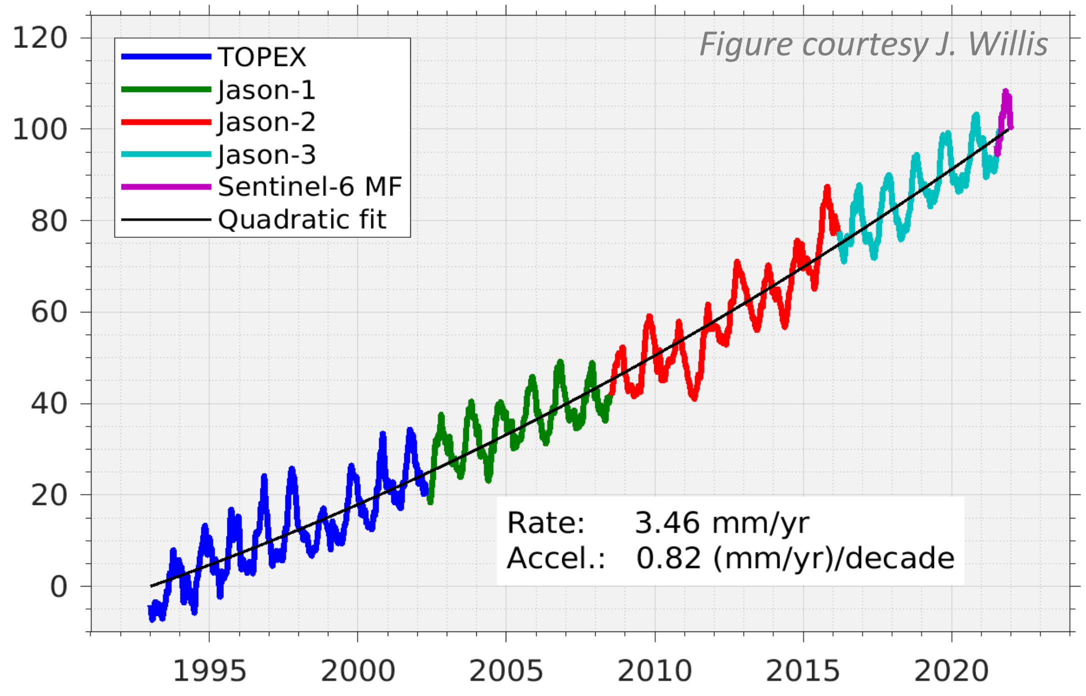
1992-2022 Global Mean Sea Level [mm]



Using satellite altimetry to obtain subsurface ocean temperatures on the Greenland Shelf

Carine van der Boog and Ian Fenty

The Greenland Ice Sheet was in near mass balance from 1972–1990. Since then it has added 13.7 mm to GMSL, half during the last 8 years.

Mouginot, J., and Coauthors, 2019: *Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. PNAS*, 116, 9239–9244

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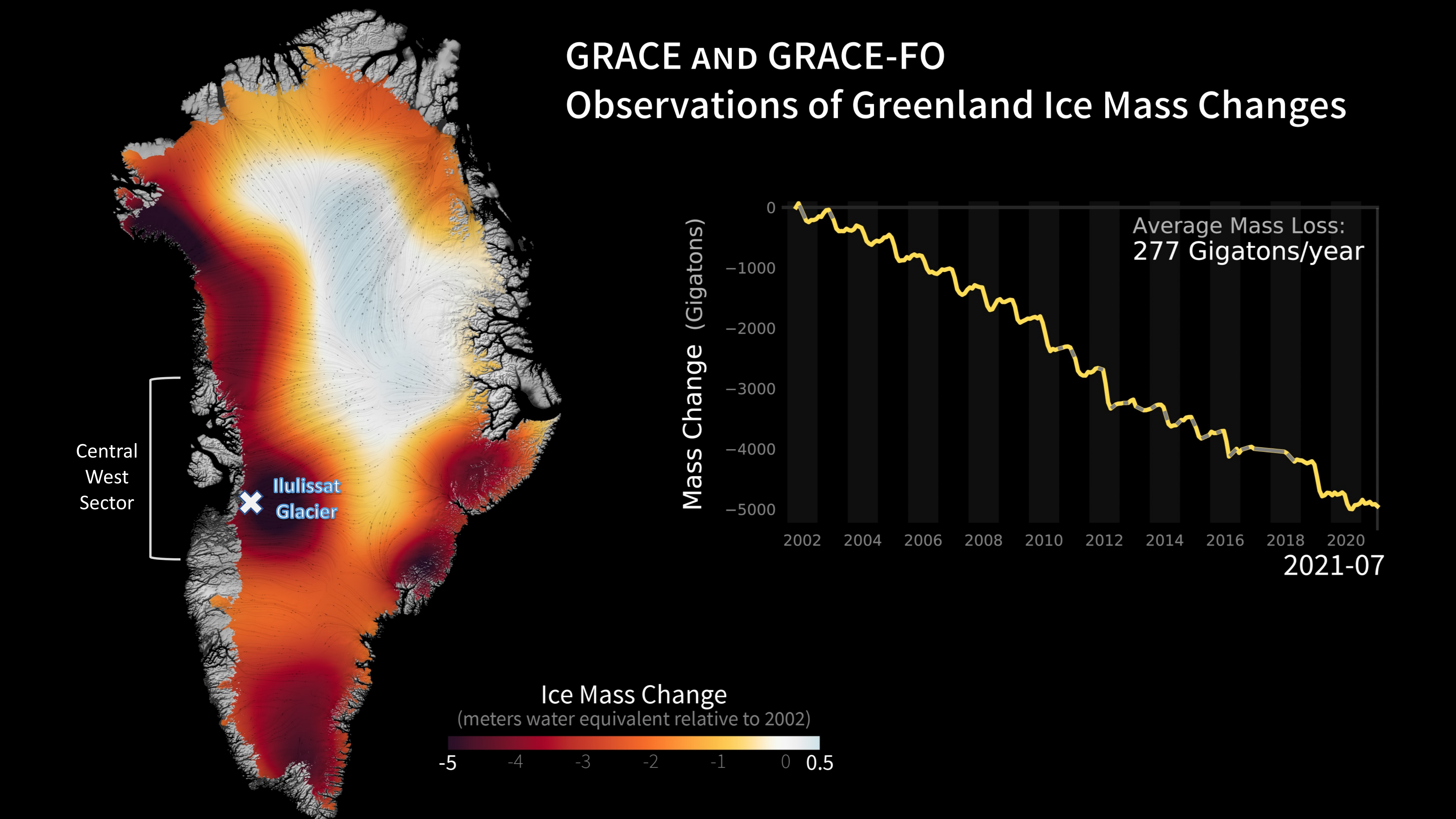
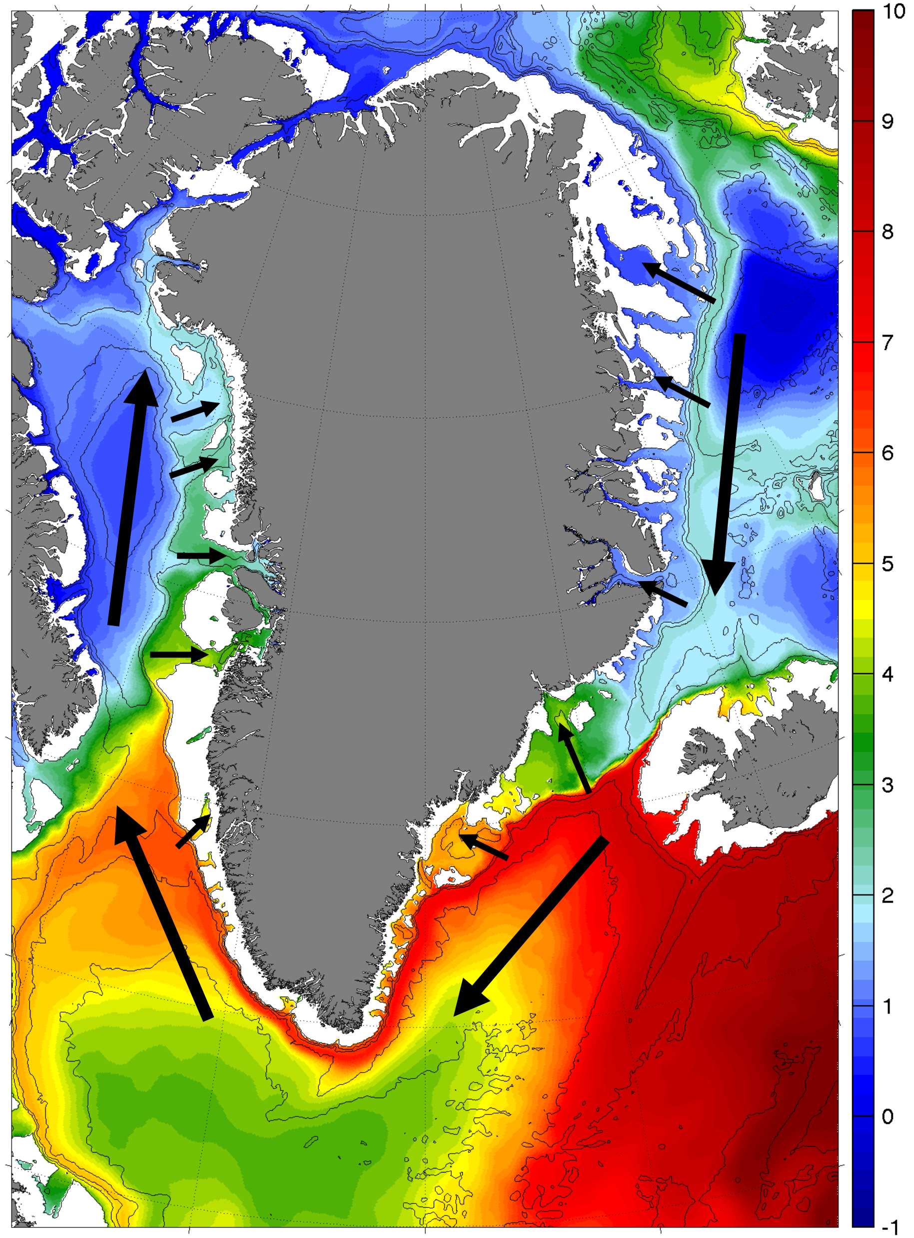
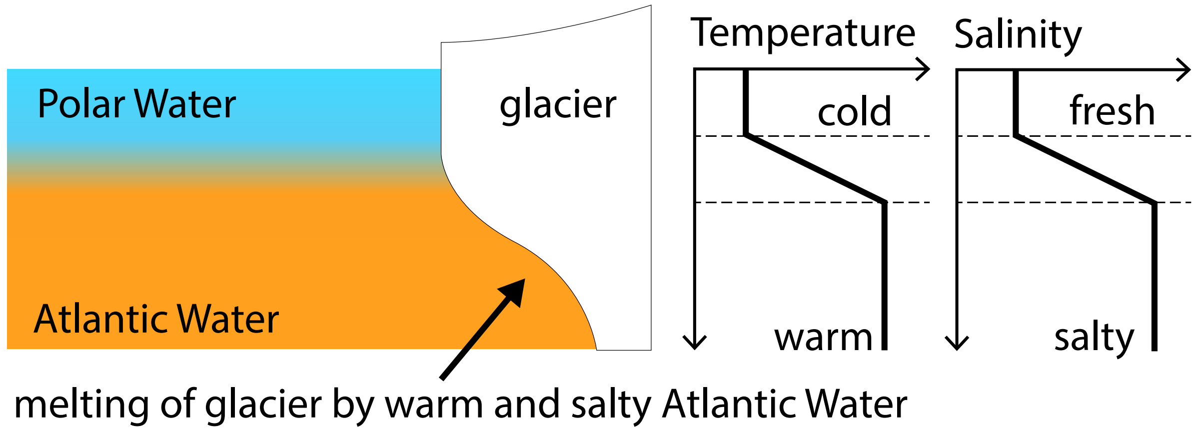

GRACE AND GRACE-FO
Observations of Greenland Ice Mass Changes
Central
West
Sector
Ilulissat
Glacier
Mass Change (Gigatons)
0
−1000
−2000
−3000
−4000
−5000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Average Mass Loss:
277 Gigatons/year
2021-07
Ice Mass Change
(meters water equivalent relative to 2002)
-5
-4
-3
-2
-1
0
0.5

Ocean temperature at 250m from ECCO





Subsurface warm and salty Atlantic Water reaches Greenland's glaciers after crossing the continental shelf in deep submarine canyons.

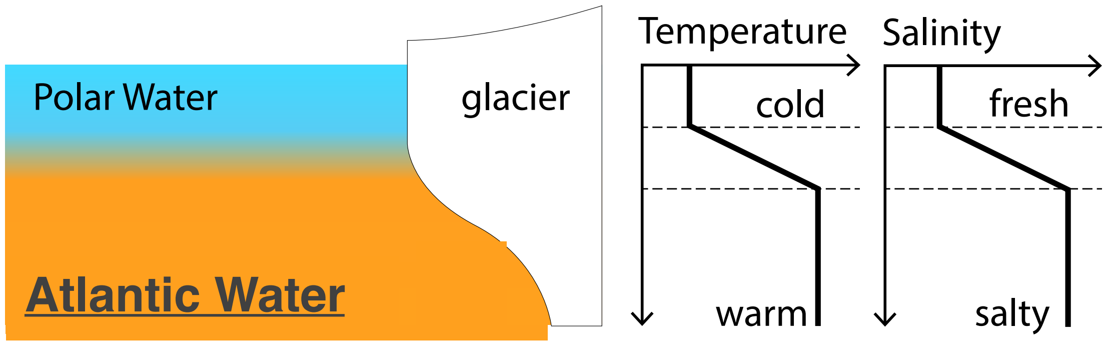
NASA's 2016-2021 **Oceans Melting Greenland** (OMG) mission showed:

- warmer Atlantic Water → more glacier melt
- colder Atlantic Water → less glacier melt

Can we monitor Atlantic Water temperatures close to the Greenland Ice Sheet using satellite altimetry?

Hypothesis: Atlantic Water temperatures close to the Greenland Ice Sheet can be estimated from sea level anomalies

Sea level anomaly
- **<u>sterodynamic</u>**
  - **<u>heat = thermosteric</u>**
  - salt = halosteric
- barystatic



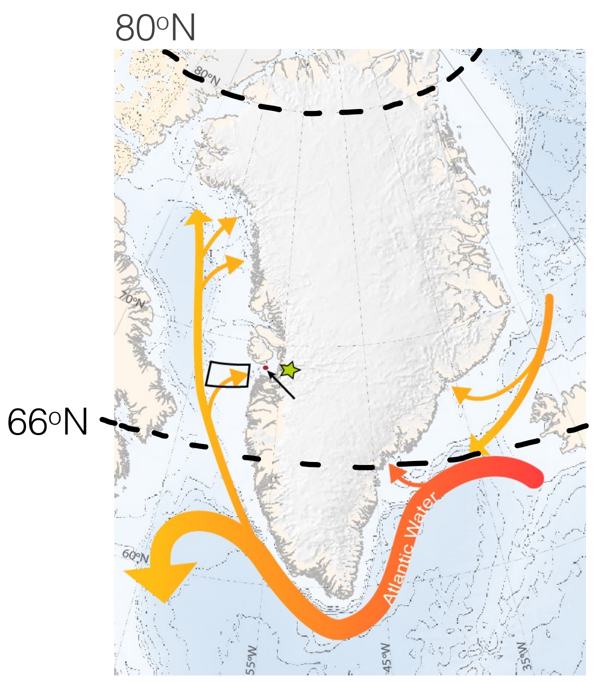
Willis et al. (2004):
- Large-scale upper ocean heat content variations can be inferred from sea level anomalies

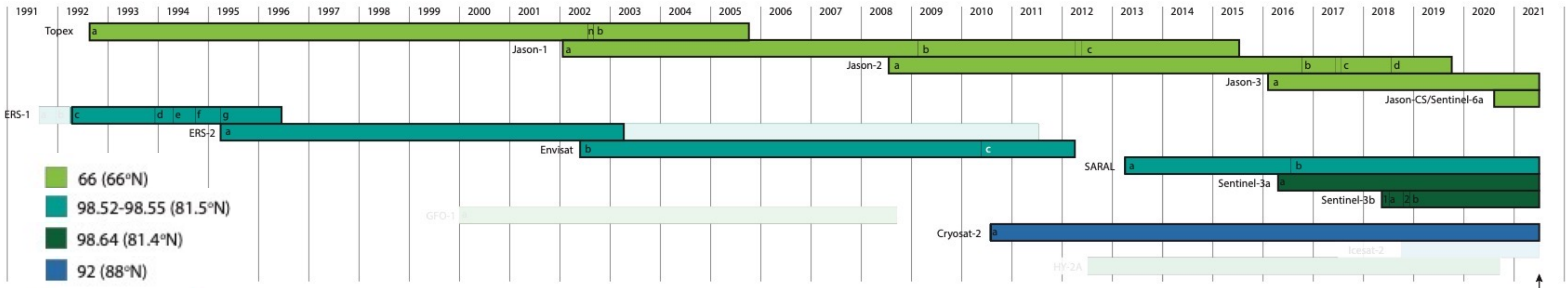
Häkkinen et al. (2013):
- 21% of the sea-level variance in the North Atlantic can be explained by upper ocean heat content

new in this work:
- relatively small coastal region
- attempt to link sea-level anomalies to subsurface heat

Satellite altimetry near Greenland

- Continuous coverage for almost 30 years
- Better sampled south of 66N
    - Reference orbit
    - Seasonal sea-ice mainly north of 66N

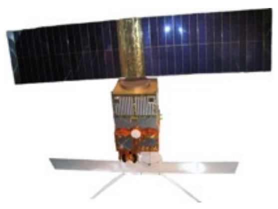


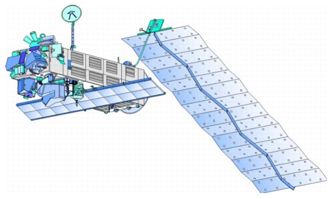
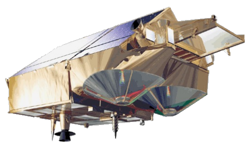
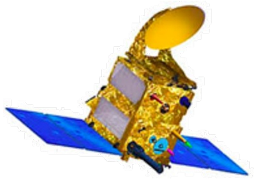


RADAR ALTIMETER DATABASE SYSTEM

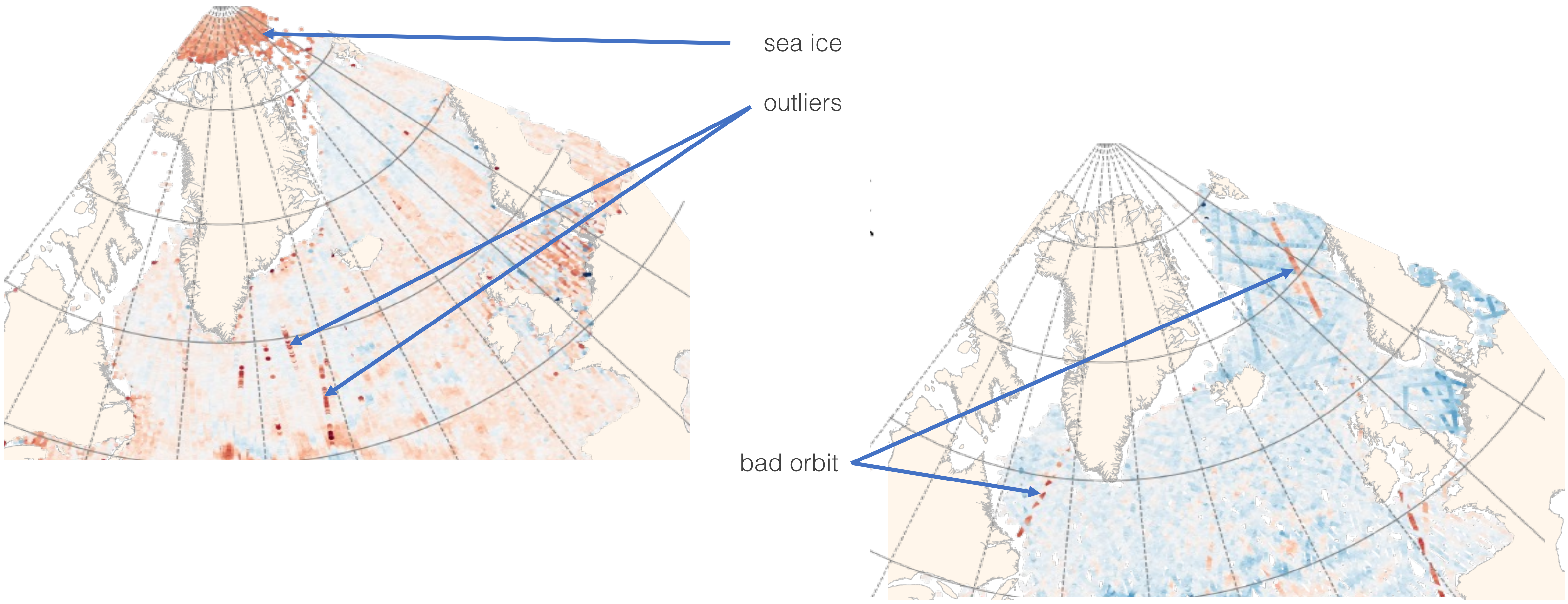
	Topex	ERS-1	ERS-2	Jason-1	Jason-2	Jason-3	Envisat	Cryosat-2	SARAL	Sentinel-3a	Sentinel-3b	Sentinel-6a
orbital altitude	alt_gdrcp	alt_slcci		alt_gdre		alt_gdrf alt_gdre	alt_slcci	alt_gdre	alt_gdrf			
range	range_ku											
dry tropospheric correction	dry_tropo_ecmwf											
wet tropospheric correction	GPD+					cycle <148: GPD+ cycle >=148: wet_tropo_rad	GPD+	cycle <127: GPD+ cycle >=127: wet_tropo_rad	cycle <36: GPD+ cycle >=36: wet_tropo_rad	wet_tropo_rad		
ionospheric correction	iono_alt_smooth	iono_nic09	iono_gim iono_nic09	iono_alt_smooth	iono_alt_smooth	iono_alt_smooth	iono_alt_smooth iono_gim	iono_gim	iono_gim	iono_alt_smooth		
atmospheric correction	inv_bar_mog2d_era				inv_bar_mog2d_era inv_bar_mog2d	inv_bar_mog2d	inv_bar_mog2d_era	inv_bar_mog2d				
ocean tide	tide_ocean_fes14											
load tide	tide_load_fes14											
sea-state bias	ssb_cls	ssb_bm3		ssb_tran2012		ssb_cls			ssb_tran2019	ssb_cls		
mean sea surface	mss_dtu15											

changed from default
default


Filtering residual artifacts in along-track SLA data

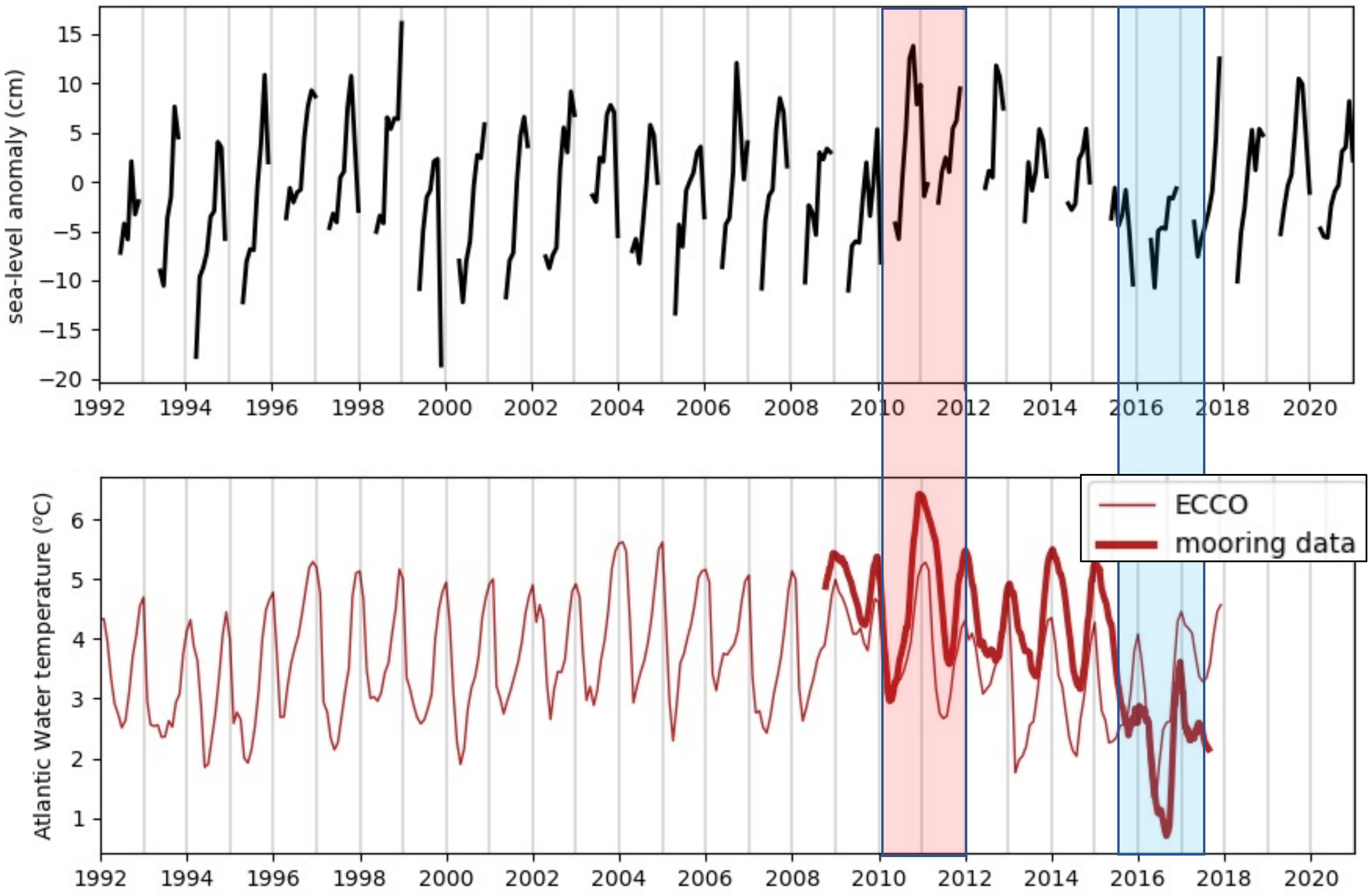


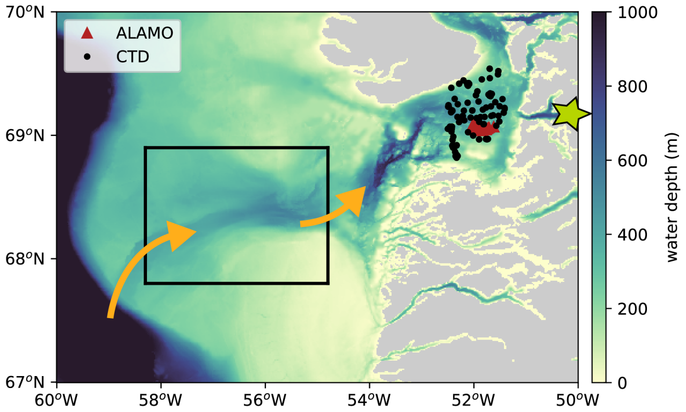
Along-track SLA in the North Atlantic: post-filters

along-track dataset

- coverage increases with time
- seasonal sea-ice
- seasonal SLA

Sea level anomalies and Atlantic Water temperatures





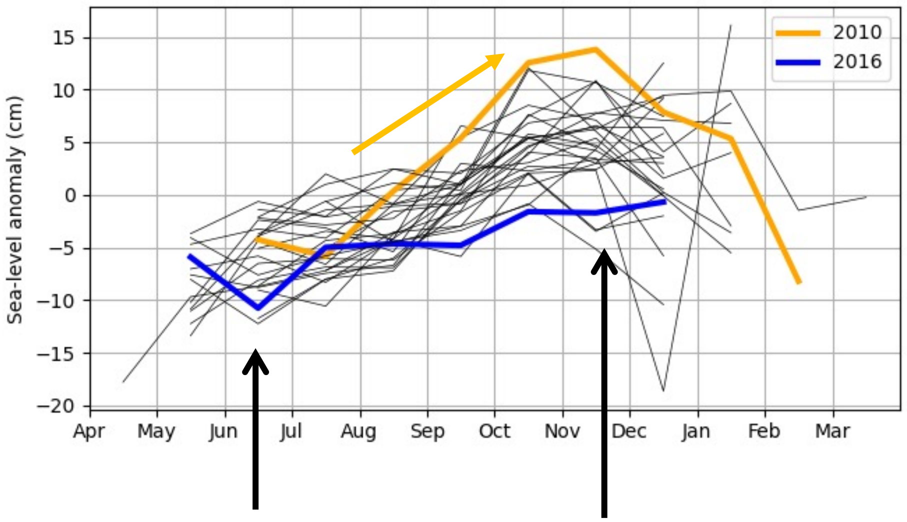
SLA in CW Greenland continental shelf
→ black box, depths > 300m

AW Temps from ECCO and upstream Davis Strait mooring at ~300m

AW Temps and SLA positively correlated
→ highest correlation when AW Temps lead SLA by 4-6 months

Sea level anomalies and Atlantic Water temperatures

Sea-level anomalies on the Greenland shelf (cm)



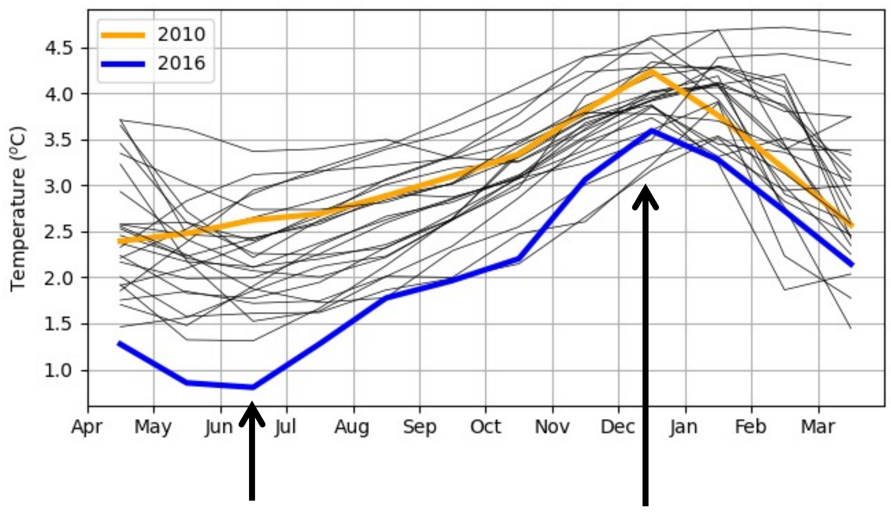
Spring/Summer

1. Seasonal minimum
2. Lowest interannual variation

Fall/Winter

1. Seasonal maximum
2. Highest interannual variation

Atlantic Water temperatures from ECCO (^oC)



Spring/Summer

1. Seasonal minimum
2. Highest interannual variation

Fall/Winter

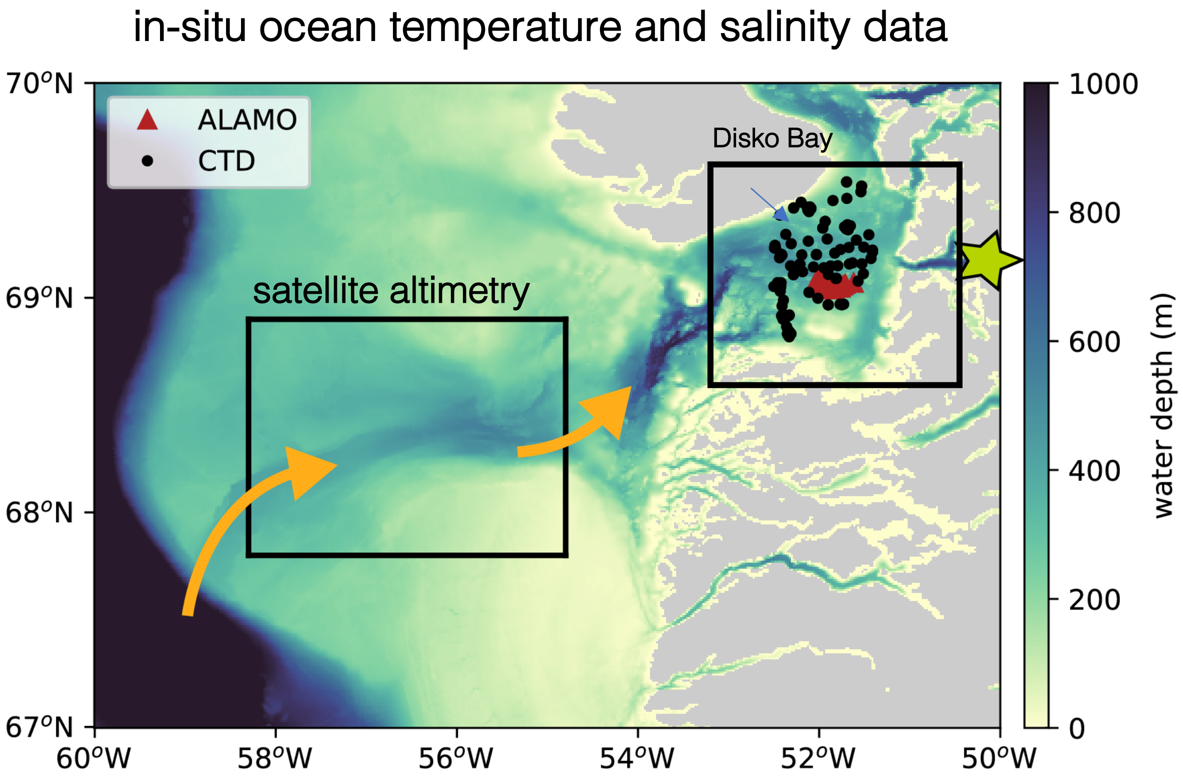
1. Seasonal maximum
2. Lowest interannual variation

Disko Bay in situ ocean T and S data

- CTD and AXCTD: 1968-2021 (including OMG mission)
- ALAMO profiling float

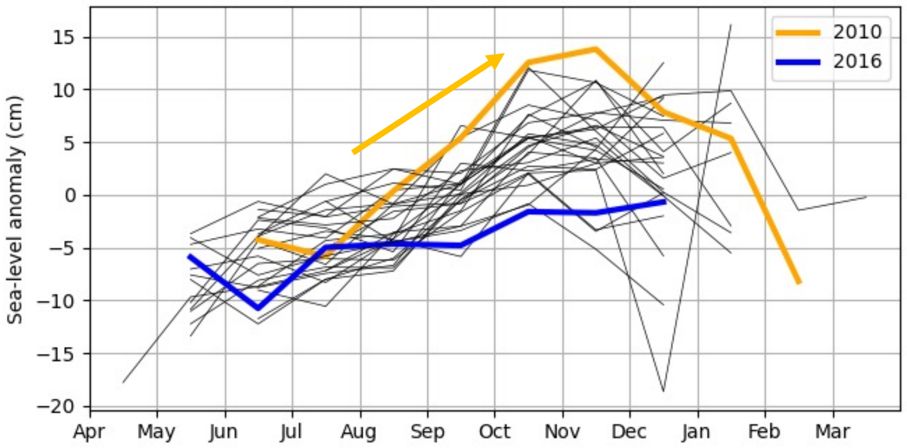
ALAMO profiling float

- Deployed in Disko Bay by OMG mission
- Once per week T and S vertical profiles
- Parked on seafloor between cycles

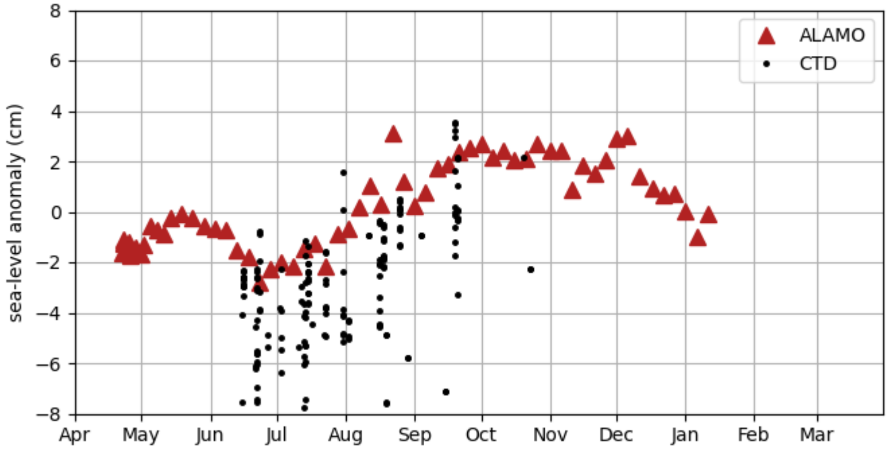


Decomposition of sterodynamic SLA from in-situ data

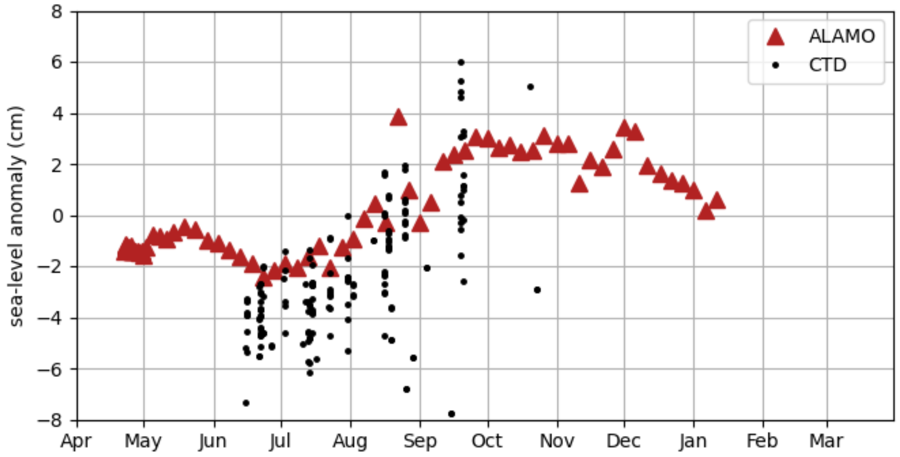
Sea-level anomalies on the Greenland shelf (cm)



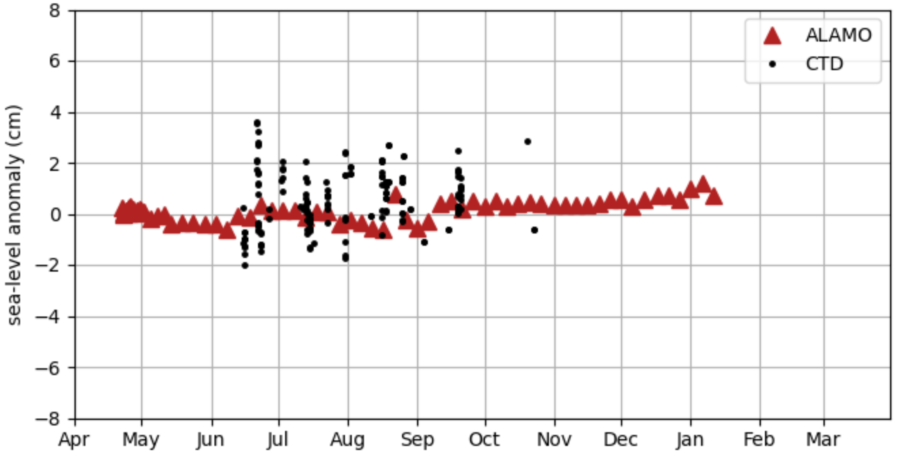
halosteric sea-level anomalies (cm)



sterodynamic sea-level anomalies (cm)



thermosteric sea-level anomalies (cm)

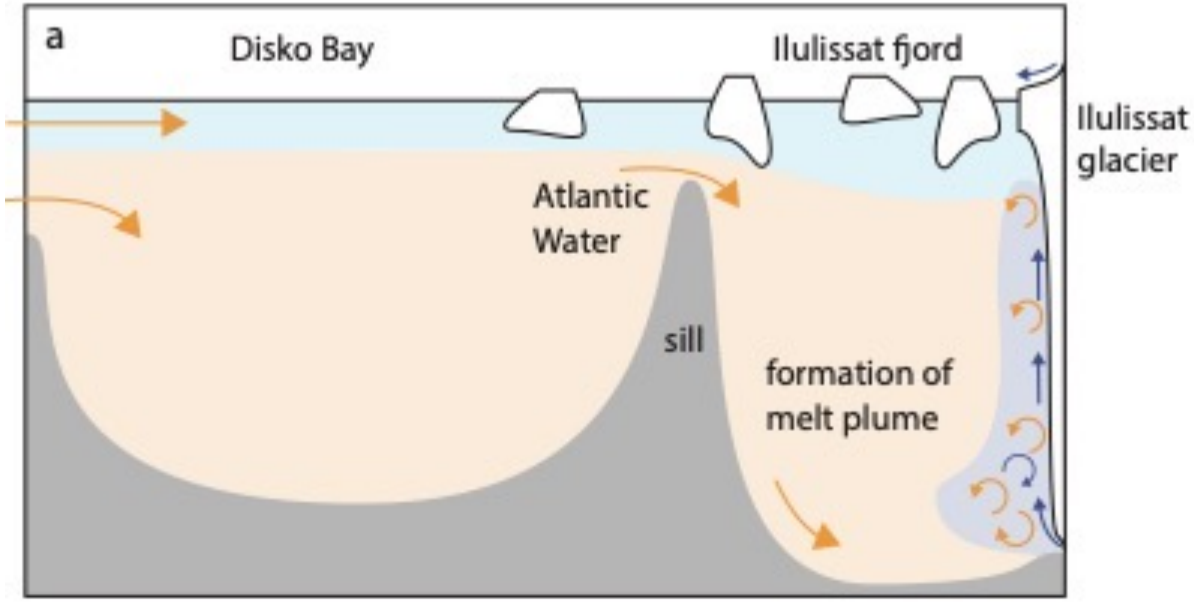


Anomalies computed from bottom to 50m depth

How subsurface AW temperature variations could affect Fall/Winter sea level

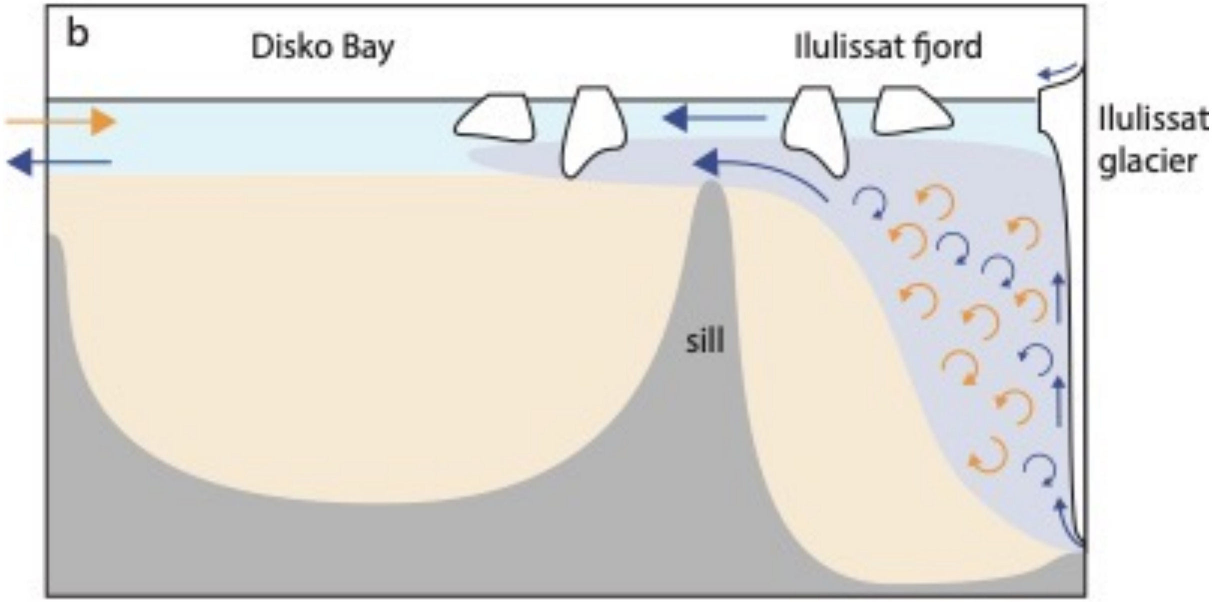
Late Spring to Early Summer:

1. Atlantic Water flows across the continental shelf, over the sill, and into the glacier fjord
2. Seasonal decrease in AW shelf temperatures
3. Relatively small decrease of thermosteric sea level



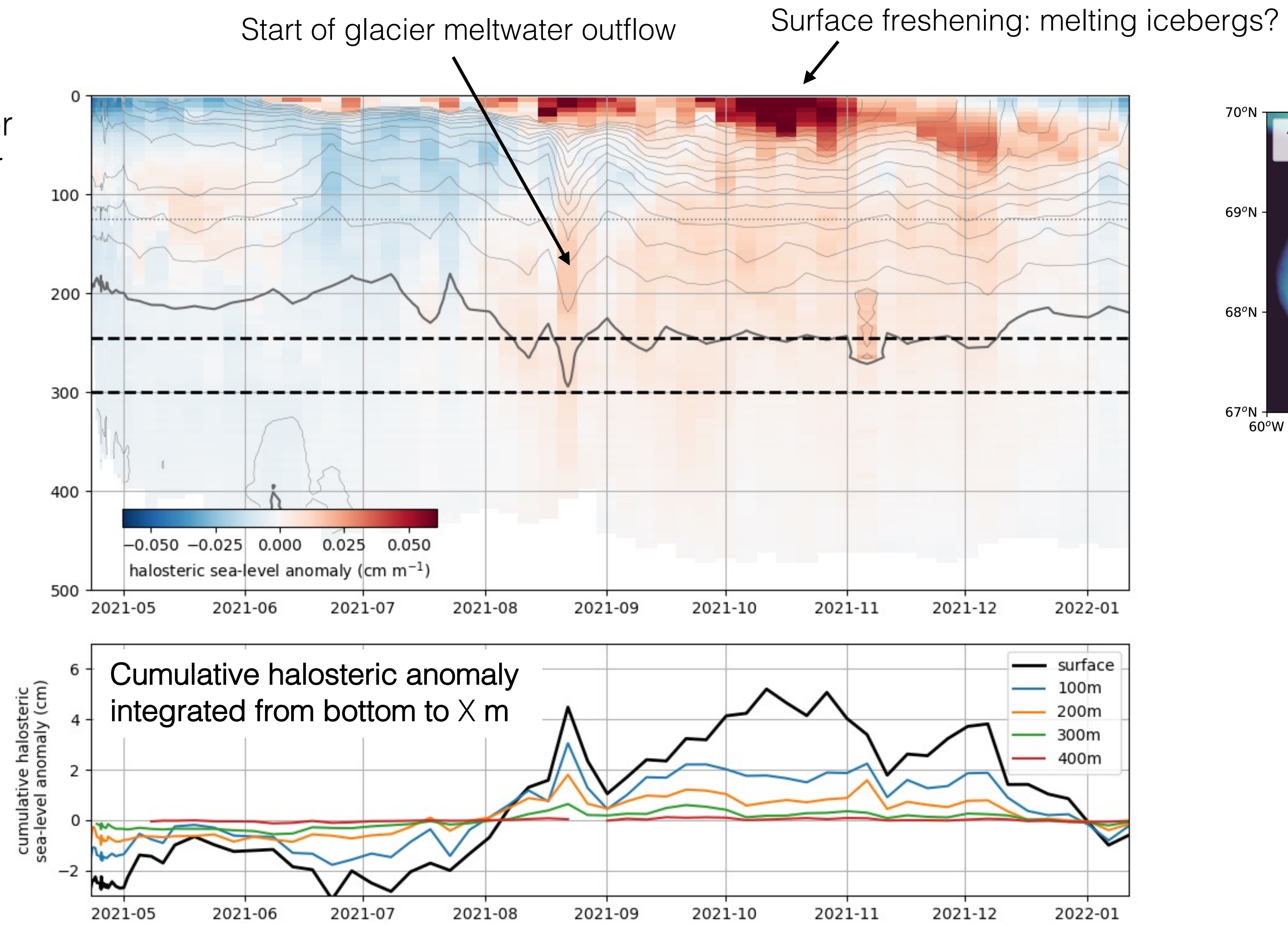
Mid Summer to Fall/Winter

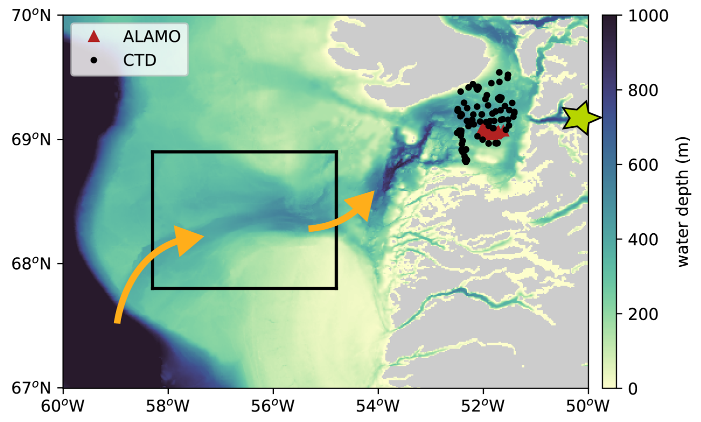
1. Glacier meltwater flows out of the fjord and onto the continental shelf
2. Freshening of shelf waters
3. Relatively large increase of halosteric sea level



Halosteric sea-level anomalies from the ALAMO profiling float

Red = fresher
Blue = saltier





Conclusions

1. SLA on the CW Greenland shelf exhibits seasonal and interannual variability of ~10 cm
   - maximum seasonal and interannual variability occurs in Fall/Winter
2. Fall/Winter sterodynamic SLA anomalies are almost entirely related to salinity

+ AW temperature → + glacier melt → + shelf freshwater → + halosteric SLA

3. Can we estimate AW temperatures close to Greenland from sea-level anomalies?
   - Not yet; direct AW thermosteric SLA signal may not be large enough.
   - However, SLA signal from fresh meltwater is large and *melt = f (AW temperature)*
4. *in situ* ocean T and S data from profiling floats on the shelf are extremely useful
   - Unique, ground-truth measurements of AW temperature and steric sea-level variability near the glaciers
   - Continuing these observations would enhance the value of satellite SLA on the shelf

<u>New questions:</u>

1. Can we estimate **summer melt** from **fall/winter** sea-level anomalies?
2. If yes, can we estimate the AW temperatures responsible for the summer melt?
3. Can ICESat-2 and SWOT provide useful SLA measurements on the Greenland shelf?

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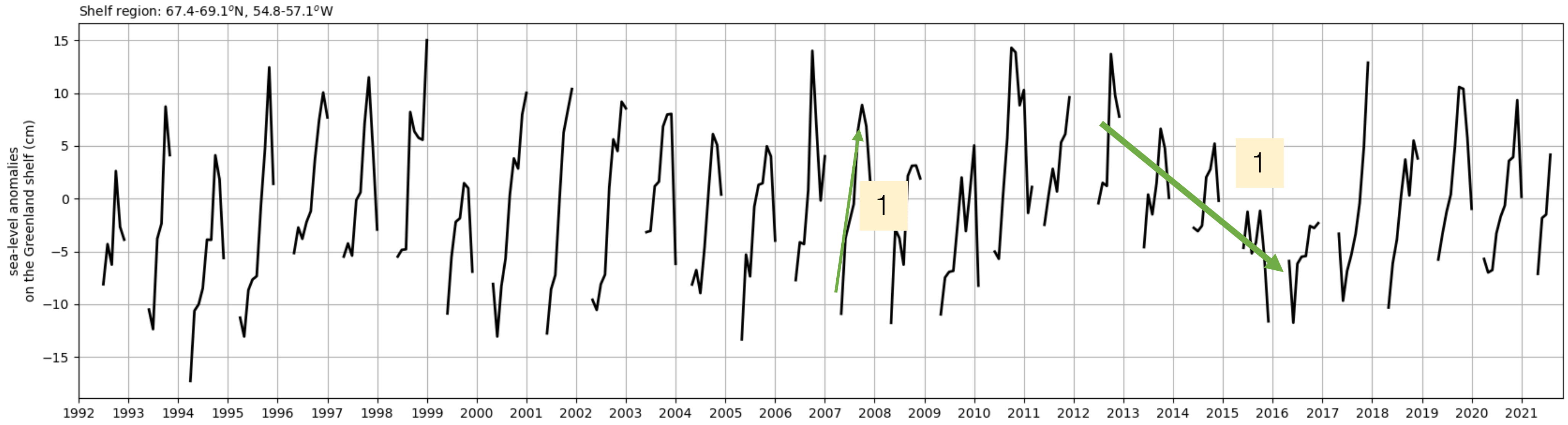
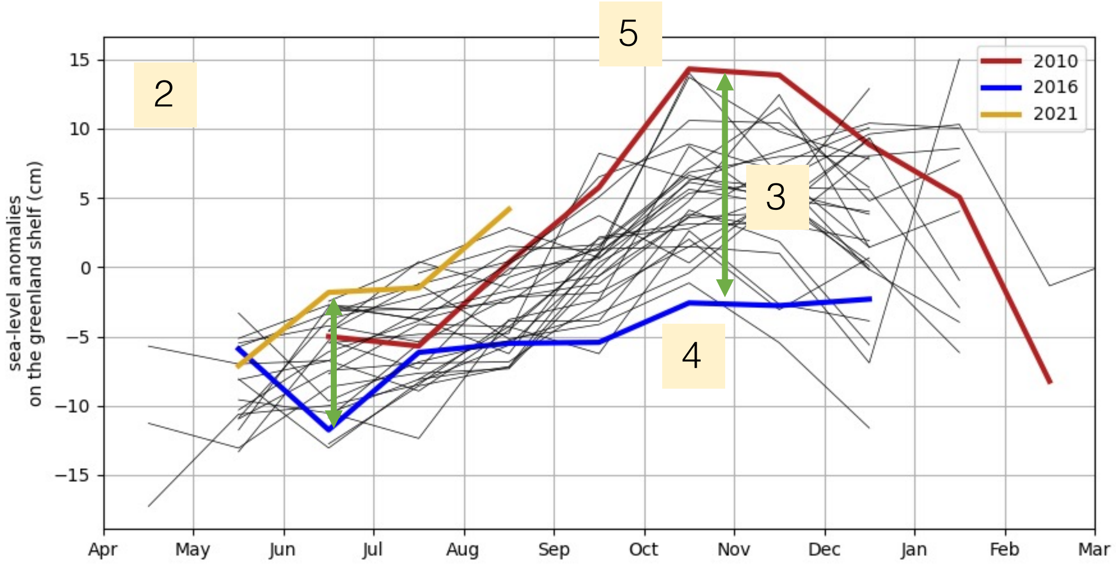


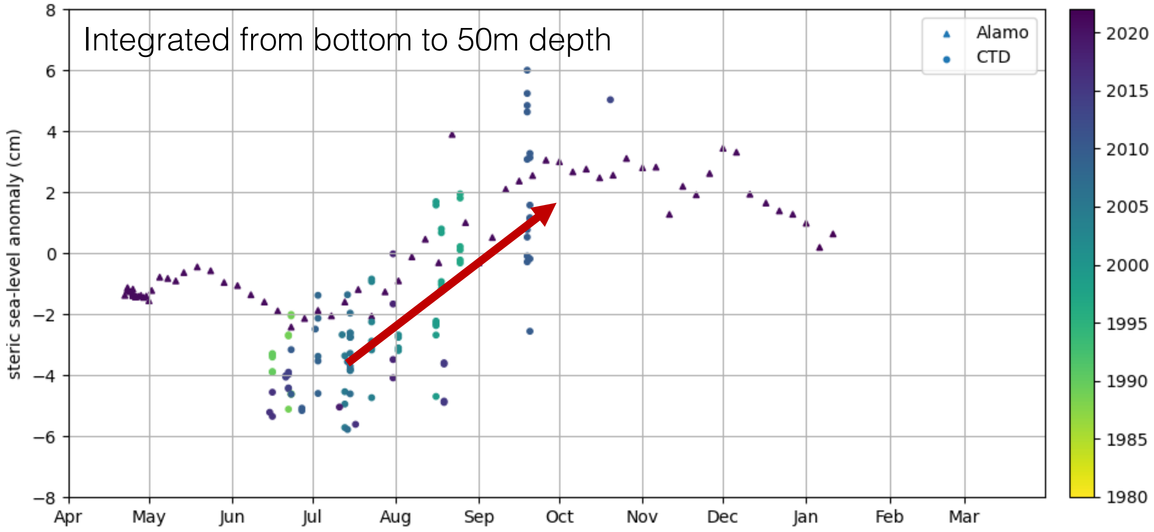
What to see in this figure:

1. sea-level has two distinct signals:
   - seasonal & interannual
2. sea-level increases in summer, decreases in winter
3. interannual variability is bigger in fall than in summer
4. cold year (2016) has low SLA maximum in fall
5. Warm year (2010) has high SLA maximum in fall

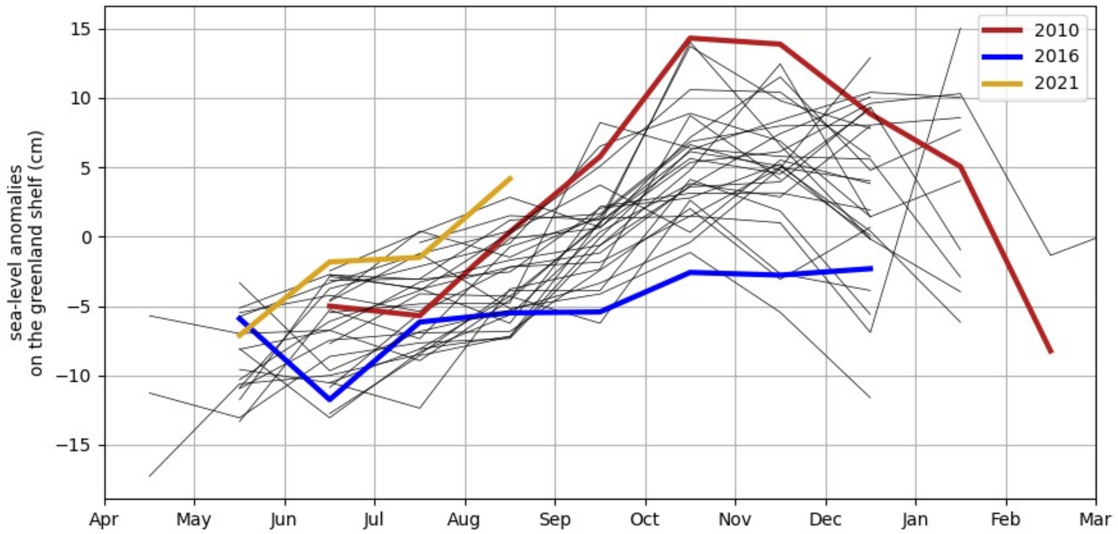


Next step: calculate the expected steric anomalies on shelf from ECCO

Steric sea-level anomalies from in-situ measurements



Total sea-level anomalies from satellite altimetry

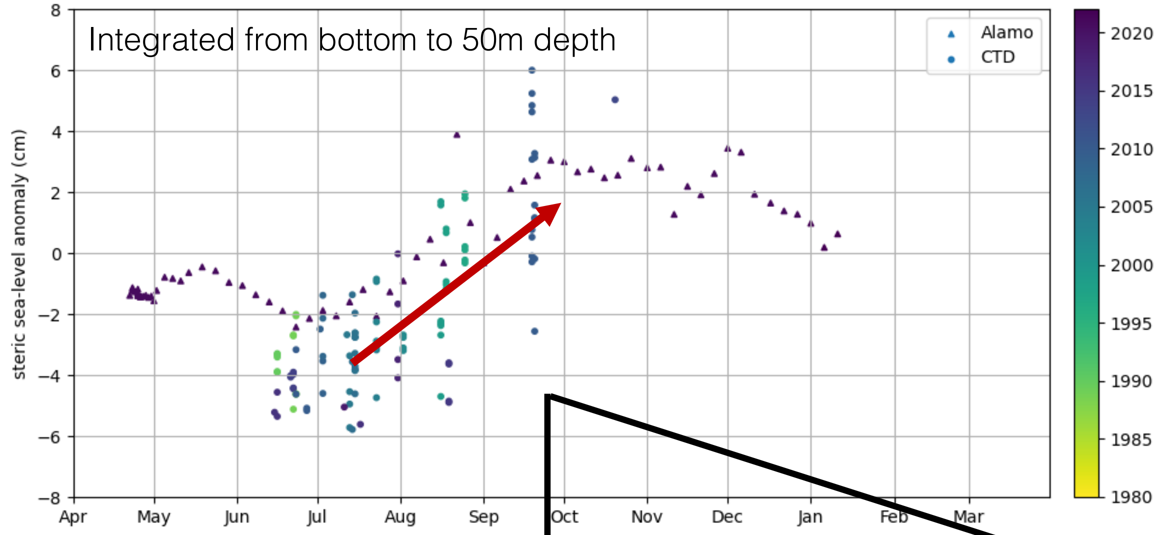


What to see in this figure:

1. Steric sea-level anomalies same pattern as total sea-level anomalies
2. Steric sea-level anomalies are ~50% of total sea-level anomalies
    1. Note that we don't integrate up to surface due to bad data!

3. Big variations in properties → be careful when averaging data over summers!

Steric sea-level anomalies from in-situ measurements



What to see in this figure:

1. Seasonal cycle is dominated by salinity variations
2. Temperature alone cannot explain the interannual variability

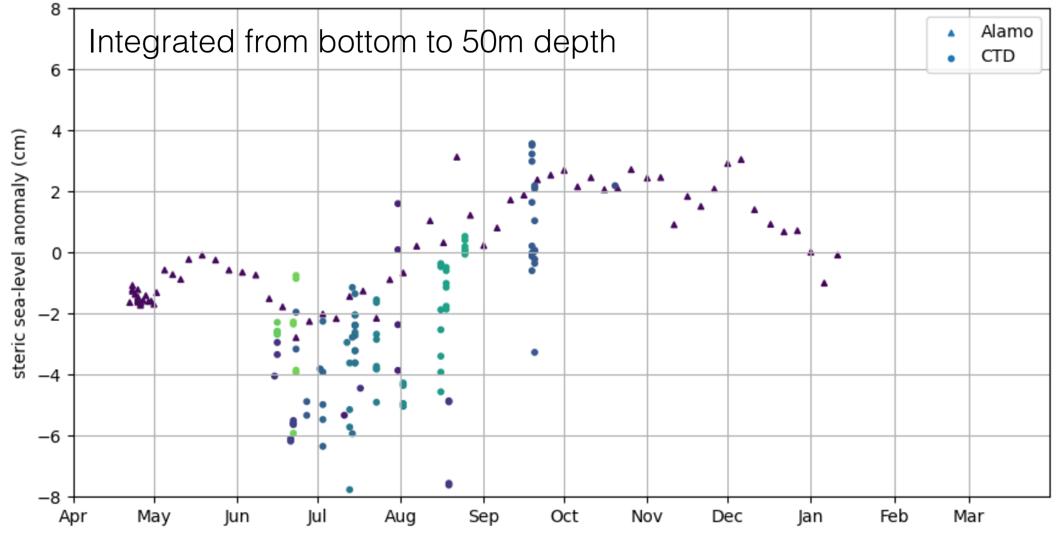
Remaining question:

Why does temperature of AW is such a good match with the sea level?

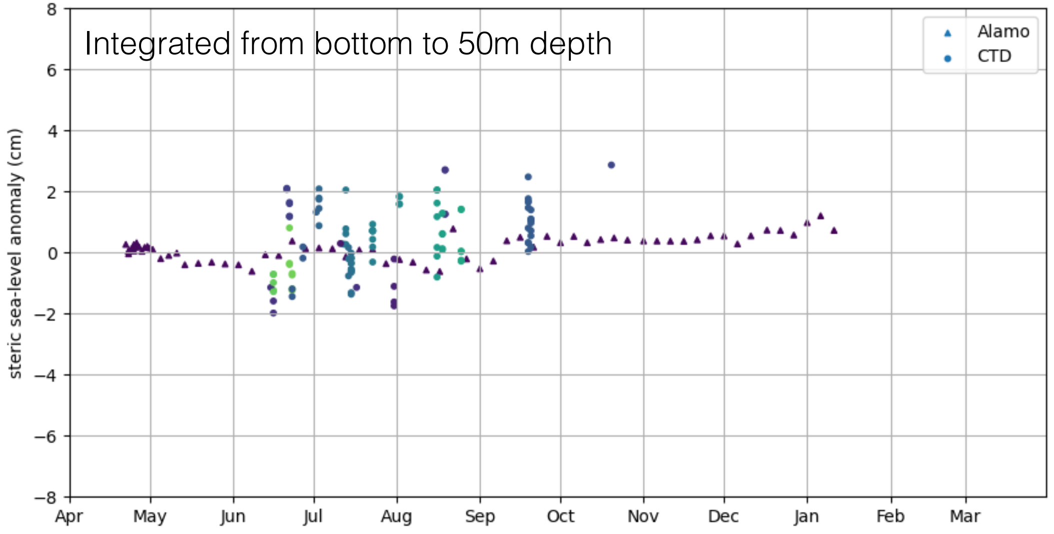
Simple first step:

1. look at seasonal cycle

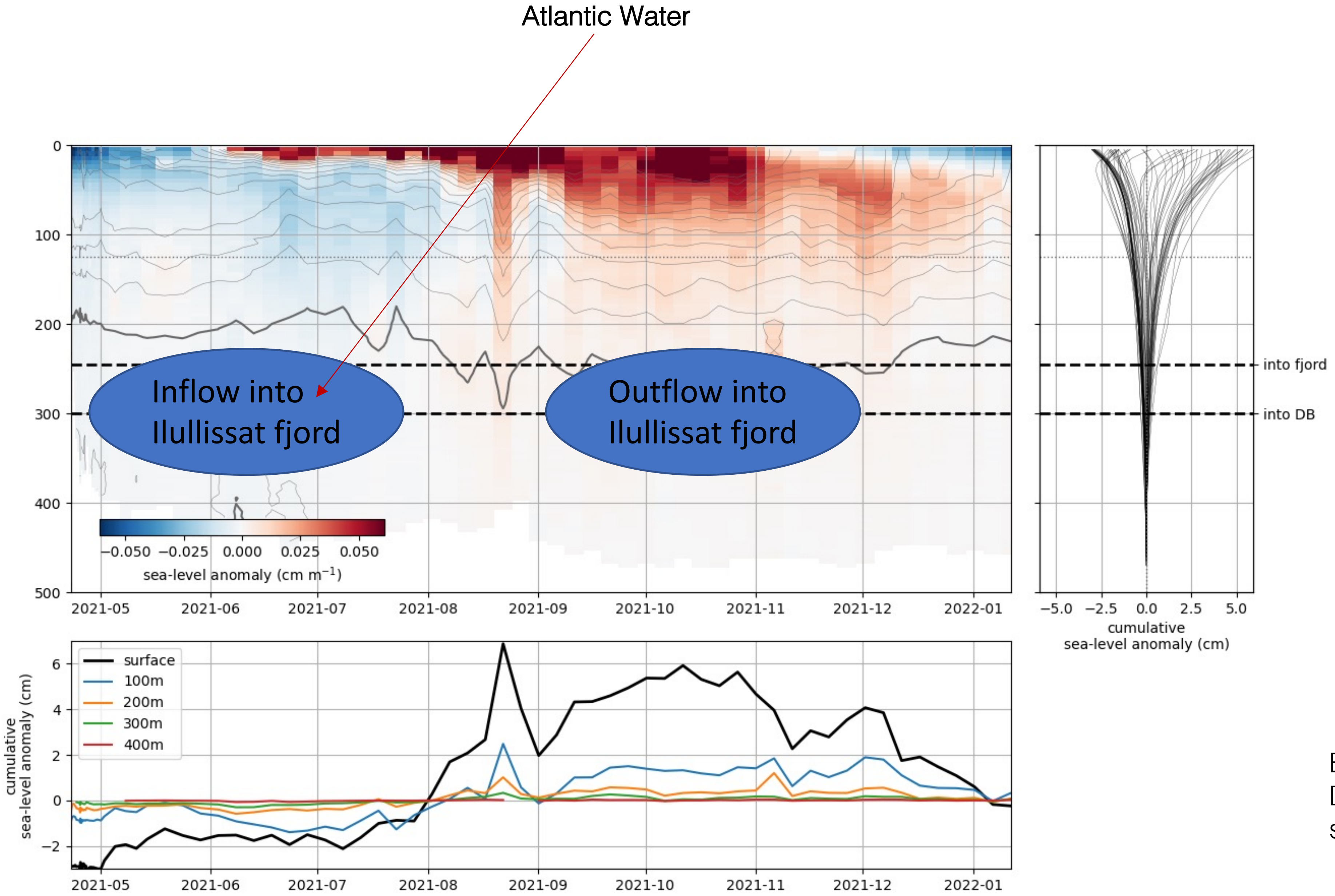
Halosteric sea-level anomalies



Thermosteric sea-level anomalies



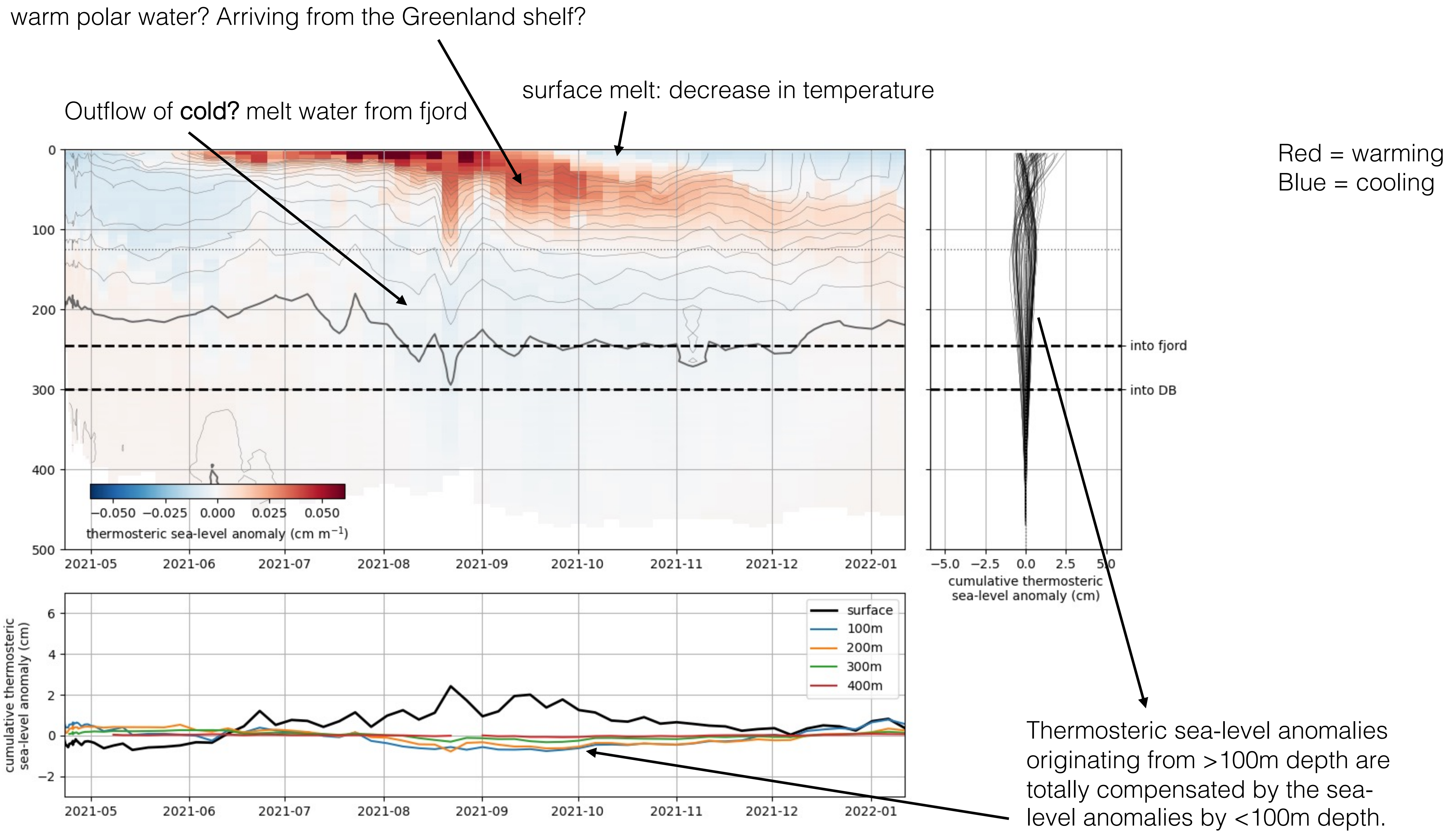
Sea-level anomalies



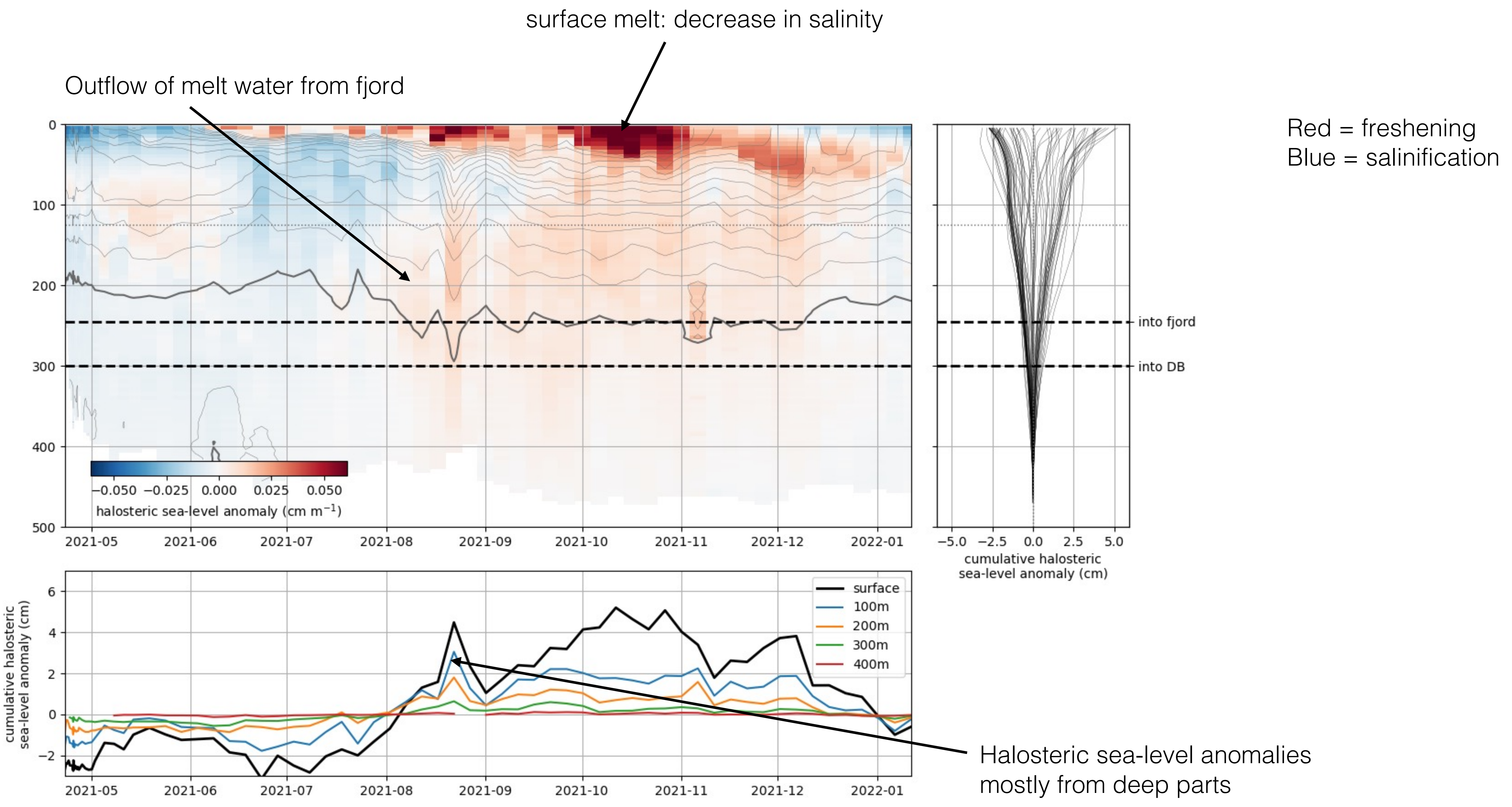
Red = lighter
Blue = denser

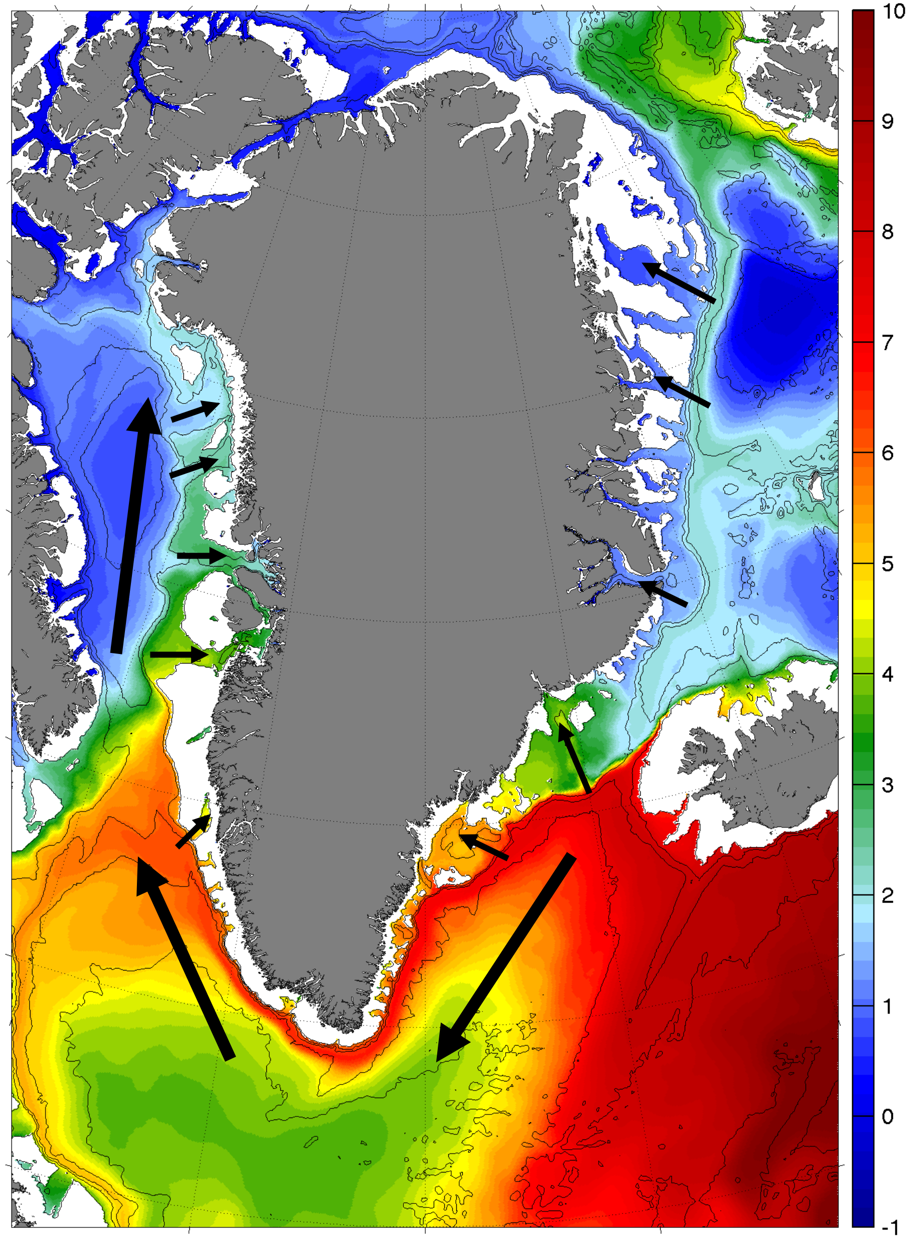
Biggest signal from upper ocean. Deep and upper ocean have same signal.

Thermosteric sea-level anomalies

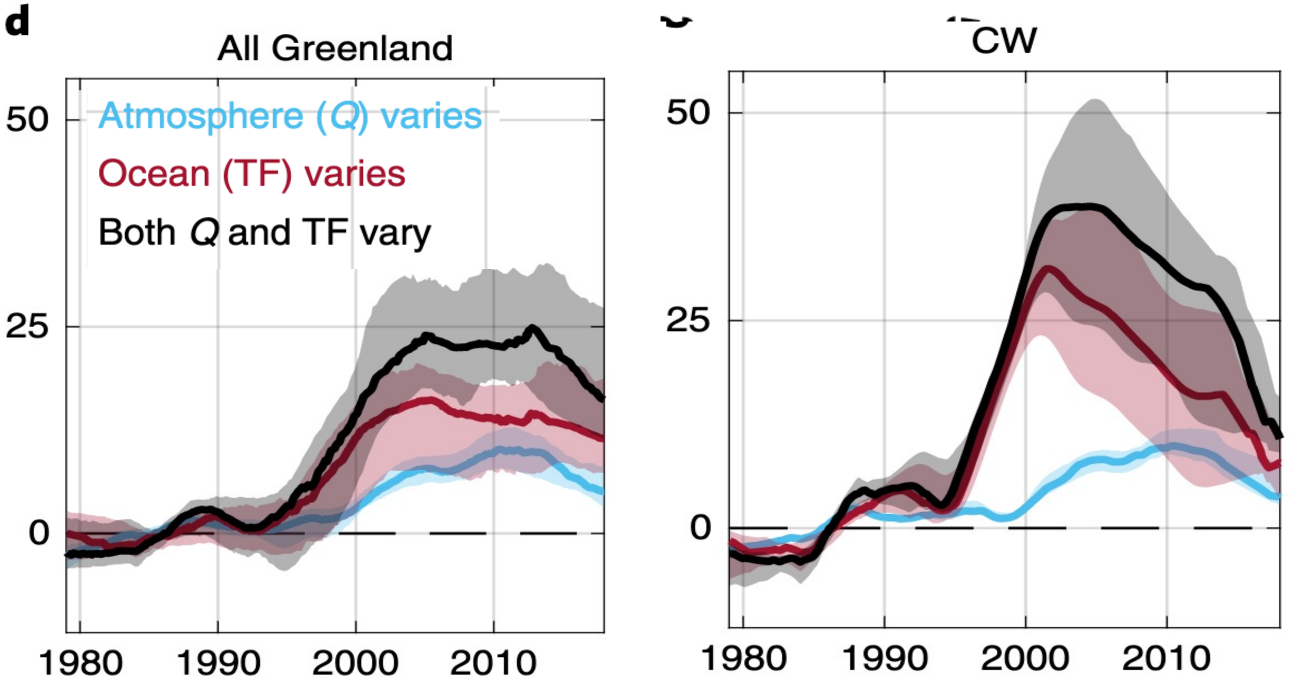


Halosteric sea-level anomalies



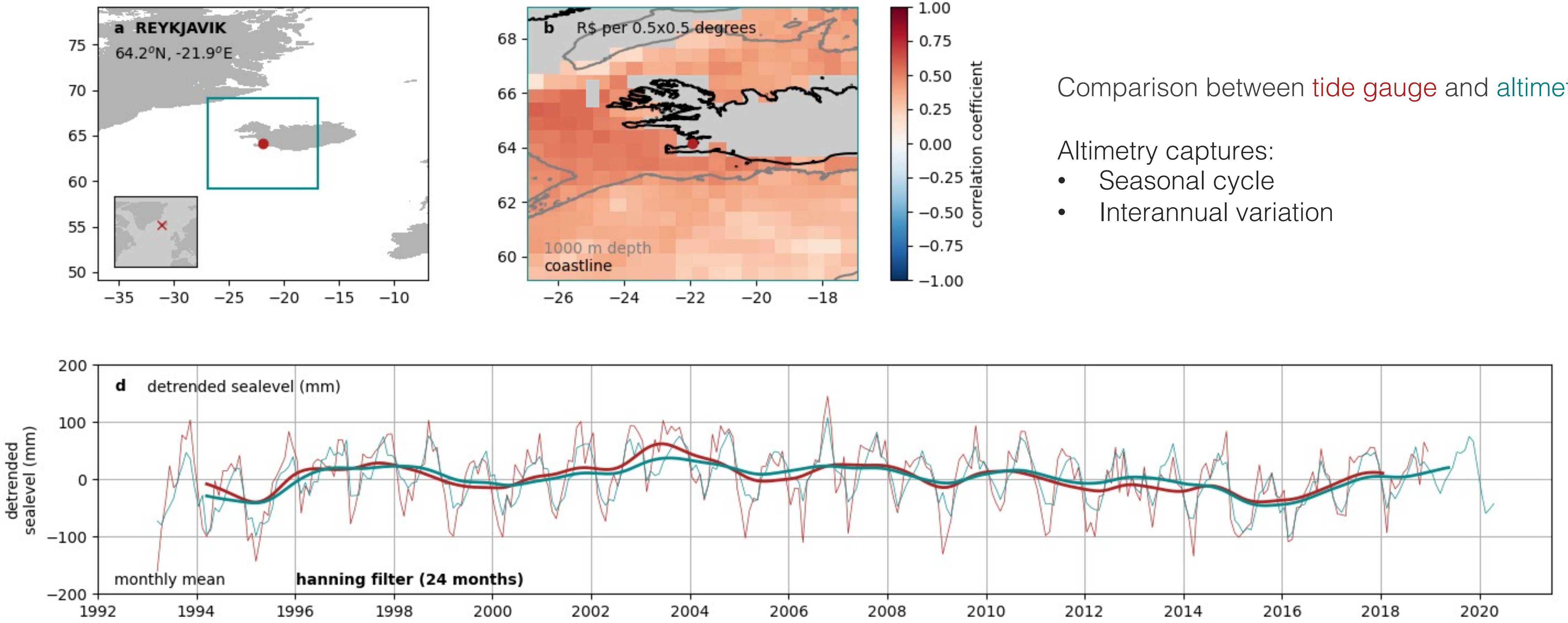


Change in submarine melt rate versus 1979–1993 (%)



Slater, D. A., and F. Straneo, 2022: Submarine melting of glaciers in Greenland amplified by atmospheric warming. *Nat Geosci*, **15**, 794–799, https://doi.org/10.1038/s41561-022-01035-9.

Satellite altimetry in the North Atlantic: validation



Comparison between tide gauge and altimetry

Altimetry captures:

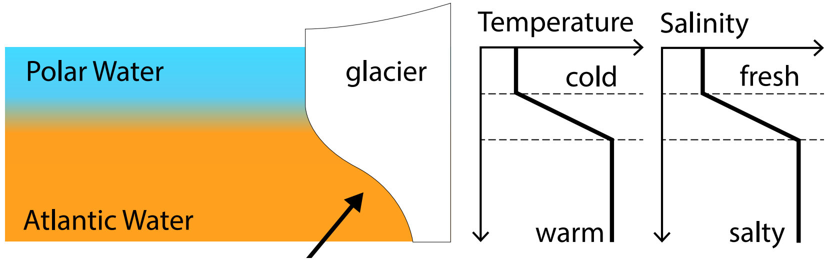
- Seasonal cycle
- Interannual variation

Estimating the expected sea-level anomalies

how?

Idealized profiles of temperature and salinity

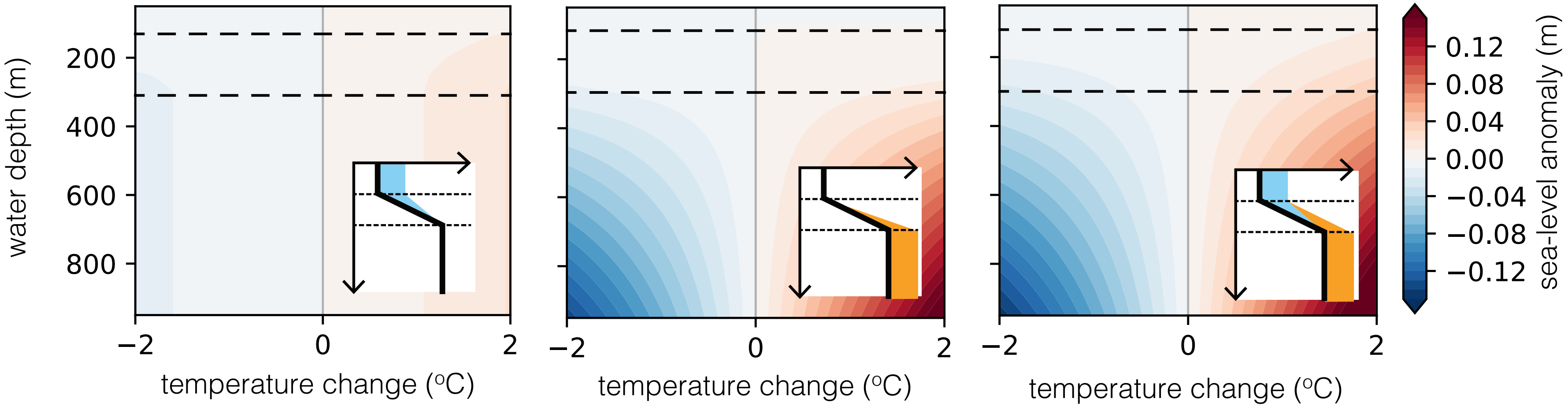
- Polar Water: -1.5°C 33 psu <100m depth
- Atlantic Water: 3°C 35 psu >300m depth



what do we find?

temperature change in Polar Water does not result in large sea-level anomalies

depending on the water depth, ΔT in Atlantic water can result in several cm sea-level anomalies



Good news: temperature anomalies are detectable by satellite altimetry