Fjords in Flux – downstream impacts of Greenland Ice Sheet melt

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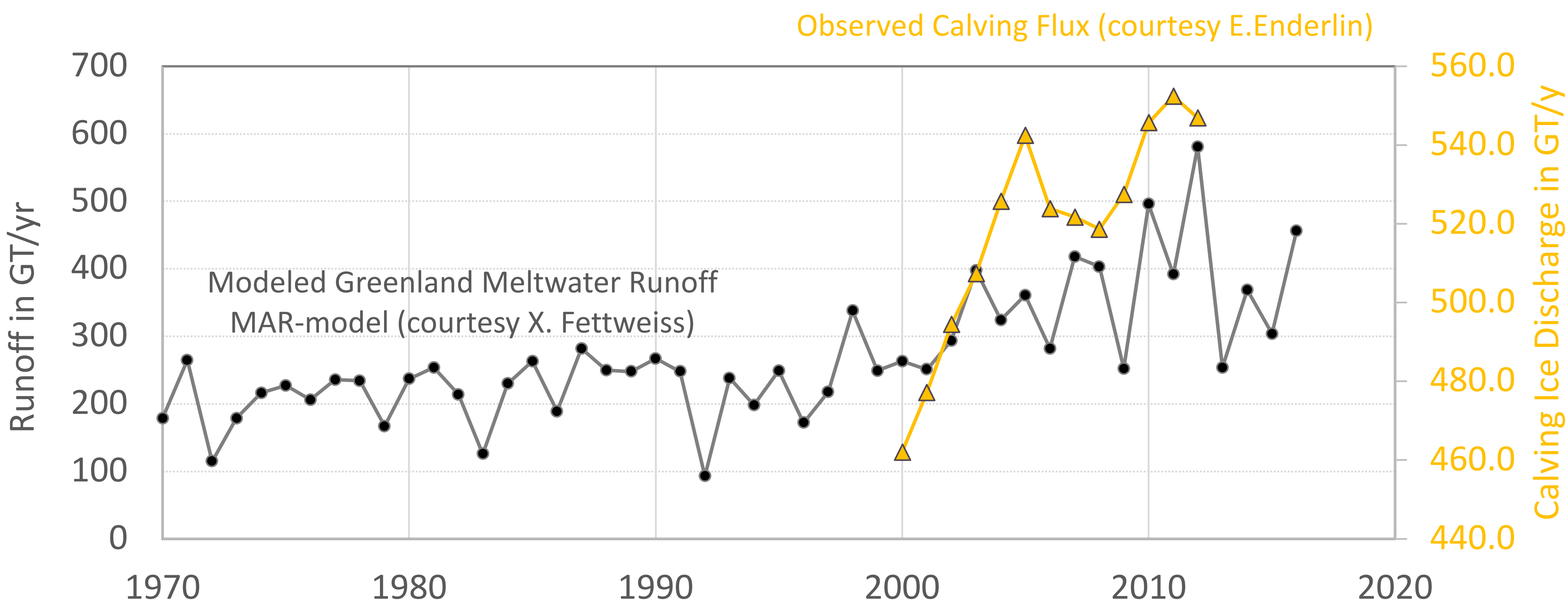
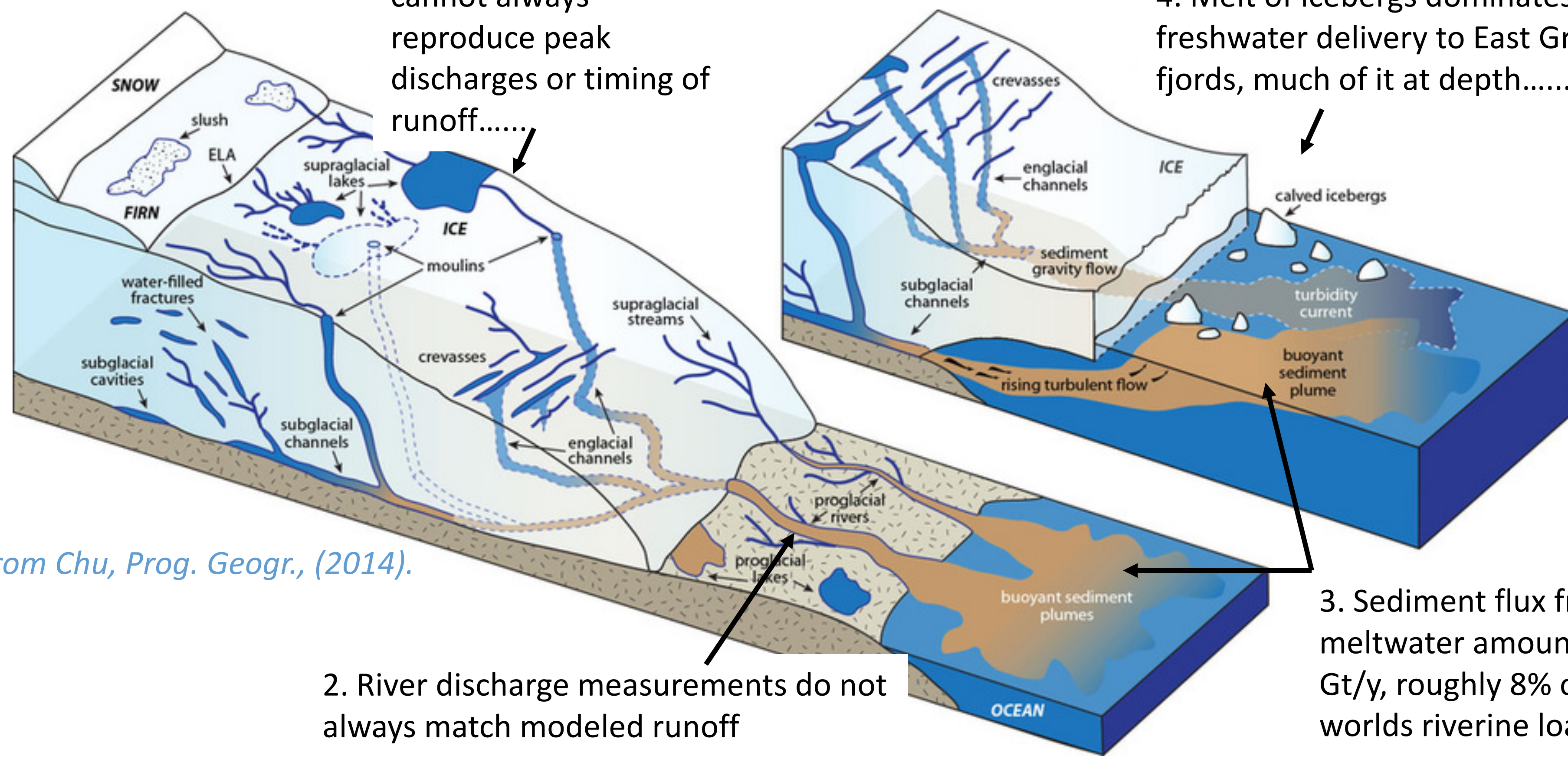
Greenland Ice Sheet Runoff and Ice Discharge



Effects of Greenland Ice Sheet Melt and Calving?

1. Current models cannot always reproduce peak discharges or timing of runoff……

4. Melt of icebergs dominates freshwater delivery to East Greenland fjords, much of it at depth……..

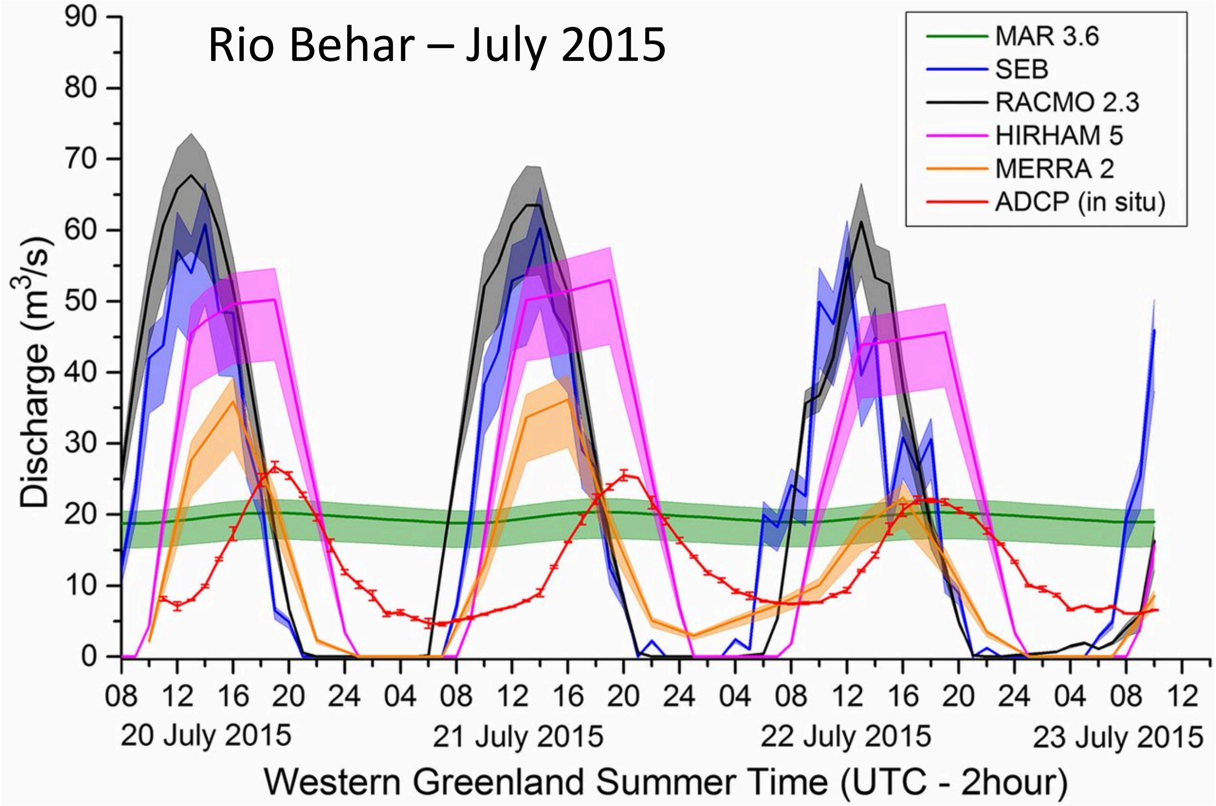


From Chu, Prog. Geogr., (2014).

3. Sediment flux from meltwater amounts to 0.9 Gt/y, roughly 8% of the worlds riverine load……..

2. River discharge measurements do not always match modeled runoff

Greenland Ice Sheet Hydrology



From: Smith et al. PNAS 2017

Storage of water in bare ice

From: Cooper et al. 2018, TC.

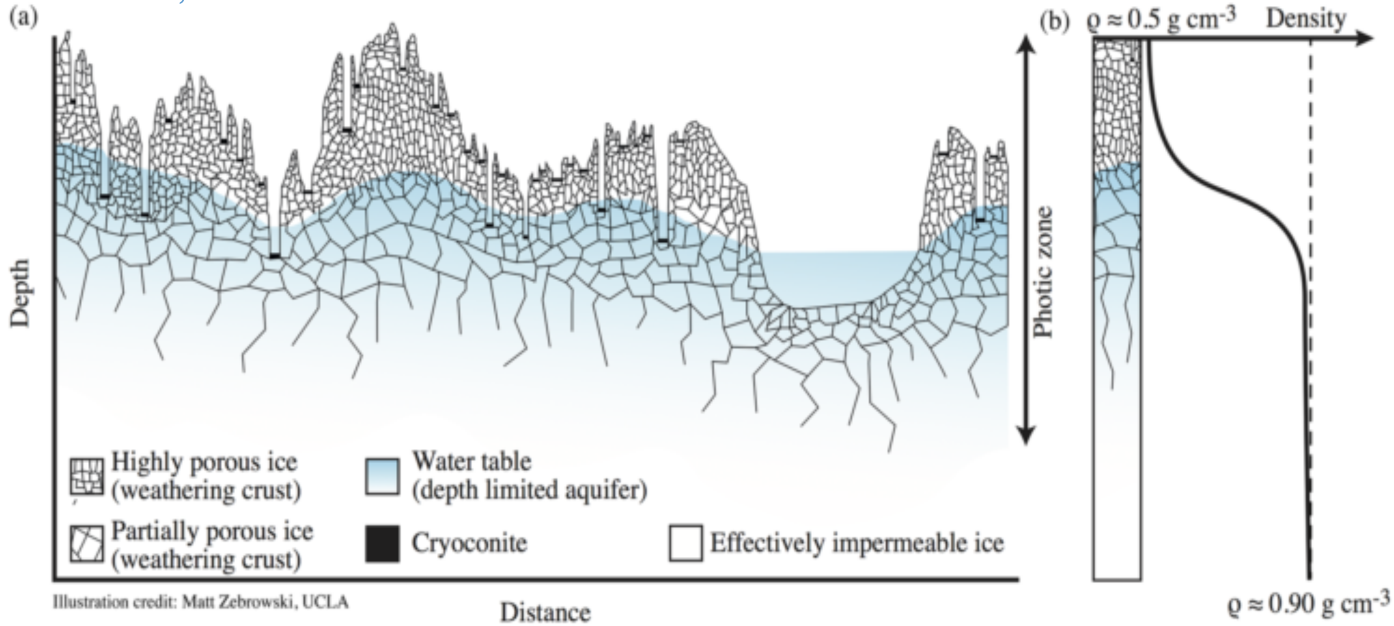
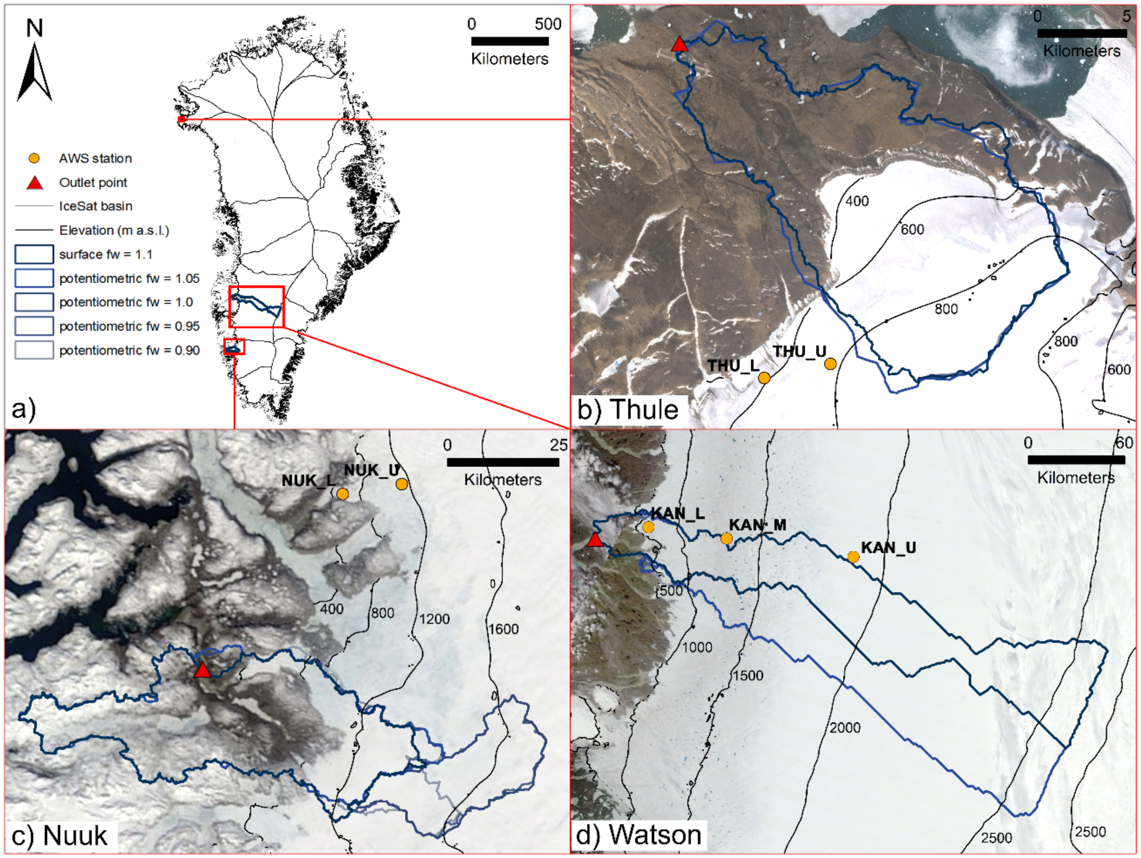


Figure 1. (a) Conceptual diagram of weathering crust structure, highlighting the porous ice layers, cryoconite holes, and saturated water table (adapted from Irvine-Fynn and Edwards, 2014 and Müller and Keeler, 1969). **(b)** Theoretical subsurface depth-density profile showing the non-linear increase in ice density from the highly porous, low density near-surface ice to higher-density, unweathered glacier ice (adapted from LaChapelle, 1959). Illustration credit: Matt Zebrowski, UCLA.

How does numerical model perform? river discharge – per catchment

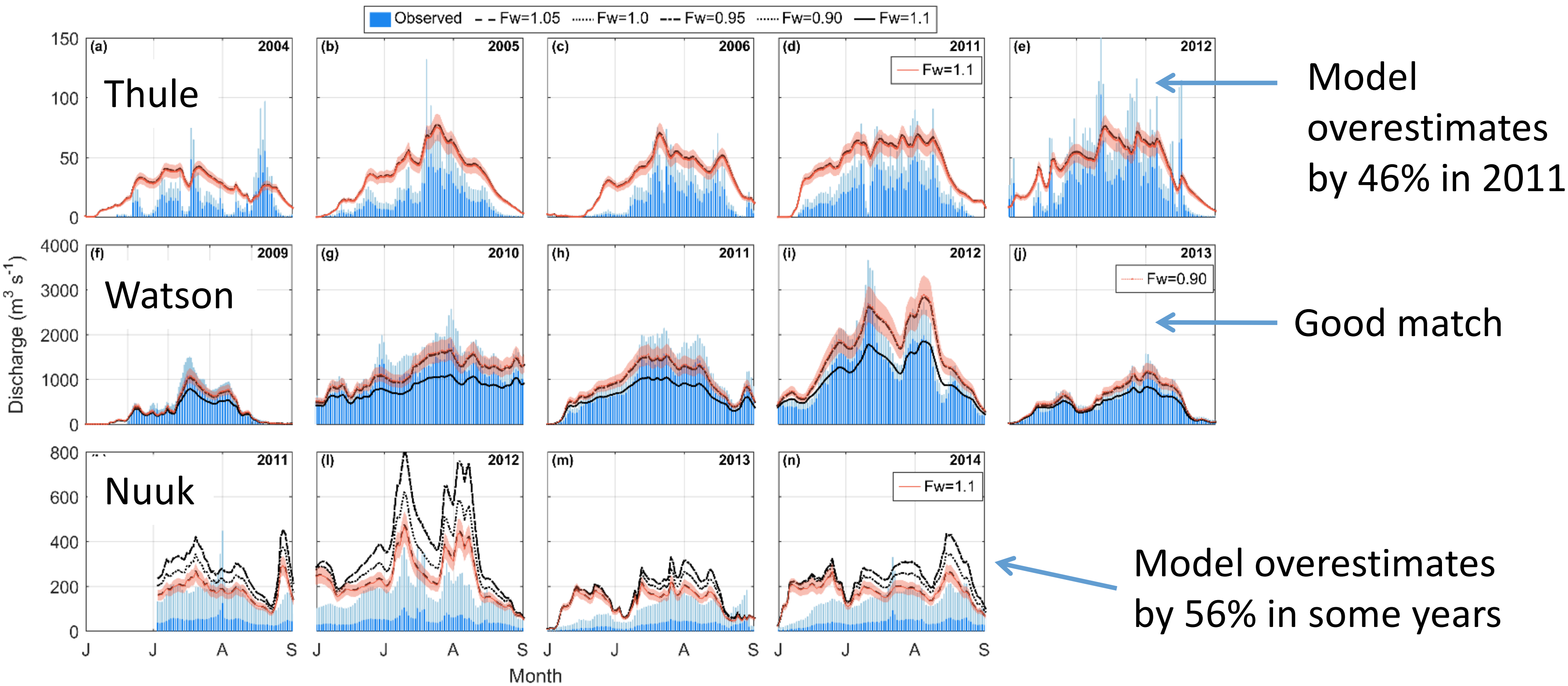


Moustafa et al., in review JGR

Only 3 rivers are monitored, Longest record is barely 10 years

Catchment delineation is uncertain, discharge measurements are challenging.

Model compared to observations



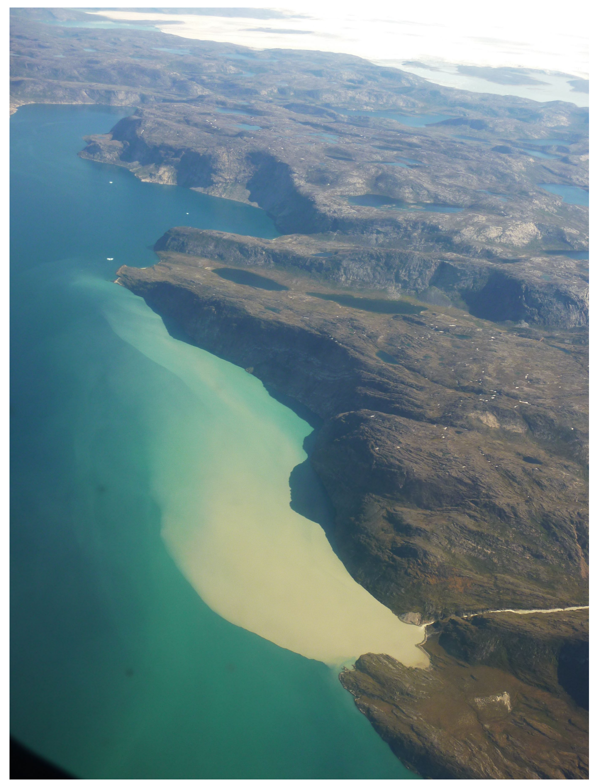
Moustafa et al., in review JGR

Greenland Ice Sheet Meltwater and Sediment

High turbidity in glacial rivers

Naujat Kuat River
2011-2017

High turbidity plumes into the fjords



Motivation

In their seminal book on 'River Discharge to the Global Ocean' Milliman & Farnsworth (2011) state: "as far as we know, no global sediment budget has taken into account the impact of glacial erosion in high-latitude landmasses, particularly Greenland ….".

Bhatia et al., 2014, showed samples of a river in Greenland contained bio-available iron. If scalable to the entire ice sheet, then the annual flux of dissolved and potentially bioavailable particulate iron to the North Atlantic Ocean would be ~0.3Tg.

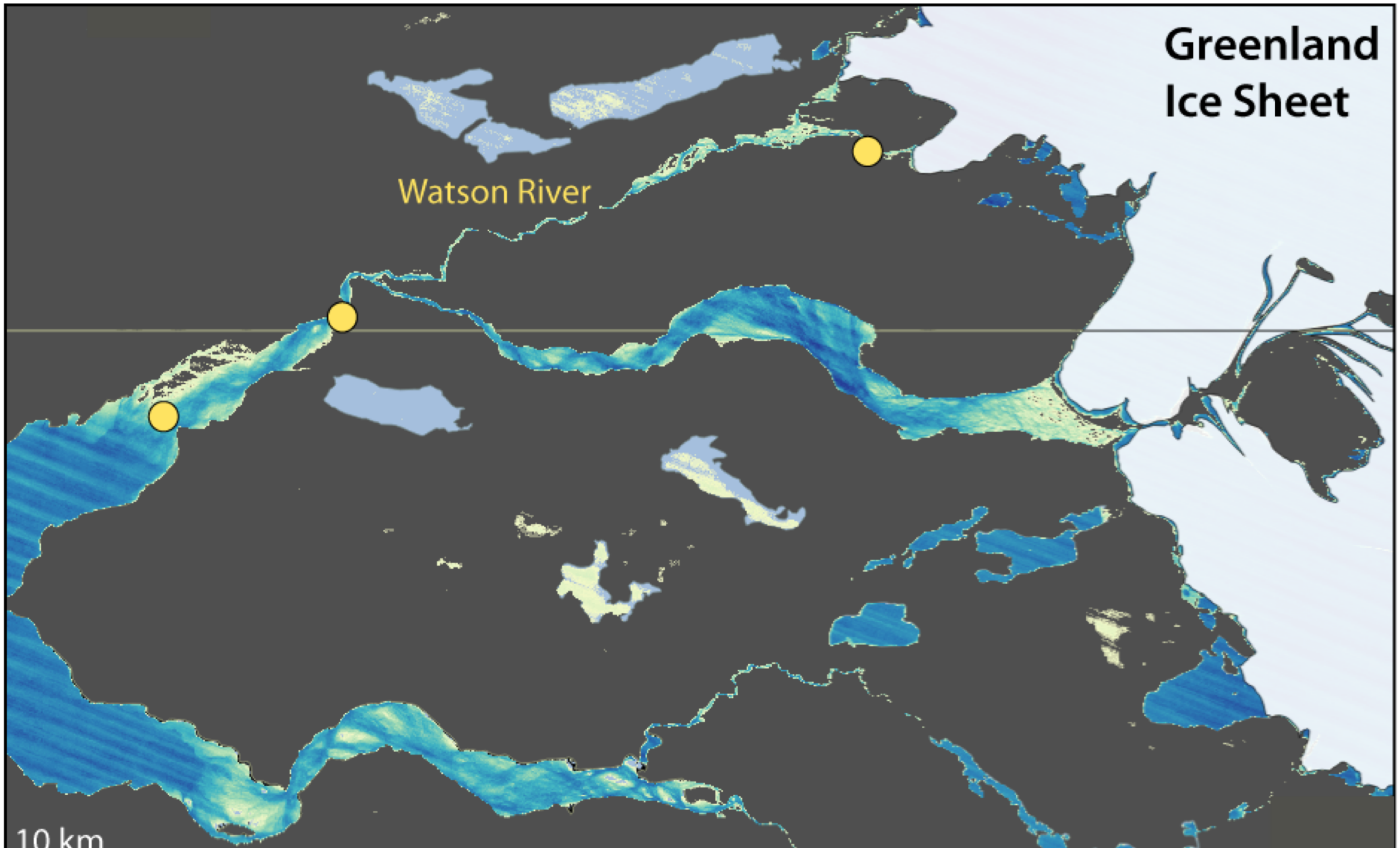
- What is the magnitude of the modern sediment flux from Greenland?
- How is the suspended sediment flux distributed around Greenland?
- What processes control the flux magnitude and distribution?

Field Campaigns 2007-2016

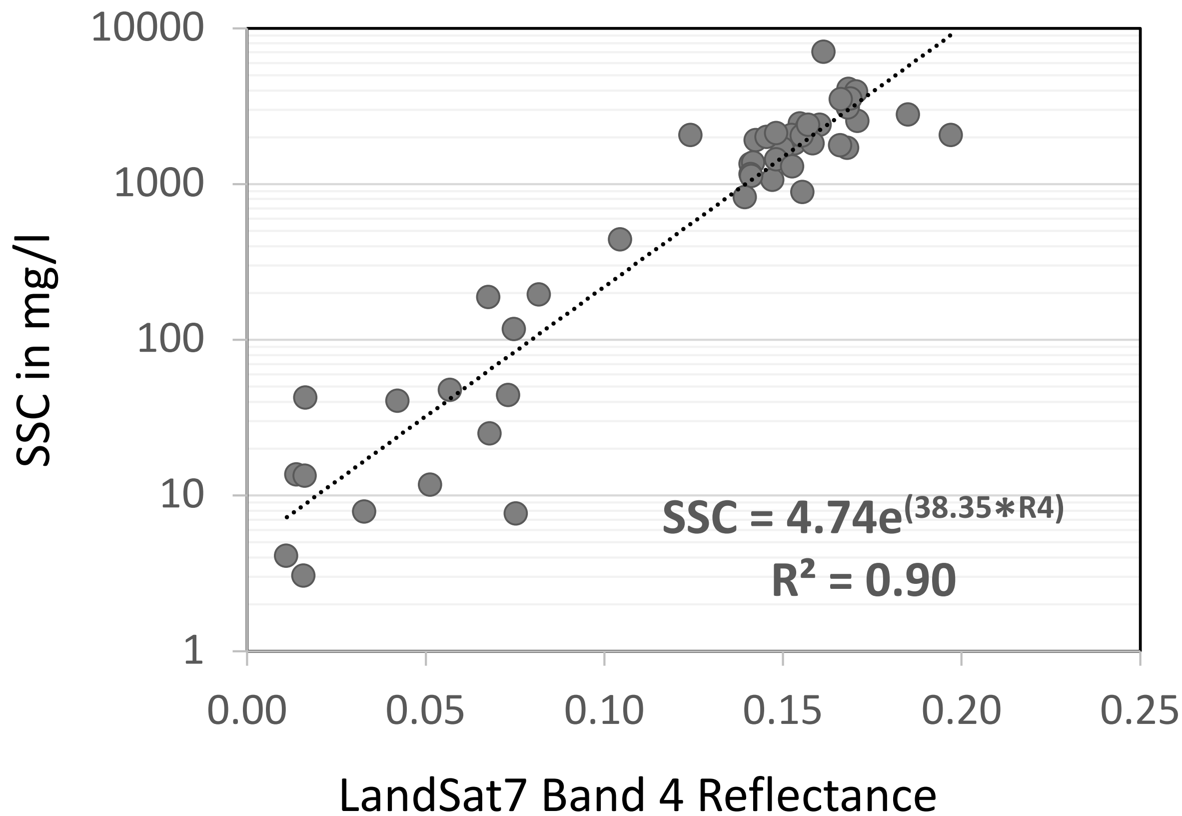
River gauging stations
- Bottle water samples
- Automatic suction samples
- Discharge

Small boat oceanography in the river mouths
- CTD and attenuance casts of 15m depth
- Grainsize measurements
- More bottle samples

SSC Samples Matched to Satellite Imagery

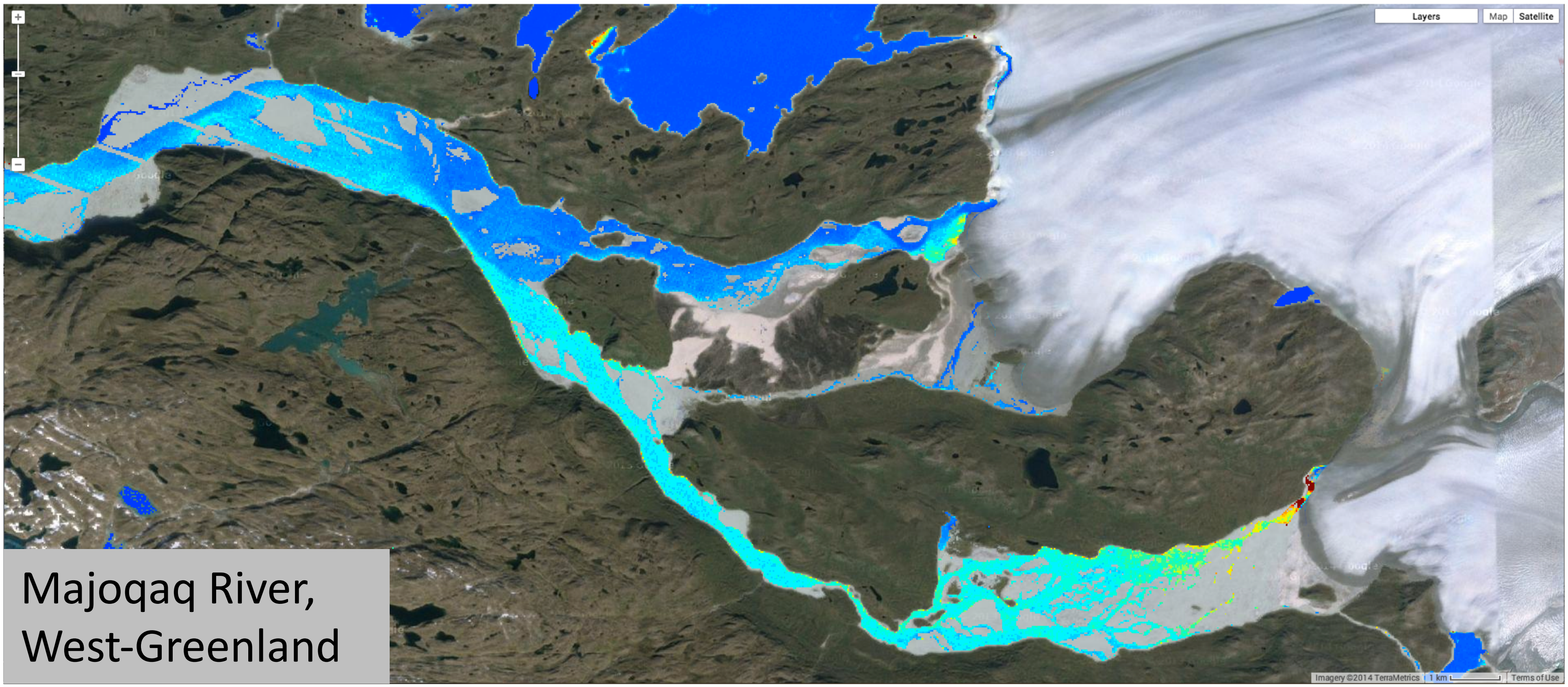


Suspended Sediment Concentration – Satellite Reflectance

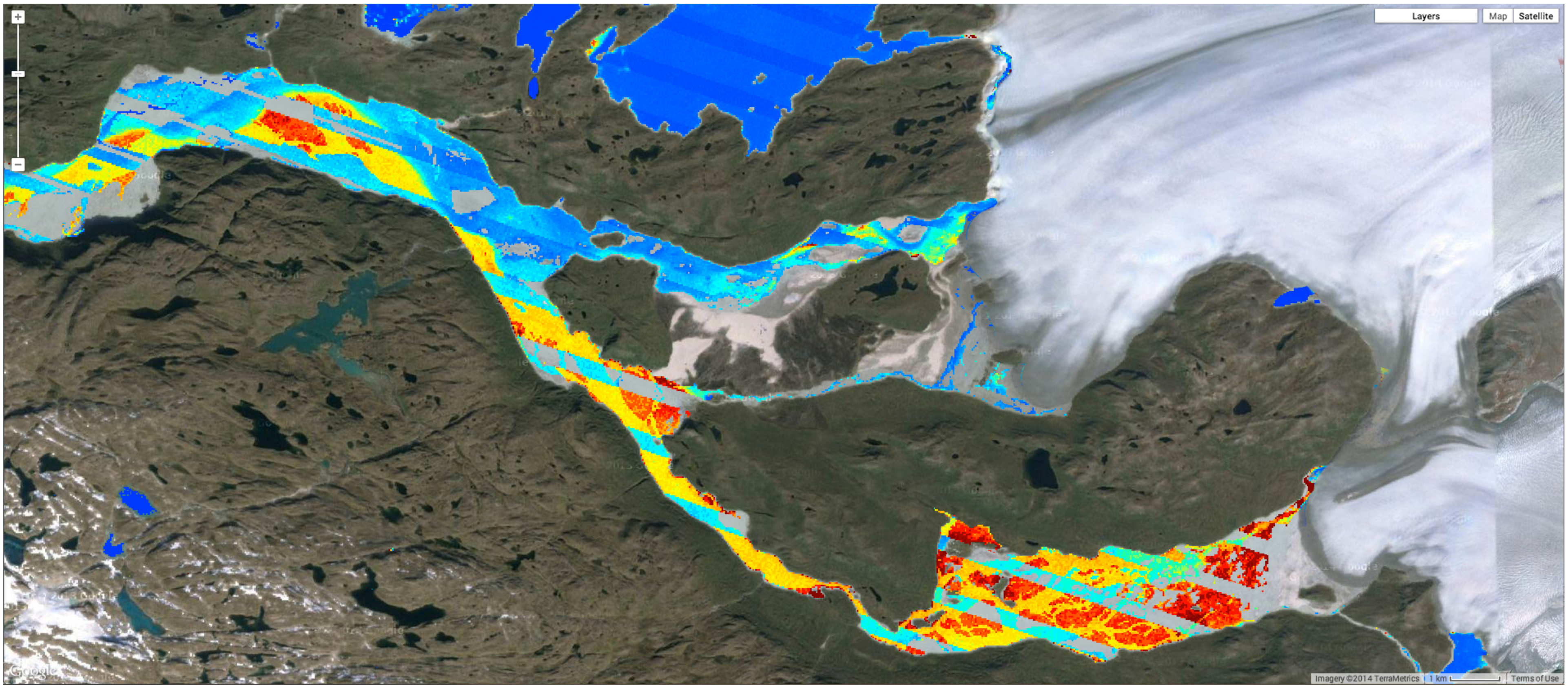


(Hudson et al., TC, 2016; Overeem et al., Nature Geoscience, 2017).

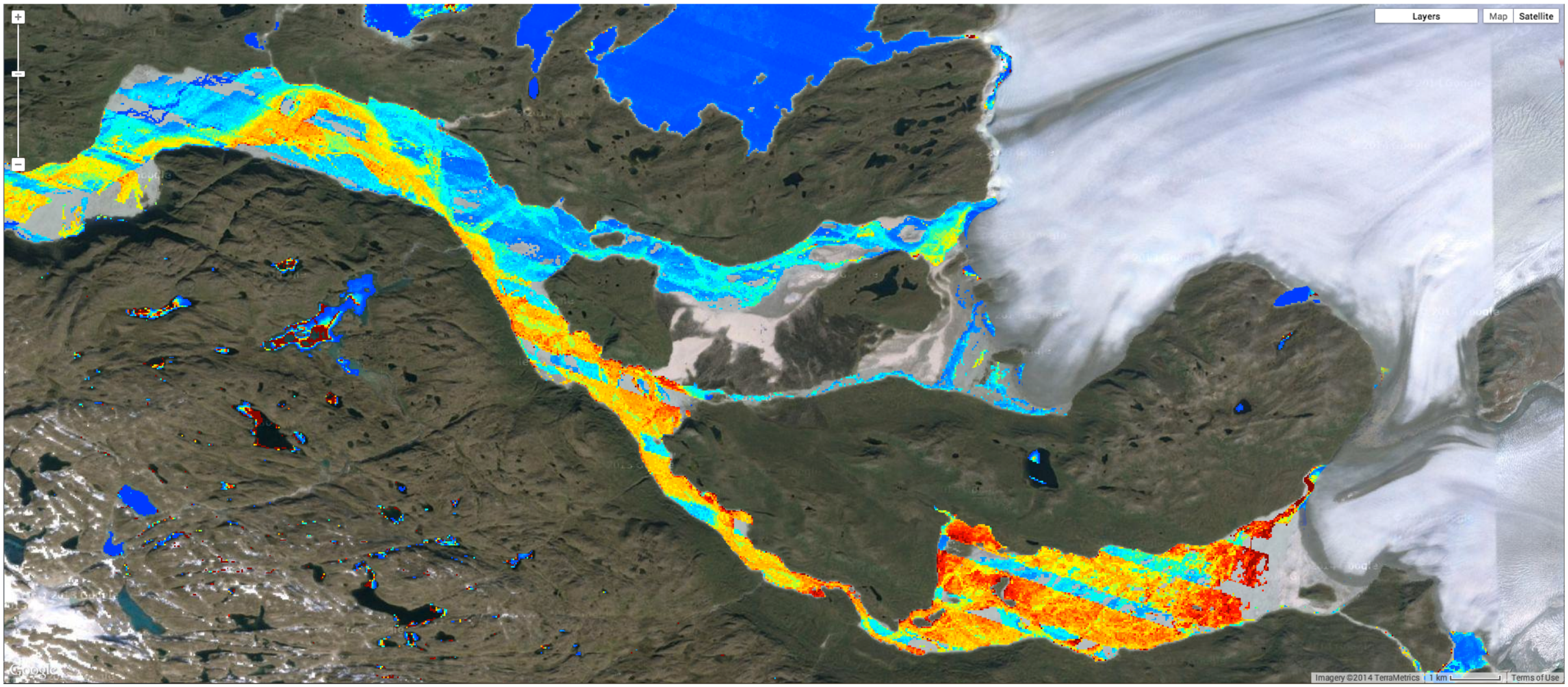
Suspended Sediment Map: 1 image



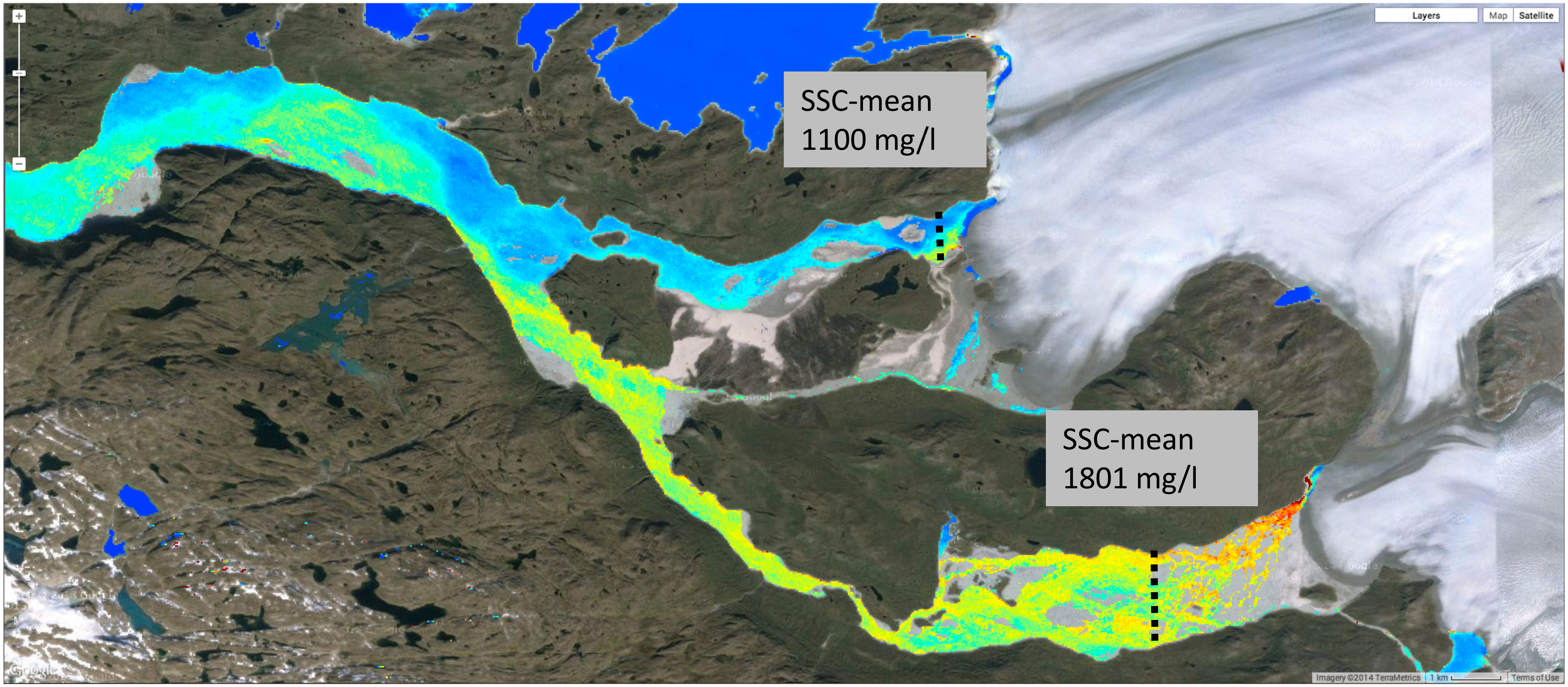
Suspended Sediment Map: 2 images



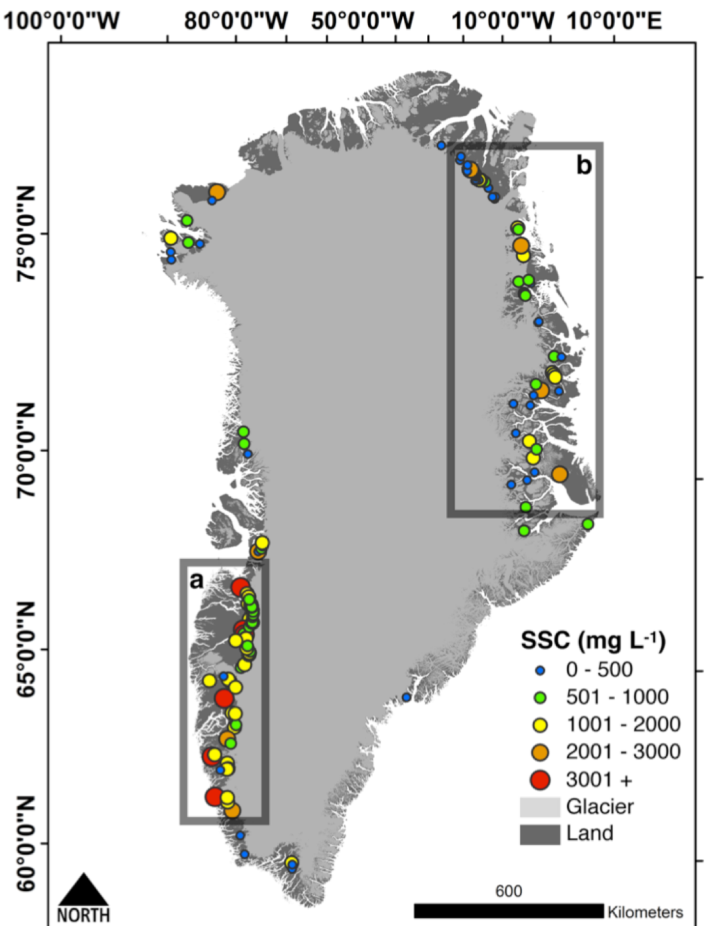
Suspended Sediment Map: 6 images

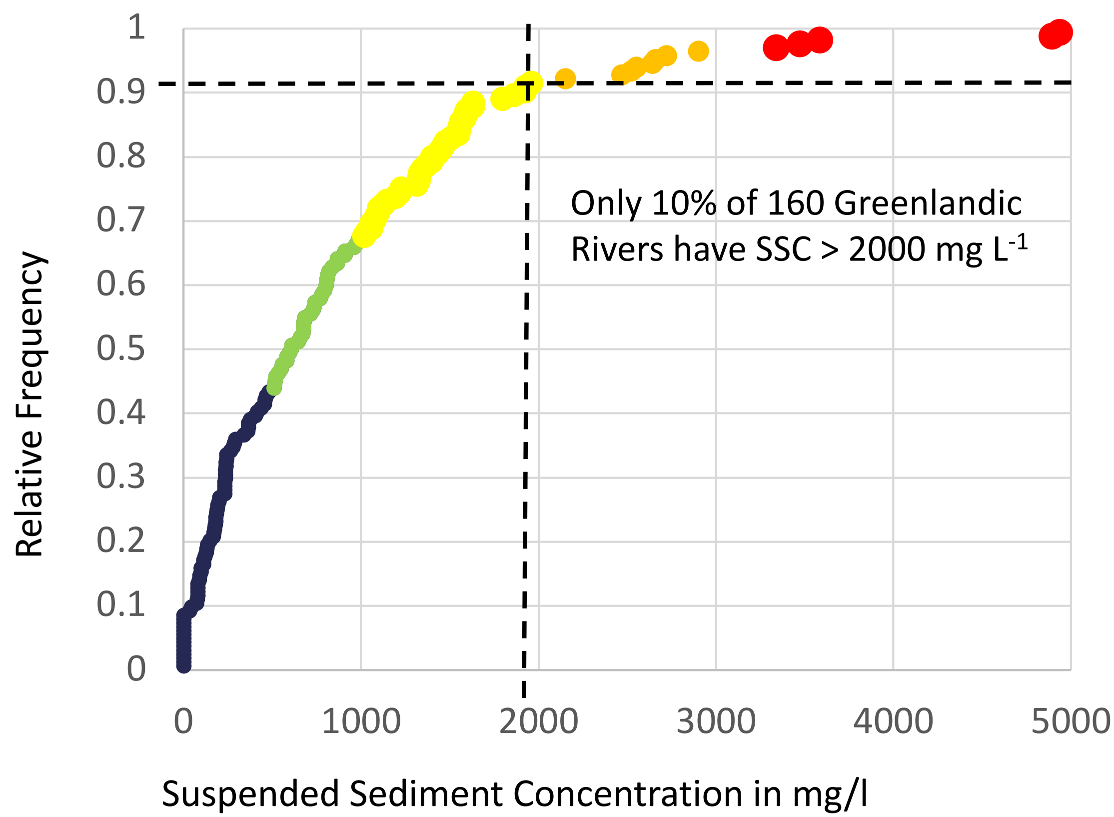


Suspended Sediment Map: 60 images



Processed LandSat7 Archive (1999-2013)





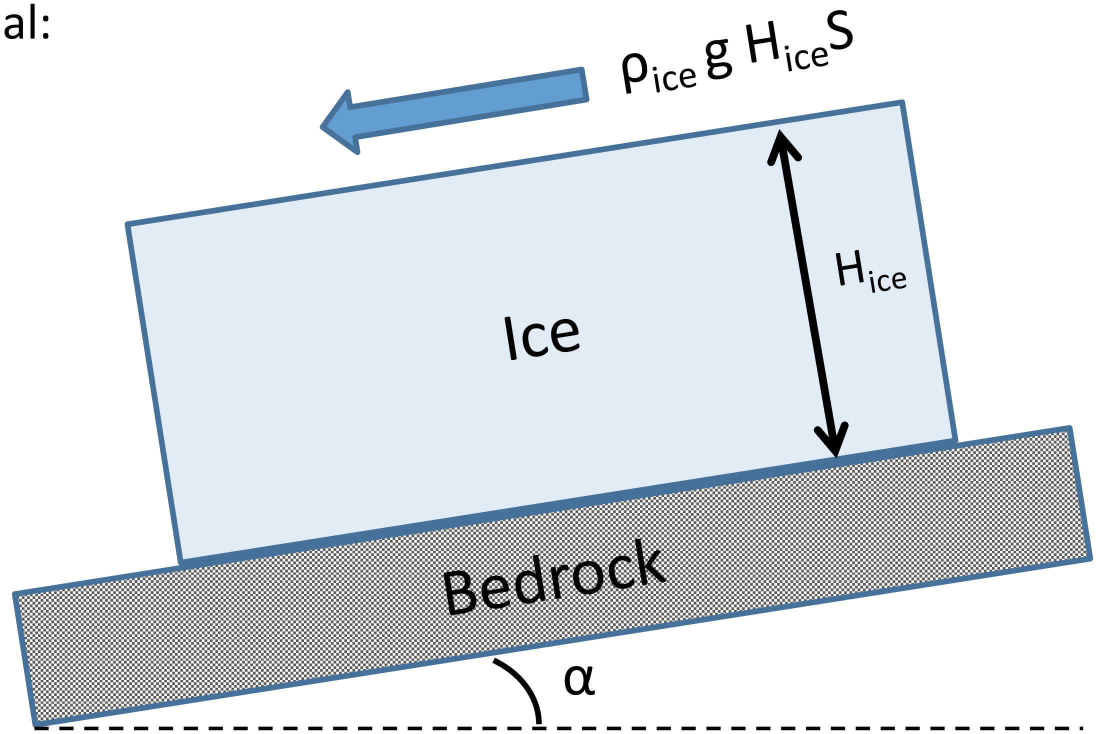
Proxy for Glacial Sediment Production

First-order formulation of Erosion Potential:

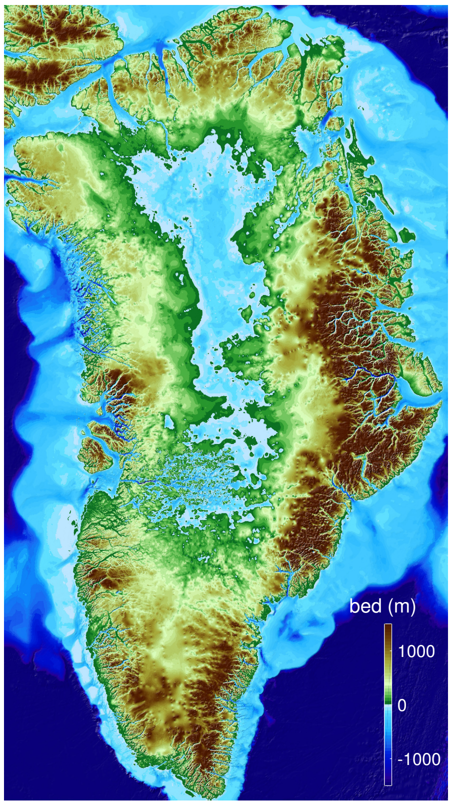
$Ep = \boldsymbol{\tau}\, u_{sliding}$

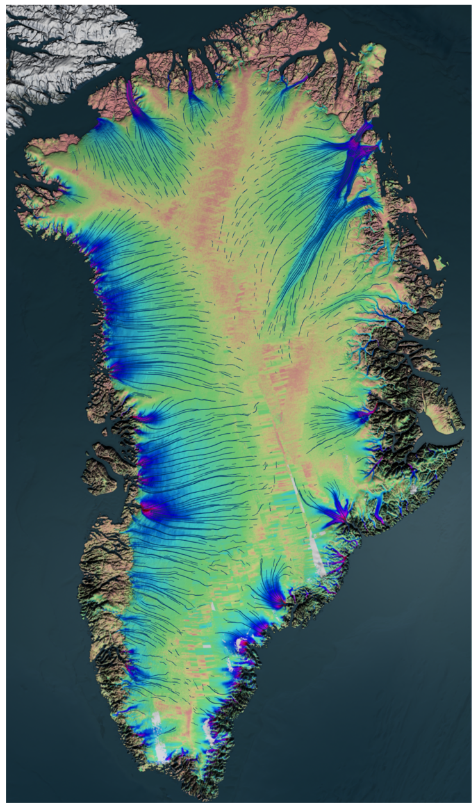
$Ep = 0.8\, u_{surf}\, \rho_{ice}\, g\, H_{ice}\, S$

Ep	= erosion potential (Pa m yr^{-1})
$u_{sliding}$	= basal sliding velocity (m y^{-1})
u_{surf}	= glacier surface velocity (m y^{-1})
$\boldsymbol{\tau}$	= basal shear stress (Pa)
ρ_{ice}	= ice density (kg m^{-3})
g	= gravitational acceleration (m s^{-2})
H_{ice}	= ice thickness (m)
S	= ice surface slope (-)



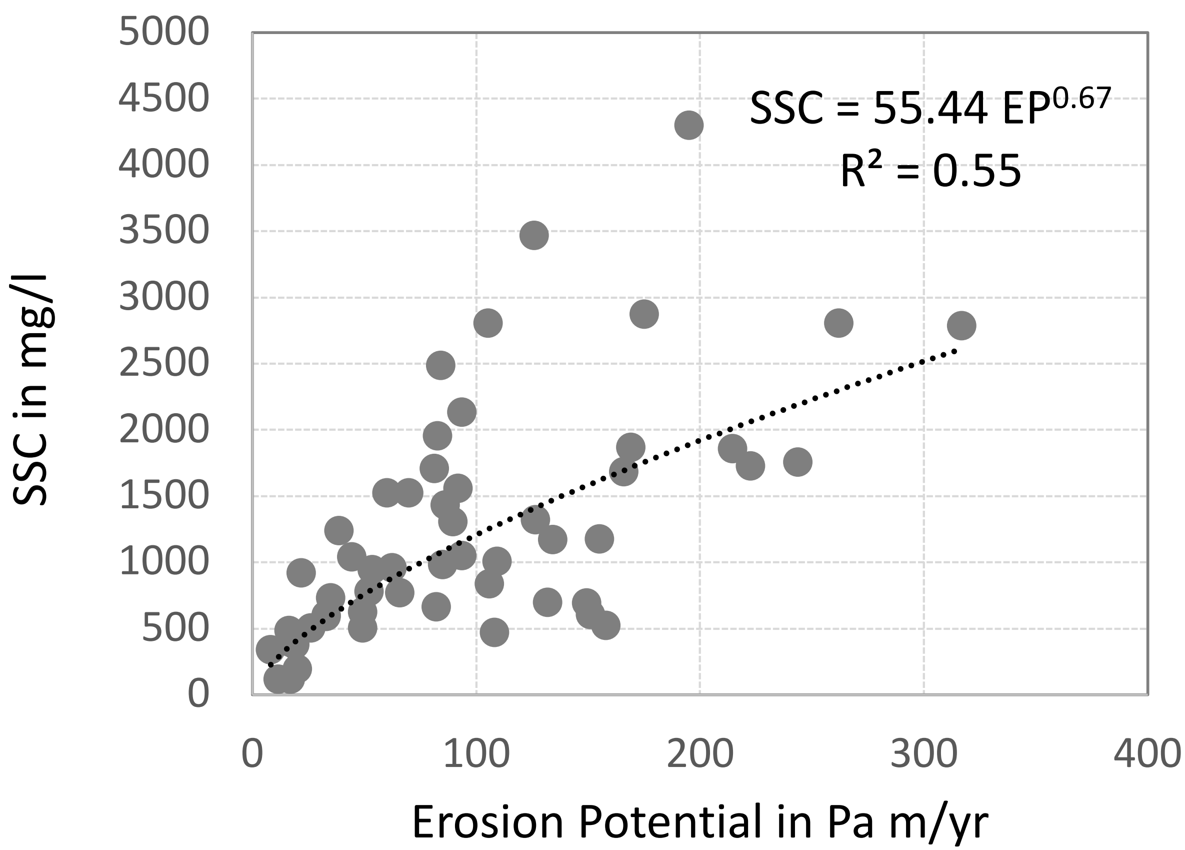
Bed Map, Ice Thickness and Velocity Datasets

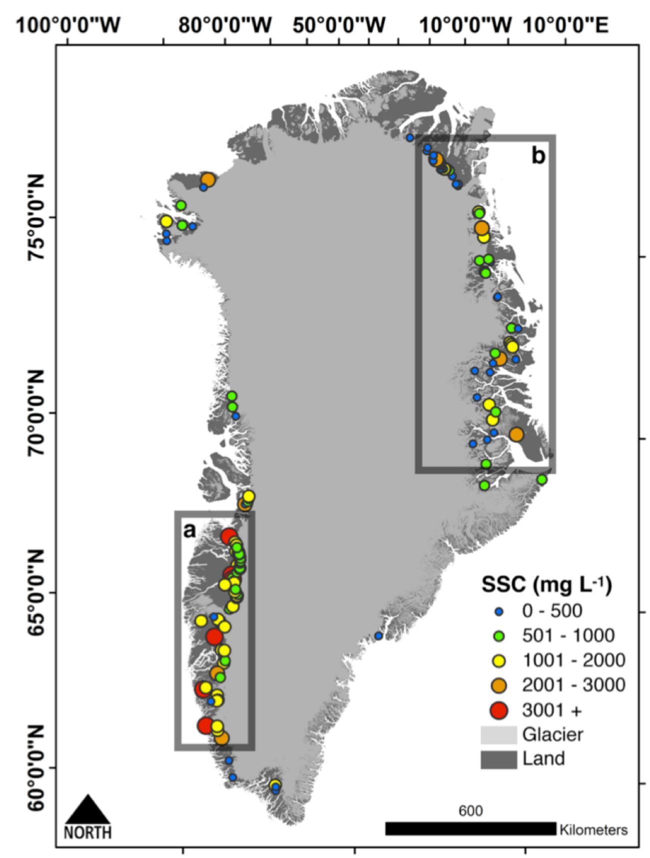




- Bed map and Ice thickness data from airborne radar data (*Morlighem et al., 2014*).
- Annual Ice velocity from InSar data (MEASURES v2, *Joughin et al., 2016*).
- For each 'glacio-hydrological catchment' calculate mean erosion proxy for the melt affected area:
- $Ep_{mean} = 1/n \sum Ep_i$

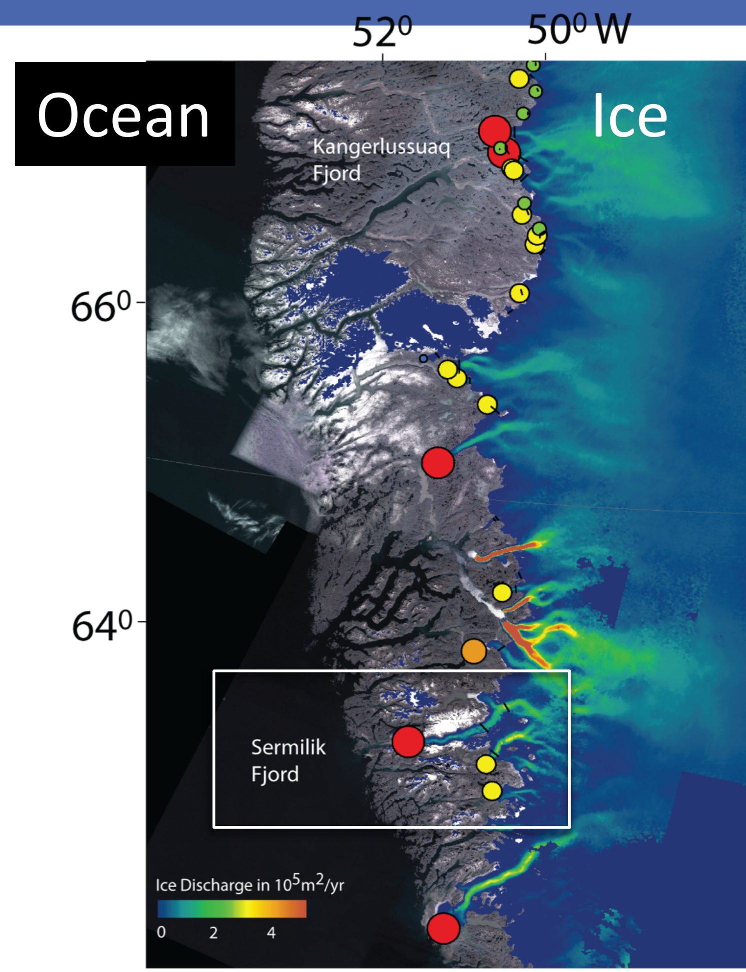
SSC controlled by Ice Dynamics





Hotspots in sediment transfer

Sermilik fjord drains surface plume of 10’s of km into Davis Strait.
(MODIS satellite compilation image).



Calculate Decadal-scale Sediment Load

Annual Sediment Load (Qs) of each river outlet, i:

$Qs_i = SSC_i \; Q_i$

Qs = sediment load (t/yr)
SSC = suspended sediment concentration (kg/m^3)
Q = annual total water discharge (m^3)

Determine annual runoff for each catchment
from numerical model surface mass balance (RACMO2.3)

Decadal-scale Suspended Sediment Load

Greenland Regions	Water Discharge		Suspended Sediment Load
	km^3/yr	%	Gt/yr
Baffin Bay	126	28%	0.371
Denmark Strait	60	13%	0.150
Davis Strait	173	39%	0.243
Greenland Sea	48	11%	0.084
Scoresby Sound	10	2%	0.021
Arctic Ocean	28	6%	0.023
Total Meltwater flux	446	100%	**0.89 ± 0.38**

Revised Global Suspended Sediment Load

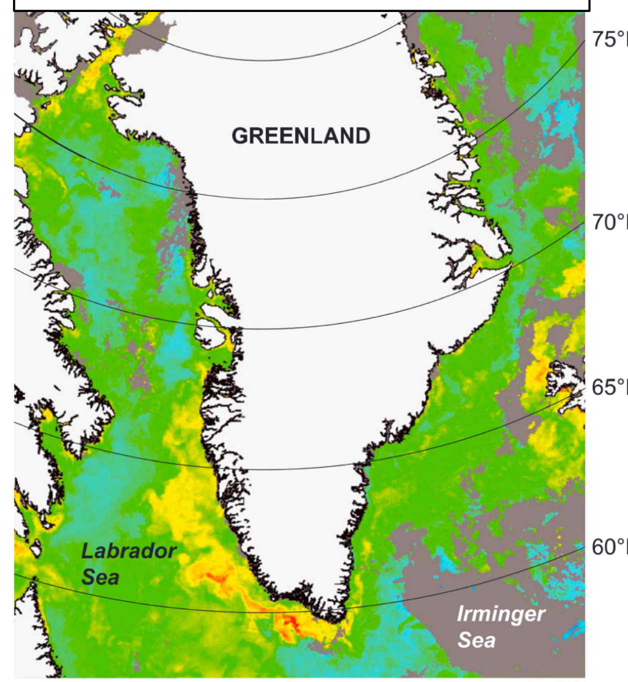
	Water Discharge		Suspended Sediment Load	
	km^3/yr	%	Gt/yr	%
GLOBAL⁺	38,510	97.4	12.88	91
Greenland	446	**1.1**	0.91 - 1.28	**7 – 9%**
REVISED GLOBAL	39,532	100	14.18	100

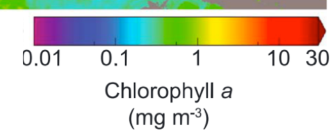
(+ Data from Syvitski and Kettner, 2011).

Global Implications?

- Does bio-available iron in the sediment flux of Greenland impact the North Atlantic phytoplankton blooms?
- Perhaps…tentative evidence: summer blooms in W-Greenland (41% of the total annual bloom Net Primary Productivity)
- North Atlantic carbon pump?
- Mechanisms and nutrient concentrations still under much debate.

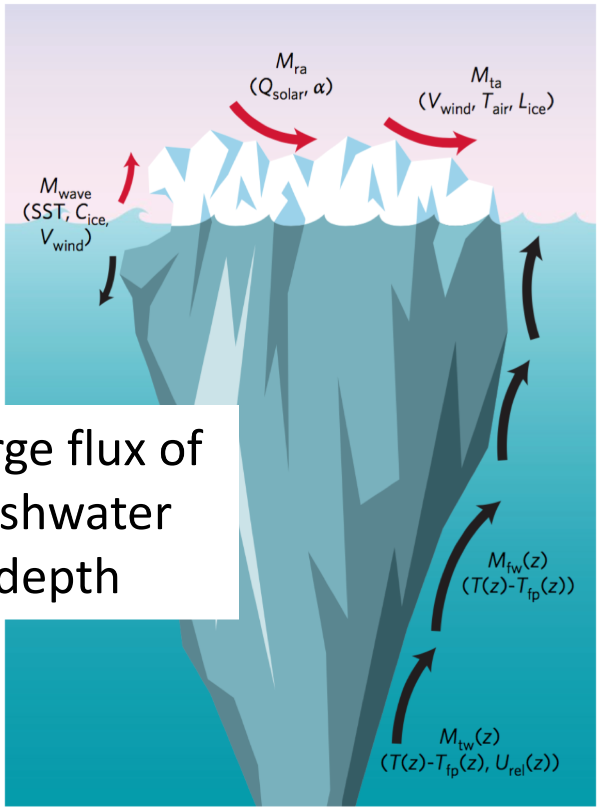
MODIS-derived chlorophyll, August 2003



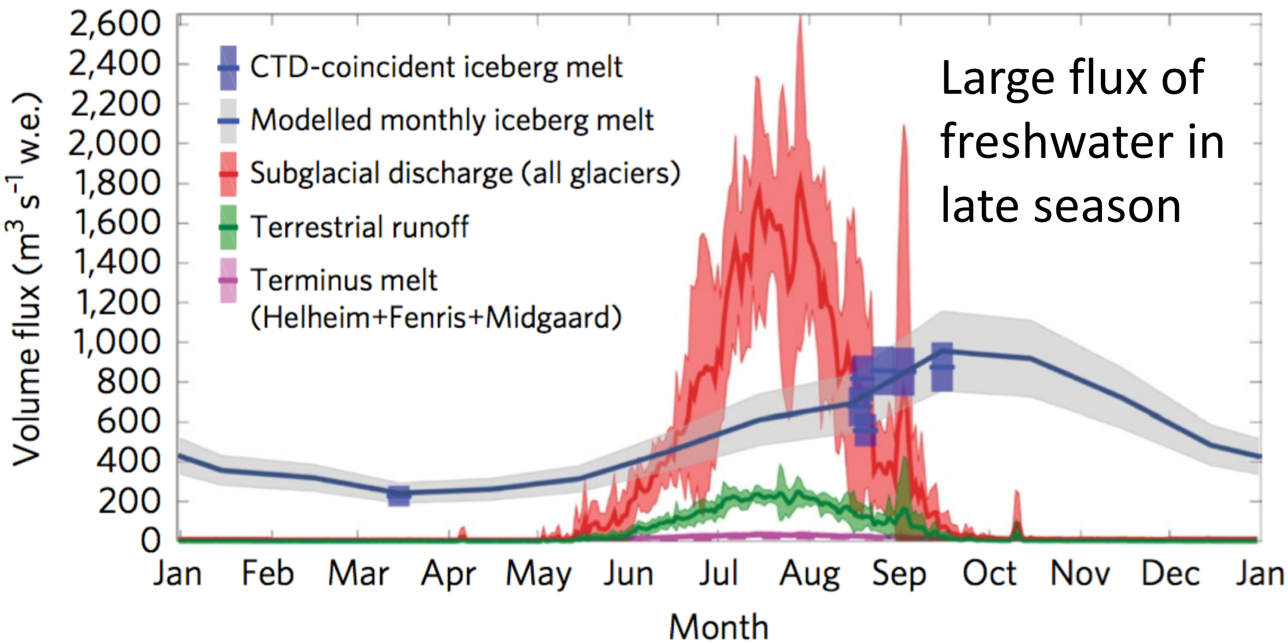


(Arrigo et al., 2017, GRL).

Freshwater from Calving Icebergs



Large flux of freshwater at depth



Large flux of freshwater in late season

From: Moon et al. Nat GeoSc 2017

Basal Sediment?

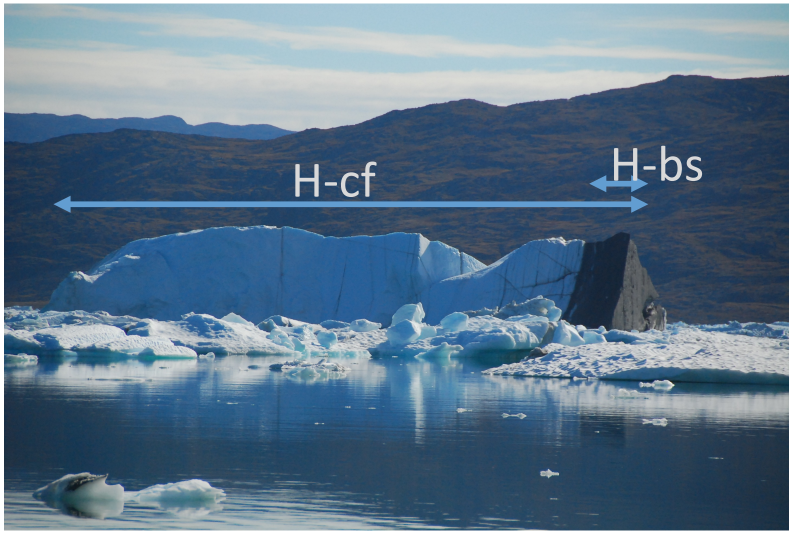
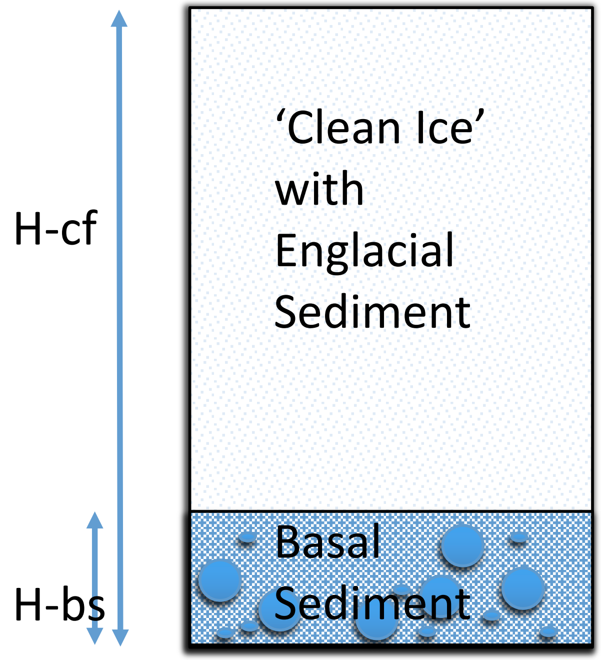


photo Michelle Koppes



H-cf = Height of Calving Front (m)
H-bs = Height of Basal Sediment Layer (m)
Syvitski, Andrews, Dowdeswell (1996); H-cf = 300m, H-bs= 3m

Conclusions

- The transfer of freshwater from 'melt' to rivers and the ocean is a complex process; storage and transfer processes are not fully resolved.
- Firn aquifers, weathered bare ice, river discharge – small scale observations are being compared to modeled runoff, not always a good match.
- Sediment transport by Greenland Ice Sheet meltwater is substantial, and it has likely ramped up significantly over the last decades. Controlled by ice dynamics.
- Freshwater flux from calving is released in fjords at depth, and the timing is depending on deeper fjord water temperatures – can be a late season flux.
- Sediment/nutrient fluxes from calving icebergs are unconstrained.

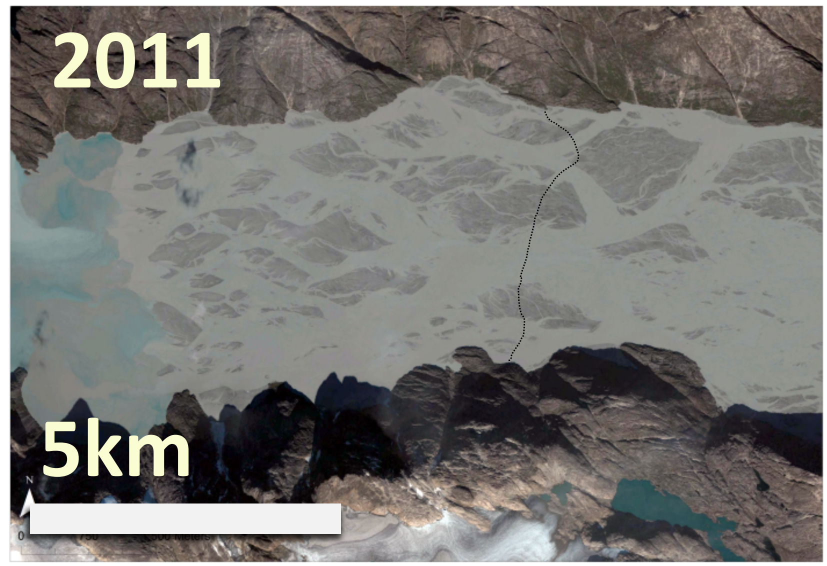
Acknowledgements

Greenlandic River Plumes as an Indicator of Ice Sheet Melt
Collaboration with Benjamin Hudson, Andreas Mikkelsen, James Syvitski, Bent Hasholt, Mette Bendixen, Michiel van der Broeke, Brice Noel, Mathieu Morlighem.

Chu, V.W. (2014). Greenland Ice Sheet hydrology: a review. Progress in Physical Geography, 38(1): 19-54, doi:10.1177/0309133313507075.

Local Implications? Deltas prograde rapidly due to glacial melt

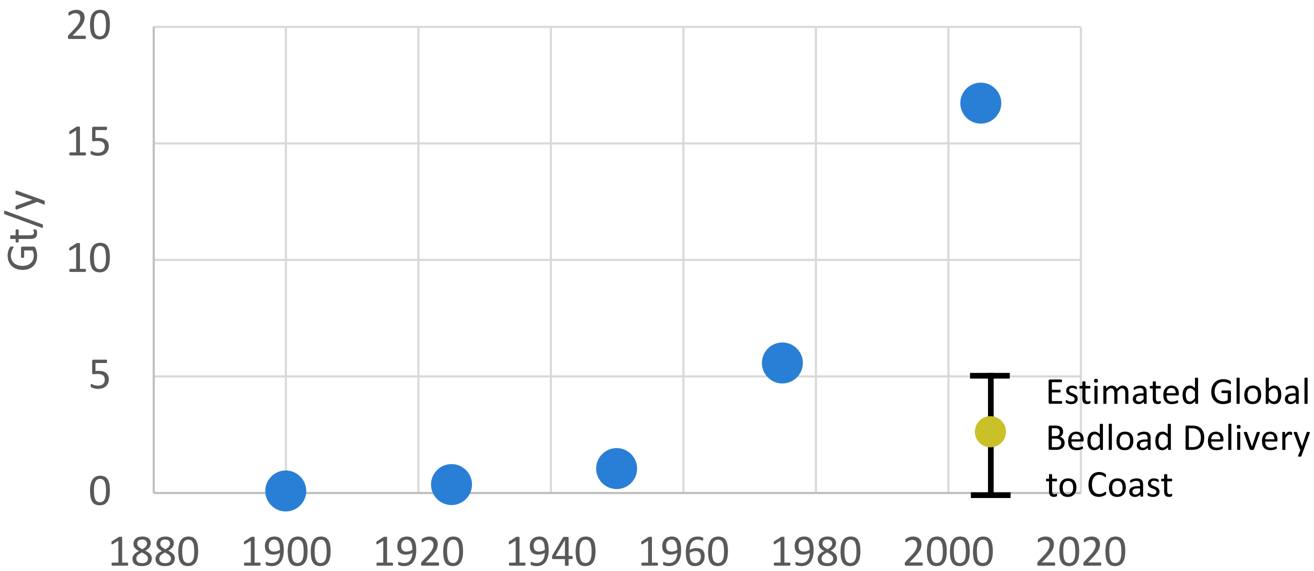
Example: Sermilik fjord



Rare WWII air photos for 121 deltas show progradation of many deltas has accelerated over the last decades compared to the 1940's to 1970's.
(Bendixen et al., Nature, 2017).

Local implications: sand as a resource

World Use of Sand and Gravel for Construction



From: Krausmann et al., 2017

INSIGHTS

LETTERS

Edited by **Jennifer Sills**

Greenland: Build an economy on sand

As A. Torres *et al.* explain in their Perspective "A looming tragedy of the sand commons" (8 September, p. 970), sand scarcity is an emerging global issue. Future urbanization and massive infrastructure improvements will further intensify our need for sand, and scarcity is expected to increase sand demand (*1*) and market prices (*2*). Torres *et al.* stress that we need innovative solutions to prevent the negative sociopolitical, economic, and environmental effects of the sand crisis. Given recent advances in the understanding of fluvial deposits along the coast of Greenland, river sediments from the world's northern regions could provide an answer.

Greenland's ice sheet produces about 8% of suspended sediments transported from rivers and glaciers to the global ocean (*3*). Greenland's high meltwater runoff drives rapid growth of delta area, extending them into the sea (*4*). Every melt season, sand and gravel are deposited into hundreds of Greenland deltas. Rivers feeding the deltas are located in regions completely free of any anthropogenic sources of upstream entrapment, such as dams (*5*). Especially in southern Greenland, these deltas constitute prime locations for dredging sand, gravel, and slurry for further processing. With continued warming, acceleration of melt and ice sheet flow may increase sediment delivery from Greenland to the ocean, as well as the extent of the deltas (*4*).

Developing commercial opportunities in Greenland would diversify Greenlandic industry, allowing Greenland to become independent from Danish subsidies (*6*), which account for roughly one-third of the Greenlandic gross domestic product (GDP). Along with current efforts to develop glacial rock flour into a source of nutrients for depleted soils (*6*), we propose that sand extraction along selected fluvial outlets could serve as a new industry in Greenland while addressing the global need for sand. If Greenland is to benefit from sand extraction, we must raise awareness about the resource both locally and globally, the Greenlandic people must learn best practices to extract the sand (*6*), and the industry must guarantee that extraction methods minimize potential negative impacts on the local environment.

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3. I. Overeem *et al.*, *Nat. Geosci.* **10**, 859 (2017).
4. M. Bendixen *et al.*, *Nature* **550**, 101 (2017).
5. G. Gomby, *Science* **358**, 180 (2017).
6. J. Rosen, *Nature* **532**, 296 (2016).

10.1126/science.aar3388

PHOTO: NIKOLAJ KROGH LARSEN

Greenland's rivers deliver sediment from melting ice to the ocean.

SCIENCE sciencemag.org 17 NOVEMBER 2017 • VOL 358 ISSUE 6365 879

Published by AAAS

Greenland Regions	Water Discharge		SSC based on Glacier erosion method
	km^3/yr	%	Gt/Yr
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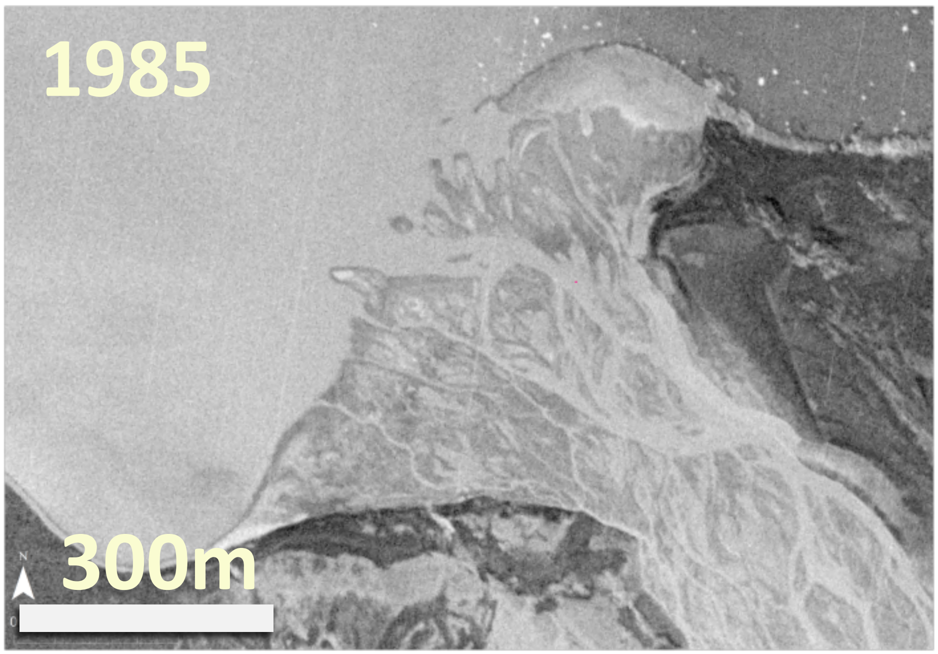
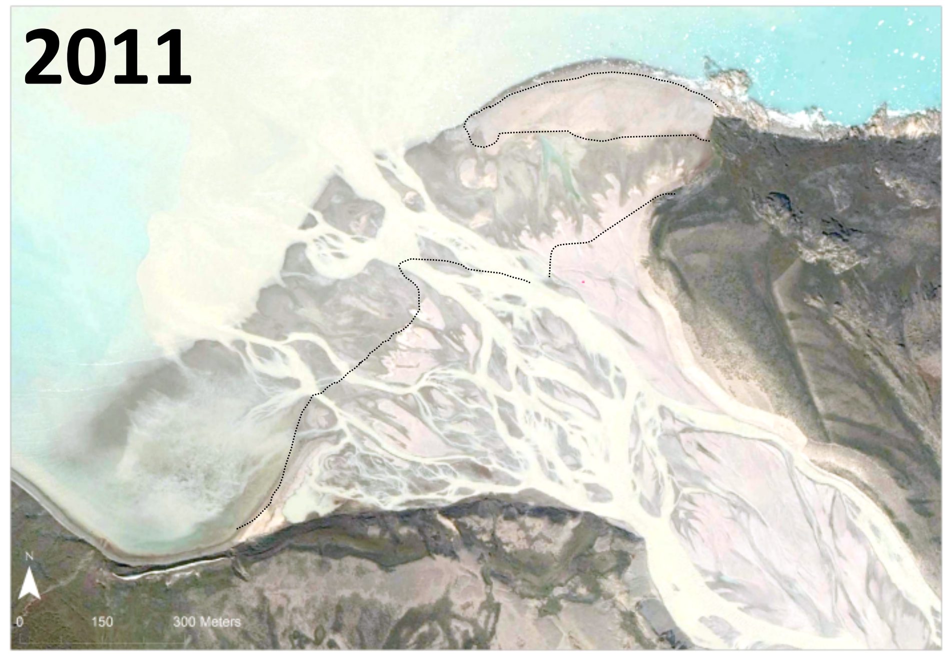
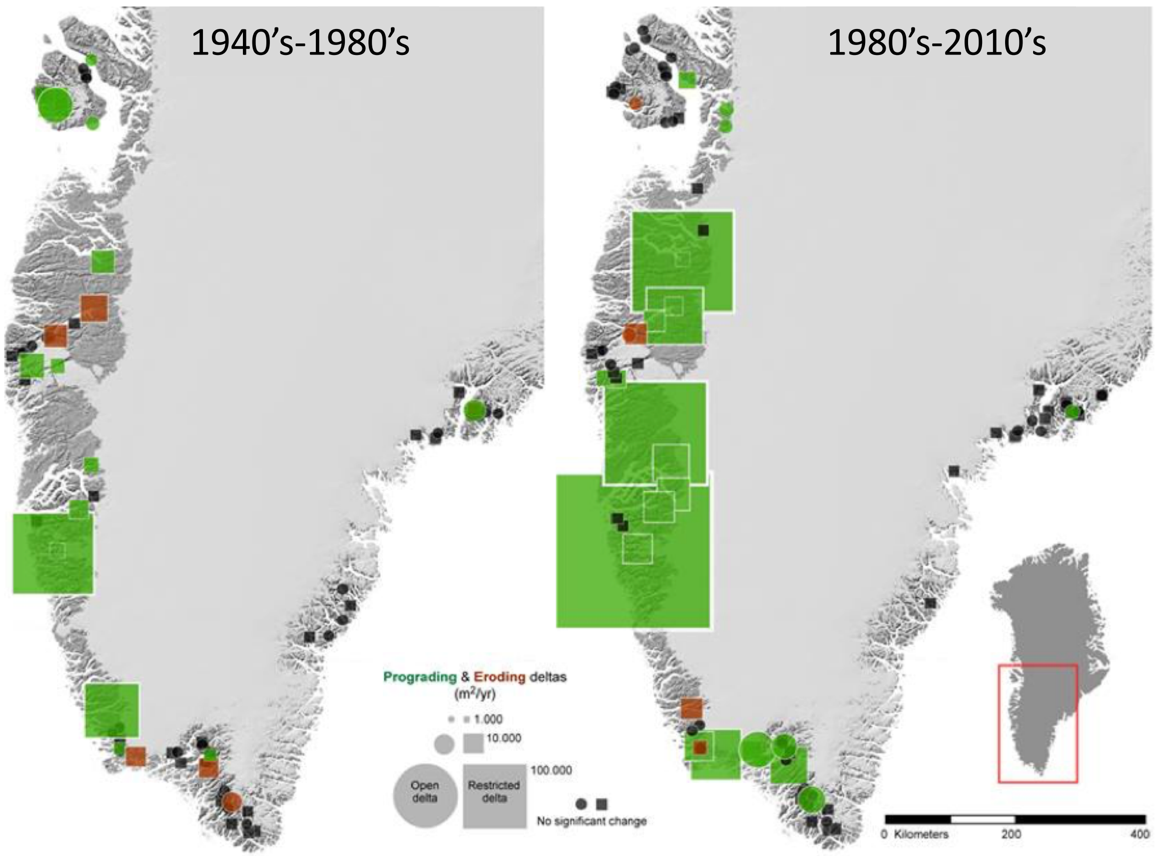
Greenland Sea	48	11	0.084
Scoresby Sound	10	2	0.021
Arctic Ocean	28	6	0.023
Total river meltwater flux	446	44	**0.89**
Ice calving flux[&]	576	56	0.014
Total Transport	1022	100	0.906
Basal ice calving flux[&]	5.7	1	**1.92**

‘Open delta’-more exposed to wave action



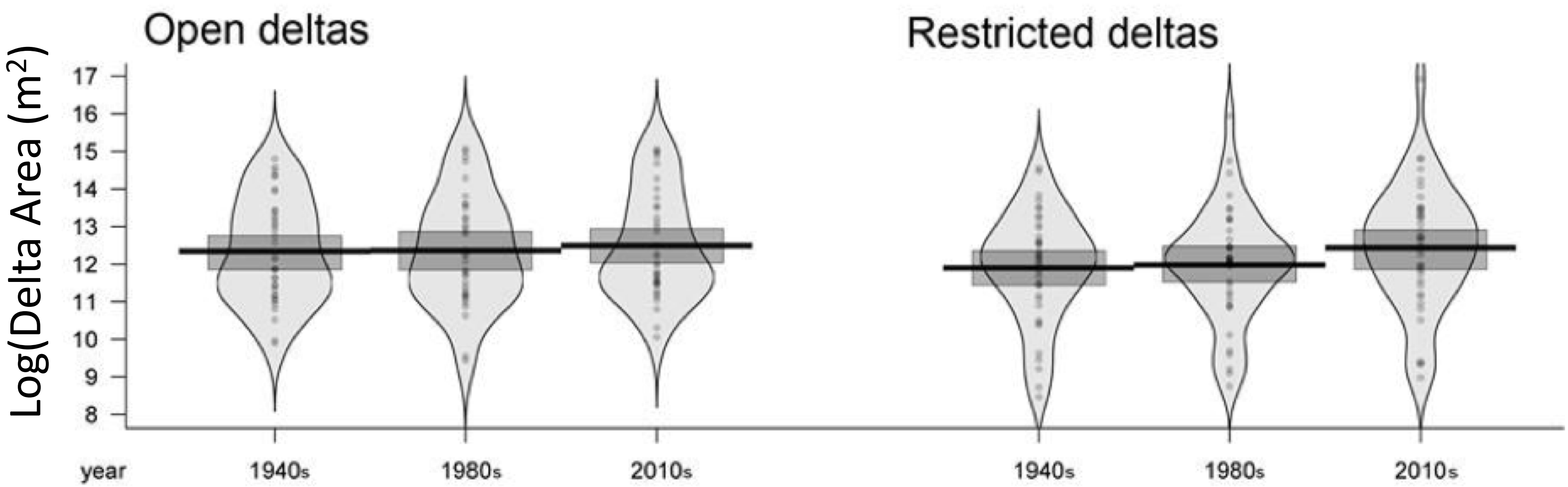


Progradation Trends



121 deltas are mapped for subaerial changes between 1940's – 1980's and the 1980's – 2010's.

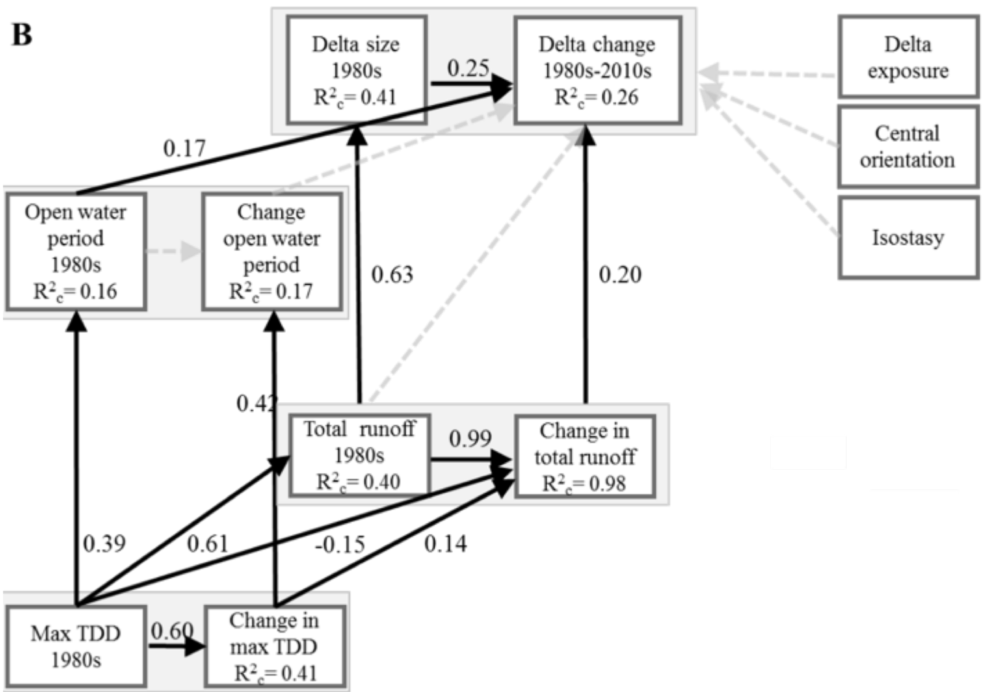
Progradation is more pronounced in protected deltas



Using aerial photo archive from 1940's, air photos 1980's and modern satellite imagery

What are the dominant controls?

Structural Equation Modeling



Dominant control is changes in runoff from ice sheet (RACMO2.3 model), reduced progradation for open deltas due to sea ice retreat?

Bedload deposition is important for subaerial progradation:

Qb = f (Q, S)