Lecture 1: Earth's cryosphere in the climate system

Polar Dynamics
GFD Week

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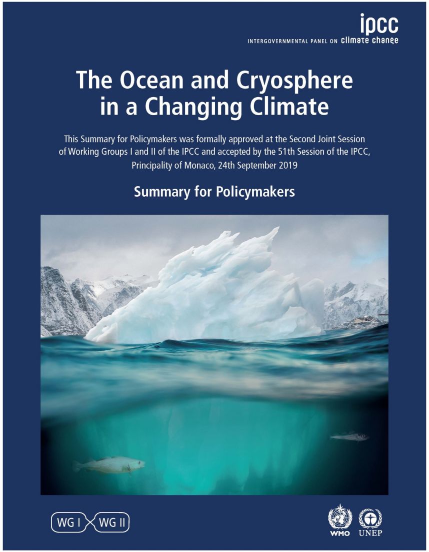
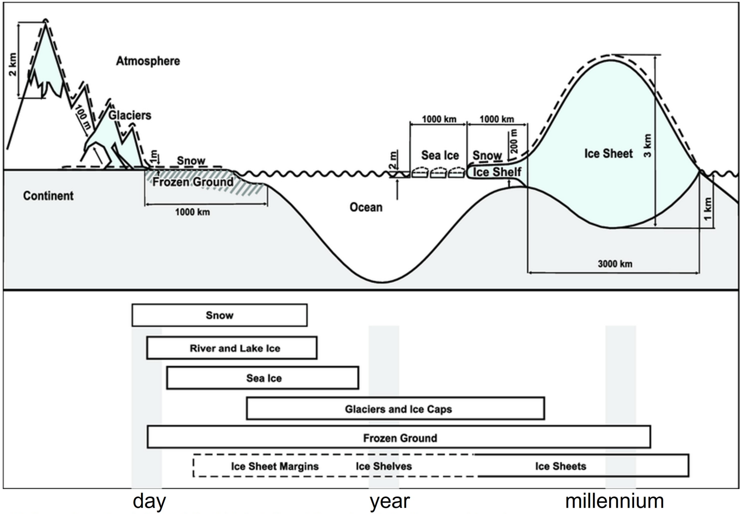


- Part of IPCC Sixth Assessment Report (AR6)
- AR1 published in 1990
- First IPCC report examining the state of Earth's farthest corners—from the highest mountains and remote polar regions to the deepest oceans
- It found that even and especially in these places, human-caused climate change is evident
- In fact, it found that the world's ocean and cryosphere have been *taking the heat* for climate change for decades
- Direct impact on sea levels as if water isn't in solid ice, it's in the ocean (or ground).

Figure 4.1. Components of the cryosphere and their time scales.



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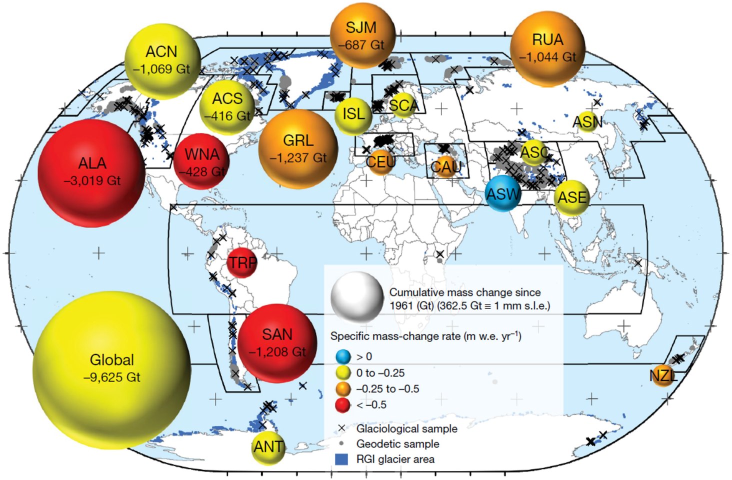
Sea-Level rise Equivalent (SLE)

- Antarctic ice sheet (AIS): 60 m
- Greenland ice sheet (GIS): 7.2 m
- Glaciers & ice caps: 0.4 m
- Frozen grounds (permafrost): 0.1 m
- Sea ice and ice shelves: 0 m

Table 5.2: Characteristic values for snow and ice albedo, from a literature review by S.J. Marshall.

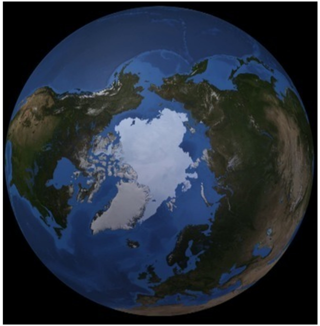
Surface type	Recommended	Minimum	Maximum
Fresh dry snow	0.85	0.75	0.98
Old clean dry snow	0.80	0.70	0.85
Old clean wet snow	0.60	0.46	0.70
Old debris-rich dry snow	0.50	0.30	0.60
Old debris-rich wet snow	0.40	0.30	0.50
Clean firn	0.55	0.50	0.65
Debris-rich firn	0.30	0.15	0.40
Superimposed ice	0.65	0.63	0.66
Blue ice	0.64	0.60	0.65
Clean ice	0.35	0.30	0.46
Debris-rich ice	0.20	0.06	0.30

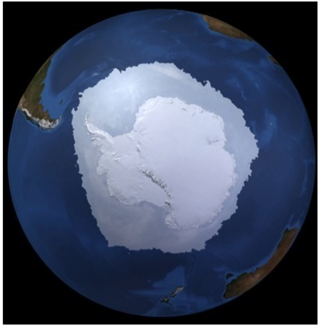
- albedo = radiosity (surf. flux leaving) / irradiance (received)
- thawing of permafrost releases greenhouse gases to the atmosphere
- sea-ice formation affects albedo, ocean salinity (albedo is 0.06) and circulation
- mountain snow cover & glaciers are important sources of freshwater



© Zemp & al (2019) *Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016.*

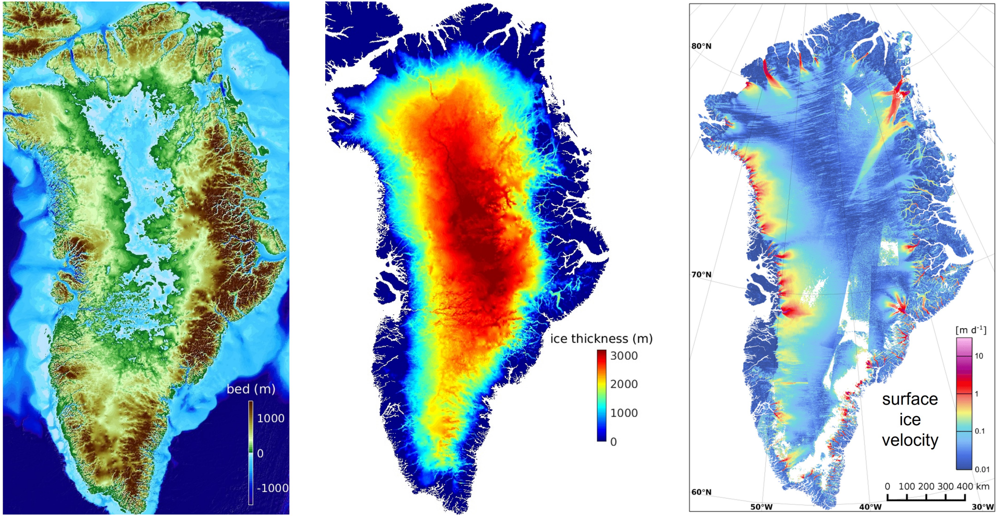
- Distinct from GIS and AIS
- About 1 mm/y post 2000
- Similar to current GIS and exceeding AIS
- Still holds 0.4 m SLE





- Largest island and autonomous territory (Kingdom of Denmark)
- 79% ice cover spanning 2.5×1 M km^2,
- 1.5 km thick
- Oldest ice about 1 Ma old

- Independent territory, separate continent 25 Ma ago
- 98% ice cover spanning 5×5 M km^2
- 2 km thick
- Oldest ice about 1 Ma old



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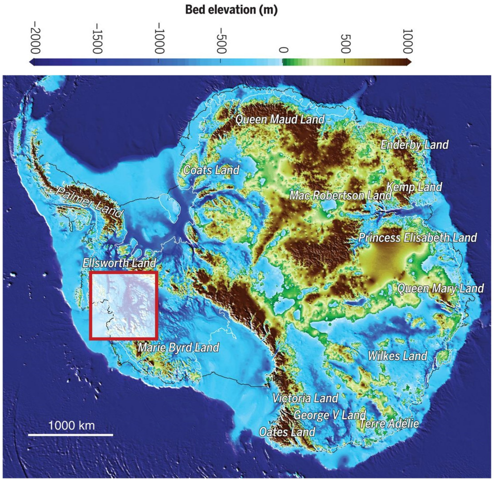
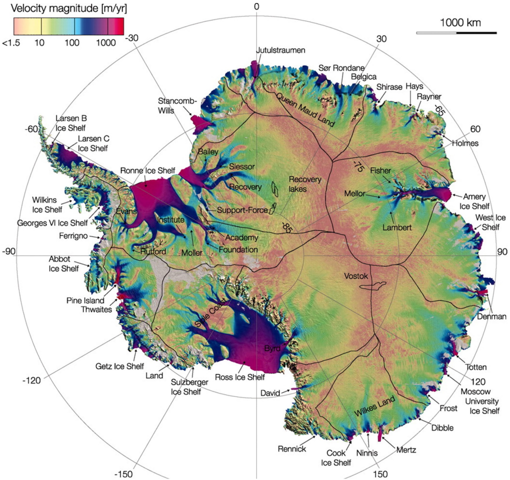
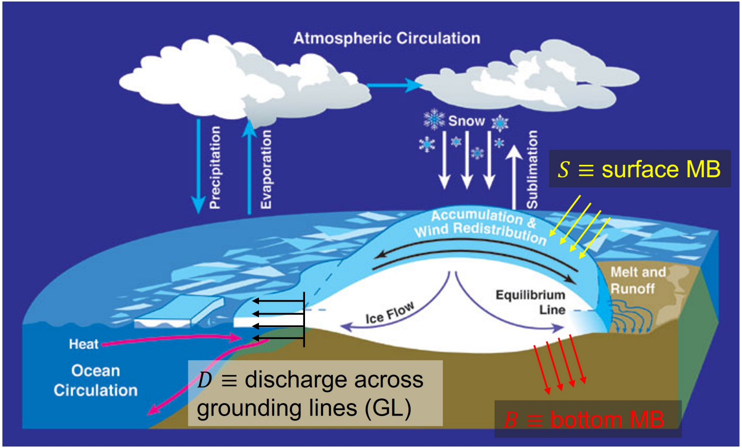




© Left: Pattyn & Morlighem (2020) *The uncertain future of the Antarctic Ice Sheet*. Right: Rignot & al (2011) *Ice flow of the Antarctic Ice Sheet*.



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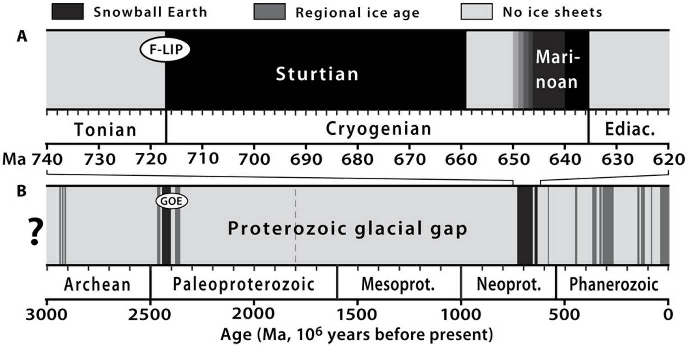
- Cold atmosphere and snowfalls drive growth at altitude
- Geothermal heating drives basal ablation
- Flow of a viscous non-Newtonian fluid away from sources
- Mass balance $MB = \dot{M}_i = S - B - D$
- Accumulation (ablation) zone where $S > 0$ ($S < 0$)
- Equilibirum line where $S = 0$

$$MB = \dot{M}_i = S - B - D \quad (1a)$$
$$S = P + R - U_s - U_{ds} - E_{ds} - M \quad (1b)$$
$$M = R + C + M_s - R_s - F \quad (1c)$$
$$D = \text{thickness} \times \text{ice velocity} \times \rho_i \quad (1d)$$

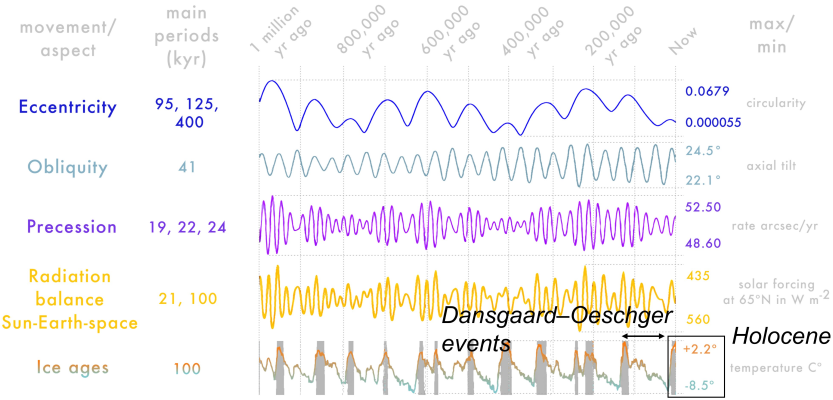
- $P \equiv$solid precipitation, $R \equiv$rainfall, $U_s \equiv$sublimation, $U_{ds} \equiv$drifting snow, $E_{ds} \equiv$erosion of snow, $M \equiv$meltwater runoff, $C \equiv$condensation, $M_s \equiv$surface meltwater production, $R_s \equiv$liquid retention by capillary forces, $F \equiv$refreezing
- Glaciers form when $S > 0$ multiple years, enabling snow $\rightarrow$ ice transf.

- S often measured locally and expressed as Specific SMB (SSMB) Σ (kg/m^2/y)
- Eisen & al (2008) *Ground-based measurements of spatial and temporal variability of snow accumulation in East Antarctica*
- Thickness measured with airborne radar ($\sim$ 10 m accuracy) or satellite altimetry ($\sim$ 100 m accuracy)
- ρ_i is tricky as depends on compaction levels between snow, firn & ice
- Basal melting plays a non-negligible role but is difficult to assess

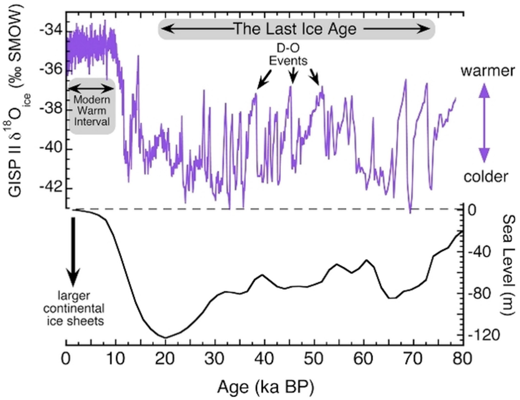


© Hoffmann & al (2017) *Snowball Earth climate dynamics and Cryogenian geology-geobiology*.

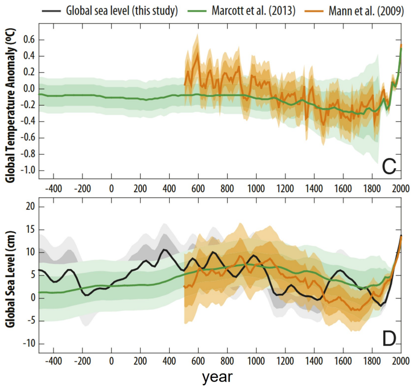
- From deep-time climate models and geological observations (e.g., isotopic fractionation)
- Glaciation (ice line latitude) varies with radiative forcings (solar & greenhouse gases)
- Snowball Earths linked to Great Oxidation Event and plate tectonics opening new CO2 sinks
- Exit through volcanic outgassing and build up of CO_2 in atmosphere

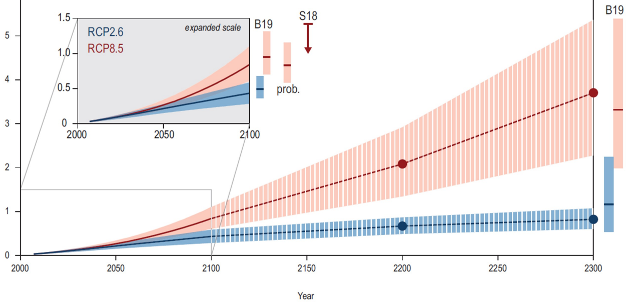


- Quaternary glaciation started 2.48 Ma ago with Arctic ice pack (regional ice age)
- Glacials and Interglacials largely driven by Milankovitch cycles
- Faster fluctuations result from AOI coupling



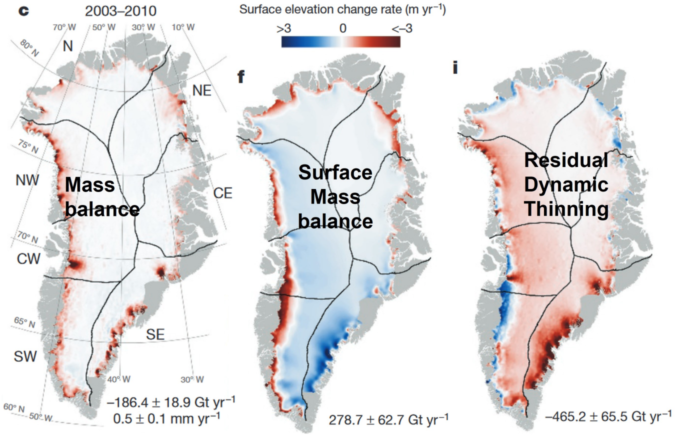
- Holocene started about 11.65 kY ago with rapid warming marking the end of the last ice age
- Sea levels rose due to warming and deglaciation (e.g., loss of Laurentide ice sheet)
- 70% continental ice vanished in about 10 kY yielding sea level rising rates of 1 cm/y
- SLR inferred from, e.g., glacial isostatic adjustments of the solid Earth





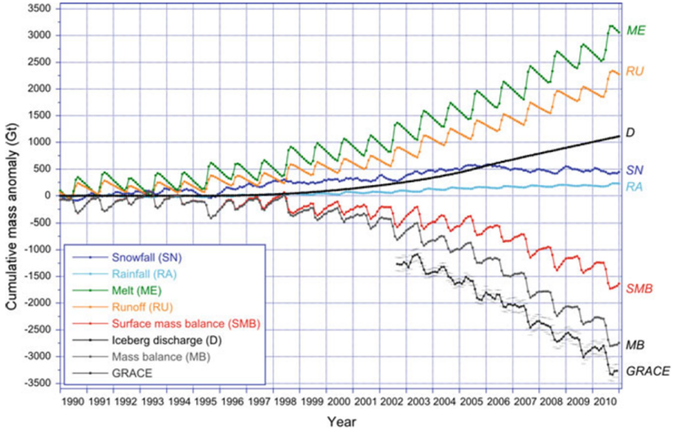
© Left: Kopp & al (2015) *Temperature-driven global sea-level variability in the Common Era*. Right: IPCC (2019) *AR6: SROCCC*.

- Anthropocene started about 2 kY ago and marked the end of the last ice age
- About 1 m sea-level rise by 2100 under RCP 8.5 discarding abrupt changes



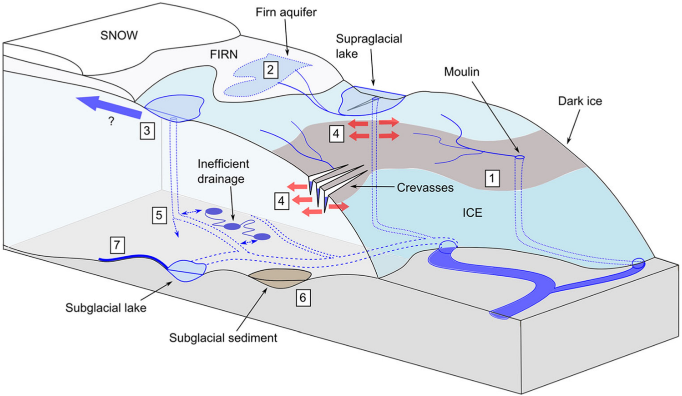
© Kjeldsen et al (2015) *Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since ad 1900.*

- GIS made of marine-terminating glaciers (little floating ice)
- GIS evolution is primarily driven by dynamic thinning and weak surface mass balance $S > 0$
- Weak SMB possibly linked to changes in atmospheric forcing and circulation



© van den Broeke & Giesen (2021) *Mass Balance* (in Karthaus Summer School Lecture Notes).

- Strong seasonality
- Based on in-situ data (incl. ice movement) and regional atmospheric model
- Satellite gravimetry GRACE data not absolute and vertically displaced for clarity (Gravity Recovery And Climate Experiment)



© Nienow et al (2017) *Recent Advances in Our Understanding of the Role of Meltwater in the Greenland Ice Sheet System.*

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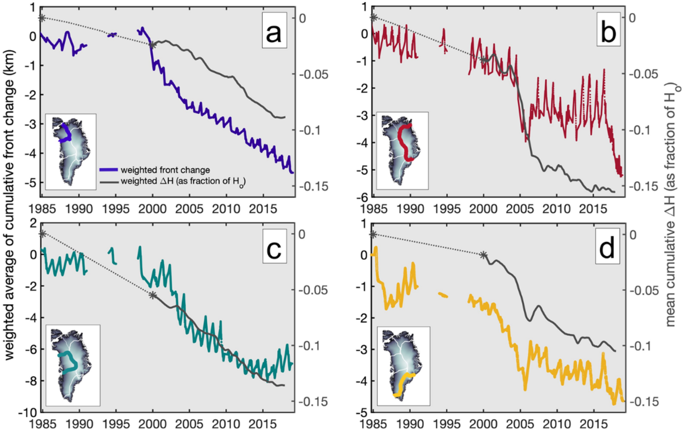
- Dynamic thinning can result from supraglacial meltwater infiltrating the ice, lubricating the bed and increasing ice velocity



© King et al (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat.*

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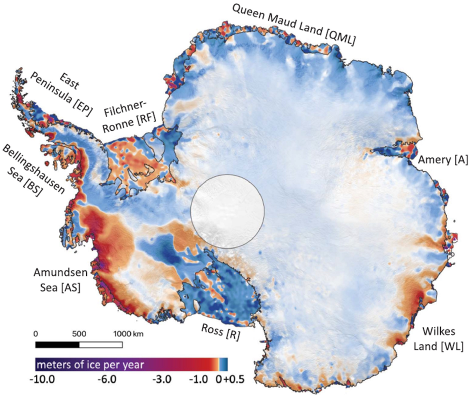
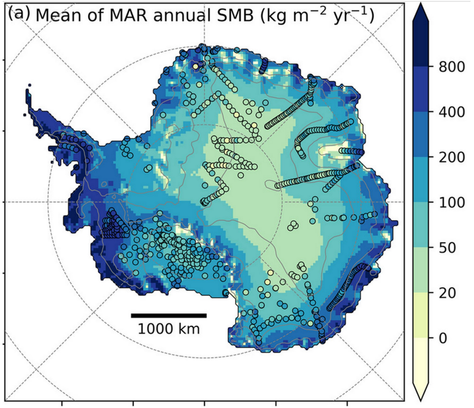
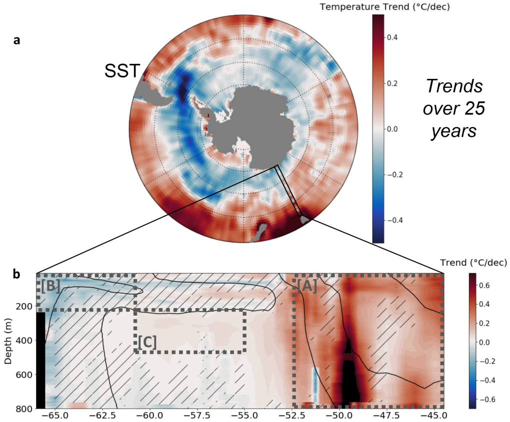
- Dynamic thinning can also result from melt-driven retreat of marine-terminating glacier fronts inland, reducing friction

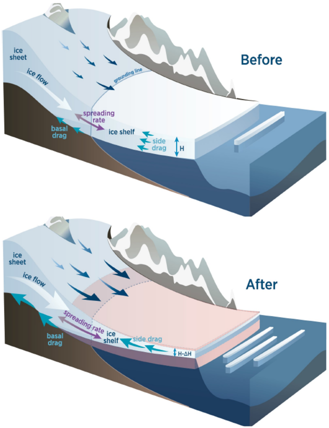




© Left: Smith et al (2020) *Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes*.
Right: Agosta et al (2019) *Estimation of the Antarctic surface mass balance […] (1979–2015) […]*.

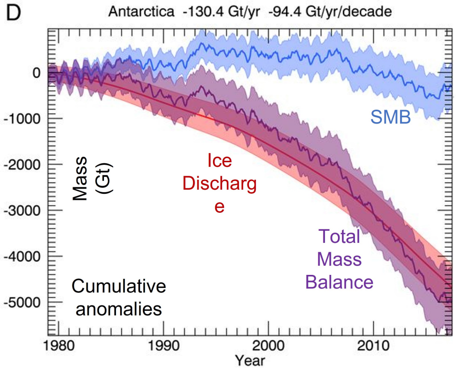
- Thinning is dynamic (more so than GIS) as SMB well above 0 ($S > 0$)
- Dynamic thinning linked to warming oceans that melt ice shelves, losing buttressing

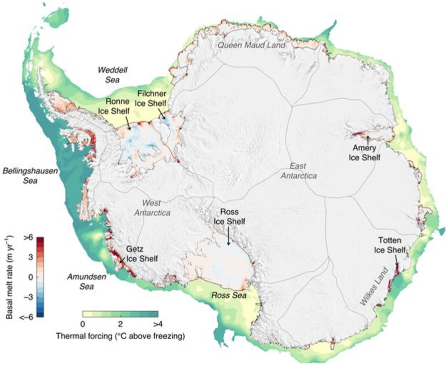




© Left: Auger & al (2021) *Southern Ocean in-situ temperature trends over 25 years emerge from interannual variability*.
Right: Gudmundson & al (2019) *Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves*.

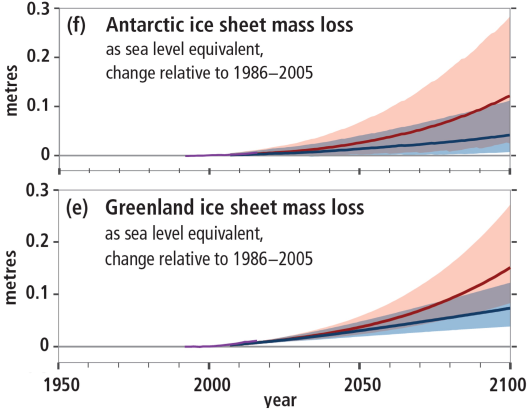
- Dynamic thinning linked to warming oceans that melt ice shelves, losing buttressing





© Left: Rignot & al (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*. Right: Adusumilli & al (2020) *Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves*.

- AIS loss accelerating but with large regional variations



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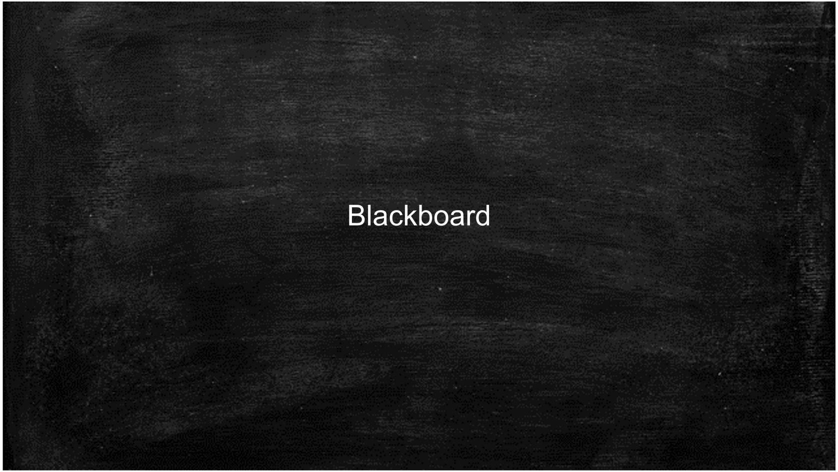
- Both GIS and AIS loss poised to increase through the 21st century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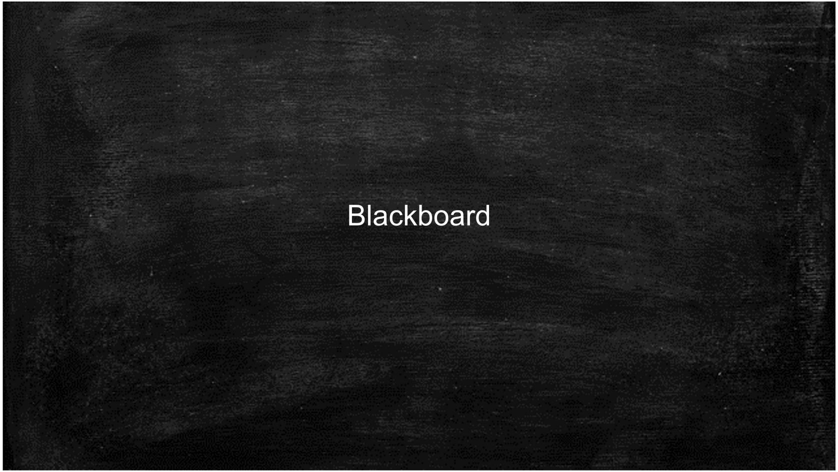

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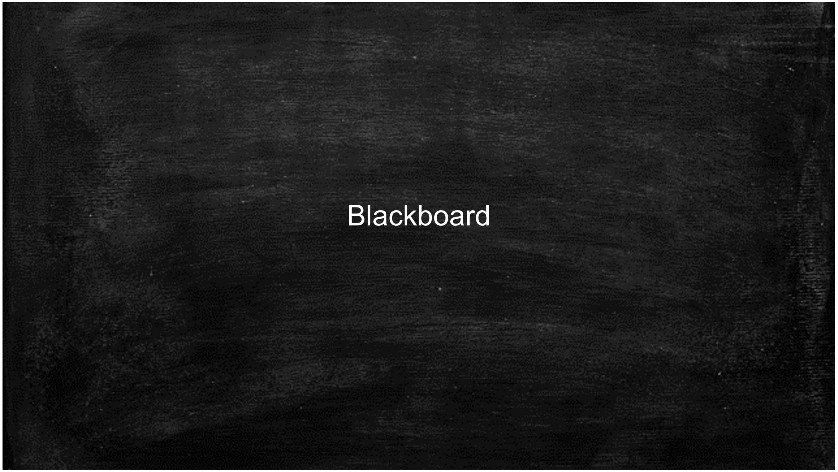

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