DTU

The Danish Meteorological Institute

Using SMB modelling and ICESat-2 to uncover ice sheet mass budget processes

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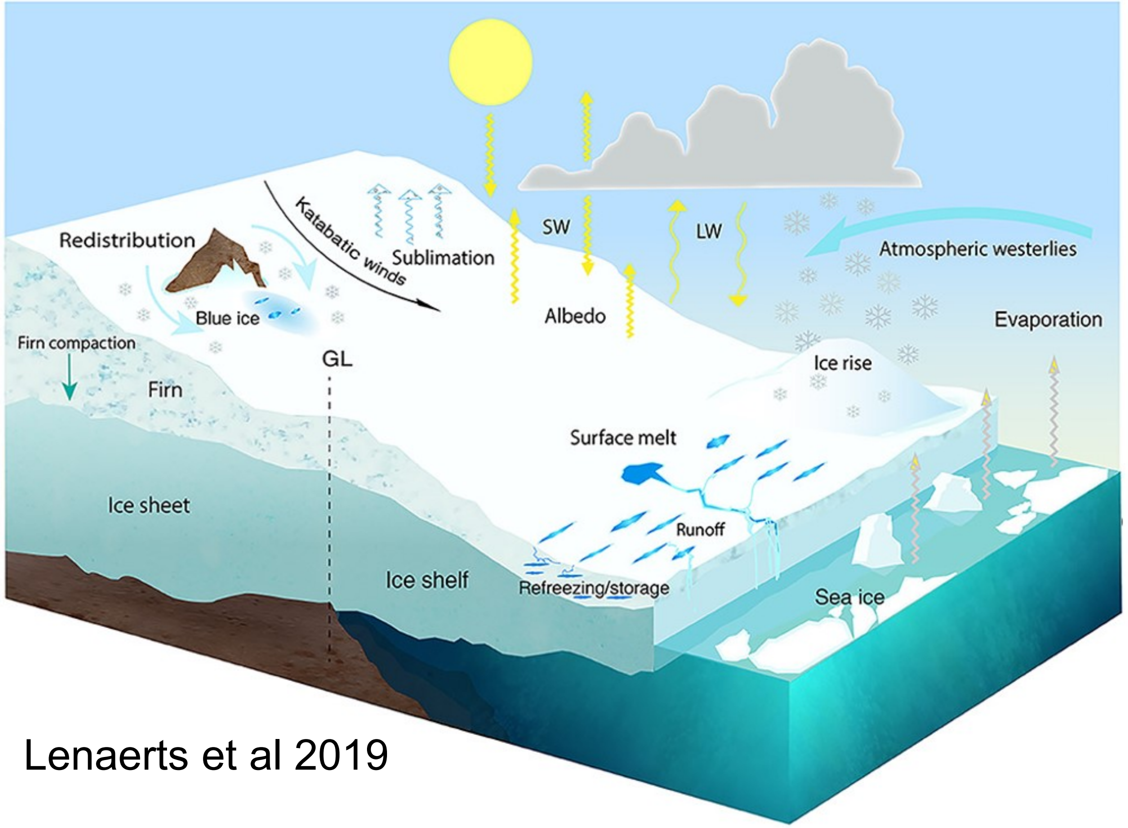
What is the (surface) mass balance?

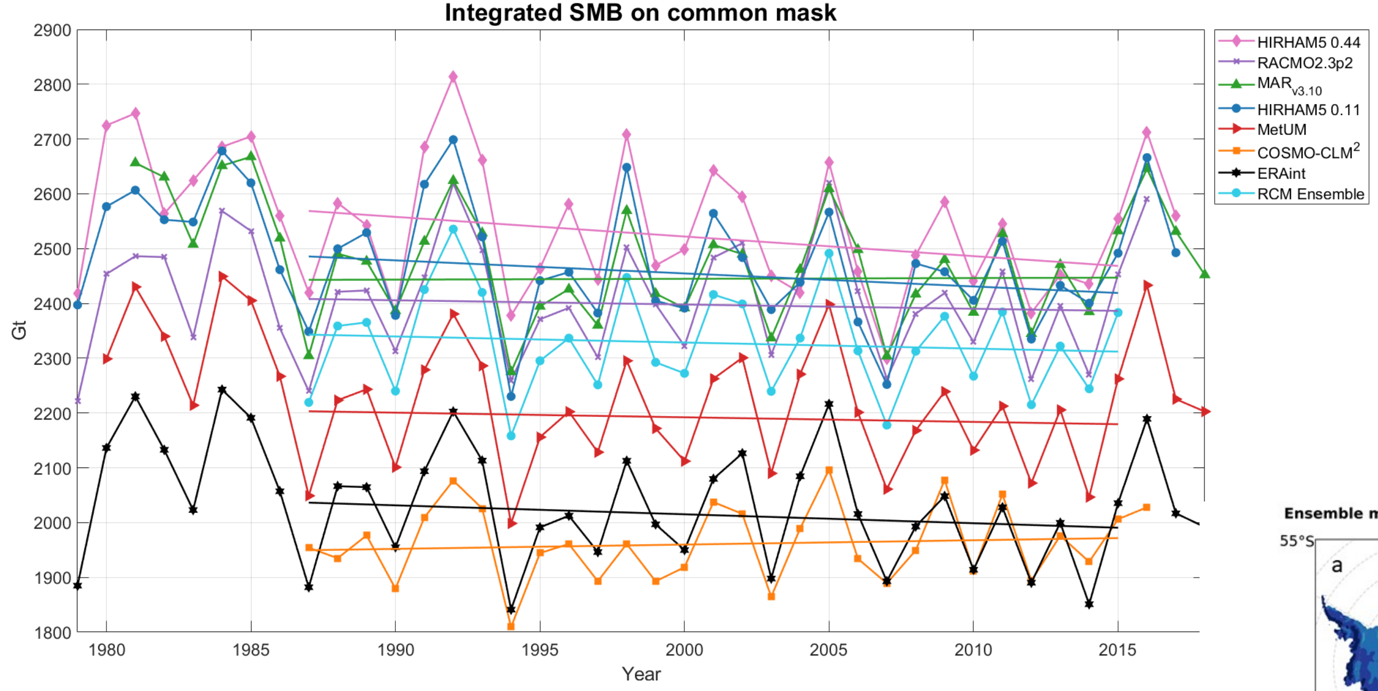
$$MB = SMB - D$$
$$SMB = precipitation - runoff - evaporation - sublimation$$
$$D = discharge$$

Discharge when crossing the GL

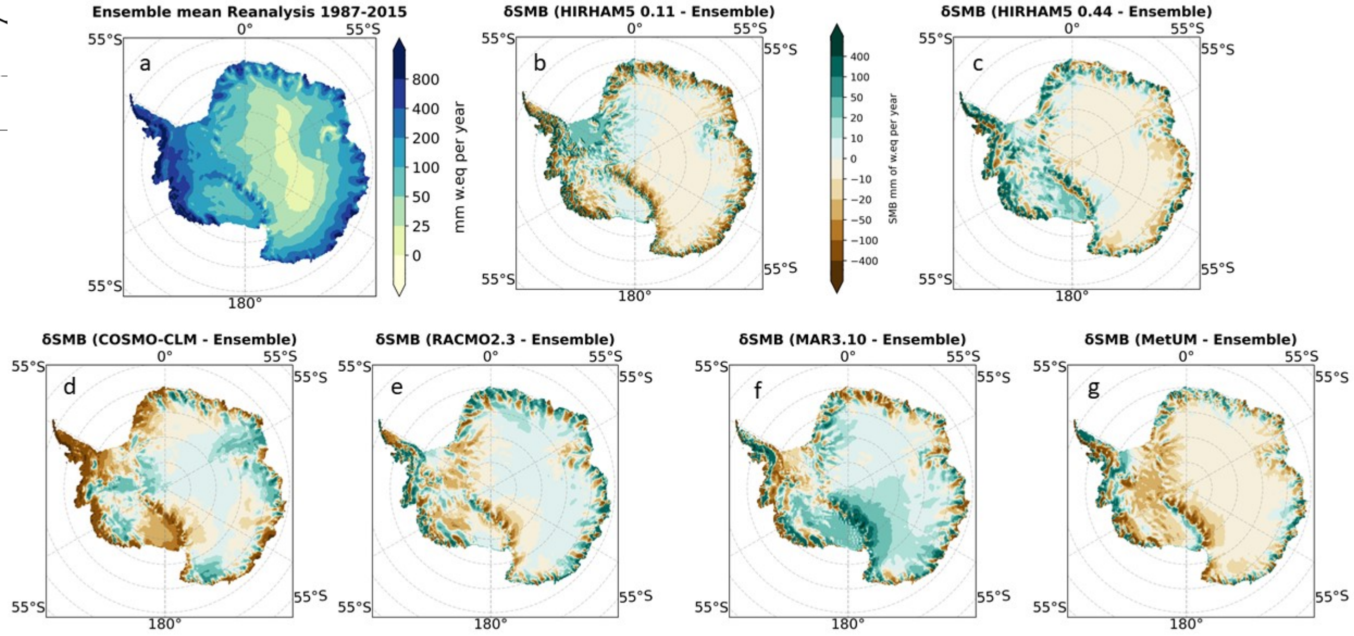


Lenaerts et al 2019

RCM SMB ensemble over Antarctica



- Ice mask => area bias
- Model spread of 550 Gt per year
  - Equivalent to nearly 2 mm sea level change per year
- HIRHAM5

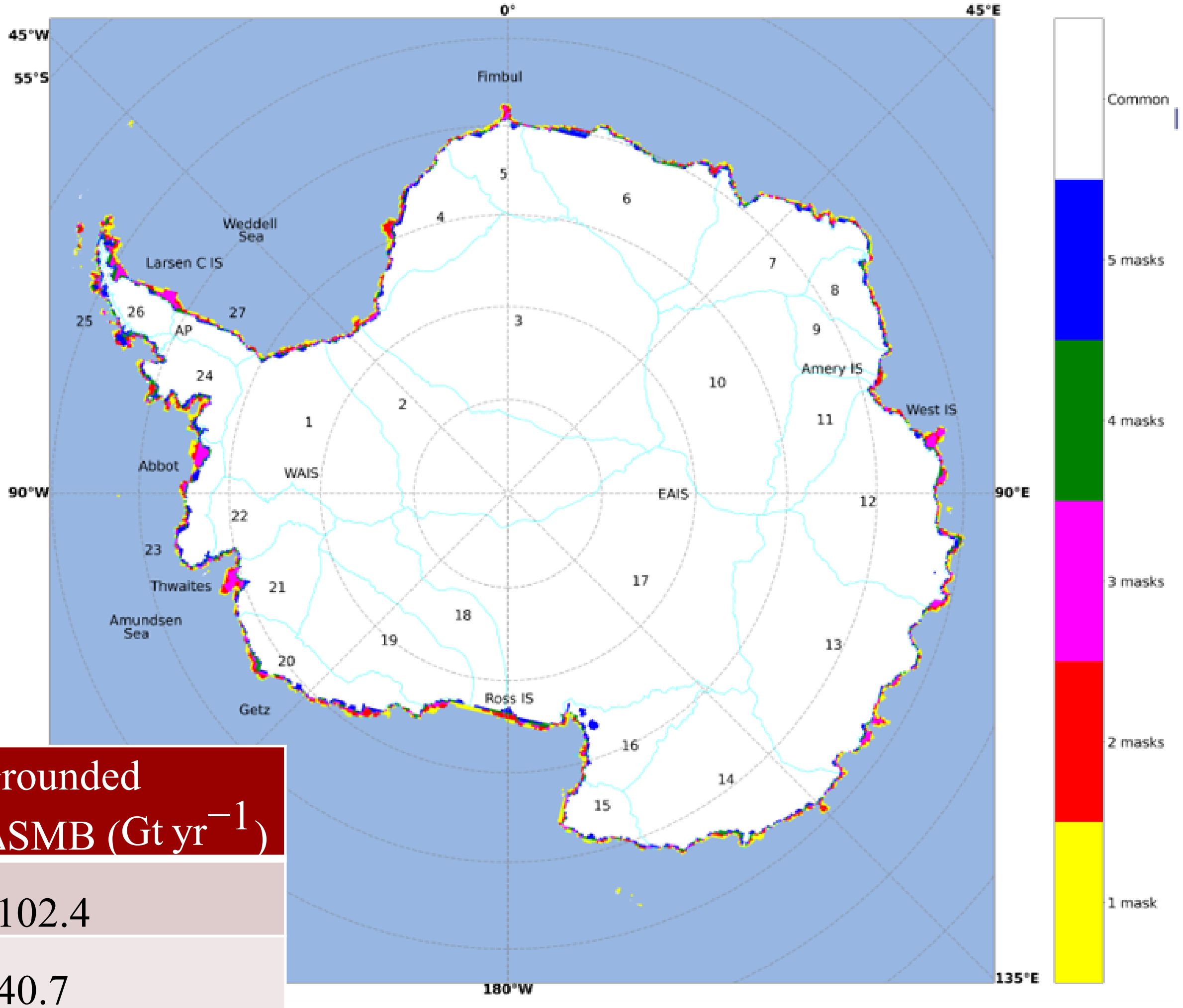


Mottram et al 2021

The ice masks results

Ensemble mean from Mottram et al 2021= 2329 Gt per year

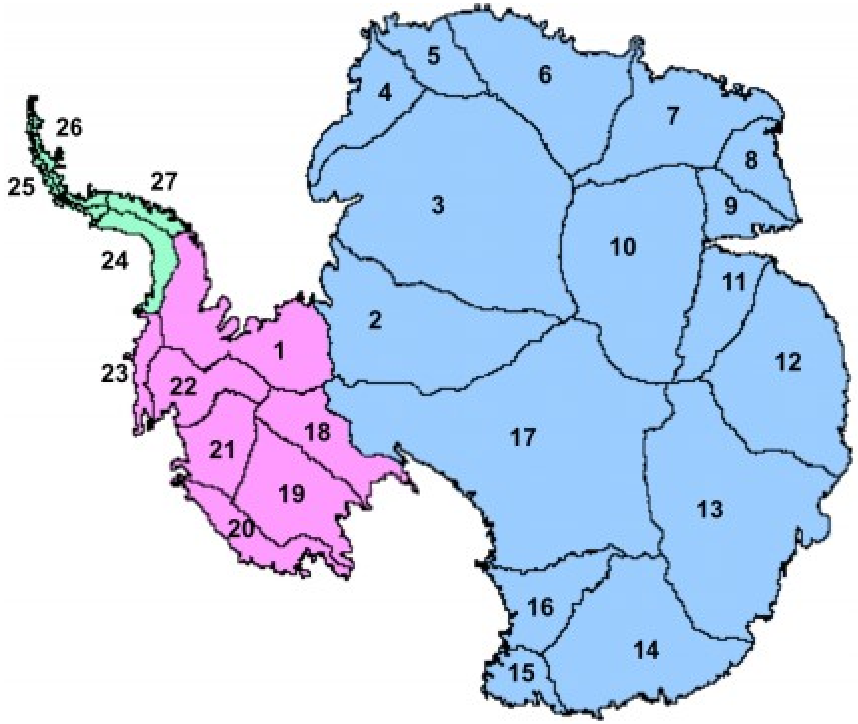
Common ice mask vs. native ice mask



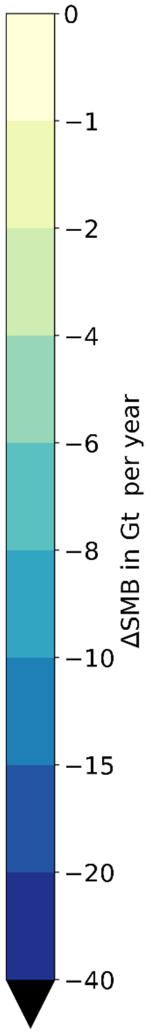
Model	Δarea (%)	ΔSMB($Gt\ yr^{-1}$)	ΔSMB (%)	SMB ($Gt\ yr^{-1}$)	Grounded ΔSMB ($Gt\ yr^{-1}$)
HIRHAM5 0.11°	−2.43	−140.6	−6.04	2452±107	−102.4
HIRHAM5 0.44°	−2.49	−69.5	−2.99	2518±118	−40.7
MARv3.10	−2.89	−91.9	−3.95	2445±91	−54.1
COSMO-CLM2	−1.94	−40.5	−1.77	1961±70	−20.1
RACMO2.3p2	−1.85	−119.6	−5.13	2399±101	−74.0
MetUM	−2.49	−57.6	−2.47	2191±101	−33.9

MB=-109±56 Gt per year

The ice masks results



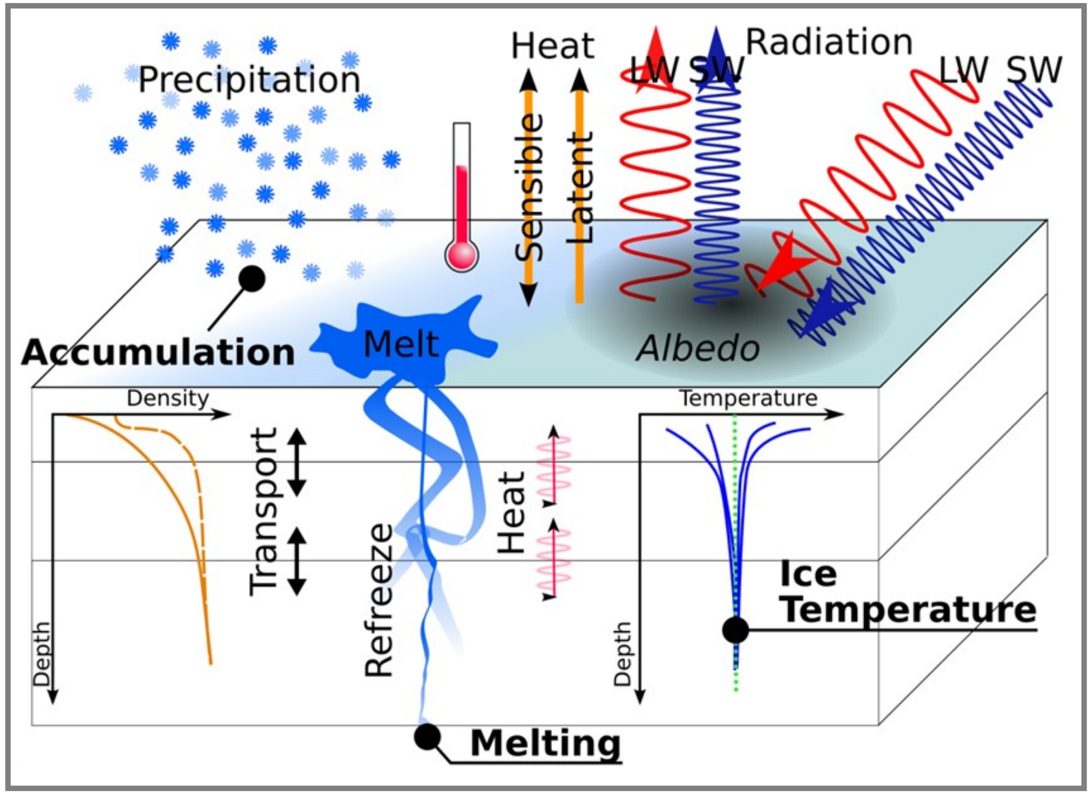
	HIRHAM5 0.11	HIRHAM5 0.44	MAR v3.10	MetUM	RACMO2.3p2	COSMO-CLM²
Basin 1	-0.45 / -0.43	-0.36 / -0.41	-0.98 / -1.10	0.44 / 0.44	-1.17 / -1.12	-0.50 / -0.68
Basin 2	-0.30 / -0.08	-0.17 / -0.06	-0.41 / -0.14	-0.25 / -0.08	-0.54 / -0.13	-0.07 / -0.05
Basin 3	-0.21 / -0.05	-0.19 / -0.05	-0.08 / -0.03	-0.07 / -0.02	-0.20 / -0.05	-0.09 / -0.04
Basin 4	-5.06 / -2.91	-2.02 / -1.75	-7.08 / -6.46	-4.20 / -2.63	-8.70 / -5.86	-3.71 / -3.97
Basin 5	-4.13 / -2.28	-3.75 / -2.10	-2.82 / -1.80	-1.88 / -0.90	-3.05 / -1.62	-2.55 / -1.98
Basin 6	-6.92 / -2.15	-3.54 / -1.53	-7.38 / -3.19	-2.29 / -0.77	-7.10 / -2.92	-4.33 / -2.71
Basin 7	-9.30 / -2.47	-4.81 / -1.87	-6.25 / -2.82	-3.13 / -0.89	-8.42 / -2.67	-3.59 / -2.16
Basin 8	-3.30 / -4.14	-1.31 / -2.58	-1.98 / -4.24	-0.36 / -0.83	-4.32 / -3.87	-1.39 / -3.31
Basin 9	-3.04 / -0.96	-0.67 / -0.26	-3.83 / -1.83	-2.55 / -0.87	-4.20 / -1.57	-0.39 / -0.35
Basin 10	0.00 / 0.00	-0.18 / -0.03	-1.43 / -0.25	-0.23 / -0.03	-1.48 / -0.23	-0.09 / -0.05
Basin 11	-0.29 / -0.05	-1.19 / -0.33	-1.55 / -0.33	0.00 / 0.00	-1.19 / -0.27	-0.15 / -0.05
Basin 12	-4.91 / -1.60	-3.03 / -1.35	-2.62 / -1.49	-2.82 / -1.08	-3.00 / -1.21	-2.05 / -1.29
Basin 13	-2.88 / -0.71	-1.45 / -0.46	-1.36 / -0.69	-1.63 / -0.42	-2.15 / -0.62	-0.95 / -0.55
Basin 14	-5.06 / -1.49	-2.73 / -1.07	-3.57 / -1.68	-3.79 / -1.17	-4.82 / -1.55	-1.52 / -0.82
Basin 15	-13.14 / -5.62	-3.54 / -3.11	-7.69 / -6.22	-6.00 / -3.23	-10.32 / -5.62	-6.45 / -4.55
Basin 16	-2.77 / -3.80	-1.80 / -2.71	-1.49 / -2.71	-2.62 / -2.42	-3.12 / -3.34	-1.35 / -2.65
Basin 17	-0.76 / -0.24	-0.14 / -0.09	-0.45 / -0.33	-0.53 / -0.17	-0.84 / -0.33	-0.25 / -0.26
Basin 18	-0.21 / -0.15	-0.37 / -0.44	-0.75 / -0.66	-0.57 / -0.33	-1.03 / -0.74	-0.05 / -0.15
Basin 19	-0.20 / -0.13	-0.15 / -0.13	-0.02 / -0.03	-0.17 / -0.13	-0.12 / -0.09	-0.11 / -0.13
Basin 20	-6.80 / -4.52	-3.84 / -3.03	-8.87 / -8.97	-5.22 / -4.32	-9.97 / -7.55	-4.49 / -5.23
Basin 21	-2.46 / -0.93	-1.88 / -0.93	-0.68 / -0.47	-1.26 / -0.66	-1.51 / -0.73	-0.78 / -0.60
Basin 22	-0.47 / -0.21	-0.69 / -0.48	0.62 / 0.62	-0.52 / -0.28	-1.04 / -0.62	-0.46 / -0.55
Basin 23	-13.98 / -8.83	-9.90 / -8.30	-10.95 / -12.52	-4.18 / -4.48	-12.81 / -11.46	-9.03 / -10.41
Basin 24	-8.74 / -4.72	-4.27 / -3.58	-6.01 / -7.62	-7.88 / -5.79	-9.21 / -7.08	-4.51 / -6.55
Basin 25	-50.79 / -40.49	-24.19 / -24.54	-36.03 / -41.10	-14.67 / -13.50	-36.74 / -32.52	-26.16 / -40.49
Basin 26	-3.63 / -2.73	-1.70 / -3.03	-2.02 / -3.79	-1.62 / -2.12	-2.49 / -2.73	-0.99 / -2.12
Basin 27	-5.17 / -5.48	-3.38 / -4.57	-3.90 / -5.71	-3.41 / -3.42	-4.82 / -5.48	-4.10 / -4.79
Total SMB	-140.58	-69.56	-91.88	-57.60	-119.56	-40.46



The SMB model

- Models the physical properties of the firn
  - Melt-albedo feedback
  - Densification
  - Grain growth
  - Water/snow/ice fractions
  - Temperature

- 1-D columns
- Offline model



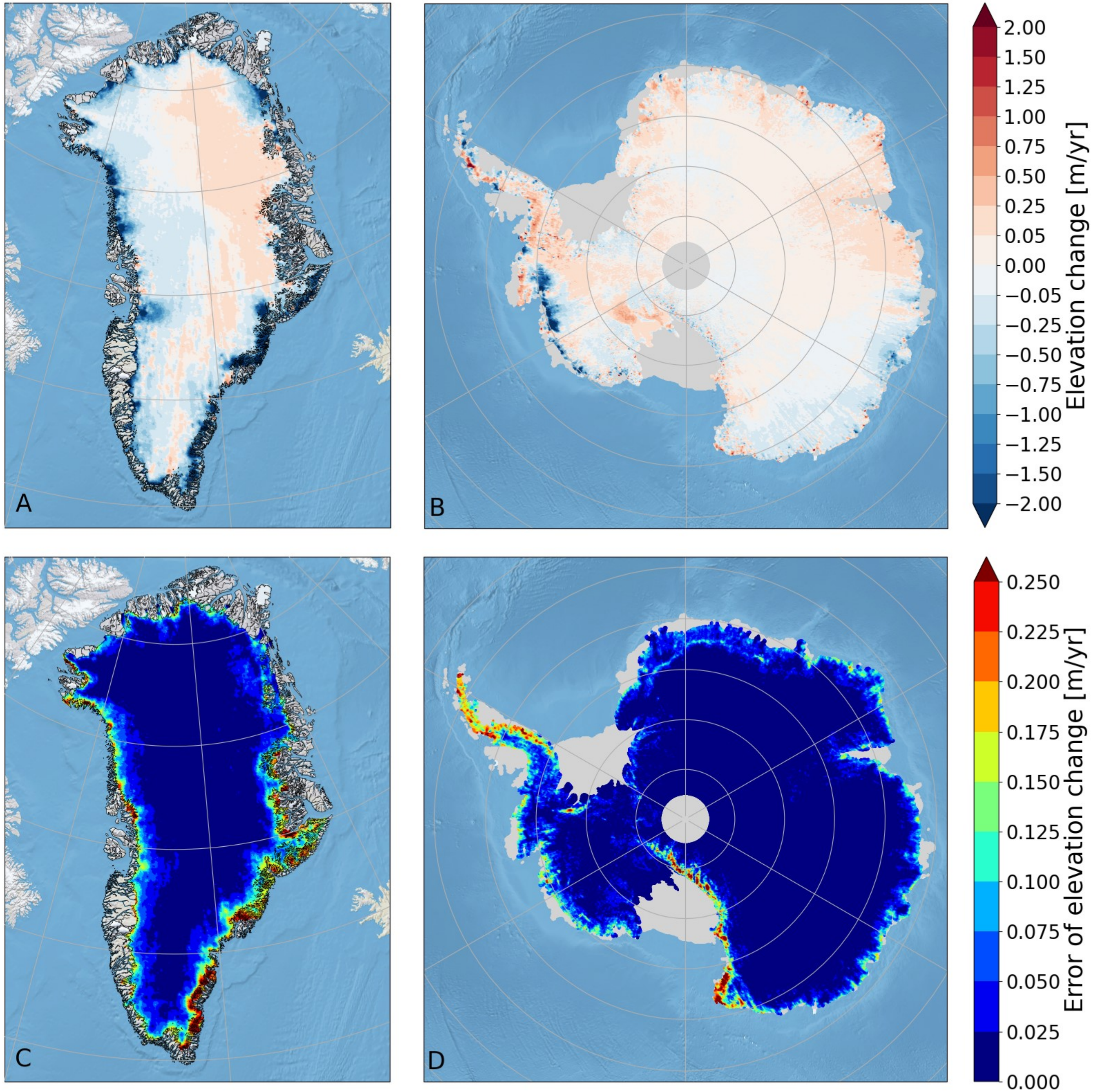
Quick outline of our ICESat-2 study

- We use ICESat-2 to derive the surface elevation change over the ice sheets
- October 2018 to September 2021
- Our methodology closely follows the Sørensen et al. (2011) repeat track method for ICESat
- We update the ICESat-2 processing chain and the model assumptions
- We make a new density parameterization for deriving mass balance in a consistent manner for both ice sheets

SEC as seen by ICESat-2

$$\frac{dH}{dt} = \frac{\dot{b}}{\rho} + w_c + w_{ice} + \frac{\dot{b}_m}{\rho} + w_{br} - u_s\frac{dS}{dx} - u_b\frac{dB}{dx}$$

$\dot{b}$	*SMB*
ρ	*density*
w_c	*firn compaction*
w_{ice}	*vertical ice velosity*
$\dot{b}_m$	*basal melt*
w_{br}	*vertical bedrock movement*
u_s	*horizontal ice velocity at the surface*
u_b	*horizontal ice velocity at the bed*



SEC as seen by ICESat-2

$$\frac{dH}{dt} = \frac{\dot{b}}{\rho} + w_c + w_{ice} + \frac{\dot{b}_m}{\rho} + w_{br} - u_s\frac{dS}{dx} - u_b\frac{dB}{dx}$$

$\dot{b}$	*SMB*
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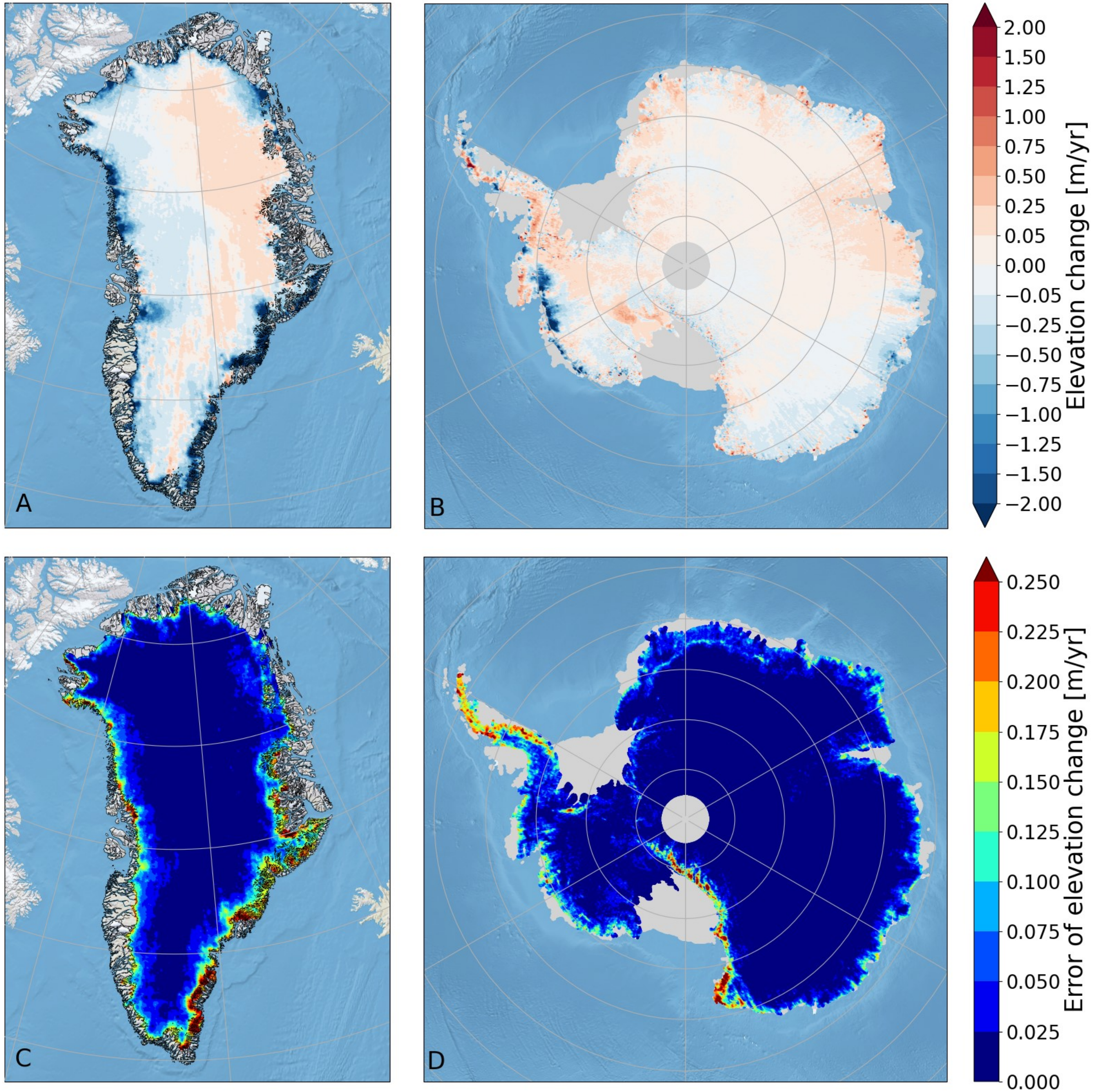
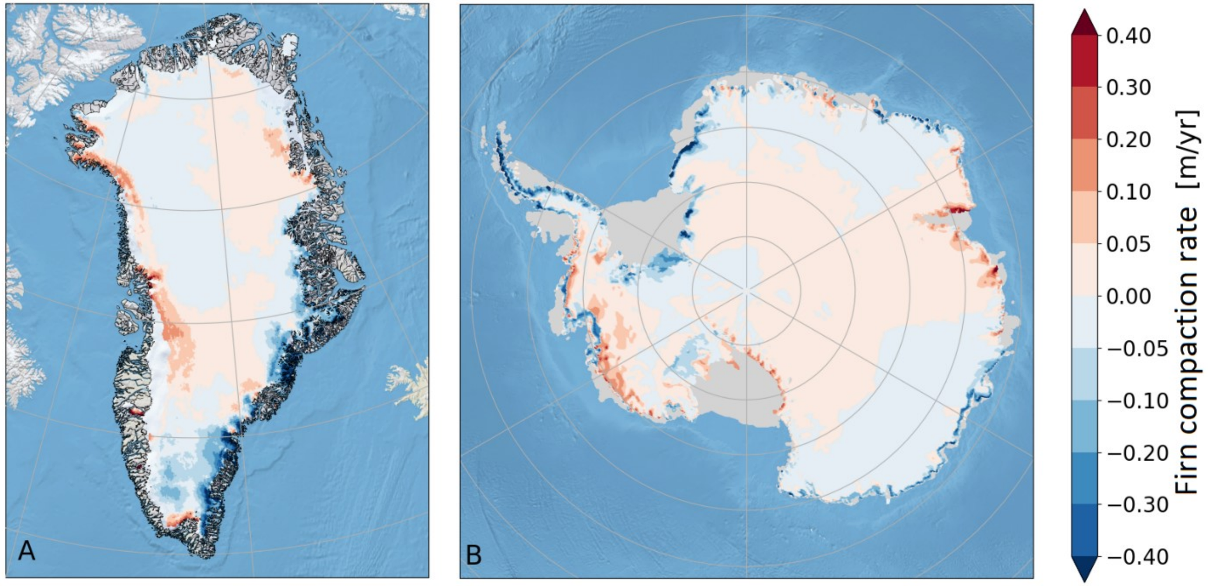
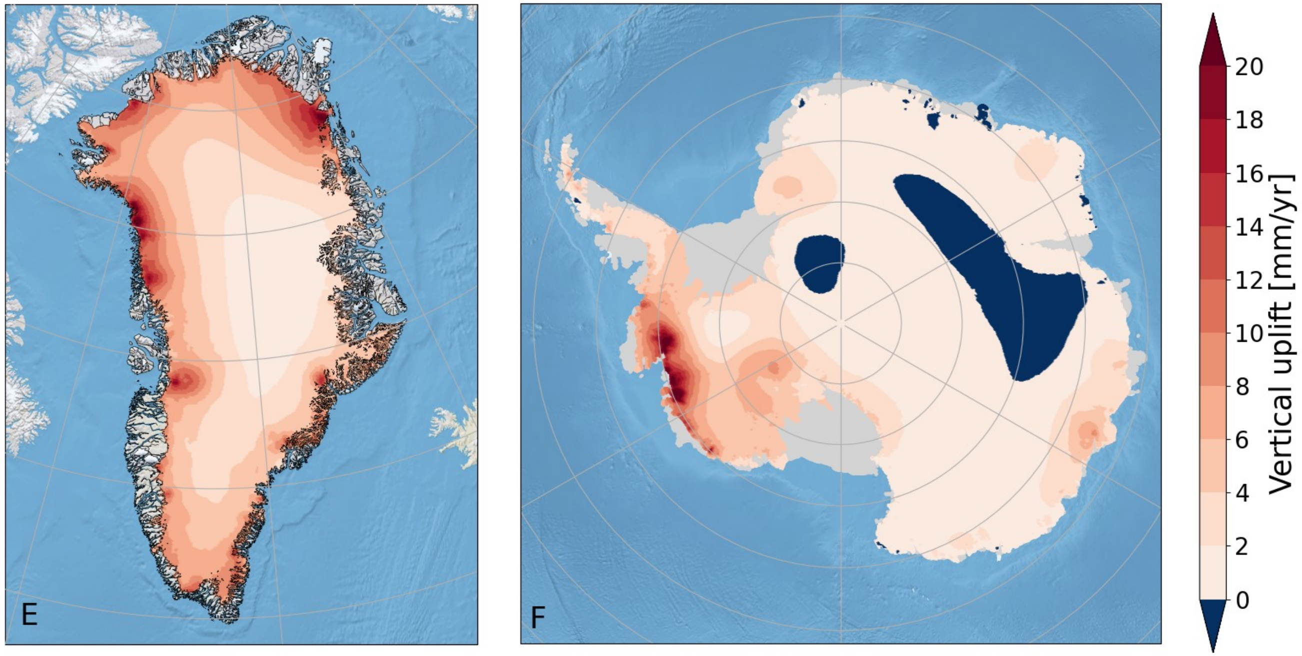


Firn compaction and bedrock movement are non-mass-related processes



GIA + ER

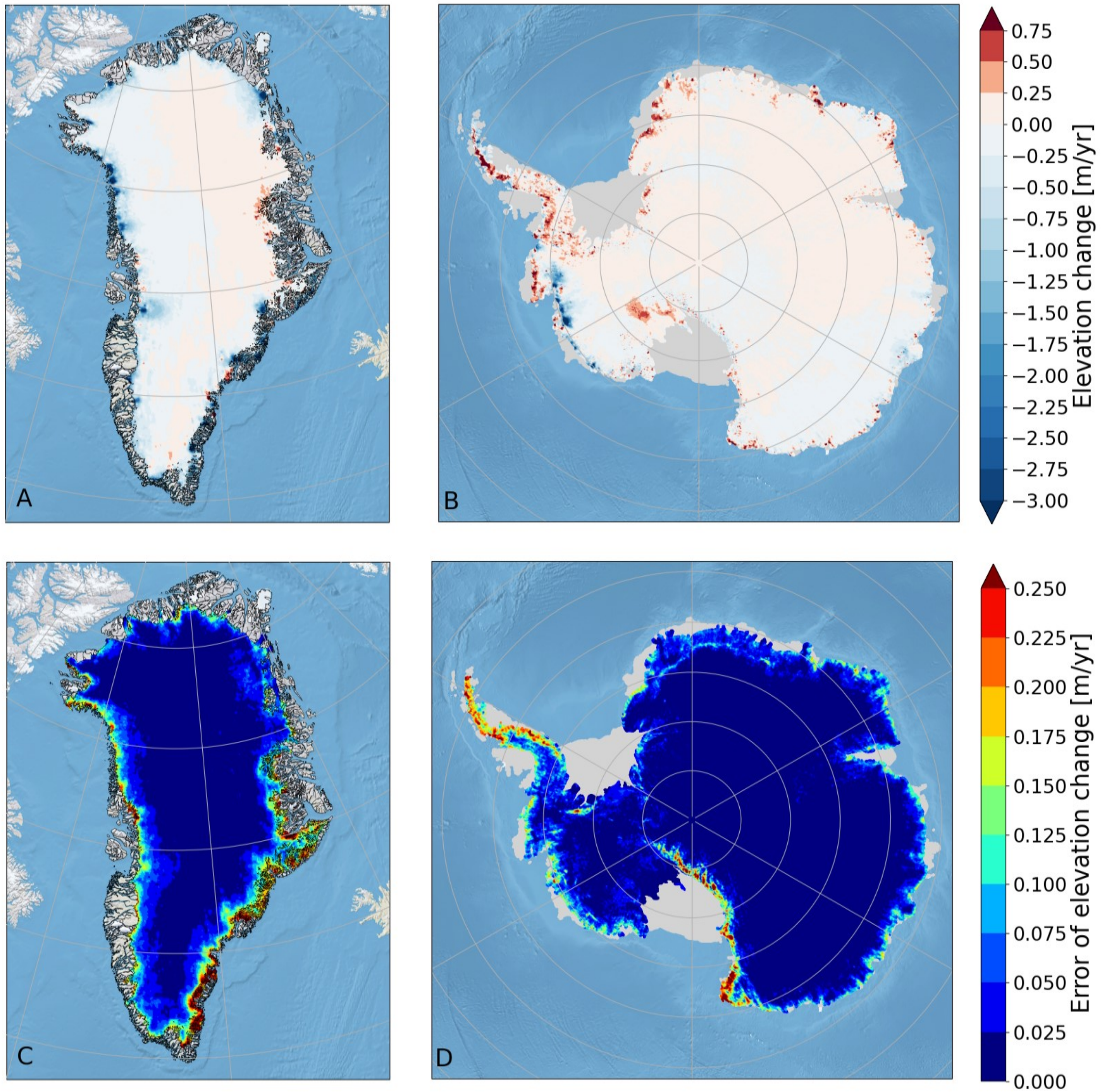


Corrected surface elevation change

Dynamical ice build-up in Kamb ice stream (Shepherd et al., 2019)

Volume to mass conversion

$$\frac{dM}{dt} = \frac{dH_{corrected}}{dt}\tilde{\rho}$$



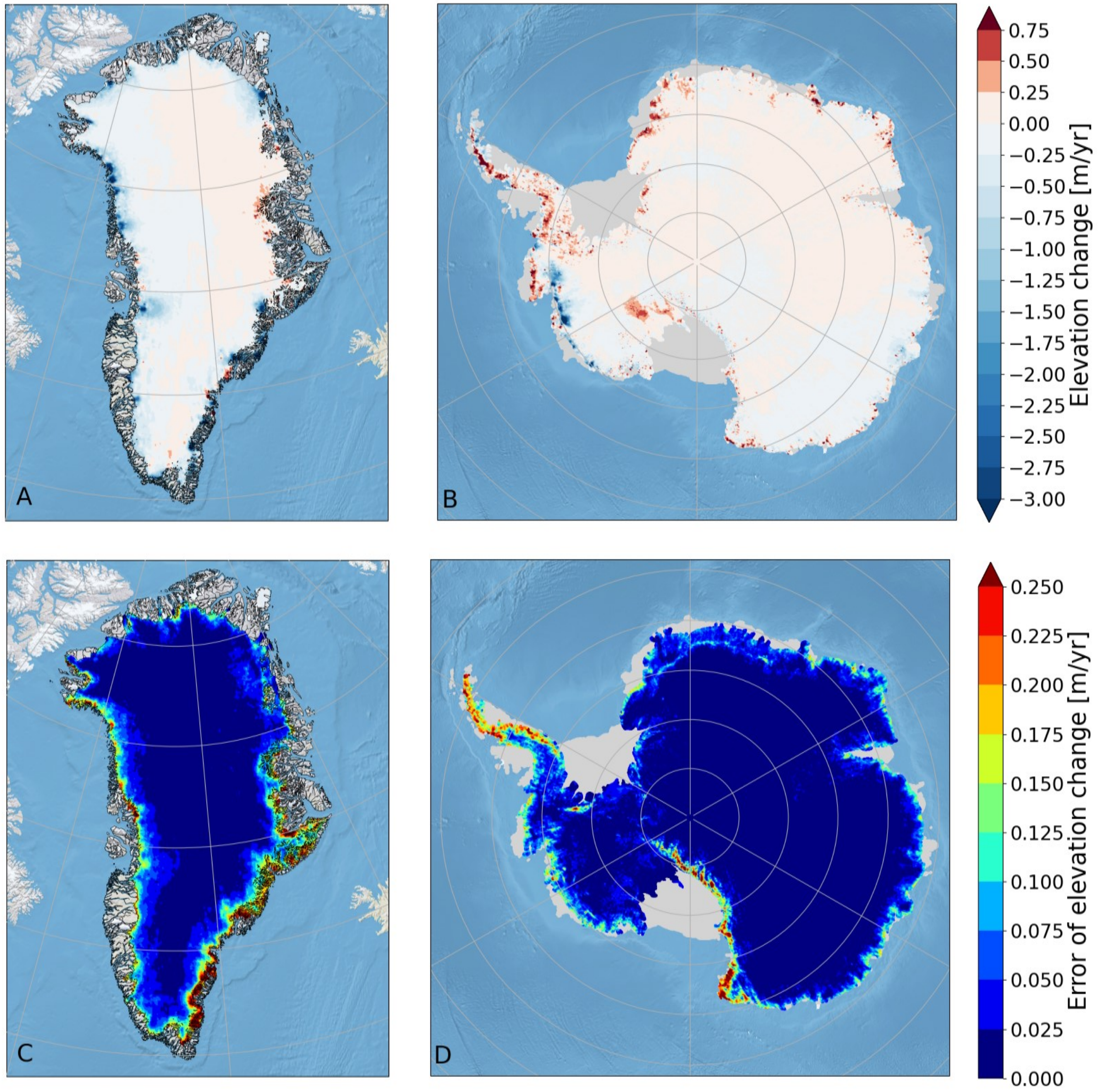
Corrected surface elevation change

Dynamical ice build-up in Kamb ice stream (Shepherd et al., 2019)

Volume to mass conversion

$$\frac{dM}{dt} = \frac{dH_{corrected}}{dt}\tilde{\rho}$$

What is $\tilde{\rho}$?

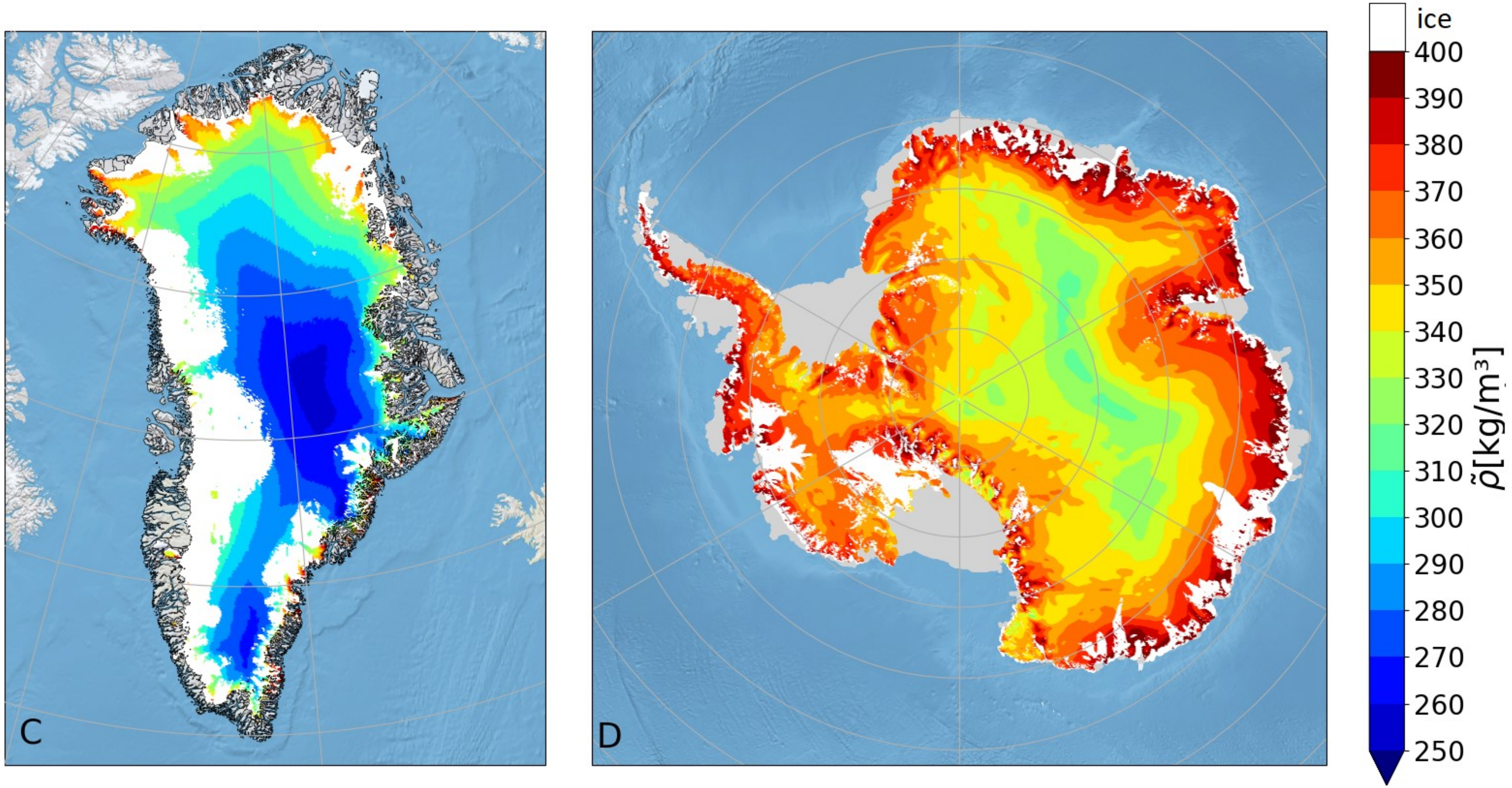


Volume to mass conversion

$$\tilde{\rho} = \begin{cases} \rho_i, if\ Vsurf > 30\ \dfrac{m}{yr}\ \ and\ \dfrac{dH_{corrected}}{dt} \leq 0 \\ \rho_i, if\ H \leq ELA \\ \rho_i\ , if\ dynamical\ ice\ build\ up\ is\ known \\ \rho_s, elsewhere \end{cases}$$

Volume to mass conversion

$$\tilde{\rho} = \begin{cases} \rho_i, if\ Vsurf > 30\ \dfrac{m}{yr}\ \ and\ \dfrac{dH_{corrected}}{dt} \leq 0 \\ \rho_i\ \ if\ H \leq ELA \\ \rho_i'\ if\ dynamical\ ice\ build\ up\ is\ known \\ \rho_s, elsewhere \end{cases}$$



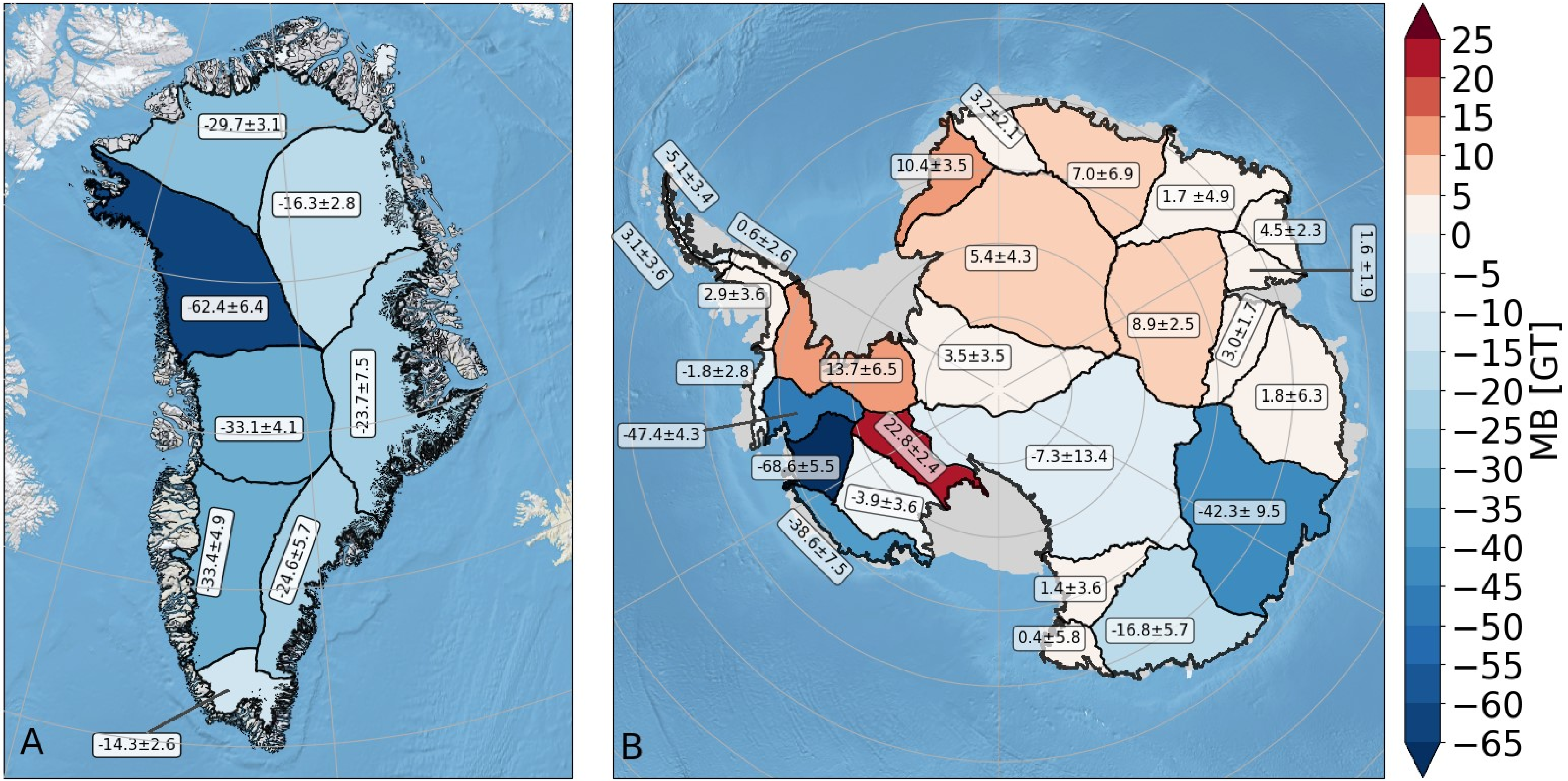
Results

		Greenland			Antarctica			
	Unit	Total	>2000 m	<2000 m	Total	AP	WAIS	EAIS
ICESat-2	Km^3/yr	-279.3±21.0	-19.3±7.4	-260.1±13.6	-42.9±54.0	11.0±12.9	-103.4±22.9	49.5±47.2
Firn Corr.	Km^3/yr	-21.5± 4.5	-14.8±2.4	-6.7±2.2	-46.7±9.4	-17.1±2.2	-1.5±6.0	-28.0±6.9
Vert. Corr.	Km^3/yr	8.10±0.01	3.29±0.00	4.81±0.01	21.80±0.03	0.80±0.01	11.22±0.02	9.78±0.02
MB	Gt/yr	**-237.5±14.0**	-18.7±3.6	-218.8±10.7	**-135.7±27.3**	1.5±6.7	-123.7±13.1	-13.5±23.0

The combined mass loss from AIS and GrIS is **-373.2 ±41.3** Gt per year, or 1.03 ± 0.11 mm global sea level rise per year

Results mass balance on basin scale

-237.5 ±14.0 **-135.7 ±27.3**



Compare to GRACE-FO

Barbara Jenny et al. 2023 (EGU23)

Jenny et al. compare different GRACE-FO solutions in the time period.

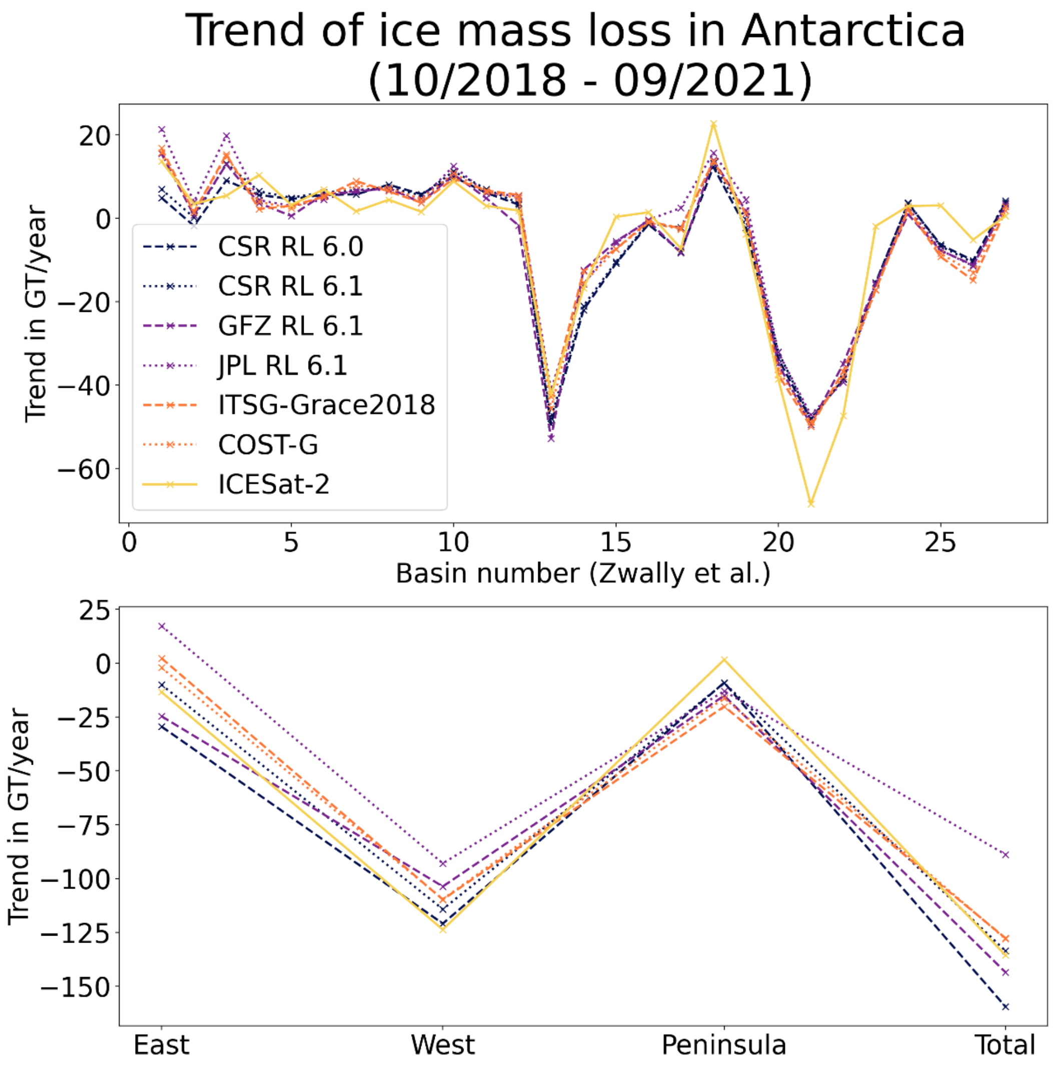
Notice: JPL is an outliner.

All numbers are in Gt per year.

Uncertainty analysis is not done yet for the GRACE-FO results

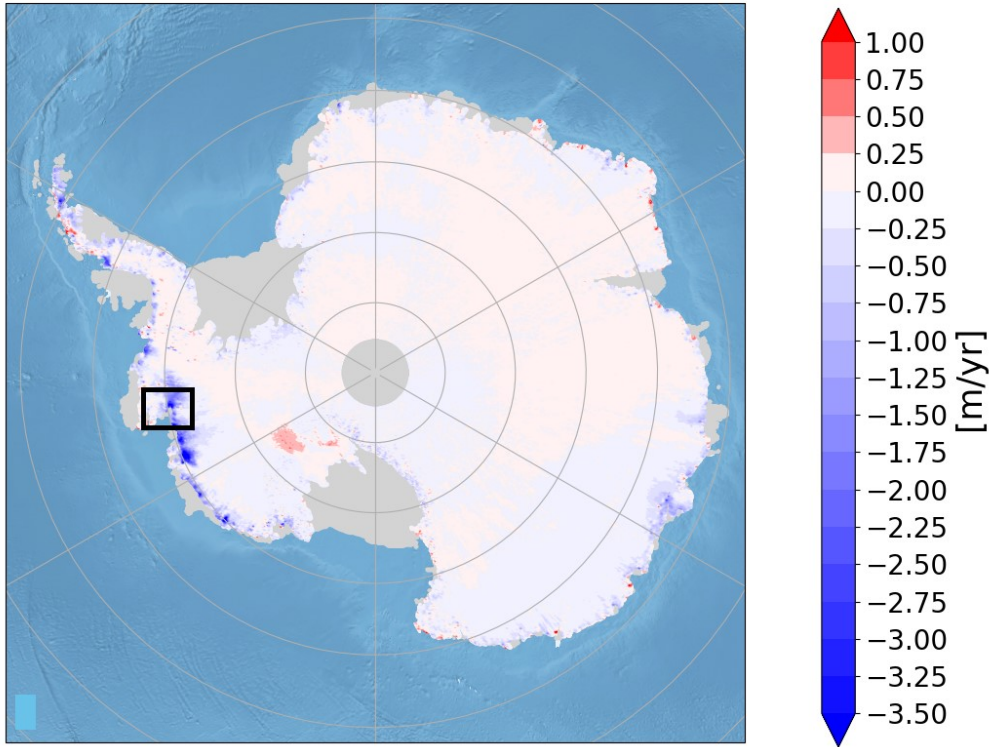
GRACE-FO might underestimate the MB in basins 21 and 22 due to leakage

	East	West	AP	Total
CSR0600	-29.5	-120.9	-9.1	-159.6
CSR0601	-10.1	-114.3	-9.3	-133.7
ITSG	2.2	-109.8	-20.2	-127.7
GFZ	-24.7	-103.7	-15.2	-143.6
JPL	17.2	-93.0	-13.1	-88.9
COSTG	-2.2	-109.6	-16.3	-128.1
ICESat-2	-13.5±23.0	-123.7±13.1	1.5±6.7	-135.7±27.3



Overall the GRACE-FO agrees with our ICESat-2 analysis

Potential impact of ice mask



Take away

- The grounded AIS has lost **135.7 ±27.3** Gt per year GrIS has lost **237.5 ±14.0** Gt per year
- We emphasize the importance of accurately representing **the density** of snow and firn
- New **density parameterization** for volume-to-mass conversion

- Read our pre-print in The Cryosphere soon (submitted Monday the 24th of April)

"Revisiting ice sheet Mass balance: insights into changing dynamics in Greenland and Antarctica from ICESat-2"