# Complex pattern of ice loss in polar regions and High Mountain Asia from satellite altimetry: Implications on sea level and local hydrology


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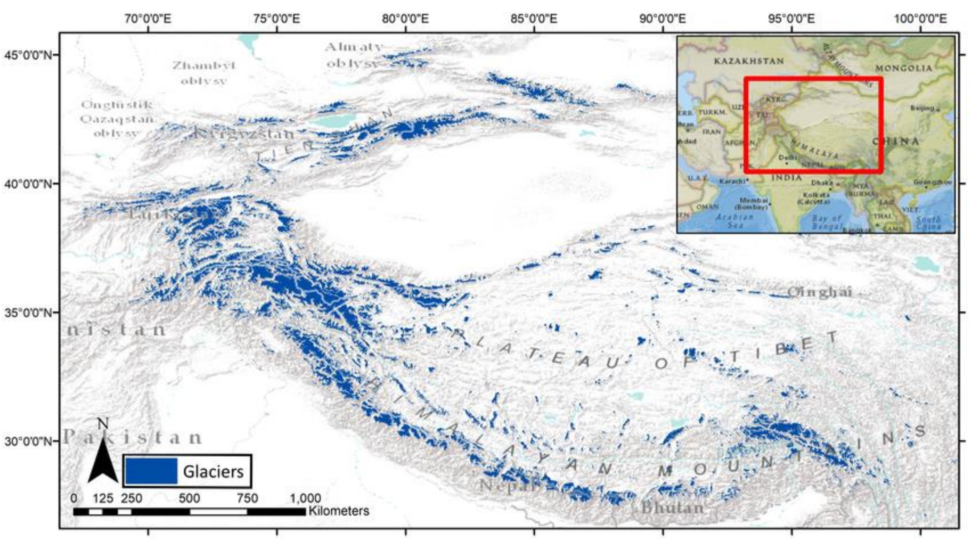
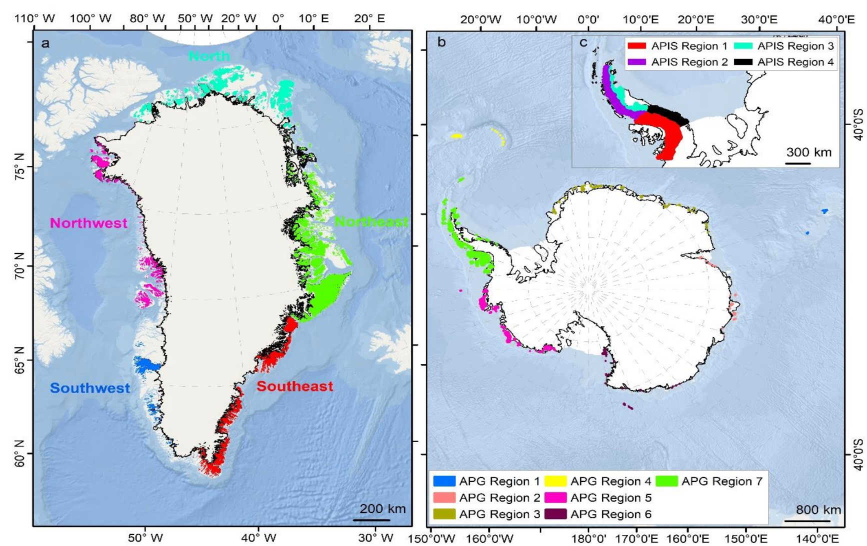
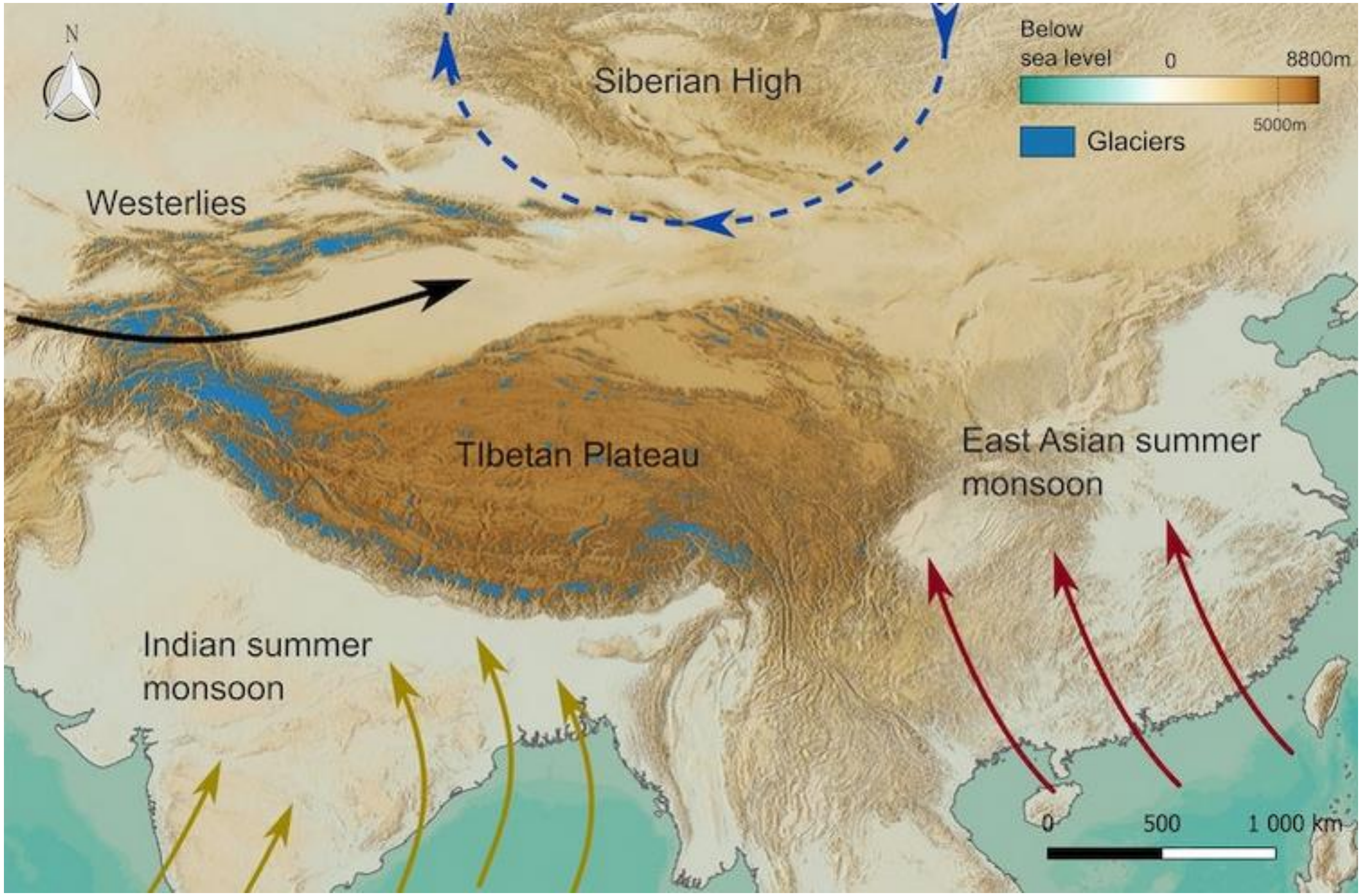


Motivation

Ice loss affect more than 250 million people (depend on water from rivers and lakes)
Risk of flood (combined with rain from monsoon)



Huge flood in 2022 in Pakistan.
Around 10% of Pakistan affected by the flood.
Combination of long and intense melt season combined with extraordinary intense monsoon

ICESat (2003-2009)

ICESat-2 (2018-2023)

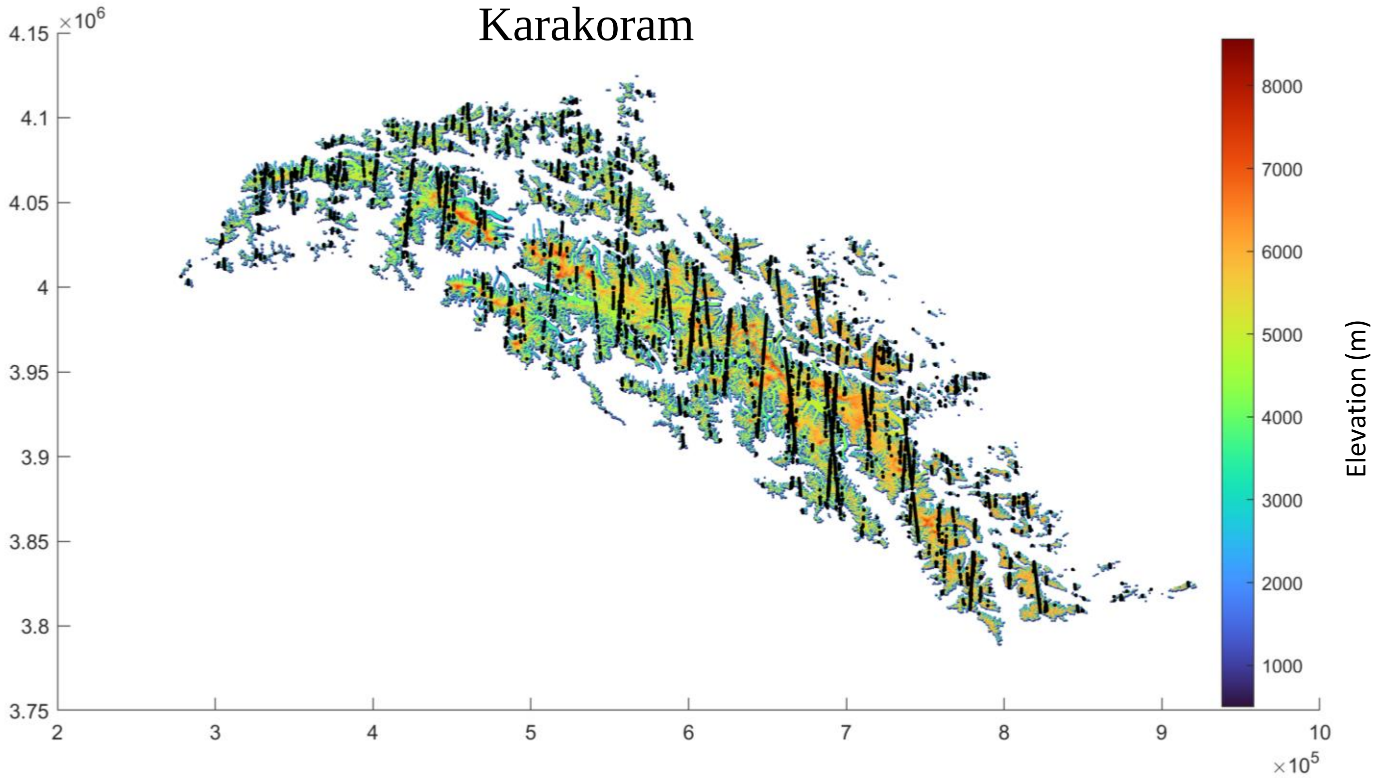
**Ice volume change:**

High Mountain Asia
Greenland peripheral glaciers
Antarctica peripheral glaciers

Method:

Create time series of elevation.

$$H(t_i) = H(t_i)_{trend} + H_{topo} + H(t_i)_{Annual}$$



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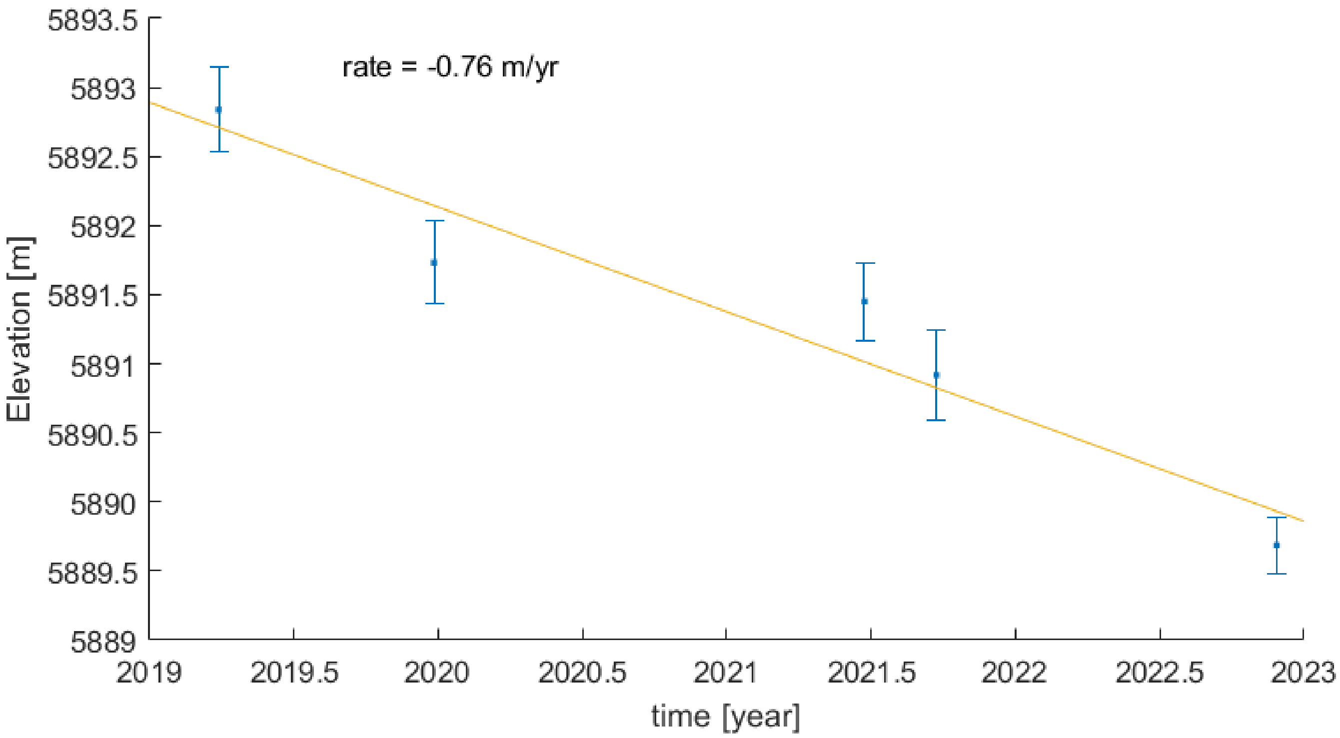
Karakoram



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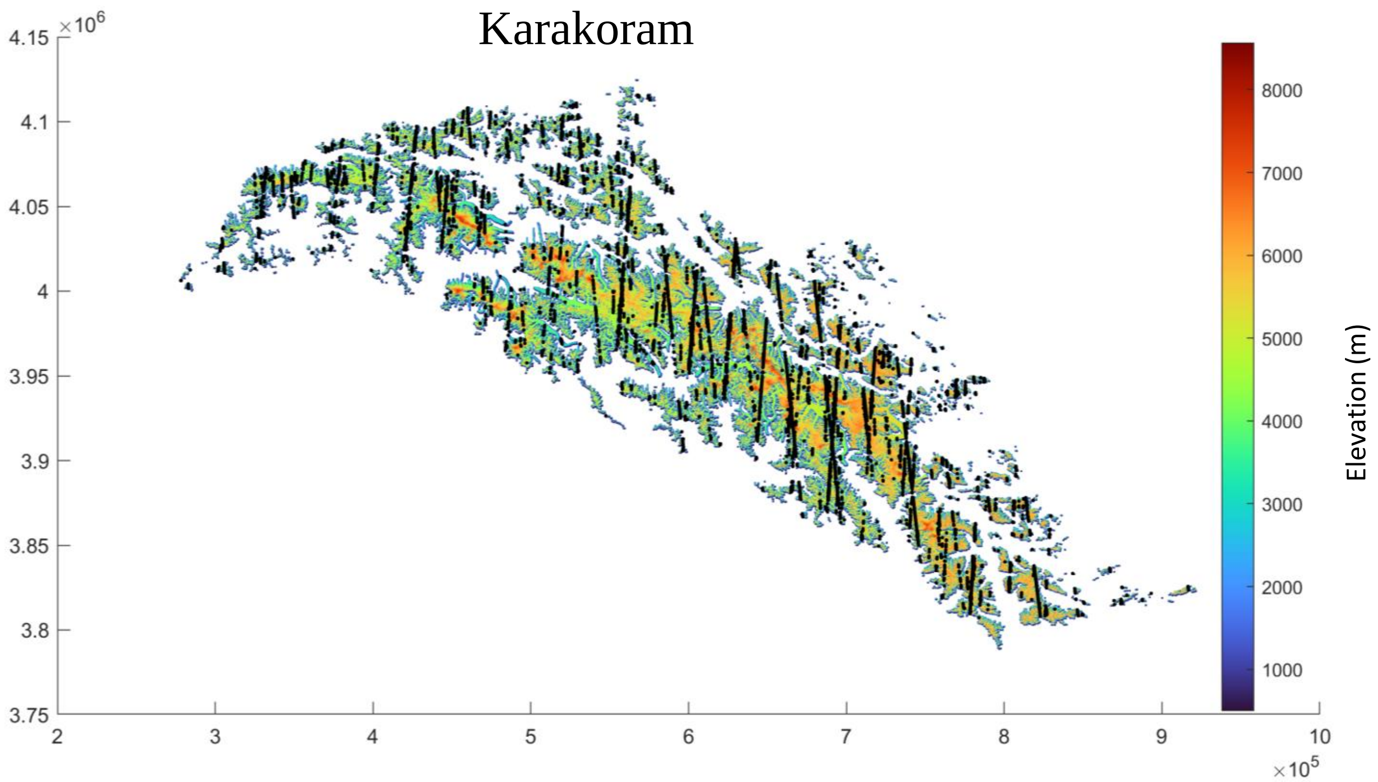

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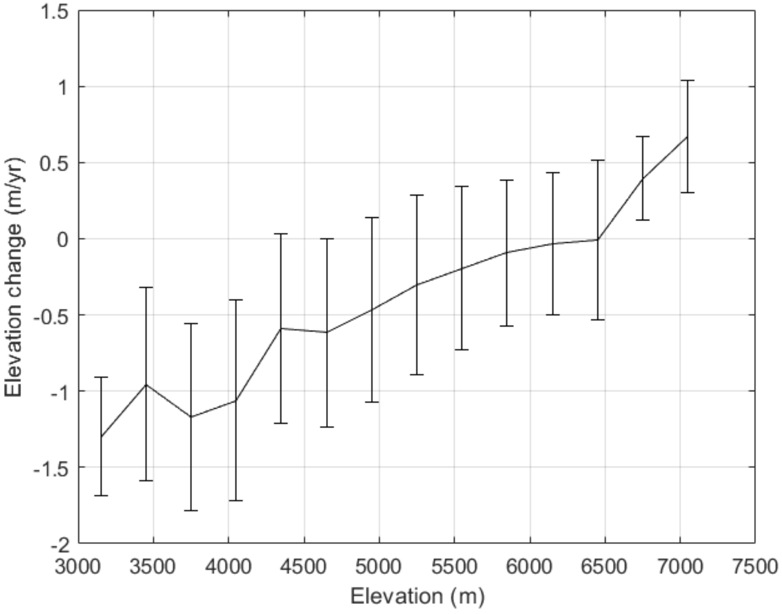


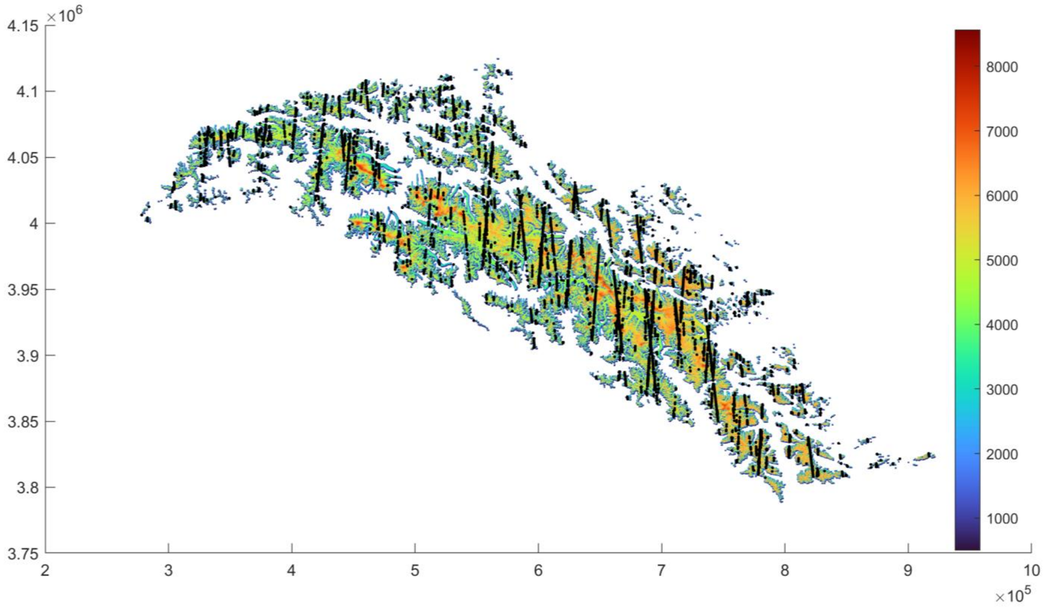

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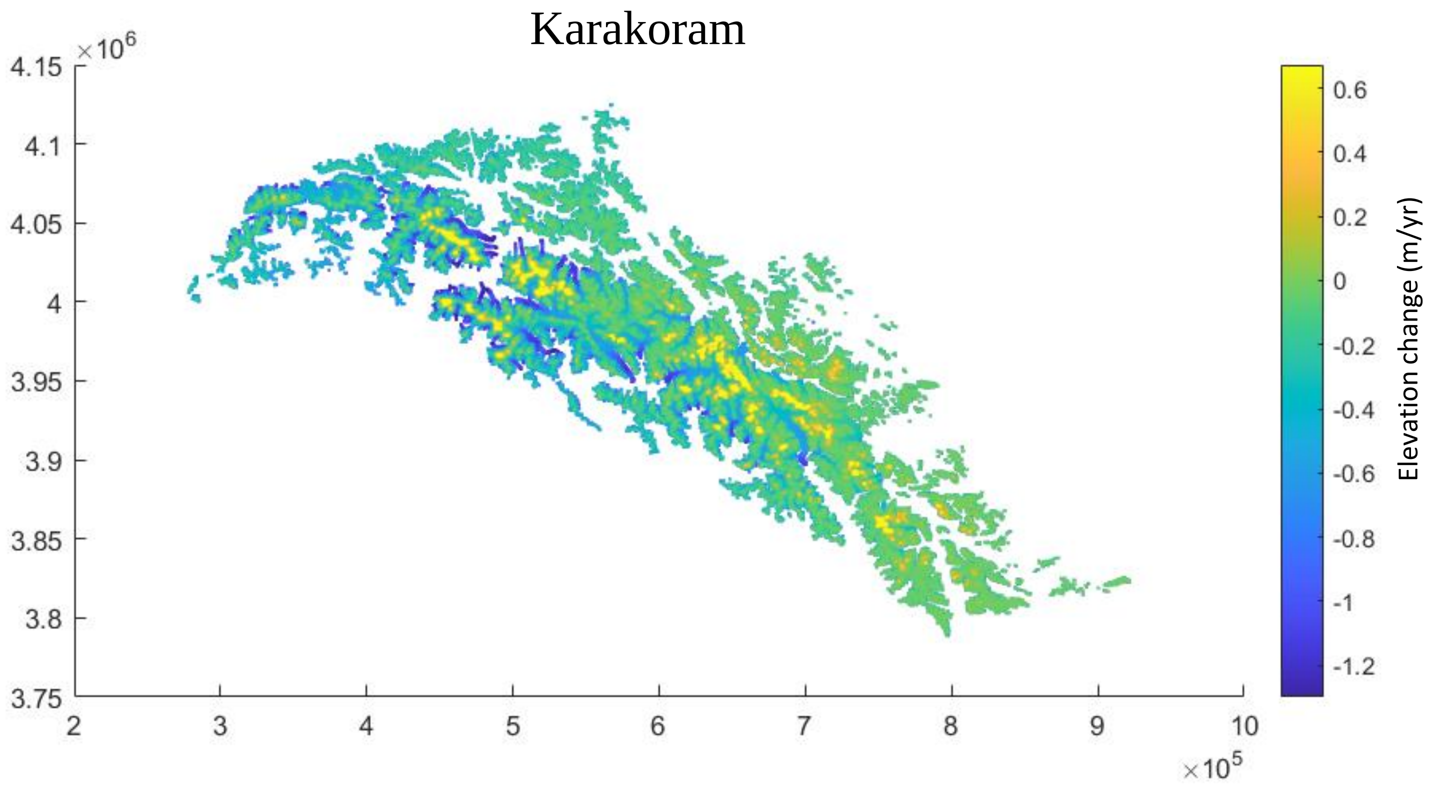
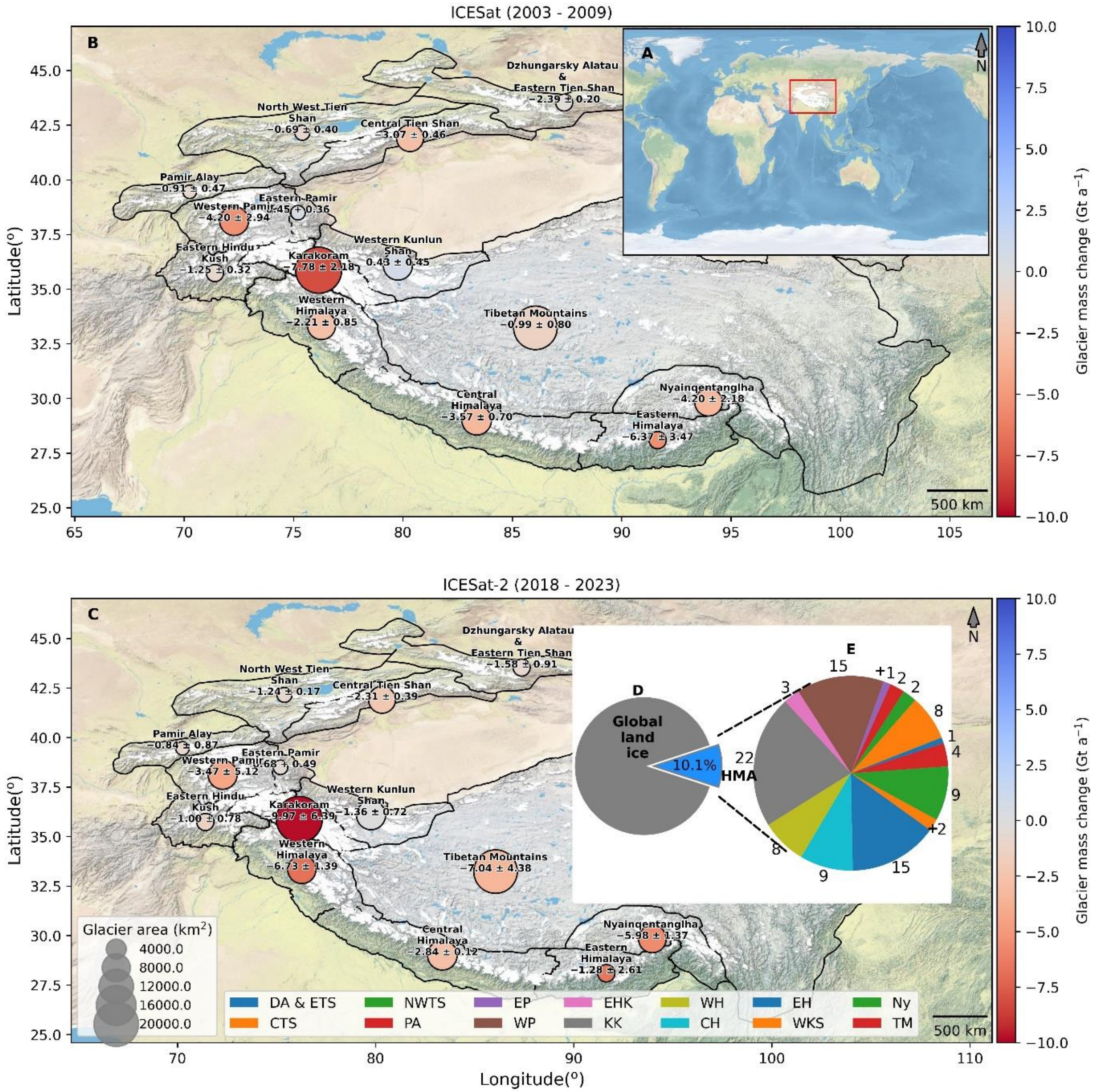
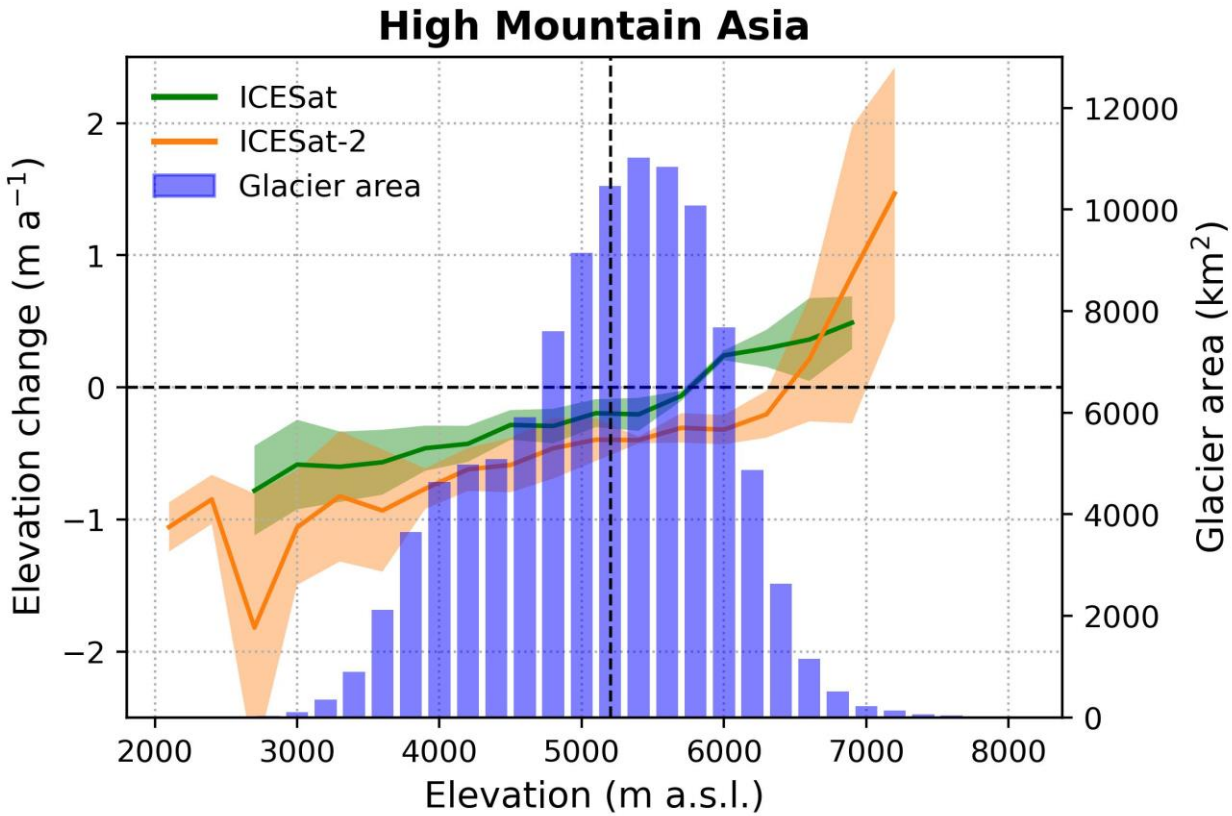


# Results: High Mountain Asia



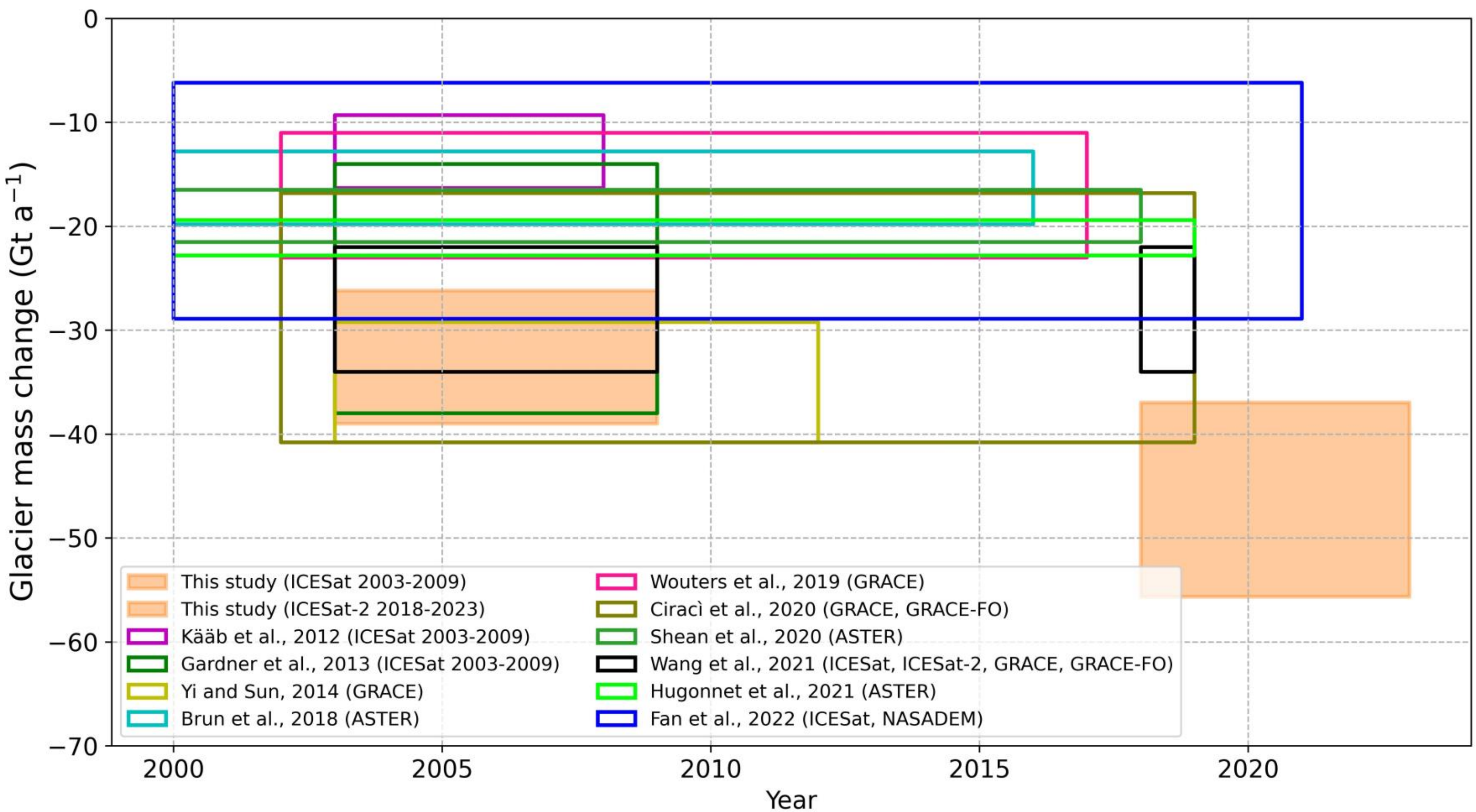
Results: High Mountain Asia



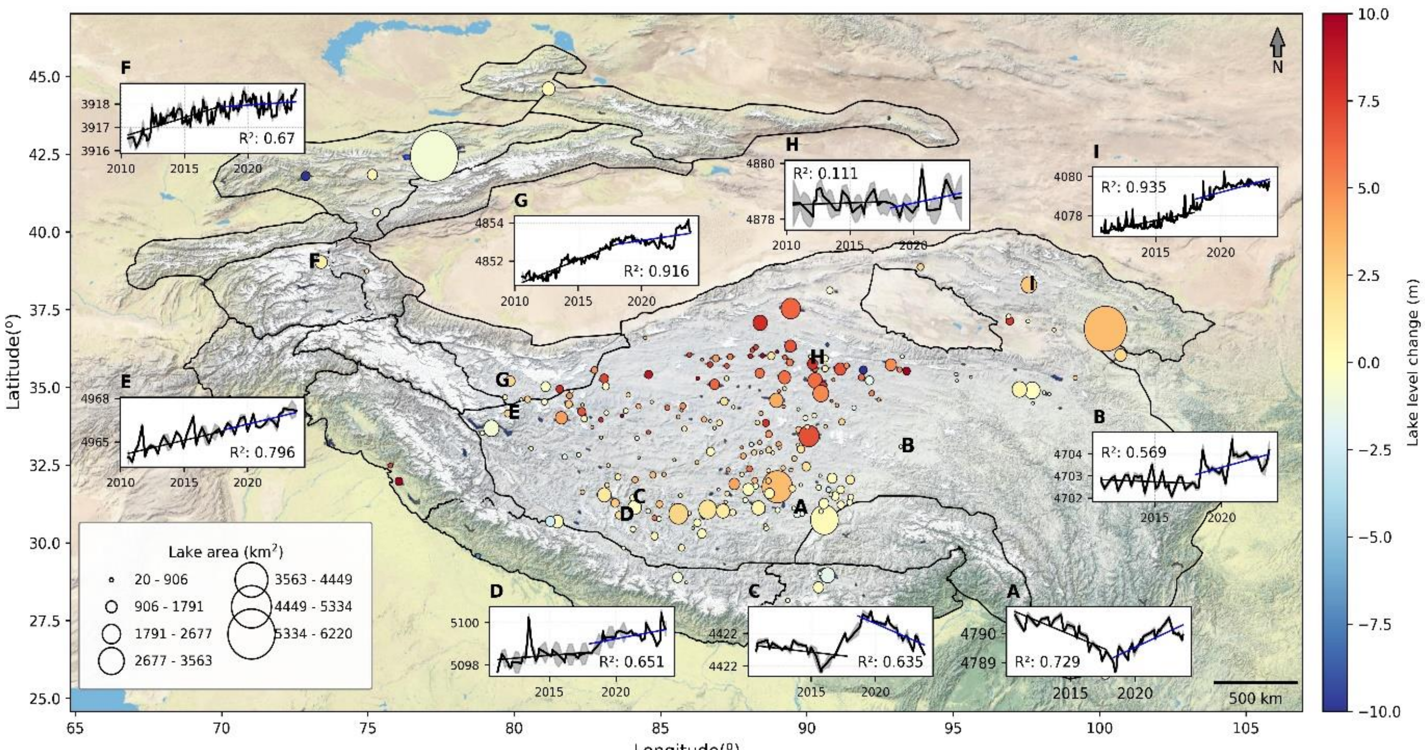

ICESat: 32.6 ± 6.4 Gt a$^{-1}$ (2003-2009)
ICESat-2: 46.3 ± 9.3 Gt a$^{-1}$ (2018-2023)

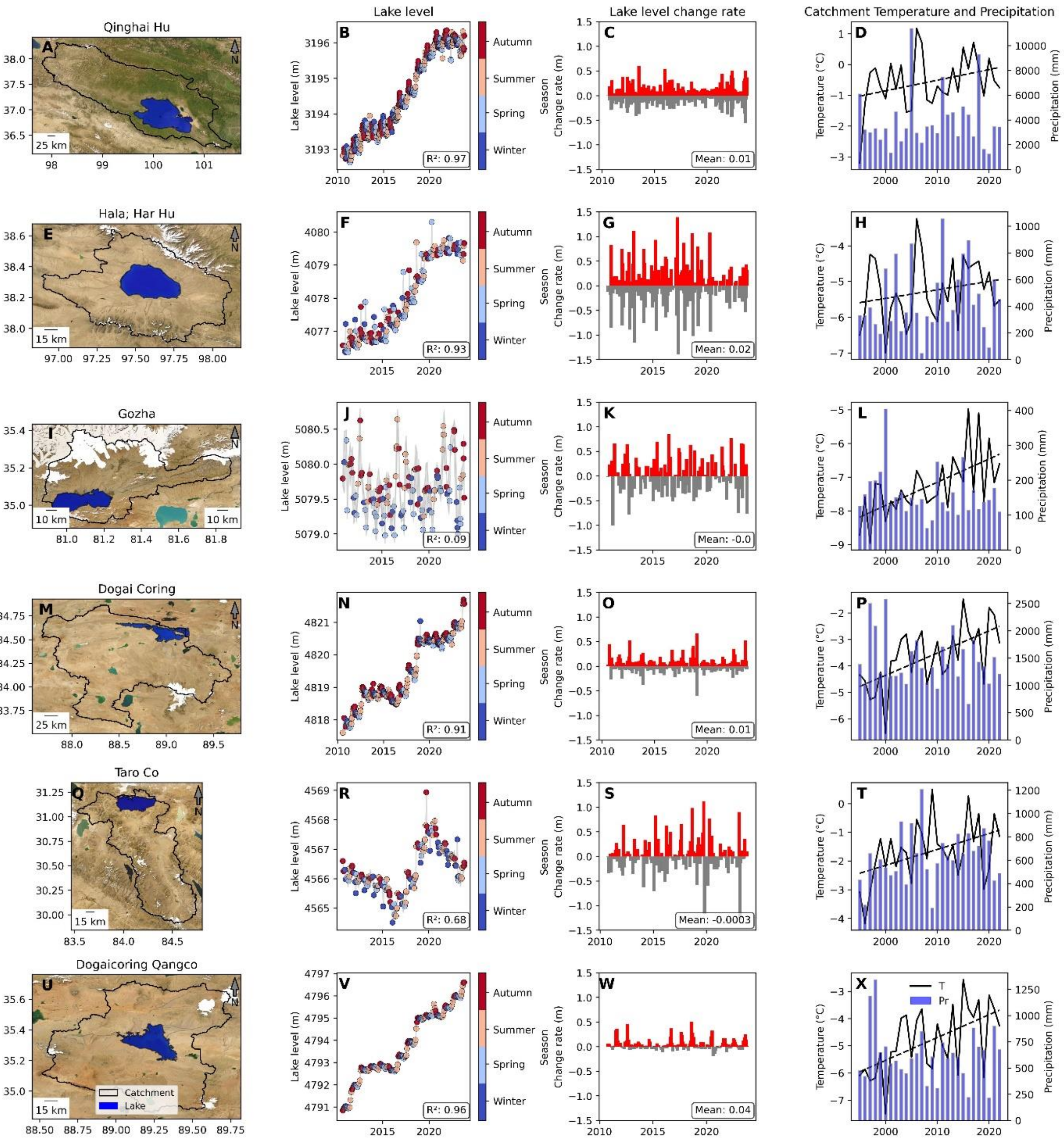
Use density of 850 kg/m$^3$
To convert ice volume to mass

# Results: High Mountain Asia

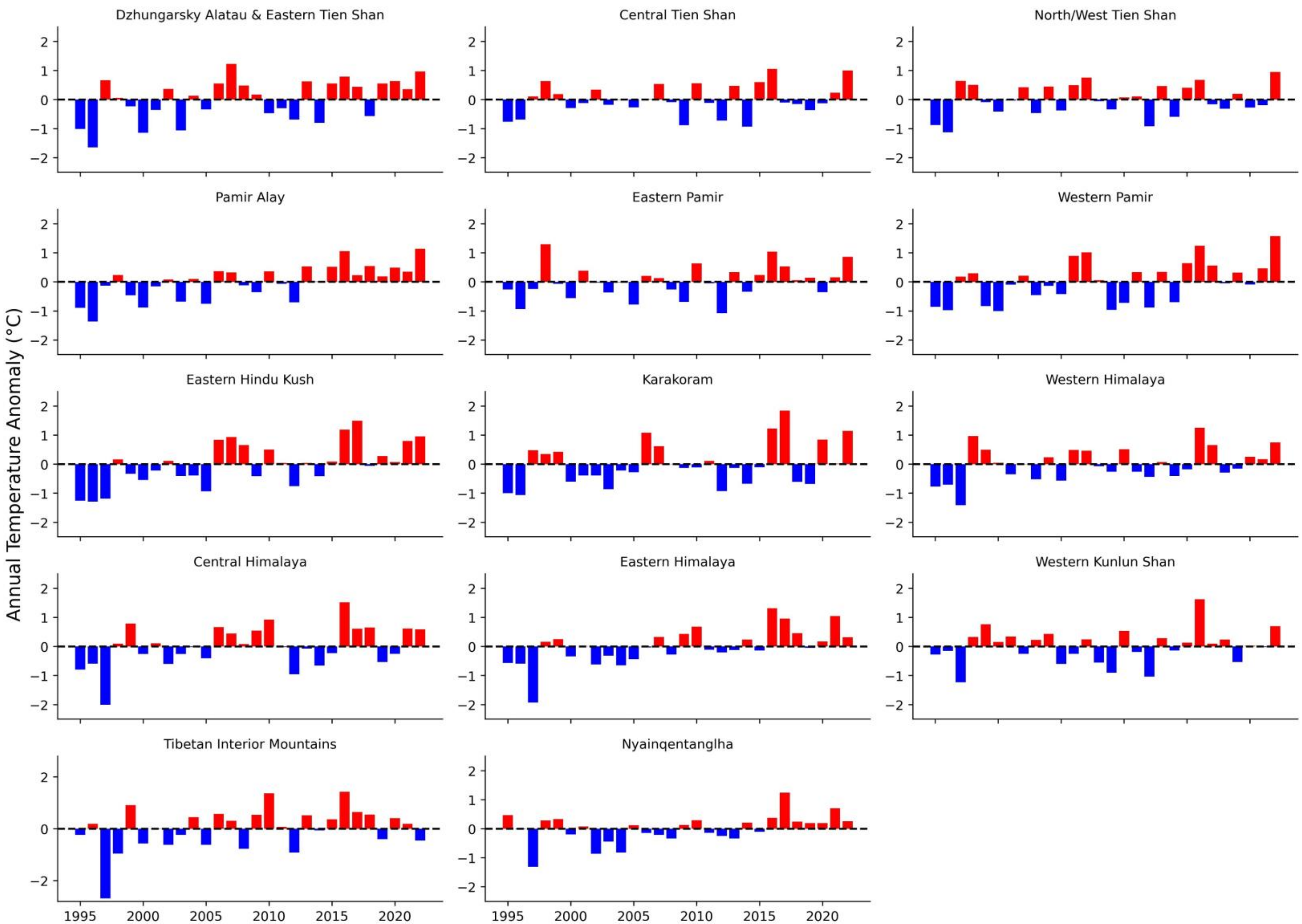


rising lake level due to
enhanced glacier melt +
enhanced rain (monsoon)




Lake level
Lake level change rate
Catchment Temperature and Precipitation
Qinghai Hu
Hala; Har Hu
Gozha
Dogai Coring
Taro Co
Dogaicoring Qangco
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
25 km
15 km
10 km
Lake level (m)
Season
Autumn
Summer
Spring
Winter
Change rate (m)
Temperature (°C)
Precipitation (mm)
R²: 0.97
R²: 0.93
R²: 0.09
R²: 0.91
R²: 0.68
R²: 0.96
Mean: 0.01
Mean: 0.02
Mean: -0.0
Mean: 0.01
Mean: -0.0003
Mean: 0.04
Catchment
Lake
T
Pr
N

# Increased annual mean temp



**High Mountain Asia**

Increased ice loss from 32.6 ± 6.4 Gt $a^{-1}$ (2003-2009) to 46.3 ± 9.3 Gt $a^{-1}$ (2018-2023)

Increased lake level

Increased annual mean temp

# Greenland and Antarctic peripheral glacier

- Peripheral glacier regions (RGI 6.0)
- Sub-division of Antarctica peripheral regions (Zwally et al., 2012)

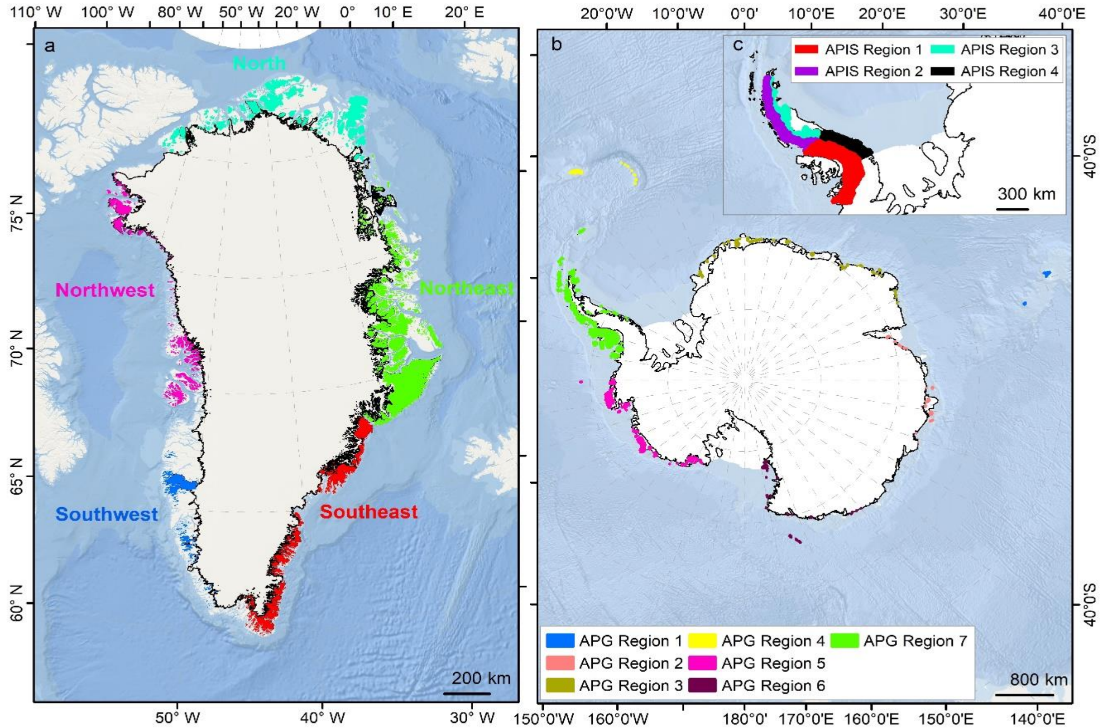
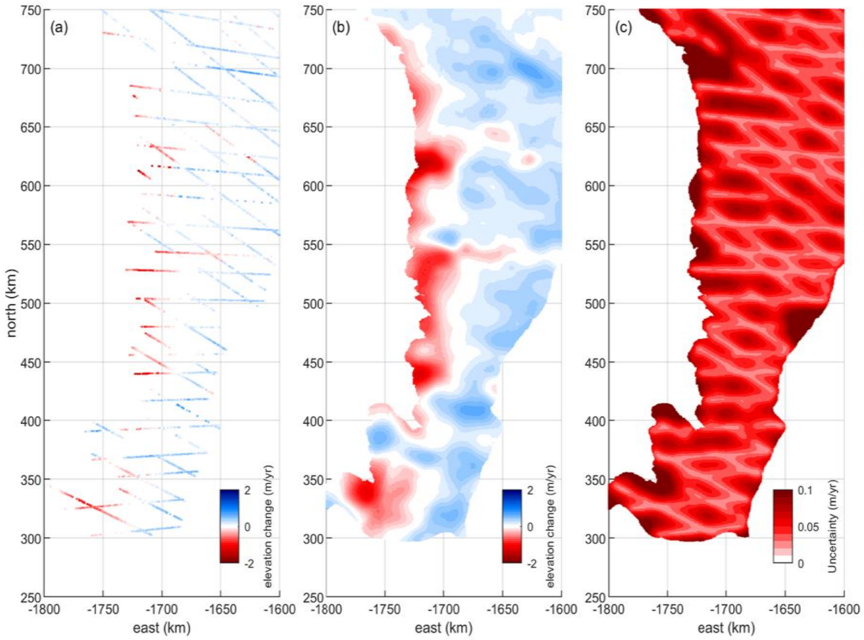



**Figure.** (a) Greenland peripheral glacier regions highlighted in colors. (b) Antarctic peripheral glacier regions (APG) highlighted in colors and (c) Antarctic Peninsula ice sheet (APIS) peripheral glacier regions highlighted in colors.

# ICESat and ICSat-2 observations

**Observed elevation changes - ICESat**



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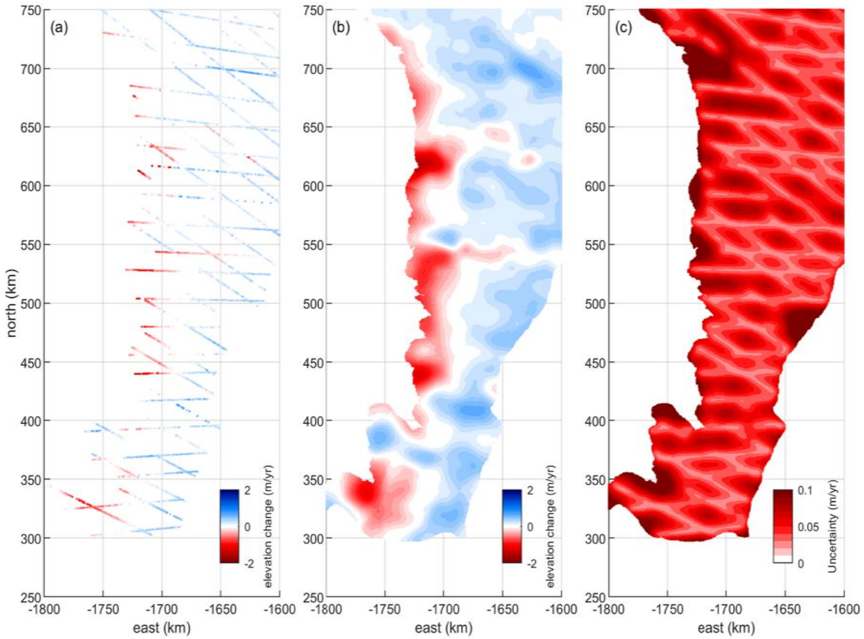
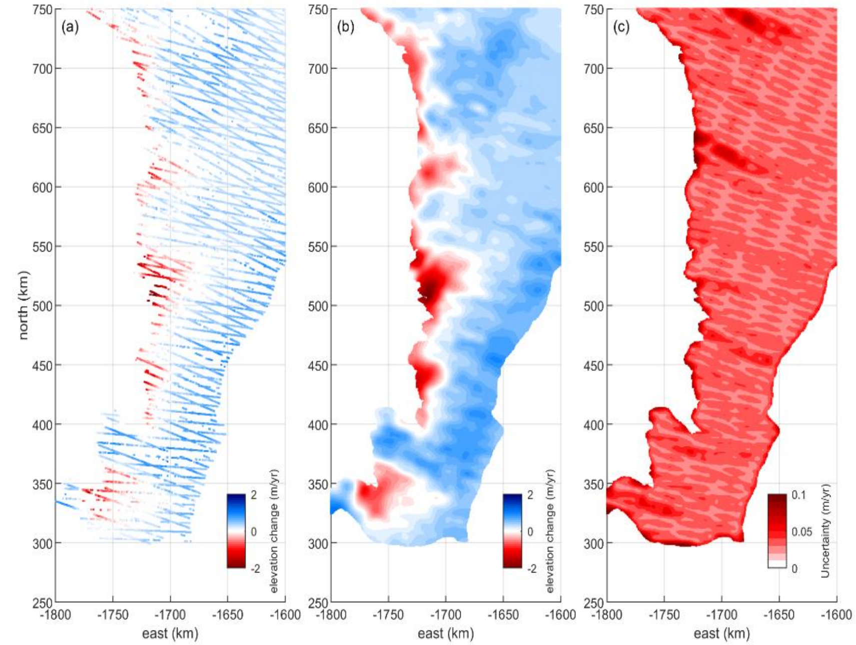


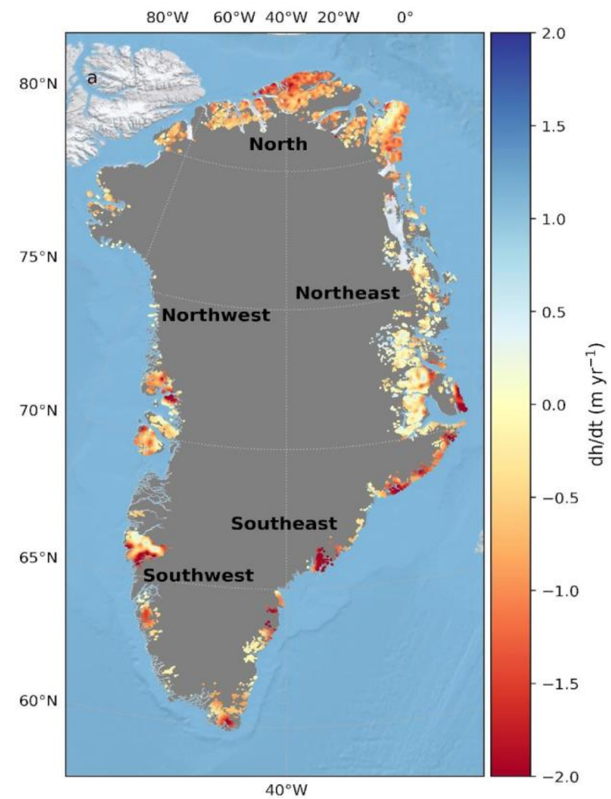

**Observed elevation changes – ICESat-2**



# Greenland peripheral glacier elevation change and ice loss

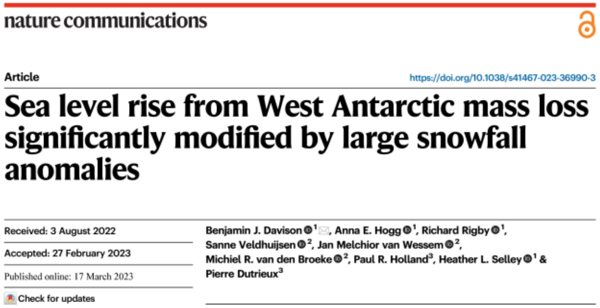
- All peripheral glacier regions in Greenland lost during 2003 to 2023
- Widespread glacier thinning is now most evident in the North, Northwest, and Southeast regions
- Northern peripheral glaciers alone contributed about 50% of the total ice loss from Greenland peripheral glaciers during 2018-2023
- There is now mass loss across all of Greenland's peripheral regions and at all elevations, except in the Southwest above 1250 m and the Northeast above 1500 m

| Region | Area ($km^2$) | 2003-2009 | 2009-2018 | 2018-2023 |
|---|---|---|---|---|
| **North** | 35003 | -6.5 ± 1.6 | -11.7 ± 1.4 | -17.9 ± 1.4 |
| **Northeast** | 21943 | -11.8 ± 2.2 | -9.4 ± 2.7 | -8.4 ± 2.3 |
| **Northwest** | 5807 | -3.4 ± 0.9 | -4.0 ± 0.9 | -2.8 ± 0.8 |
| **Southeast** | 2610 | -2.7 ± 1.3 | -0.9 ± 0.9 | -2.8 ± 1.3 |
| **Southwest** | 7011 | -2.9 ± 1.9 | -4.9 ± 1.9 | -3.8 ± 1.9 |
| **All** | **72374** | **-27.3 ± 7.9** | **-30.9 ± 7.8** | **-35.8 ± 5.3** |



# Antarctic peripheral glacier elevation change and ice loss

| Region | Area (km²) | 2003-2009 | 2009-2018 | 2018-2023 |
|---|---|---|---|---|
| APG 1 | 1155 | Na | Na | -0.4 ± 0.3 |
| APG 2 | 3414 | Na | Na | 0.6 ± 0.1 |
| APG 3 | 8345 | 0.6 ± 0.4 | 0.7 ± 0.4 | 1.1 ± 0.1 |
| | 50 | Na | Na | Na |
| APG 4 | 2836 | -1.3 ± 0.6 | Na | -2.7 ± 0.3 |
| APG 5 | 31169 | 4.2 ± 1.5 | -5.6 ± 9.2 | -0.8 ± 0.9 |
| APG 6 | 3580 | -0.002 ± 0.2 | -0.3 ± 0.2 | -0.1 ± 0.07 |
| APG 7 | 81642 | -6.2 ± 2.5 | -6.7 ± 3.8 | 0.8 ± 1.9 |
| **All** | 132191 | -2.8 ± 1.3 | -12.0 ± 5.9 | -1.5 ± 0.7 |
| **Region** | **Area (km²)** | **2003-2009** | **2009-2018** | **2018-2023** |
| APIS 1 | 61095 | 12.8 ± 3.9 | -4.9 ± 5.1 | 22.3 ± 2.7 |
| APIS 2 | 12116 | -6.9 ± 3.2 | 15.3 ± 3.7 | 16.5 ± 1.4 |
| APIS 3 | 3029 | -8.4 ± 2.9 | -5.9 ± 3.6 | -6.9 ± 1.5 |
| APIS 4 | 1913 | 1.7 ± 2.1 | -1.2 ± 2.6 | 1.5 ± 1.2 |
| **All** | 210344 | -1.4 ± 3.1 | 3.3 ± 3.8 | 33.5 ± 1.7 |

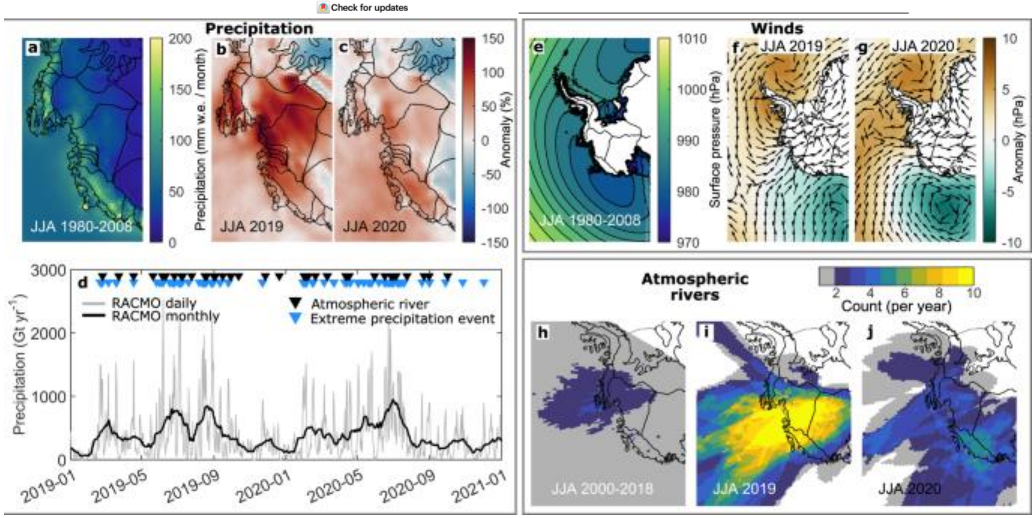

nature communications

Article https://doi.org/10.1038/s41467-023-36990-3

**Sea level rise from West Antarctic mass loss significantly modified by large snowfall anomalies**

Received: 3 August 2022
Accepted: 27 February 2023
Published online: 17 March 2023
Check for updates

Benjamin J. Davison, Anna E. Hogg, Richard Rigby, Sanne Veldhuijsen, Jan Melchior van Wessem, Michiel R. van den Broeke, Paul R. Holland, Heather L. Selley & Pierre Dutrieux



# Antarctic peripheral glacier elevation change and ice loss

## Ice volume change

| Region | Area ($km^2$) | 2003-2009 | 2009-2018 | 2018-2023 |
|---|---|---|---|---|
| APG all | 132191 | -2.8 ± 1.3 | -12.0 ± 5.9 | -1.5 ± 0.7 |
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| APIS 1 | 61095 | 12.8 ± 3.9 | -4.9 ± 5.1 | 22.3 ± 2.7 |
| APIS 2 | 12116 | -6.9 ± 3.2 | 15.3 ± 3.7 | 16.5 ± 1.4 |
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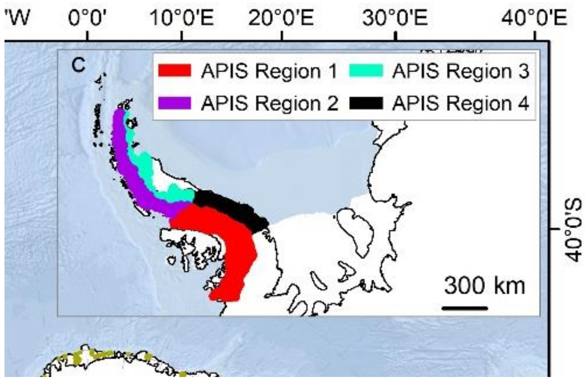
# Antarctic peripheral glacier elevation change and ice loss

## With firn model (forced by RACMO)

| Region | Area (km²) | 2003-2009 | 2009-2018 | 2018-2023 |
|---|---|---|---|---|
| APG all | 132191 | -4.2 ± 1.3 | -16.0 ± 5.9 | -9.0± 0.7 |
| **Region** | **Area (km²)** | **2003-2009** | **2009-2018** | **2018-2023** |
| APIS 1 | 61095 | 11.3 ± 3.9 | -9.9 ± 5.1 | 9.0 ± 2.7 |
| APIS 2 | 12116 | -6.6 ± 3.2 | 13.3 ± 3.7 | 3.4 ± 1.4 |
| APIS 3 | 3029 | -8.8 ± 2.9 | -4.3 ± 3.6 | -5.4 ± 1.5 |
| APIS 4 | 1913 | 1.5 ± 2.1 | -2.0 ± 2.6 | 2.3 ± 1.2 |
| **All** | 210344 | -2.4 ± 3.1 | -2.9 ± 3.8 | 9.3 ± 1.7 |



# Antarctic peripheral glacier elevation change and ice loss

## With firn model (forced by RACMO)

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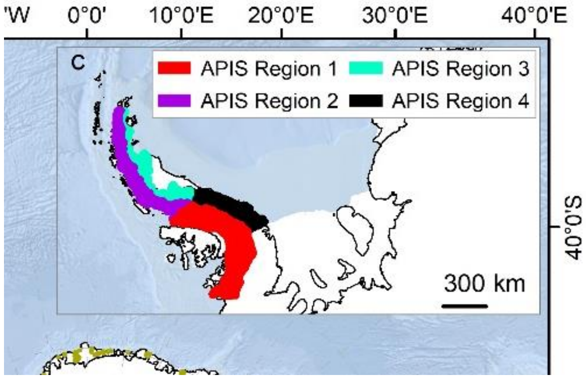
| **All** | 210344 | -2.4 ± 3.1 | -2.9 ± 3.8 | 9.3 ± 1.7 |

## With constant density = 850 kg/m$^3$

| Region | Area (km²) | 2003-2009 | 2009-2018 | 2018-2023 |
|---|---|---|---|---|
| APG all | 132191 | -2.3± 1.3 | -10.2 ± 5.9 | -1.4 ± 0.7 |
| **Region** | **Area (km²)** | **2003-2009** | **2009-2018** | **2018-2023** |
| APIS 1 | 61095 | 10.5 ± 3.9 | -4.1 ± 5.1 | 19.0 ± 2.7 |
| APIS 2 | 12116 | -5.9 ± 3.2 | 13.0 ± 3.7 | 14.1 ± 1.4 |
| APIS 3 | 3029 | -7.1 ± 2.9 | -5.0 ± 3.6 | -5.8 ± 1.5 |
| APIS 4 | 1913 | 1.4 ± 2.1 | -1.1 ± 2.6 | 1.3 ± 1.2 |
| **All** | 210344 | -1.2 ± 3.1 | 2.8 ± 3.8 | 28.5 ± 1.7 |



# Conclusion

Based on our results the current impact on global sea-level rise from Greenland's peripheral glaciers is 0.1 ± 0.02 mm $yr^{-1}$ and APG alone is estimated to be 0.05 ± 0.02 mm $yr^{-1}$ during 2003 to 2023.

**Antarctica**

- The Antarctic Peninsula, previously a hotspot for mass loss, has shown a remarkable shift towards mass gain during the ICESat-2 period
- Firn model vs constant ice density has a huge impact on mass loss estimation from Antarctica peripheral glaciers.

**Greenland.**

- Greenland peripheral glaciers have experienced accelerated mass loss, particularly in the northern regions
- Cumulative contribution of Greenland's peripheral glaciers remains significant, accounting for about 14% of Greenland's total ice loss

**High Mountain Asia**

- Increased ice loss from 32.6 ± 6.4 Gt $a^{-1}$ (2003-2009) to 46.3 ± 9.3 Gt $a^{-1}$ (2018-2023)
- Increased lake level
- Increased annual mean temp

# Highlights

**Major advances**
- In particular, ICESat-2, has greatly improved spatial resolution of dh/dt maps in polar region.

**Current challenges and gaps**
- ICESat/ICESat2: Temporal resolution needs to be improved.
- Trends vs monthly elevation changes
- Gap between ICESat and ICESat2. (can be filled by cryosat-2)

**Recommendations for the future efforts:**
- Use firn compaction model rather than constant density.

(may be important for some regions e.g. Antarctica)

Could HMA ice loss be underestimated?