.g. Lerczak et al. 2006;
MacCready & Banas 2011)



0. Barotropic
depth-average,
time-average

1. Exchange
time-average,
depth-varying

2. Fluctuating
residual

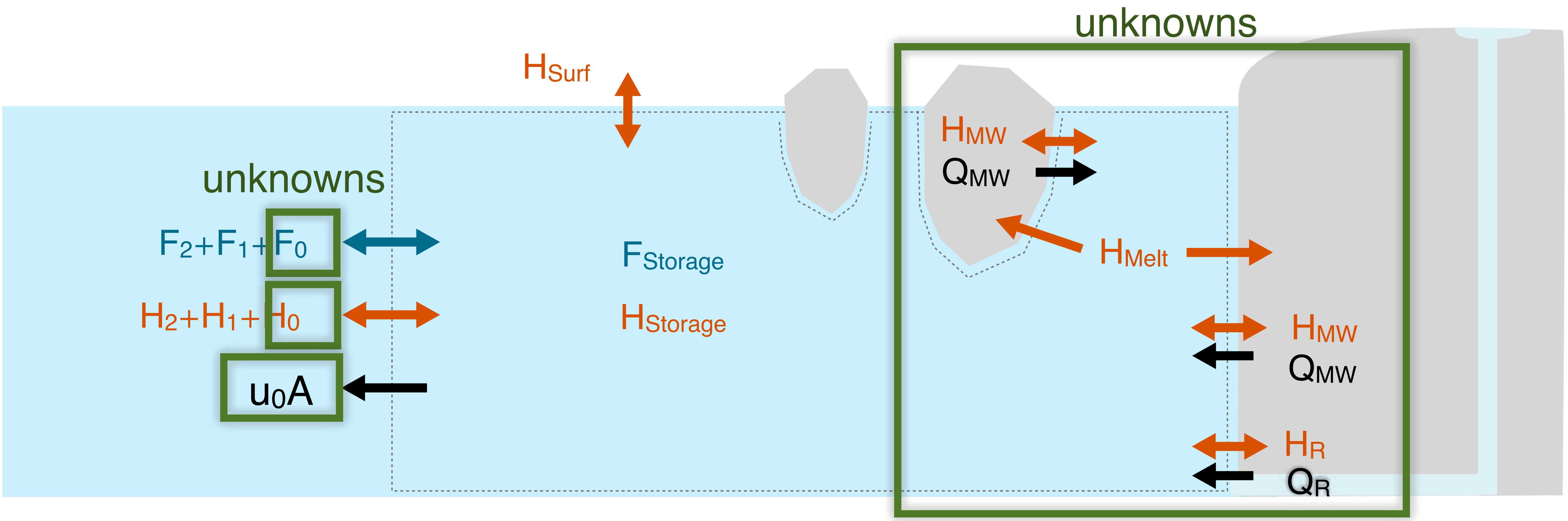
u_0 u_1 u_2

F_0 H_0

F_1 H_1

F_2 H_2

Inferring freshwater fluxes from budgets



Total freshwater flux from measurable salt budget terms:

$$Q_{FW} = \frac{1}{S_0}\left[F_1 + F_2 - F_{Storage} \right]$$

Submarine meltwater from measurable heat budget terms + total freshwater flux:

$$Q_{MW} = \frac{1}{\rho L_{adj} - \rho c_p(\theta_{MW} - \theta_R)}\left[\rho c_p Q_{FW}(\theta_R - \theta_0) + H_1 + H_2 - H_{Storage} - H_{Surf}\right]$$

Runoff from the difference:

$$Q_R = Q_{FW} - Q_{MW}$$

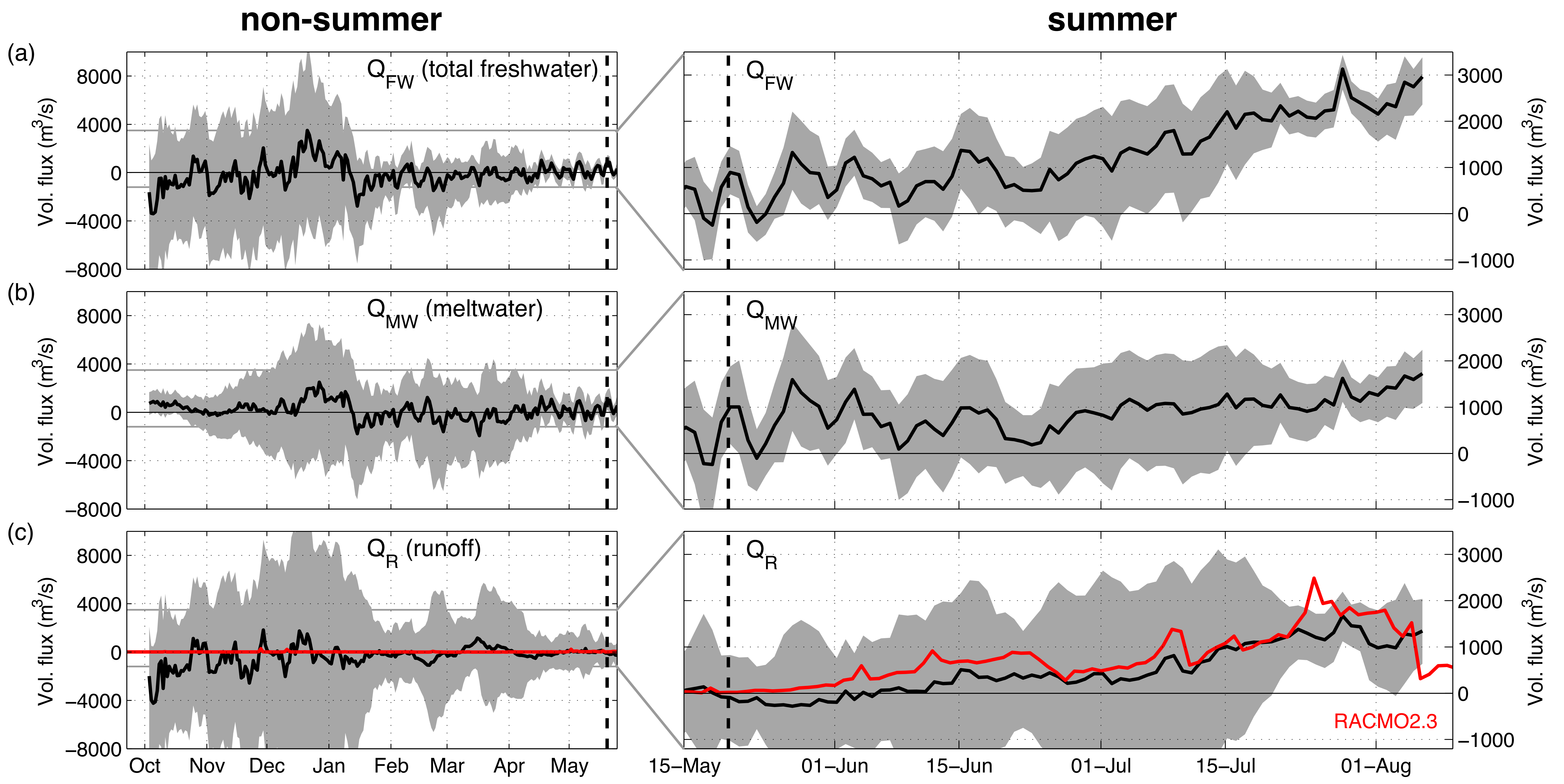
Jackson & Straneo, 2016

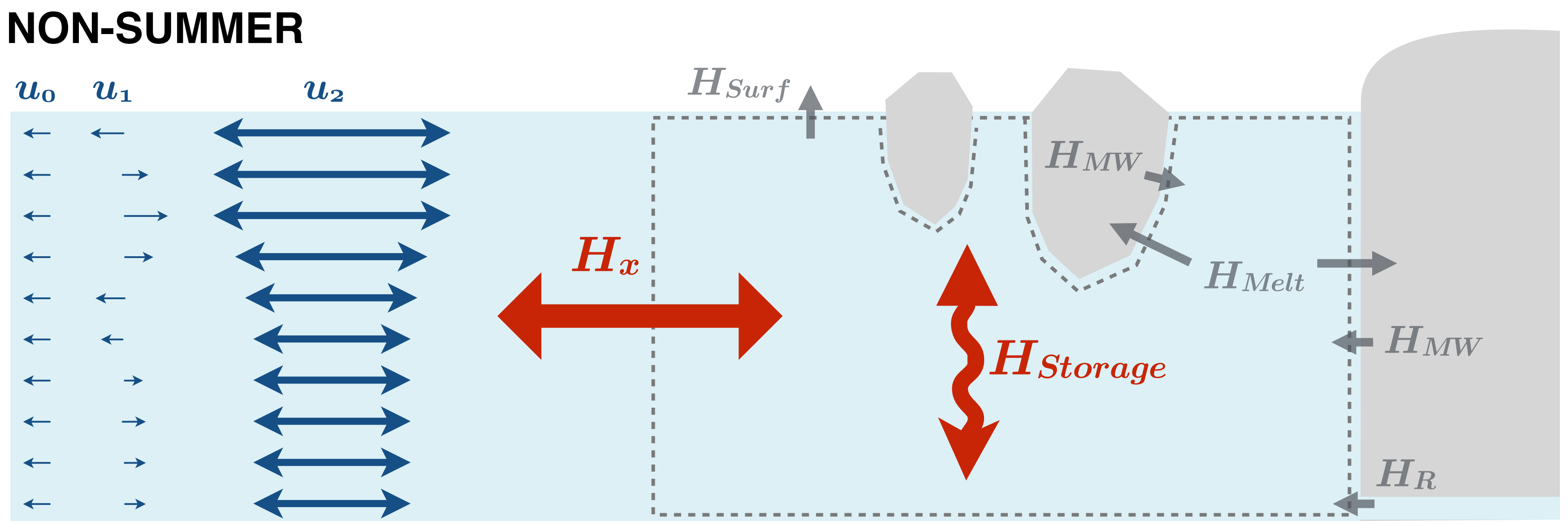
Results from Sermilik Fjord budgets

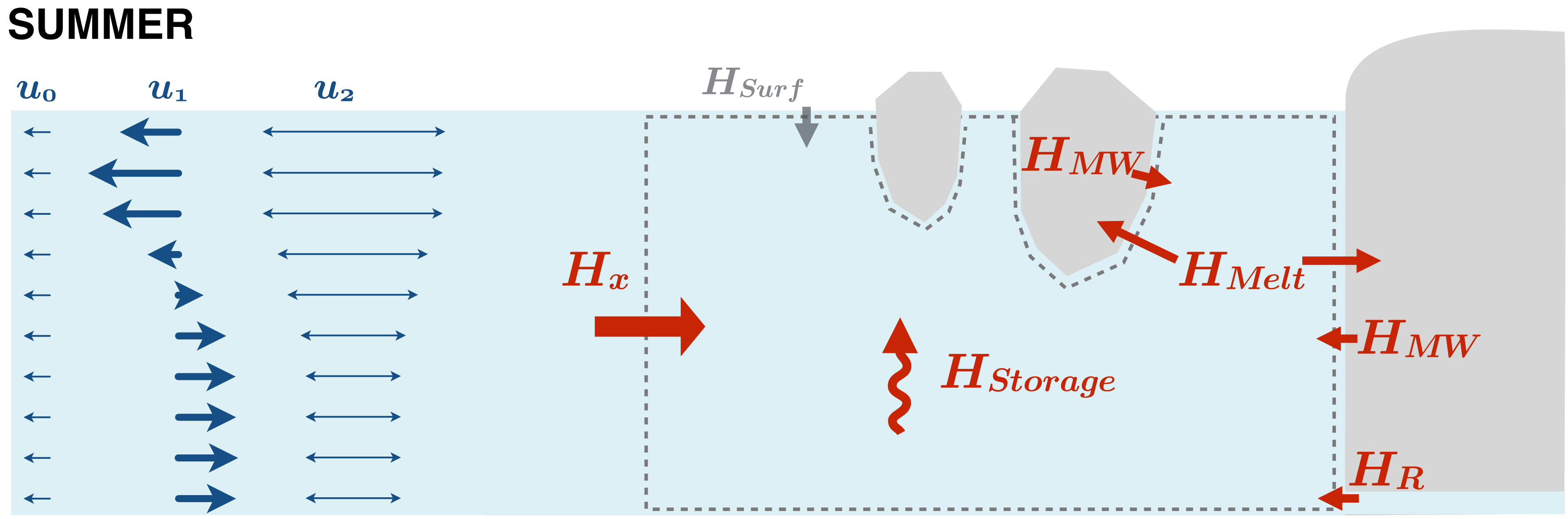
Total freshwater

Submarine meltwater

Runoff/Discharge



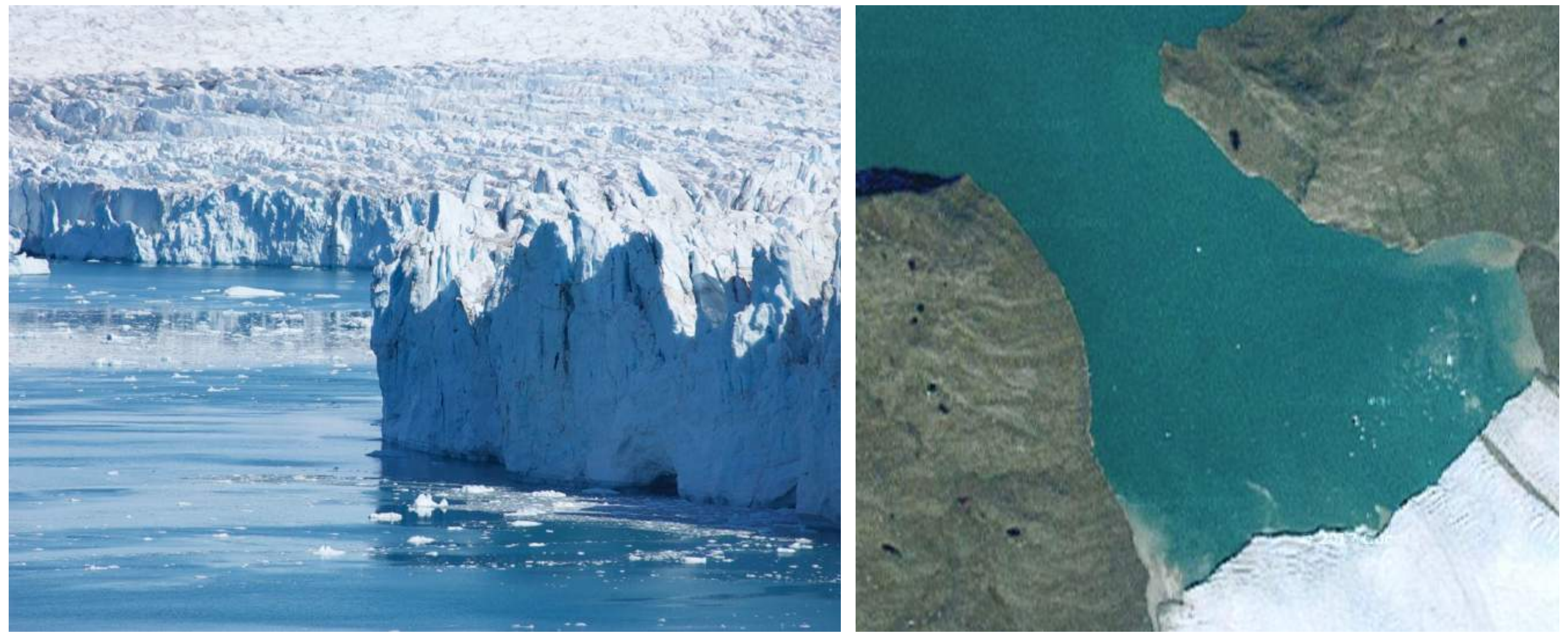




Jackson & Straneo, 2016

Evaluating fjord budgets: observational challenges

glacier with ice melange



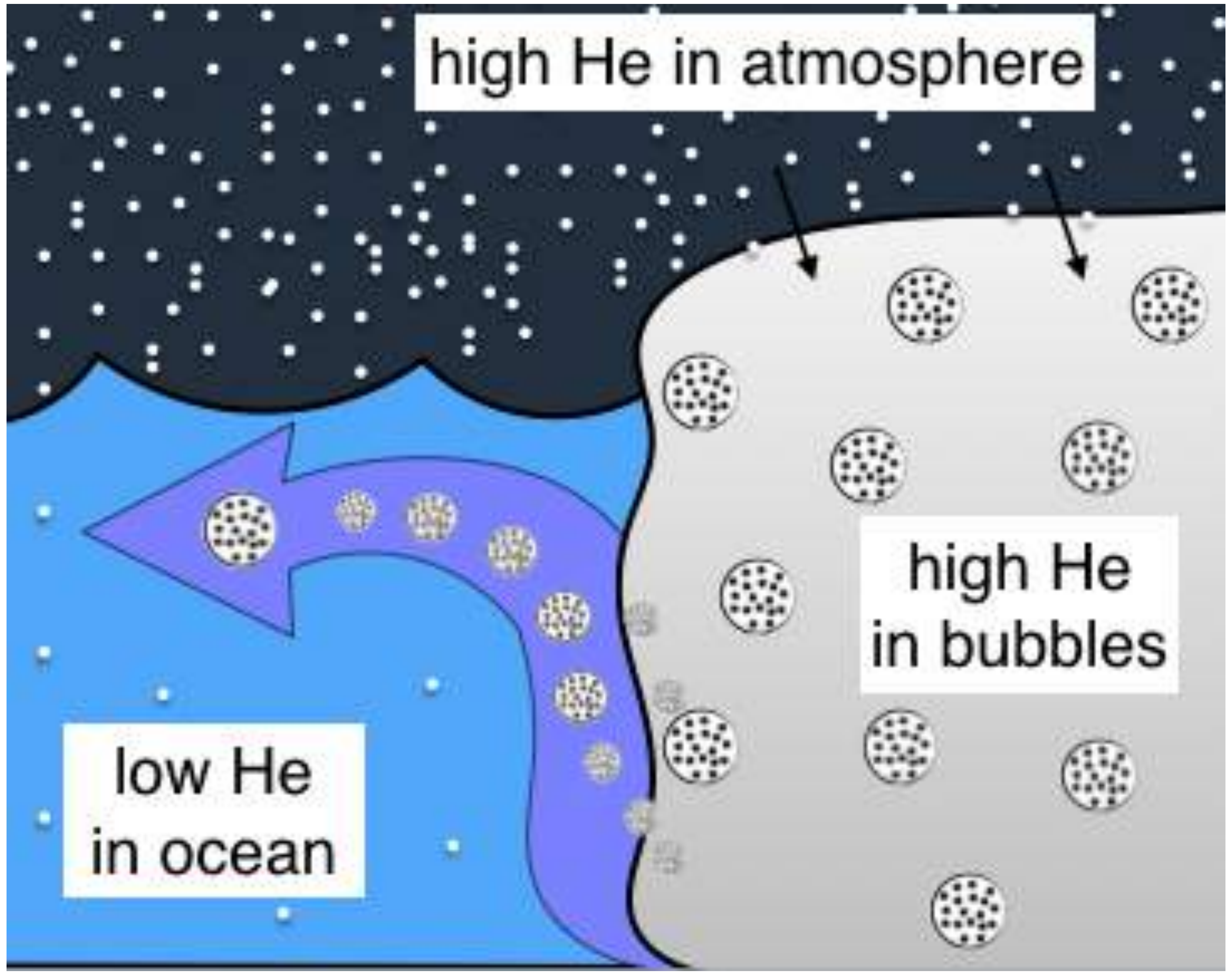
glacier with open water

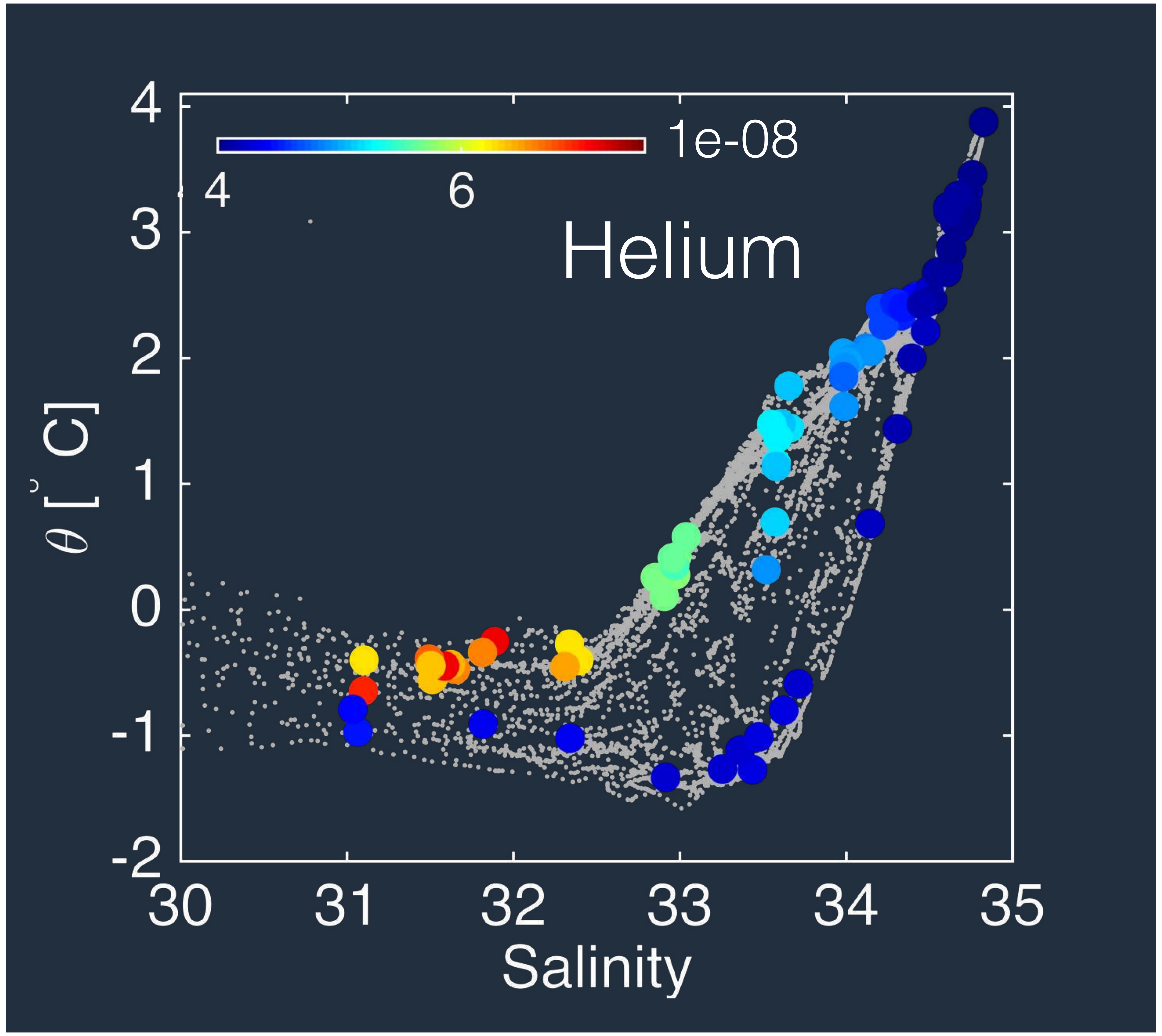
- moorings vs. synoptic surveys: temporal vs. spatial coverage

- different challenges in different fjords
  - does it help to get closer to the glacier?
    smaller storage issues, but also smaller spatial scales to resolve…

- at best, gives bulk numbers and requires extensive velocity data (hard!)

Nobles gases as tracers for meltwater in ocean



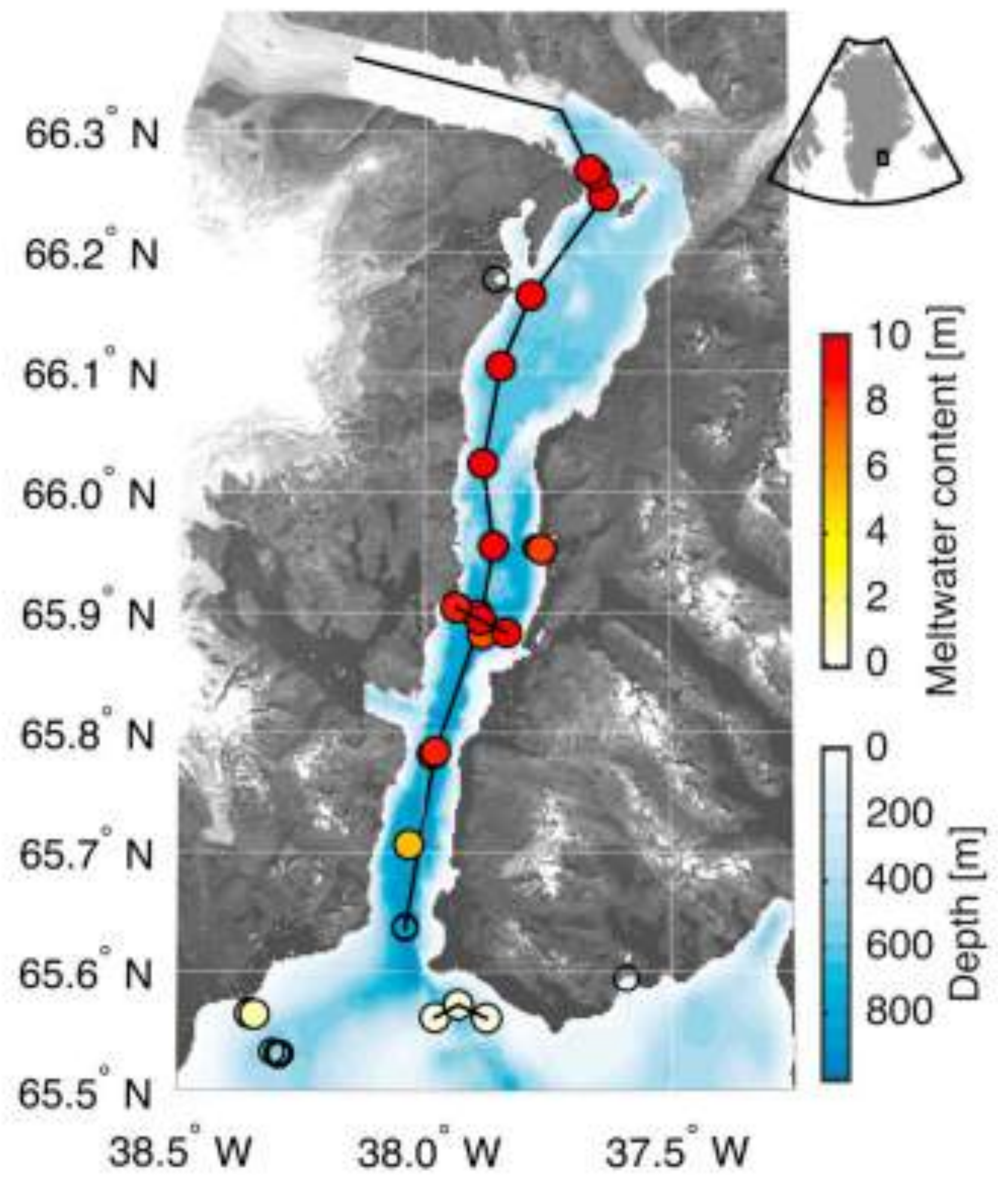


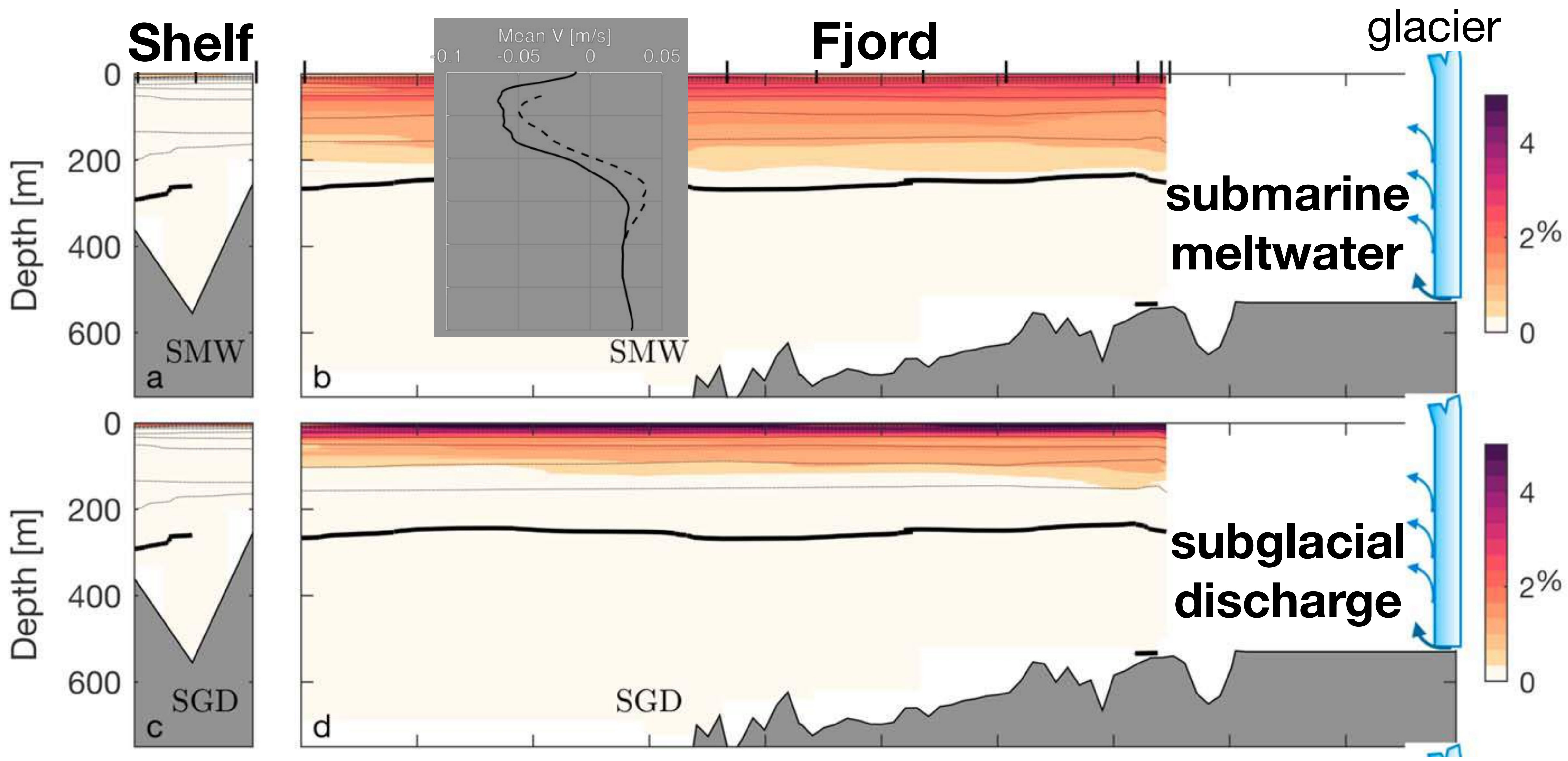
Used in Antarctica
e.g. Loose & Jenkins 2014

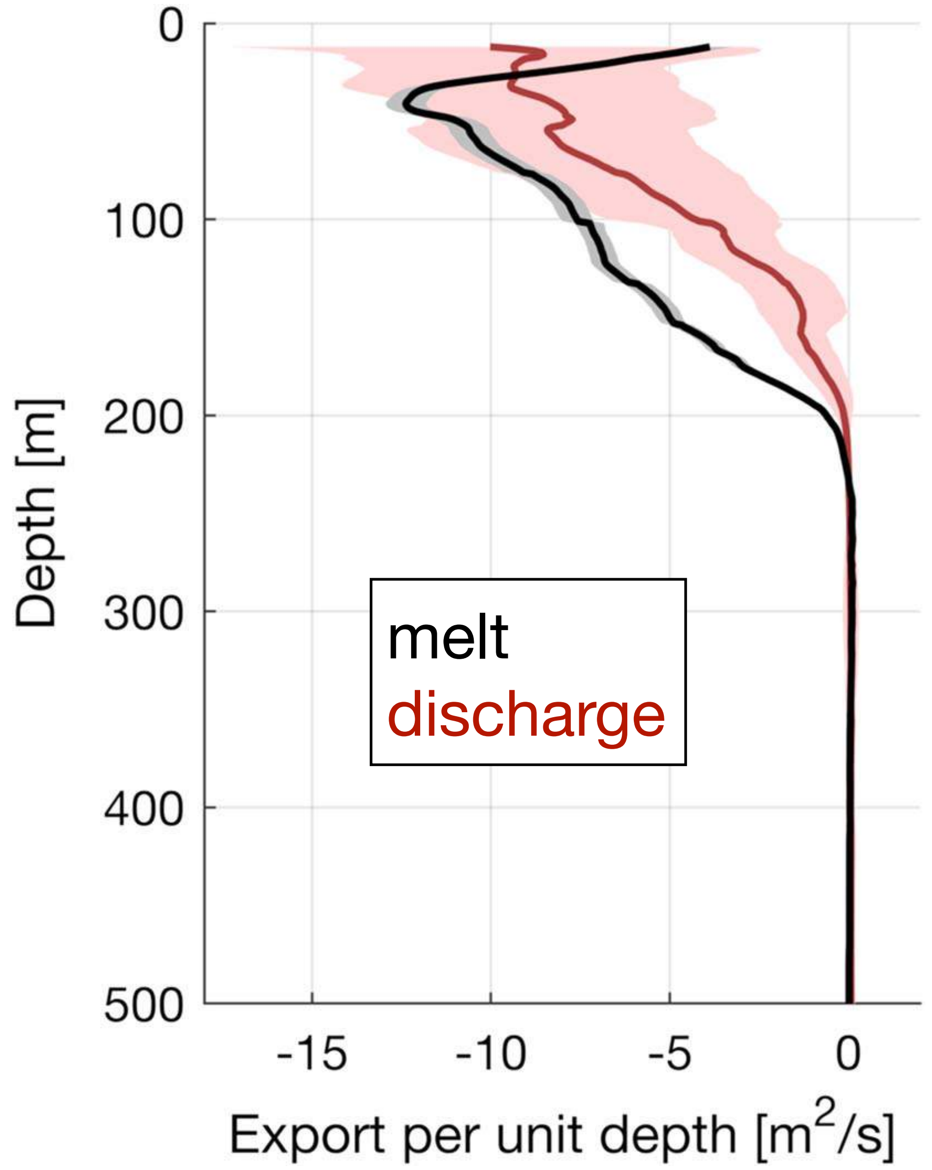
Growing use in Greenland
Beaird et al 2015
Beaird et al 2017
Beaird et al 2018
Rhein et al 2018

- **with T & S alone** → cannot determine freshwater content in most fjords (underdetermined system)
- **add noble gases** → robust quantification of submarine melt & runoff/discharge concentrations

Nobles gases reveal freshwater export pathways

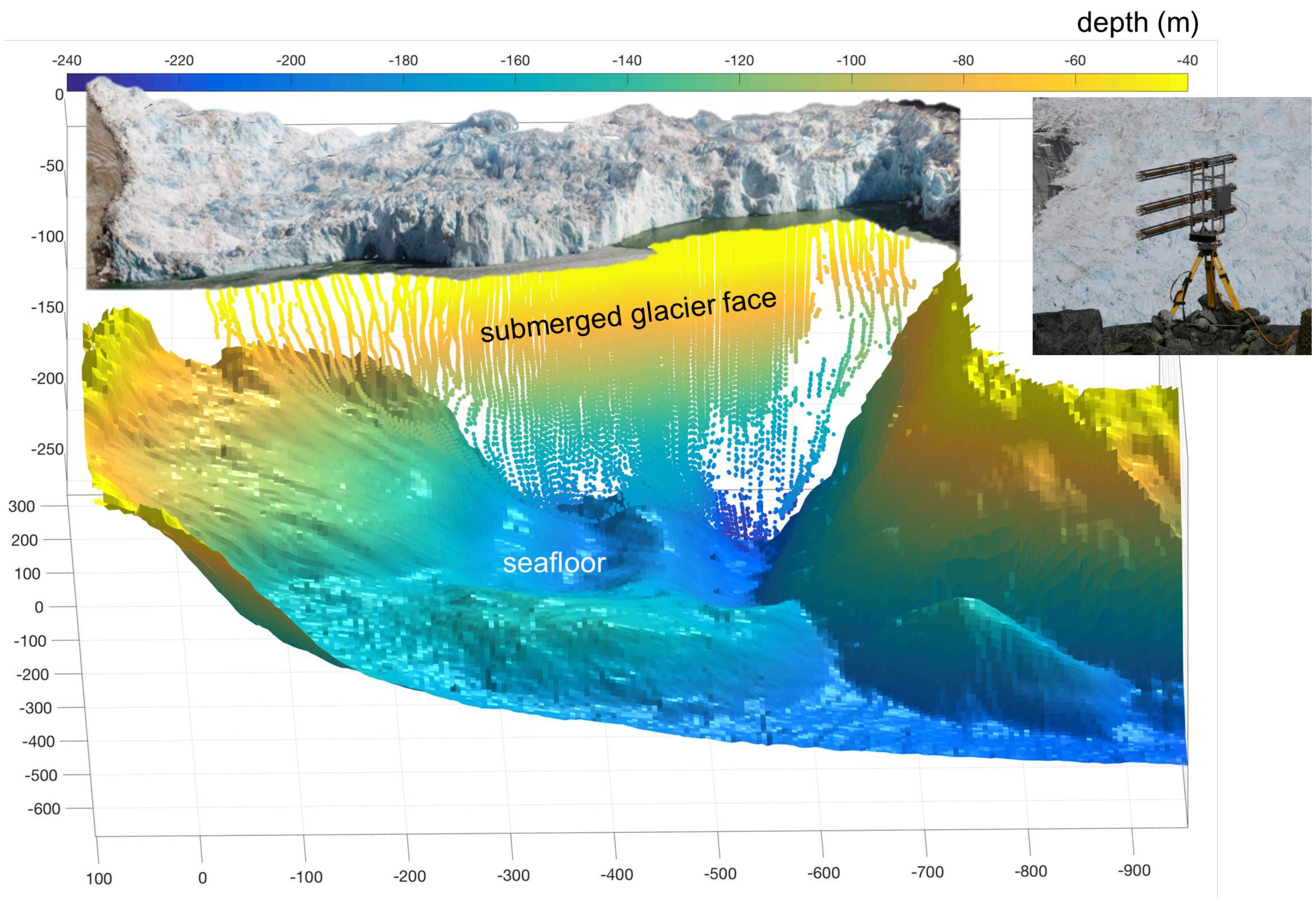


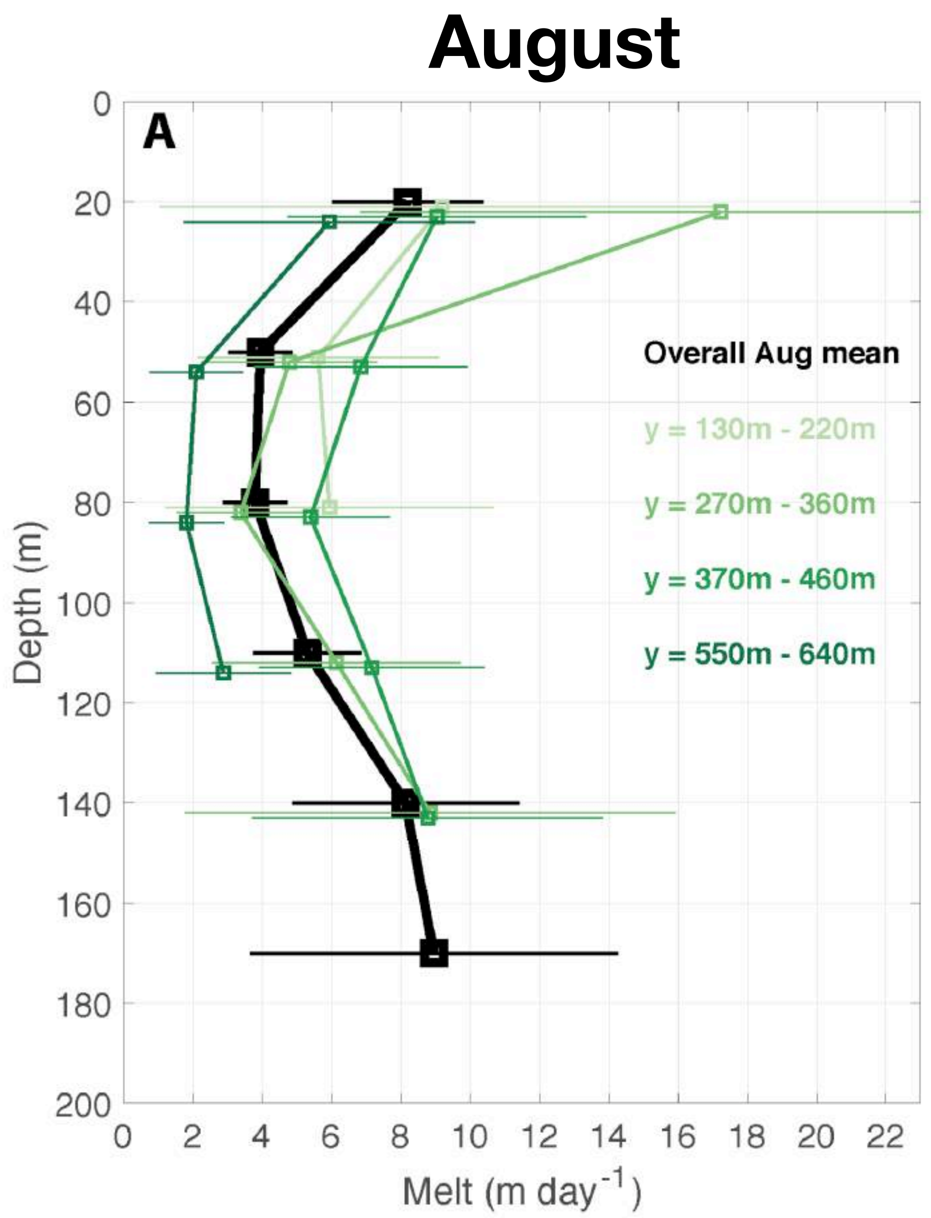


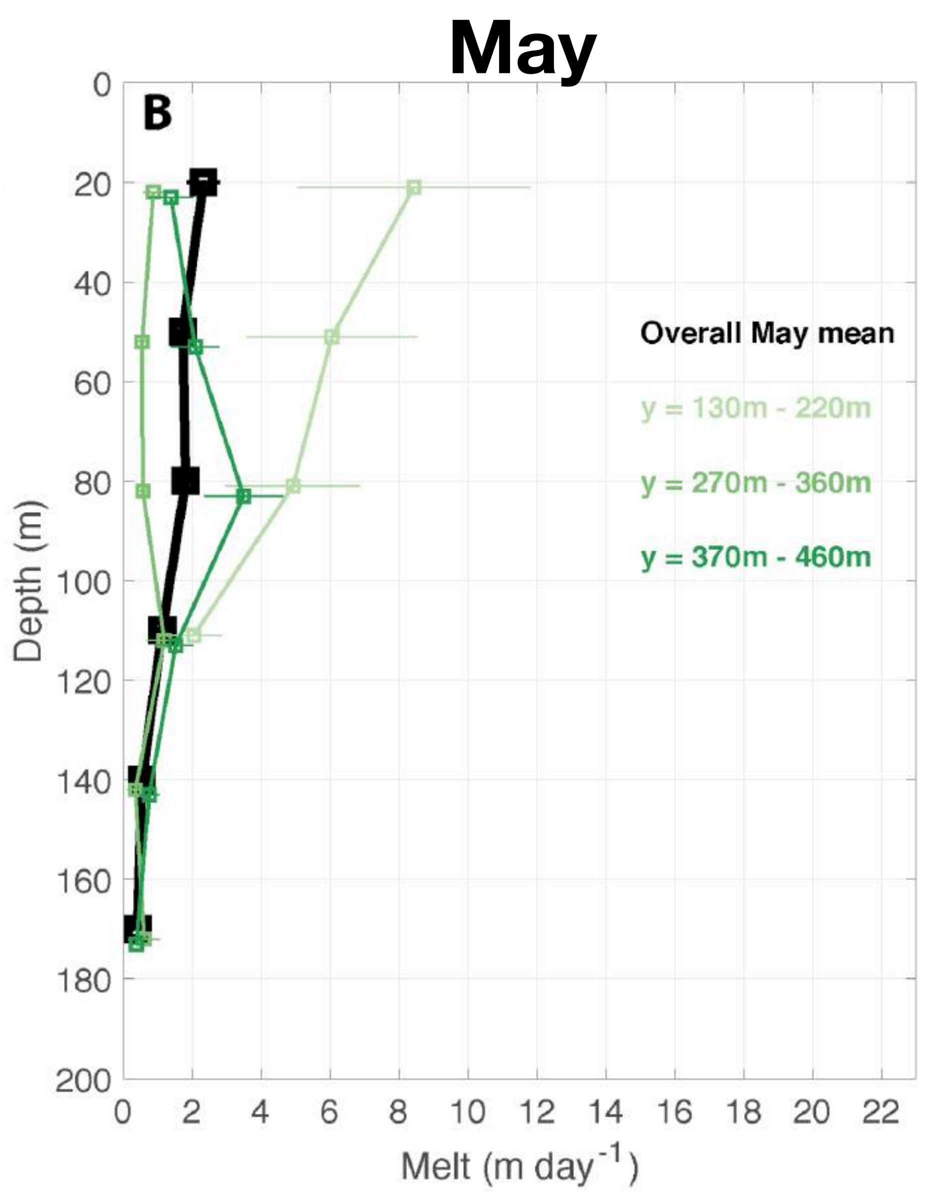


Beaird et al 2018

Multibeam sonar: repeat surveys to measure submarine melt



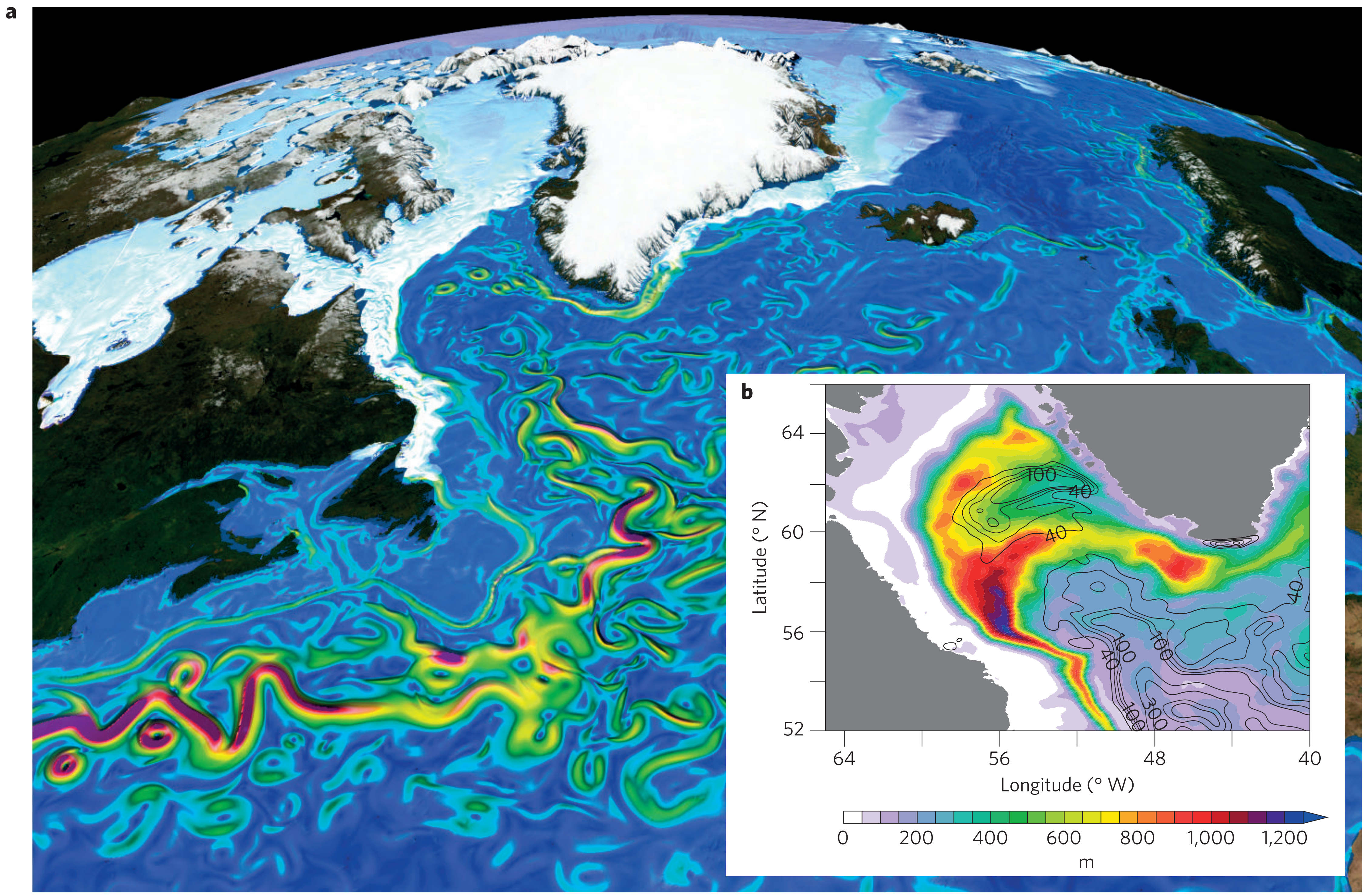




Sutherland et al, in review

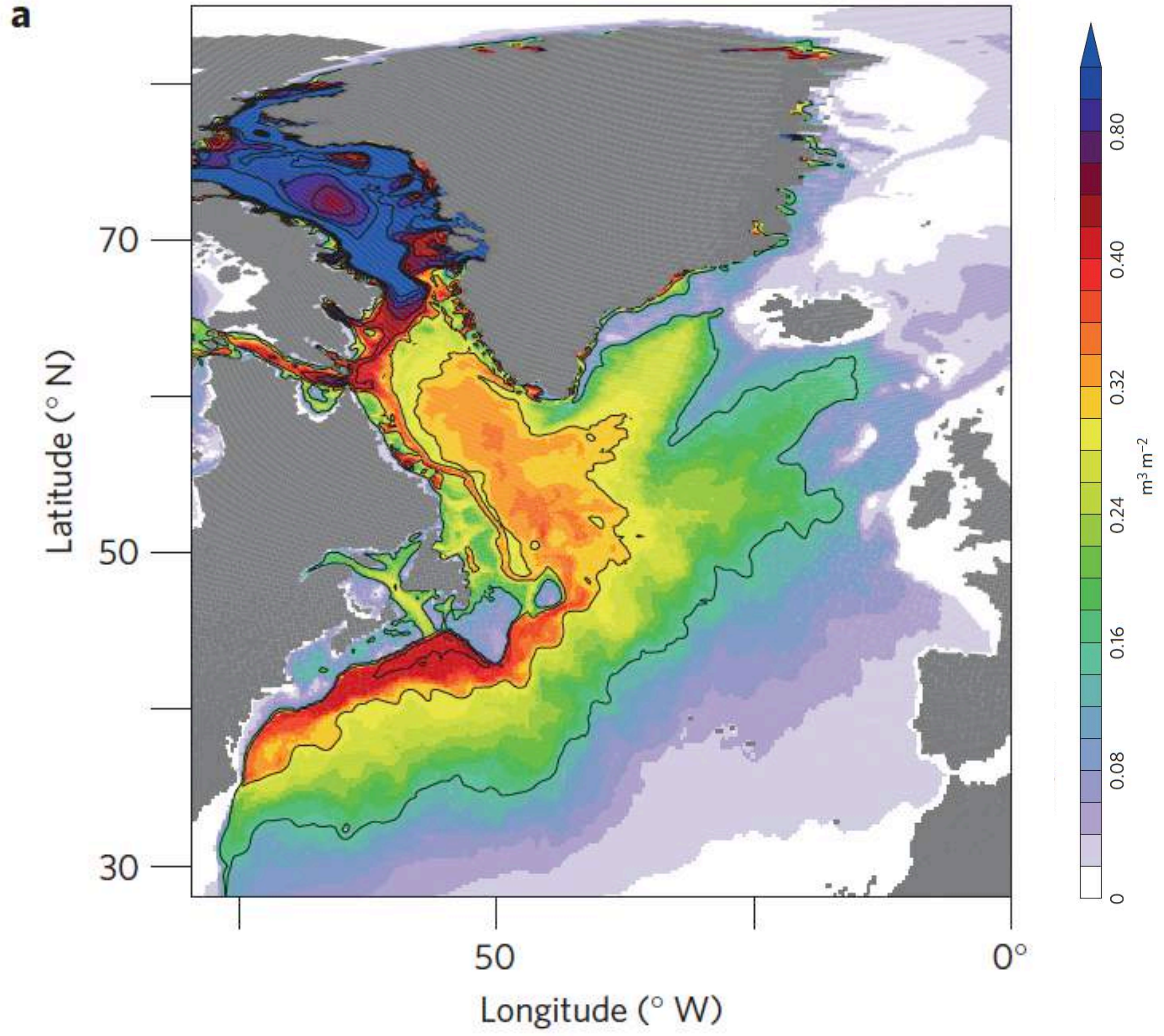
Connections to the shelf & subpolar gyre

Greenland→ocean: freshening & impacts on convection?



Böning et al 2016

freshwater content from Greenland

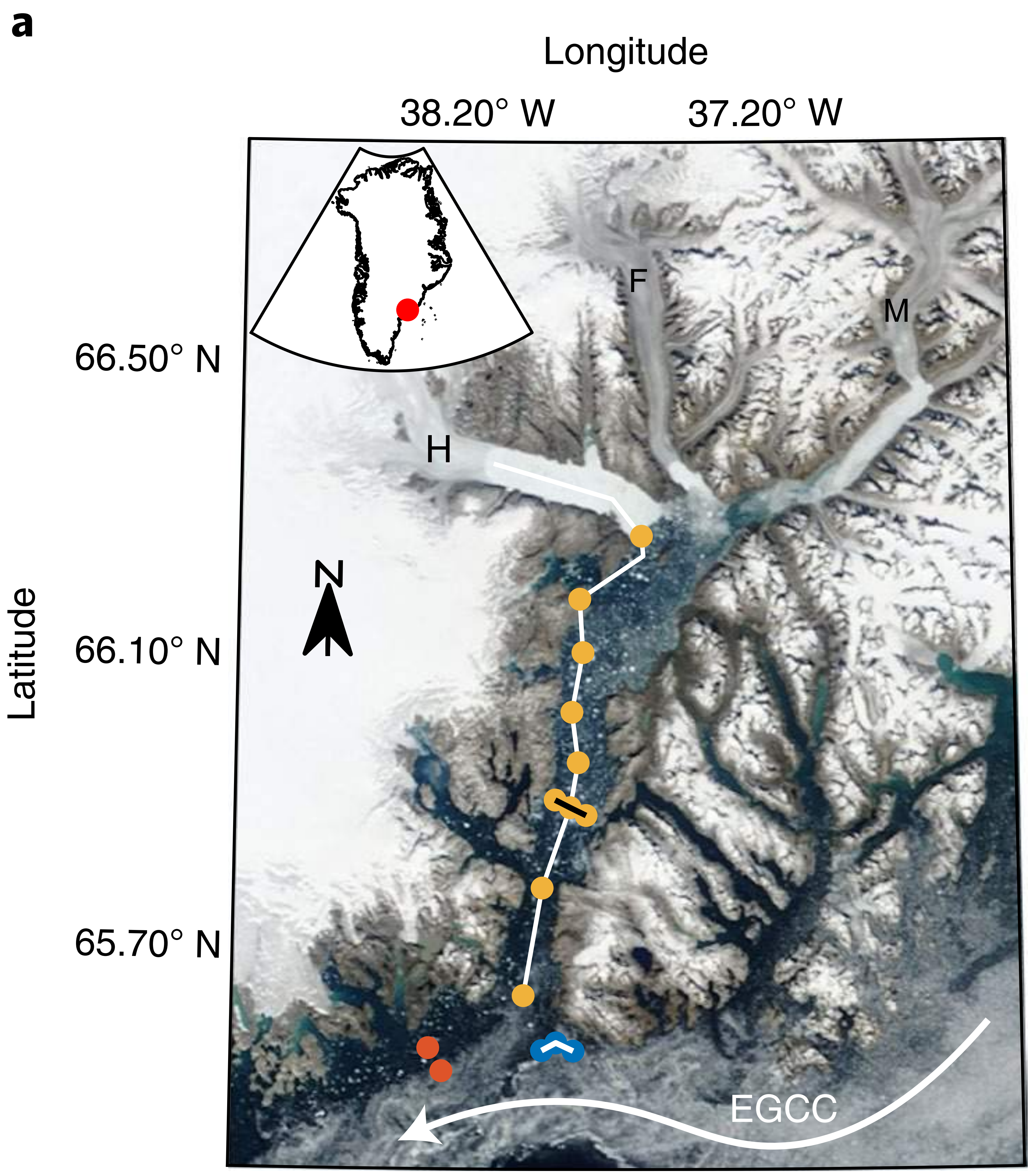


Increased meltwater from Greenland

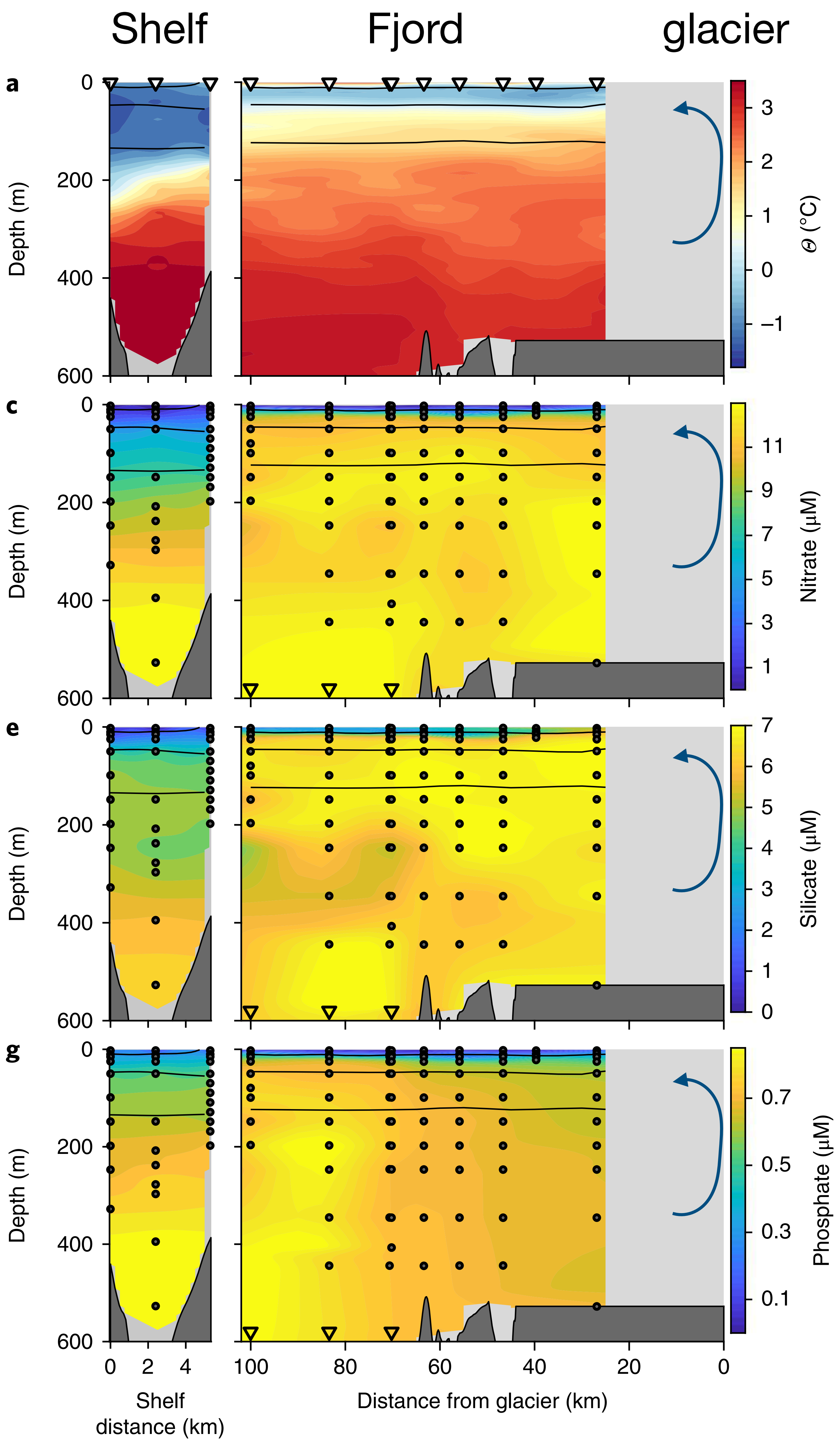
- freshening coastal current & Labrador sea
- potential impacts on deep winter convection

But freshwater from Greenland is injected into the model at the surface (in top 6m bin)…. !

Greenland→ocean: input & upwelling of nutrients



Cape et al., 2018



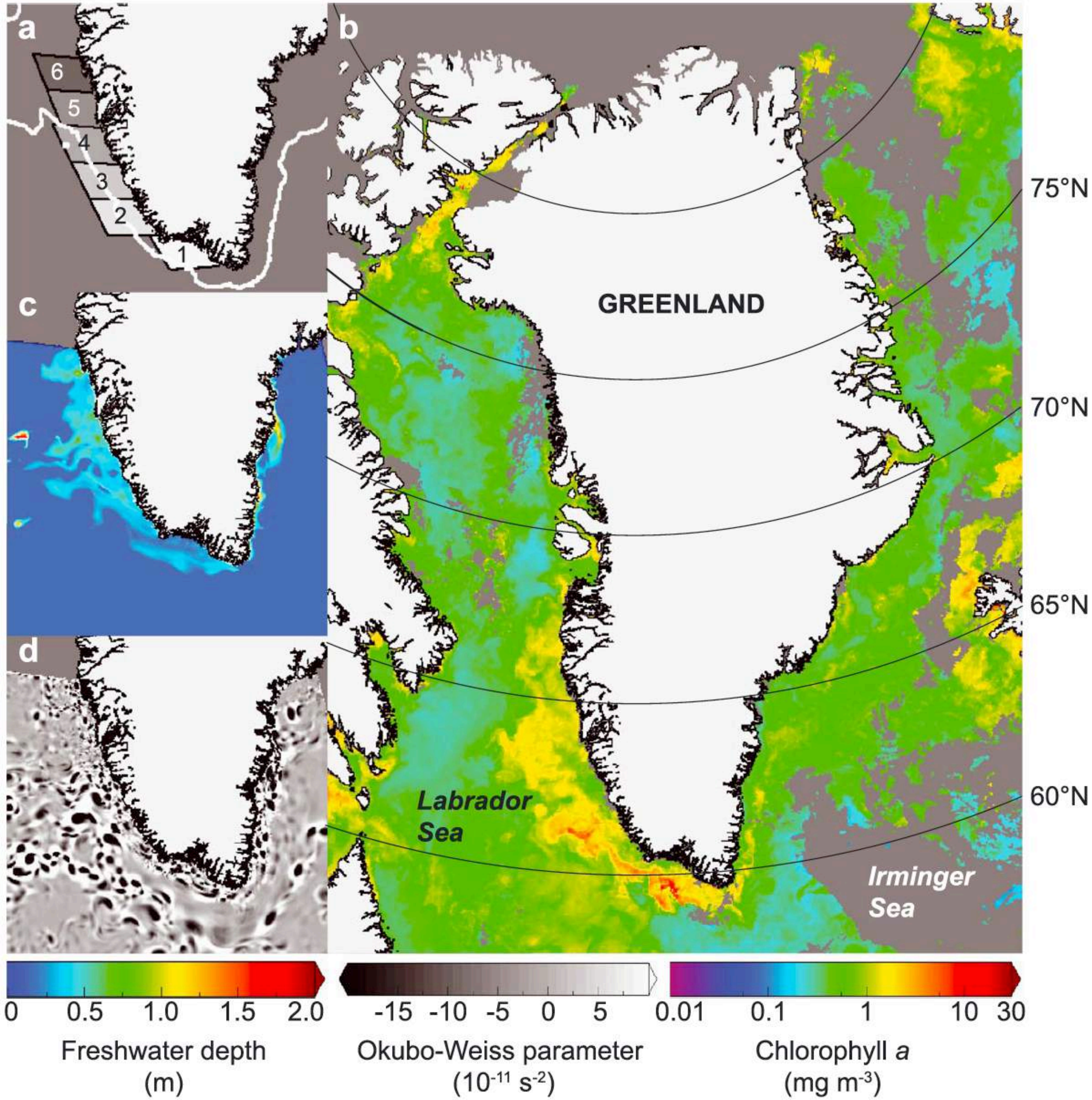
temperature

nitrate

silicate

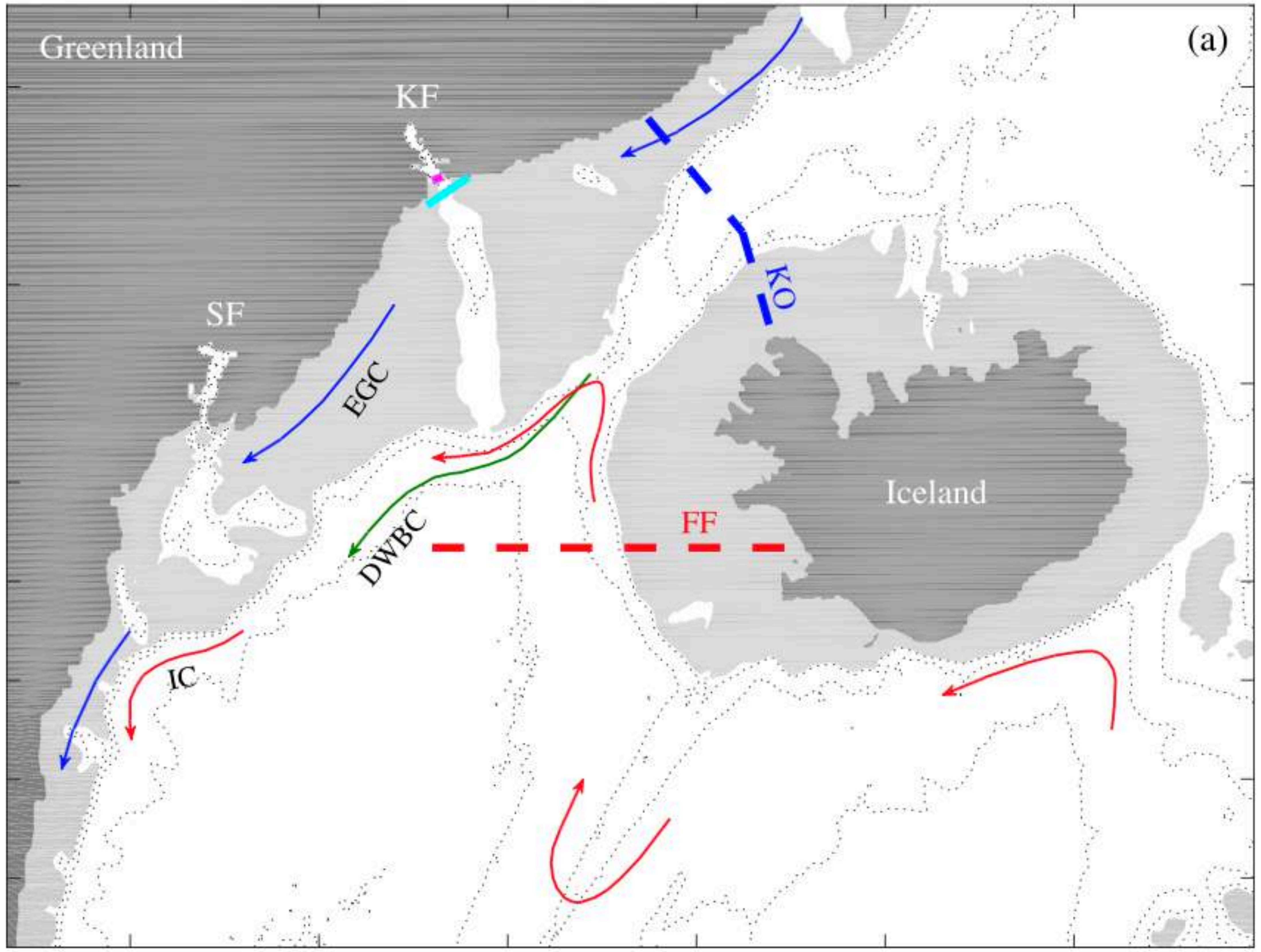
phosphate

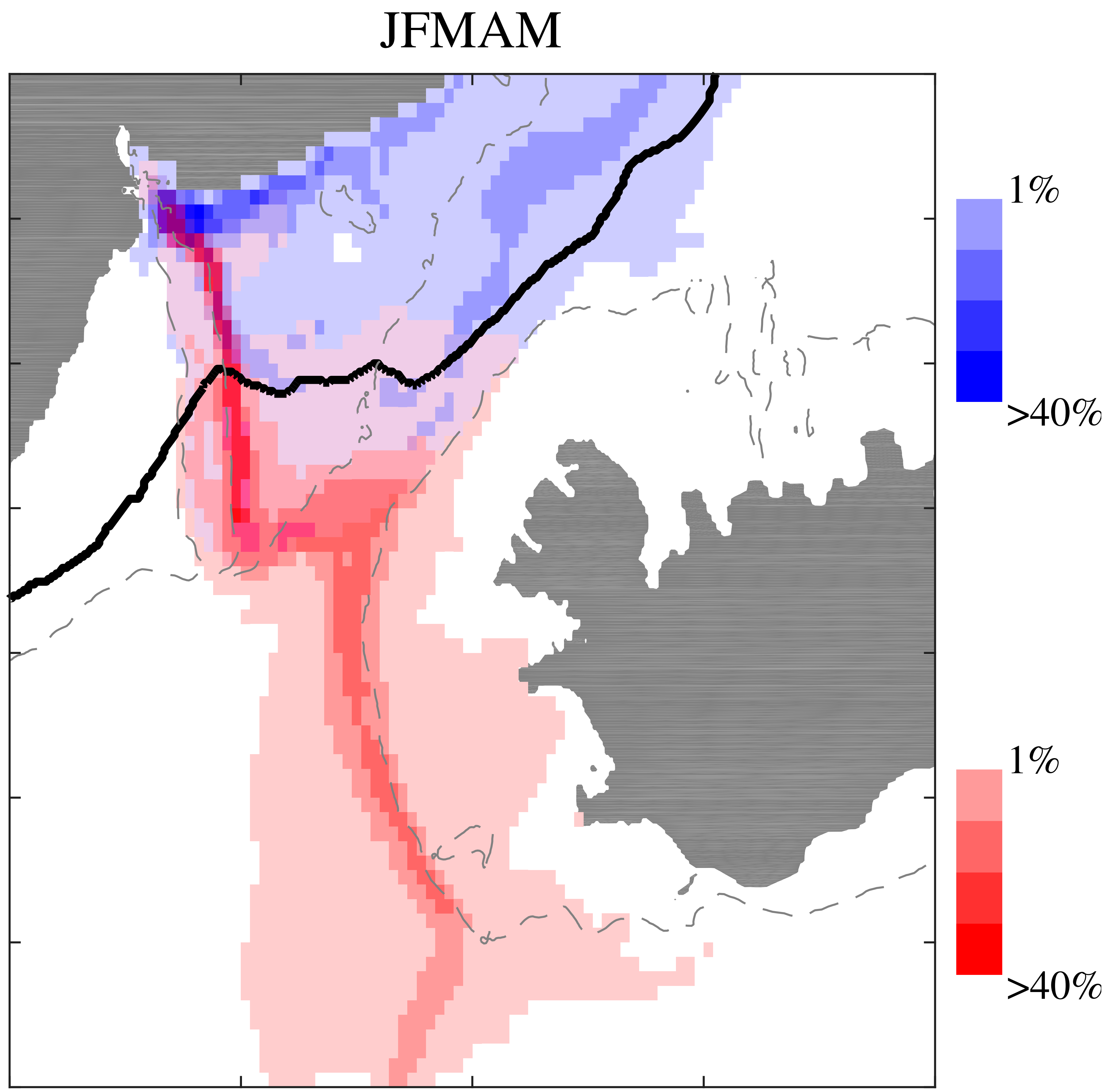
Greenland→ocean: input & upwelling of nutrients



Arrigo et al 2017

Ocean→Greenland: origin & variability of source waters



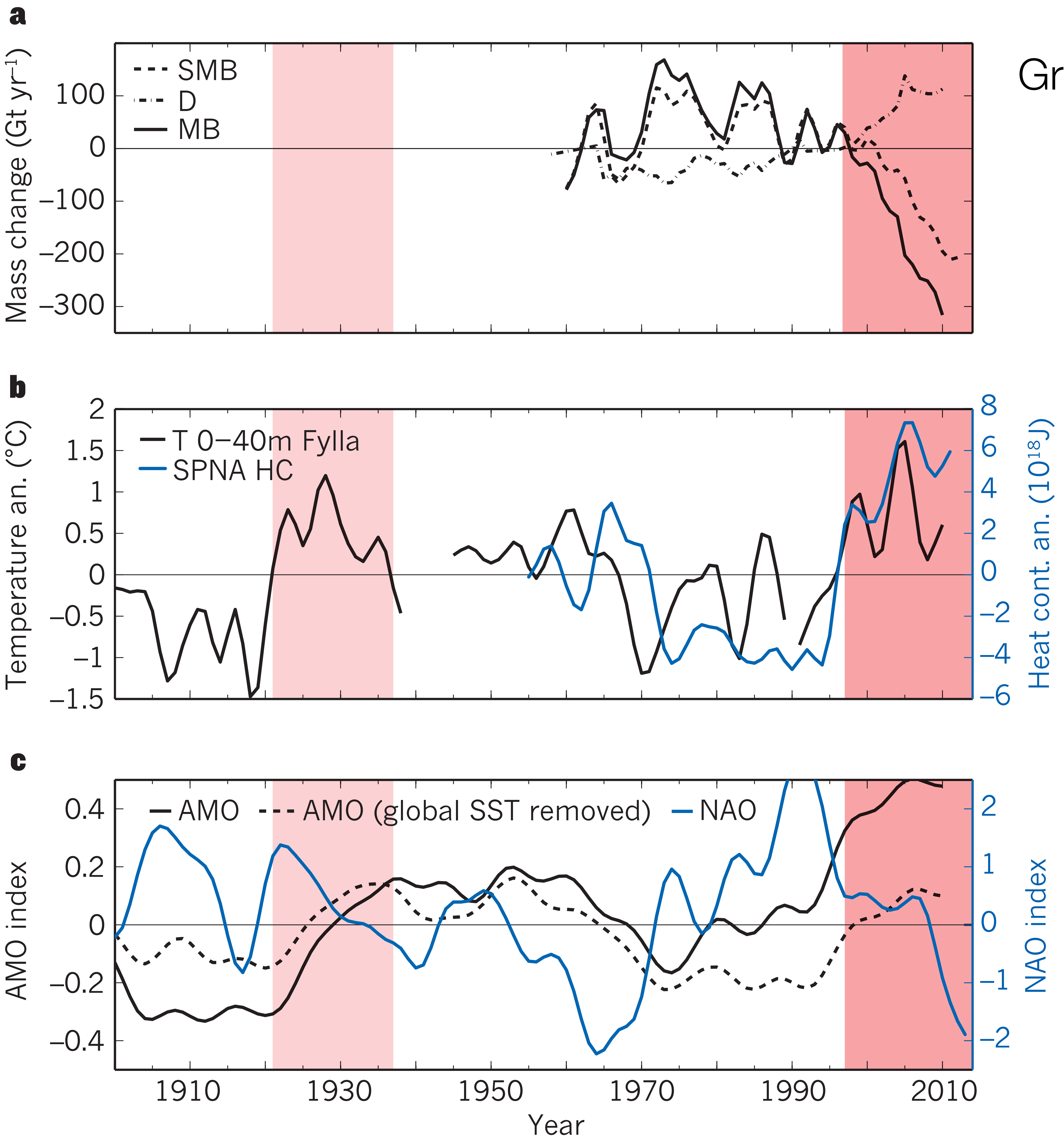


Gelderloos et al. 2017

tracing origin & variability in fjord water masses:

warm Atlantic waters & **cold Polar waters**

How to interpret correlations between ocean & Greenland Ice Sheet?



Greenland Ice Sheet

bold = mass balance

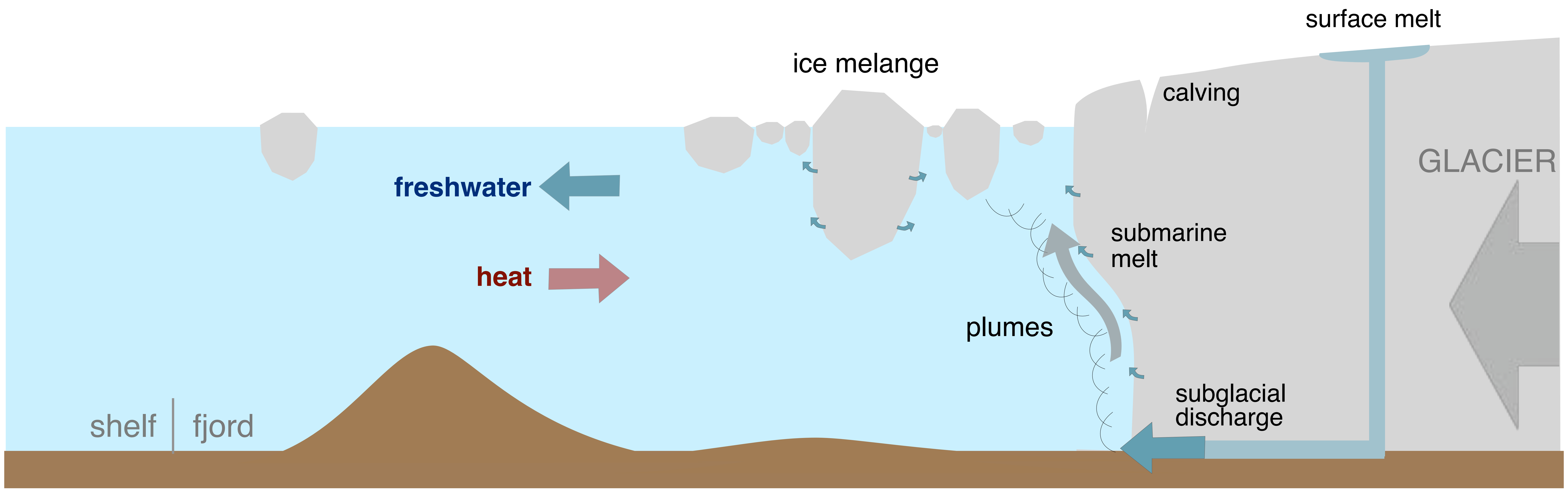
Ocean heat content

blue = heat content anomaly of subpolar N. Atlantic, 0-700 m

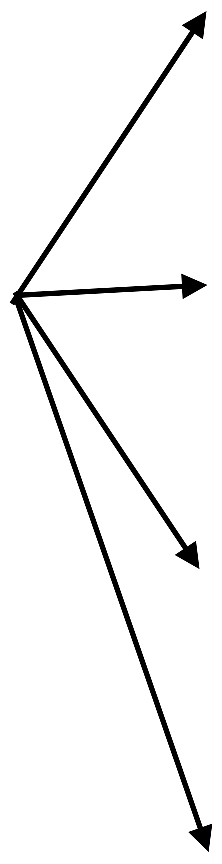
Climate indices

Straneo & Heimbach, 2013

How to disentangle potential drivers of glacier?



An example:

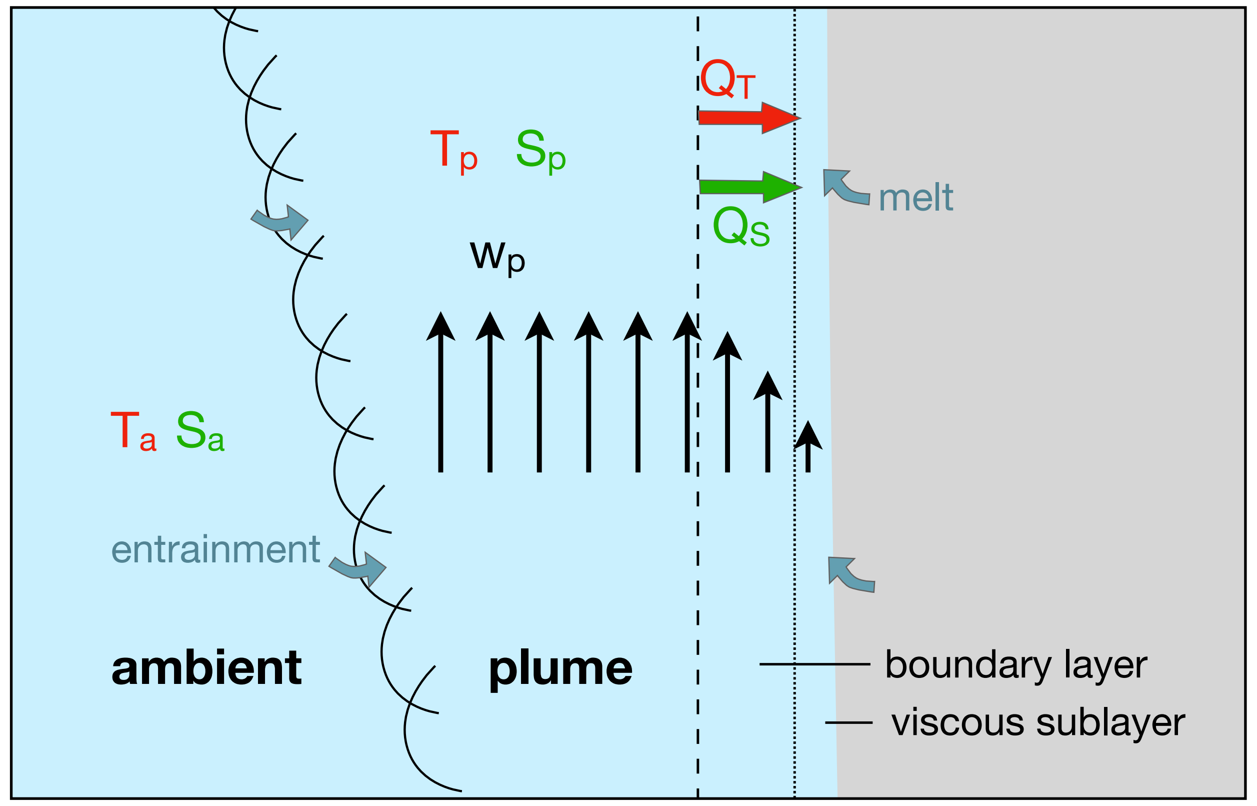


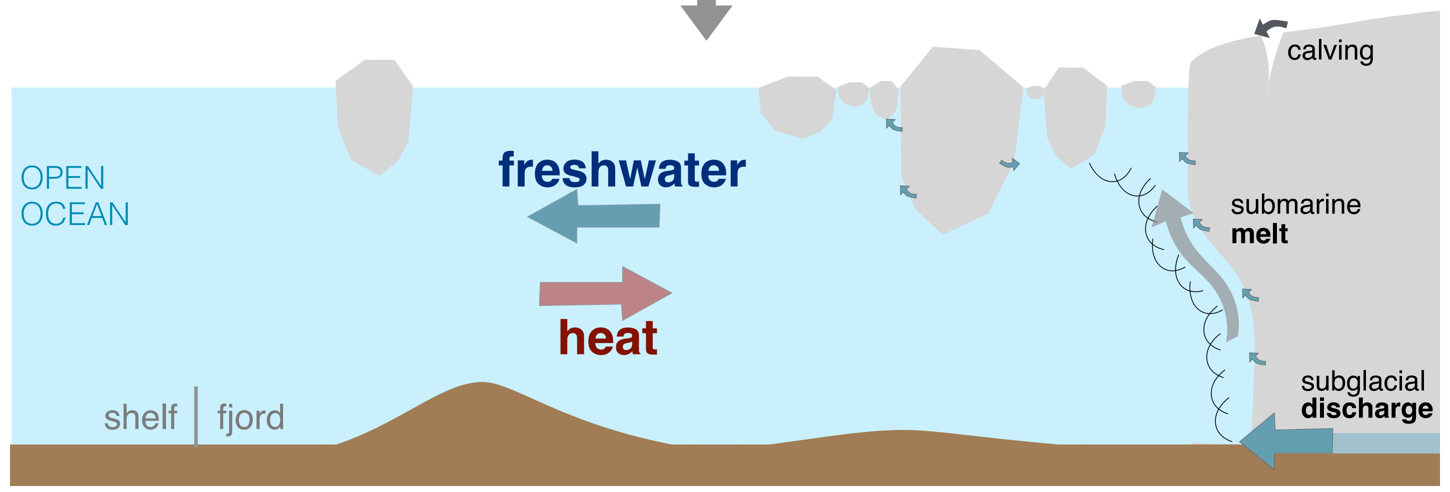
atmospheric warming

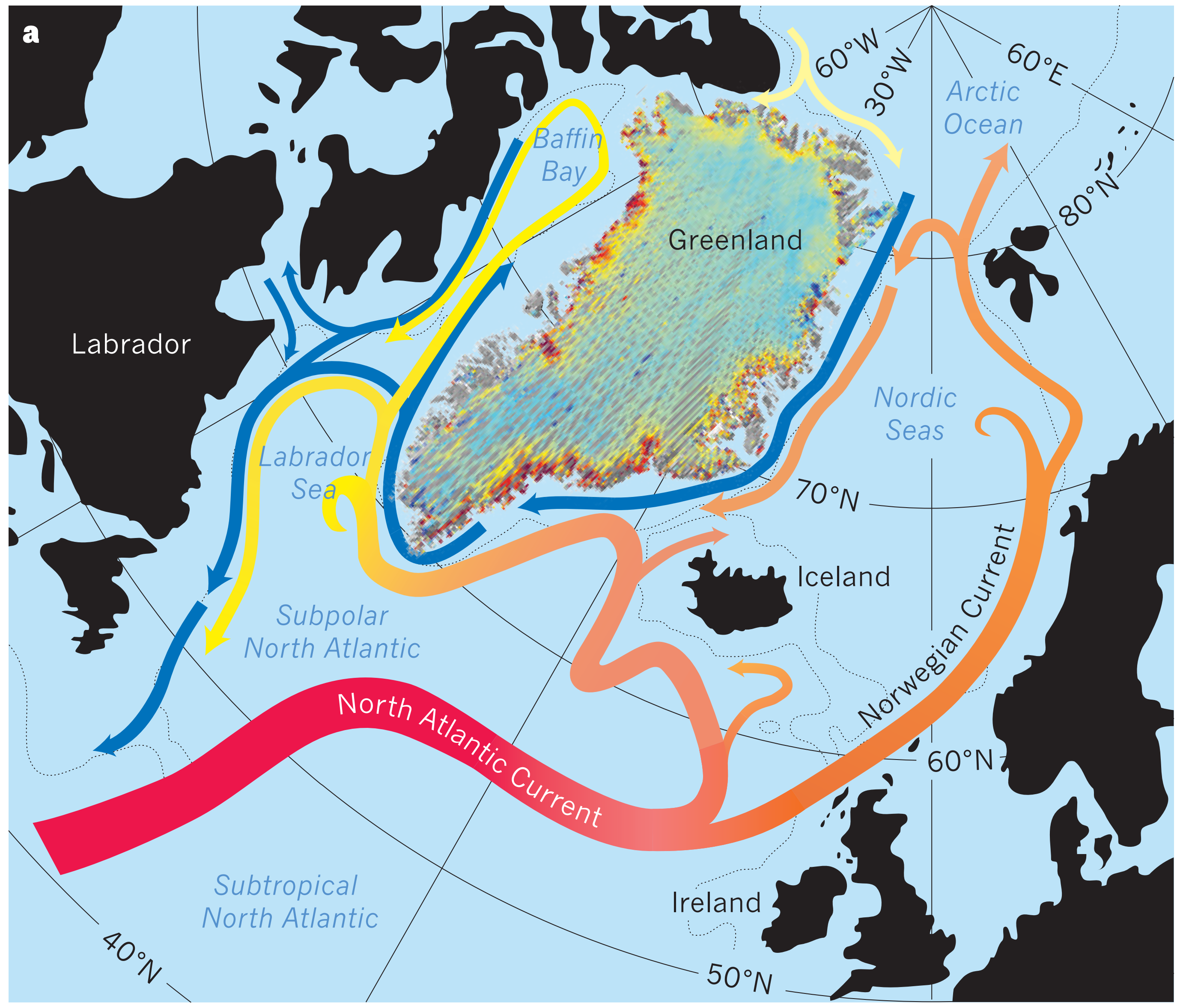
- warm ocean waters → increase submarine melt → **glacier acceleration/retreat**
- increase surface melt → increase discharge → increase submarine melt → **glacier acceleration/retreat**
- increase surface melt → increase discharge → increase basal lubrication → **glacier acceleration/retreat**
- weaken ice melange & sea ice → reduce back stress → **glacier acceleration/retreat**

Summary

- plume dynamics modulate melting & mixing
    - just starting to test parameterizations with observations – should be treated with caution!
- freshwater input at depth drives massive upwelling
    - freshwater is often exported subsurface, after it has mixed ~30:1 with deep fjord waters
    - future fjord parameterizations for large-scale ocean models need to account for this
- progress in measuring freshwater fluxes (melt & discharge) but monitoring variability is an open challenge
- increasing freshwater flux from Greenland has potential impacts on coastal currents, subpolar gyre, ecosystems, etc.
- shelf and subpolar processes control origin & variability of fjord waters that drive submarine melting
- challenge to disentangle various glacier drivers & feedbacks





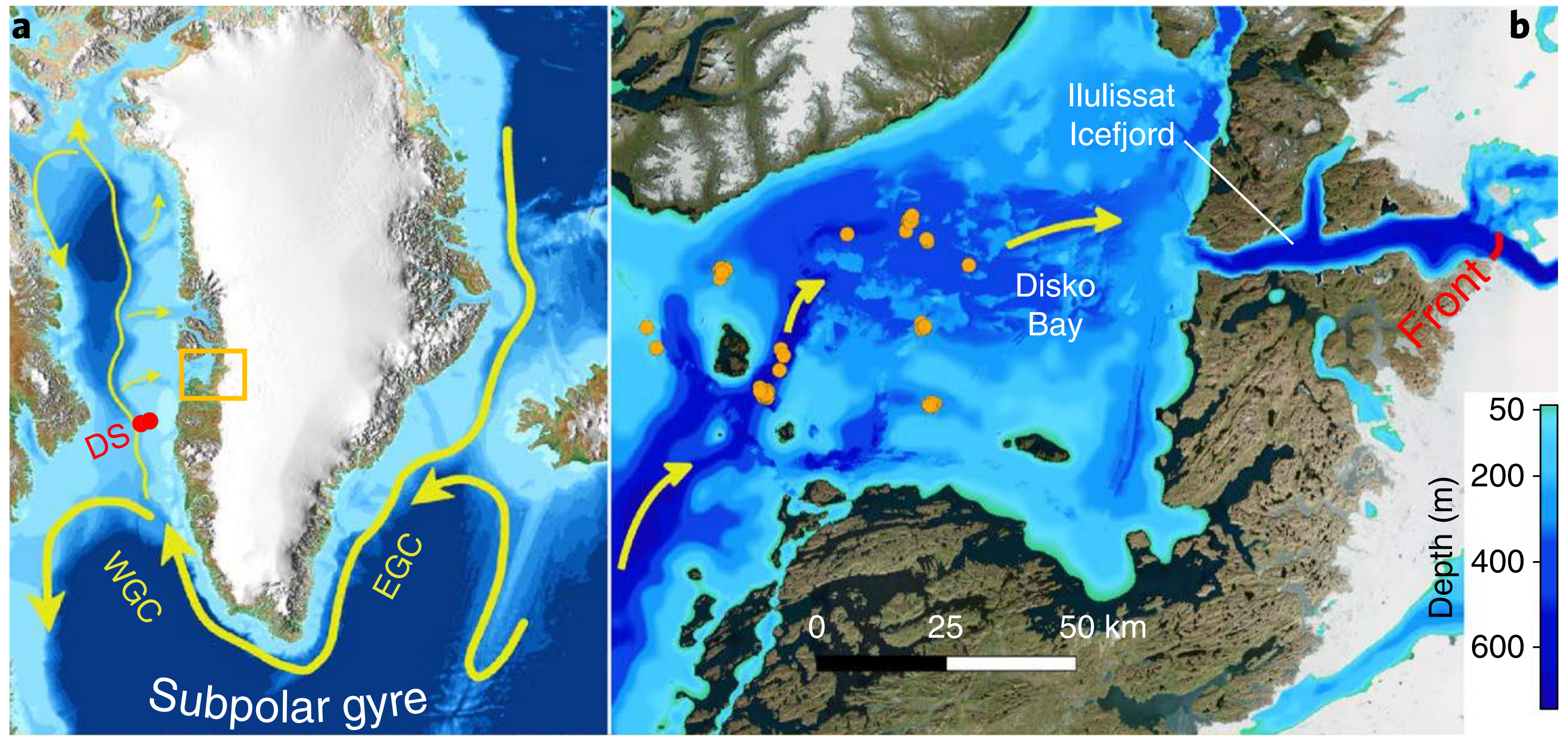


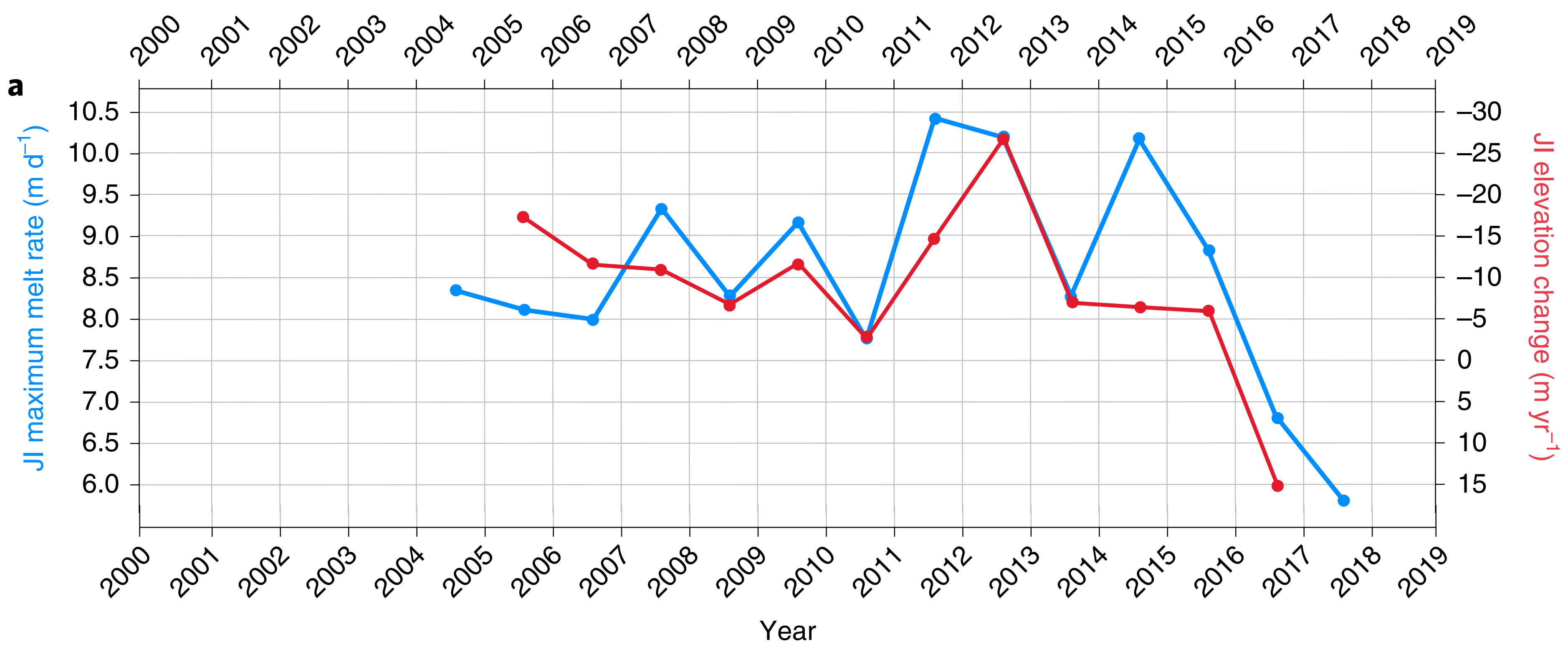
Questions?

How robust is the correlation between ocean & glacier?

Jakobshavn, W. Greenland

Khazandar et al 2019





Helheim, E. Greenland

Straneo et al. 2016