

Diverging future surface mass balance between the Antarctic ice shelves and grounded ice sheet

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Kittel et al., 2021



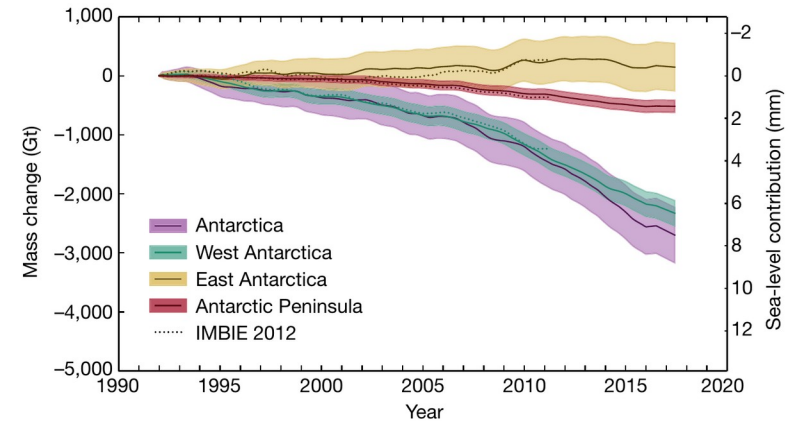
Recent Antarctic contribution to sea level rise (SLR)

The AIS has been losing mass at an increasing rate

- Warmer sub-surface ocean melts ice shelves reducing their buttressing effect
- Increasing ice discharge towards the ocean

Following a recent study (Kim et al., 2020), the abrupt change over WAIS around 2007 is also caused by a decrease in precipitation

- Links between mass and precipitation for other regions in East Antarctica (eg., Velicogna et al., 2015)



(Imbie, 2018)

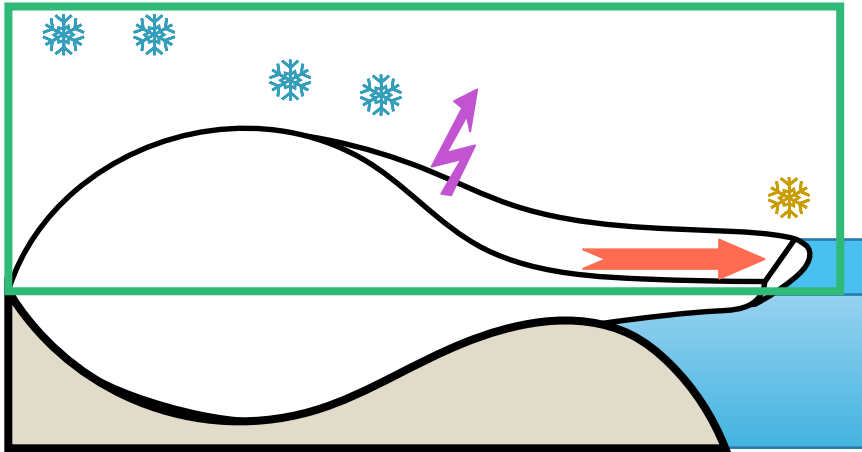
=> Importance of Surface Mass balance to explain mass change

What is surface mass balance?

Snowfall (“atmospheric” and drifting snow) + rainfall

Surface mass balance (SMB) = precipitation – drifting-snow erosion – sublimation – runoff

Surface sublimation – surface deposition



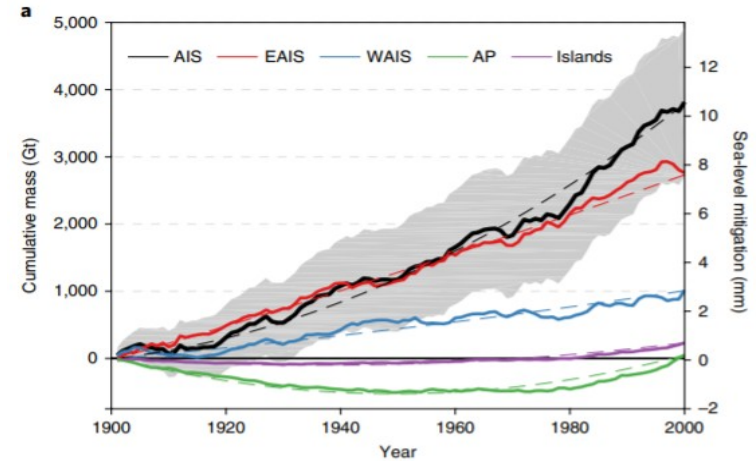
Mass balance variations reinforced / modulated by SMB changes

Over a longer period of time, changes in SMB have mitigated SLR

- Warmer air temperatures increase precipitation

Global warming should then increase Antarctic SMB?

- Global Warming signal is currently hidden by circulation changes caused by climate variability (Previdi and Polvani, 2016)



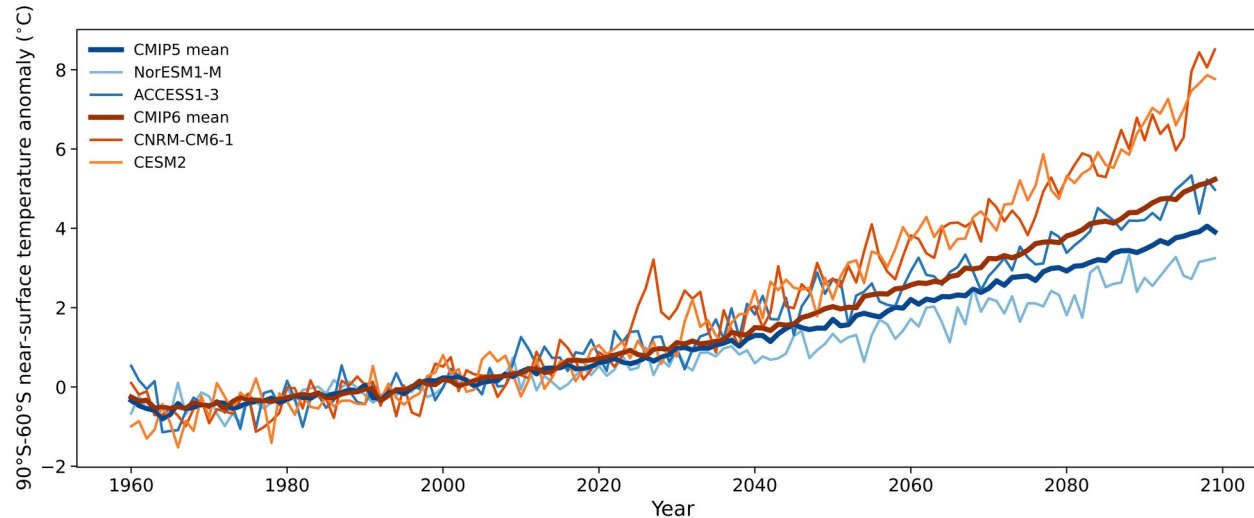
(Medley and Thomas, 2018)

SMB has direct (and indirect) contributions to mass balance, potentially the only negative contributor to SLR => Need to better project SMB changes to estimate SLR and Antarctic mass balance

Future SMB estimates using models, but which models?

Large-scale models: Global Climate Models or Earth System Models (ESMs)

- Based of the most recent Antarctic projections using CMIP5 scenarios (ie., ISMIP6 project)
- New climate projections available through CMIP6
 - Stronger warming for 2100 for CMIP6 projections than corresponding CMIP5 projections



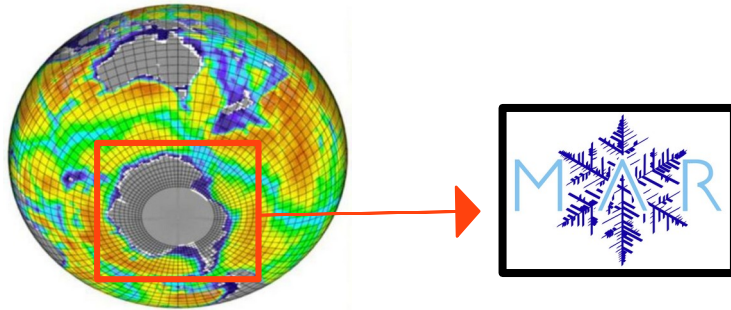
Future SMB estimates using models, but which models?

Large-scale models: Global Climate Models or Earth System Models (ESMs)

- several compromises:
 - too coarse resolution
 - missing important physical processes of polar regions

Alternative used here: downscaling ESM with the regional climate model MAR

- Polar-oriented RCM frequently used for representing Antarctic and Greenland ice sheet SMB



Methodological aspects

Downscaling of ESMs from CMIP5 and CMIP6 over 1980-2100

- Using MAR as a magnifying glass

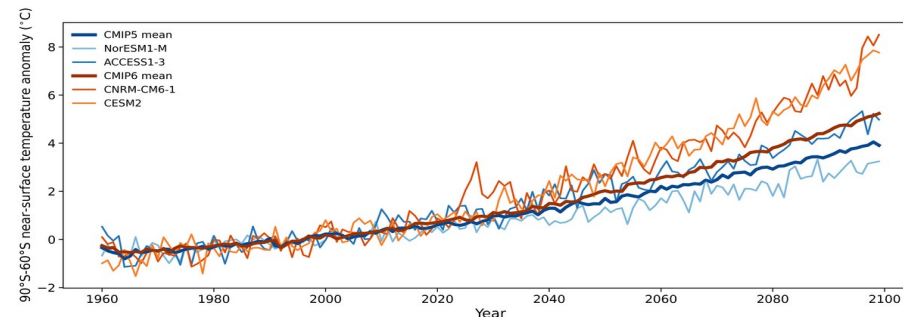


ESMs were selected according to their ability to

- Represent the current climate around the AIS (~Barthel et al., 2020)
- Diversify the projected changes during the 21st century

2 from **CMIP5** and 2 from **CMIP6**

- ACCESS1.3 and NorESM1-M
- CESM2 and CNRM-CM6

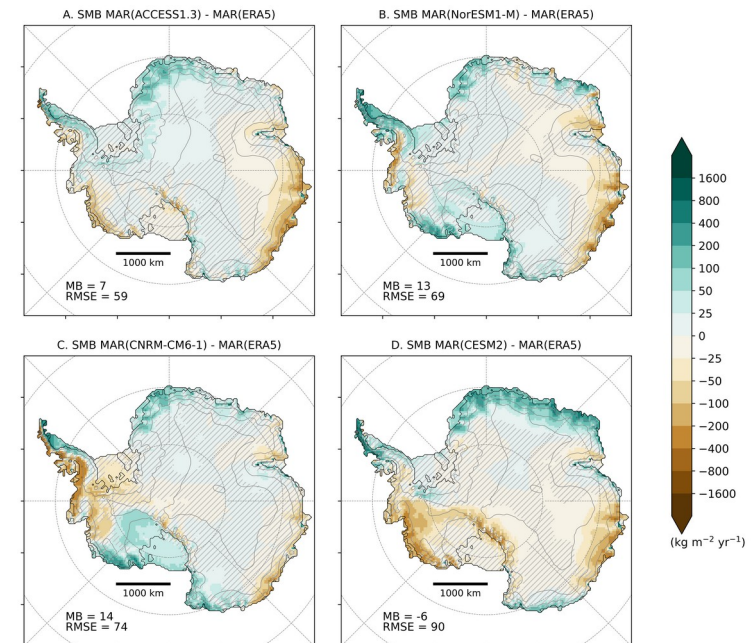


Evaluation of MAR(ESMs) simulations over the present

Present bias might have a significant influence on the projection results and remain in the future

- Comparison with the « reference » MAR forced by ERA5 over 1981-2010
- The SMB downscaled by MAR forced by the four ESMs is close to MAR(ERA5). The anomalies of the annual mean SMB are lower than the interannual variability in the SMB over the historical period
- the spatial and integrated anomalies are close to (or even lower than) the spread between several RCMs, all forced by ERA-Interim (Mottram et al., 2020)

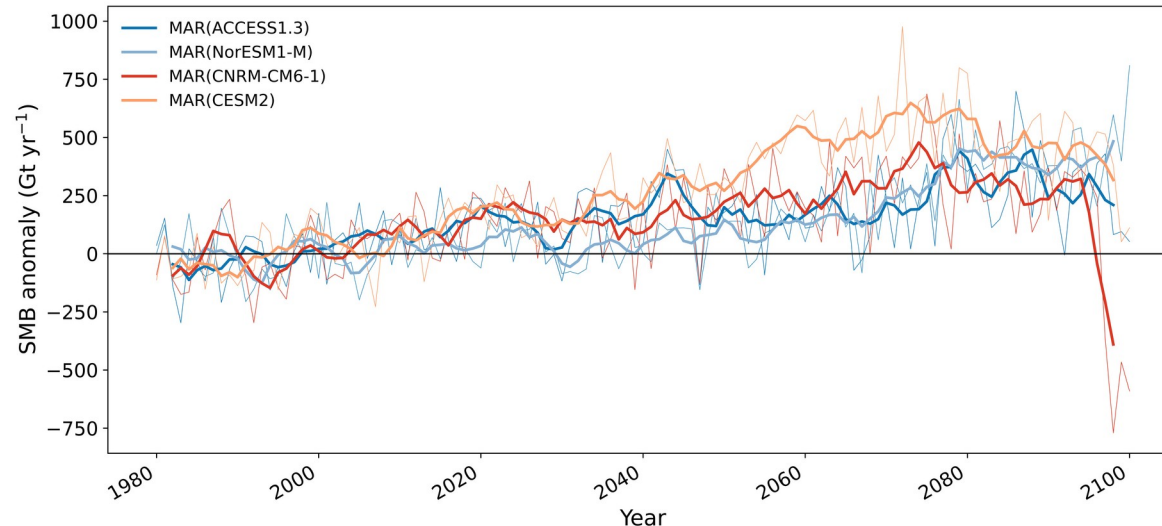
=>good ability of the different simulations to closely reproduce the SMB over the present climate



A trend towards surface mass gains by the end of the 21st century

MAR simulations forced by the high-emission scenarios ssp585 and RCP8.5 suggest a generally higher Antarctic SMB (including ice shelves) during 2071–2100 than for 1981–2010

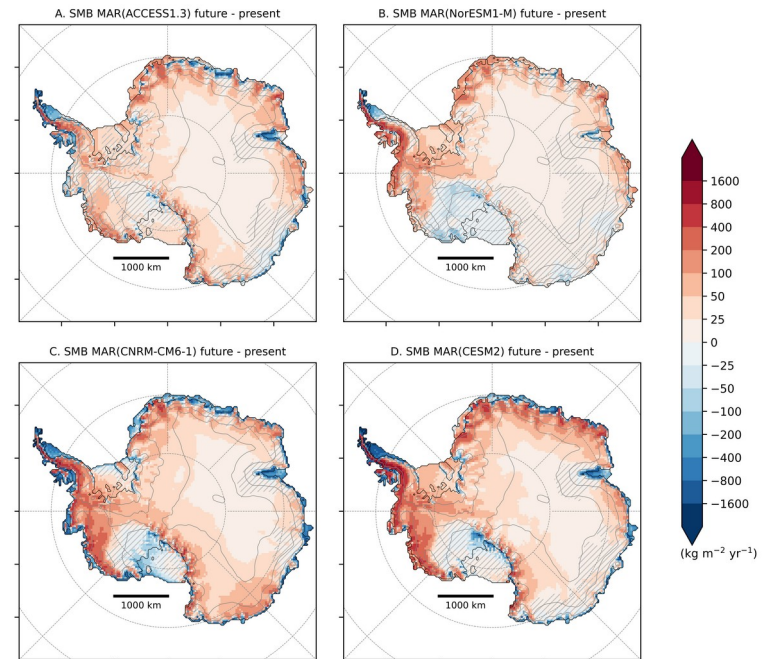
- Large spread (ie., projected changes x2) highlights the need of using several (forcing) models



Large regional diverging projected changes

The total Antarctic SMB is projected to increase but significant local differences

- Increase over the grounded ice vs decrease over the ice shelves
- Need to analyse these two regions separately
 - Different processes at play
 - Only grounded changes contribute to SLR

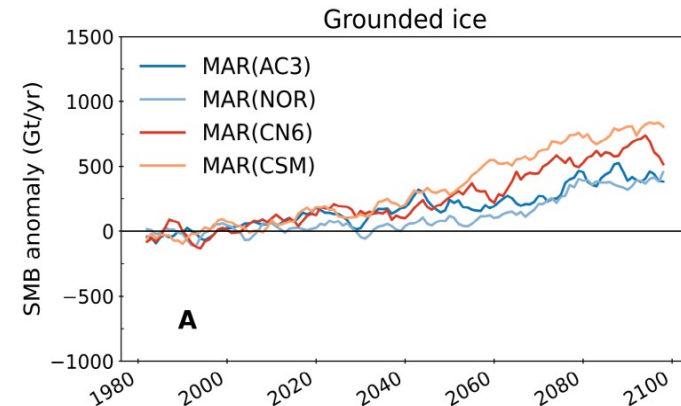


SMB changes over the grounded ice sheet

The grounded Antarctic SMB is projected to increase by +349 Gt yr⁻¹ to +751 Gt yr⁻¹ from 1981–2010 to 2071–2100

- Trend is mainly dominated by an increase in snowfall
 - Increased air moisture content associated with higher air temperatures leads to a widespread increase in snowfall
 - But local decrease linked to circulation changes
- Snowfall increase also competes with a subsequent increase in run-off over the margins
 - The future run-off contribution could compensate up to 34 % of the snowfall increase over the historical period
 - Question the use of precipitation–evaporation to compute SMB (e.g. Palerme et al., 2017; Gorte et al., 2019; **+ some ISMPI6 forcings**).

=>From 1981 to 2100, our results suggest a grounded cumulative contribution of –3.7, –5.8, –8.1, and –10.6 cm SLE



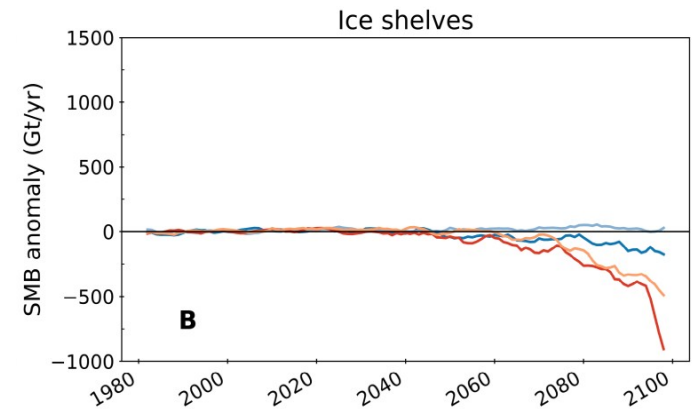
SMB changes over the ice shelves

More uncertainties depending on the forcing ESM

- From close to the present-day values to strong decrease
- Increase in total precipitation but conversion of snowfall to rainfall
 - Rainfall increase can even outpace snowfall increase
- Significant increase in surface melt
 - Large run-off production rates that explain SMB changes
 - And also large spread (+18 Gt yr⁻¹ to +558 Gt yr⁻¹)

=>Surface meltwater to project ice shelf hydrofracturing

- See Gilbert and Kittel, 2021 



Links with the ESM near-surface temperature

Our projections of the 21st-century evolution of the Antarctic SMB yield a large spread in SMB for both the Antarctic grounded ice and ice shelves

- Spread mostly attributed to different warming rates from the ESMs
- Similar projected changes for an equivalent warming
 - ie., +2°C and +4°C lead to the similar integrated and local SMB changes for all our projections

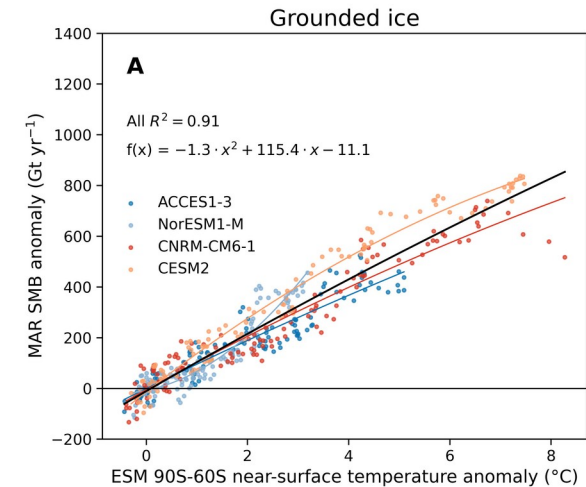
=> We associate the future annual anomalies modelled by MAR to annual near-surface temperature anomalies over 90–60° S from the forcing ESM

Links with the ESM near-surface temperature (grounded SMB)

Consistent increase in SMB between all our experiments for a same warming

Identification of a potential warming threshold

- Stronger increase in snowfall than runoff up to +7.5°C local warming
 - +7.5°C : widespread increase in melt (+ rainfall) saturating the snowpack and leading to runoff
 - Potential lower grounded-SMB increase for local warmings higher than +7.5 °C
 - Only supported by one ESM (the warmest of the CMIP5/6 database)
 - require longer projections to confirm the confidence of this threshold



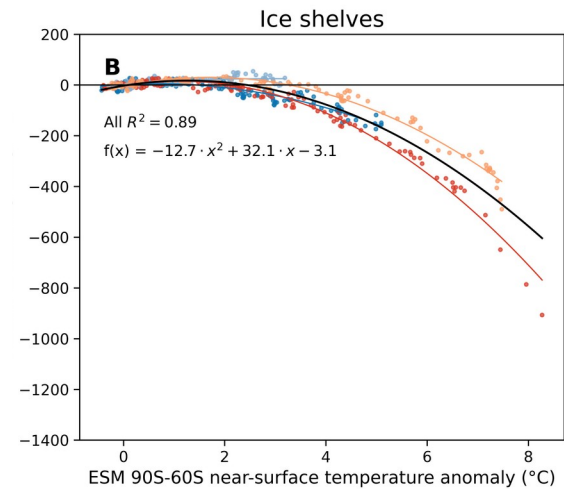
For the individual links between SMB components and warming, see 

Links with the ESM near-surface temperature (ice shelf SMB)

Consistent decrease in SMB between all our experiments

Identification of warming thresholds

- Below +2°C: larger increase in precipitation than in runoff
 - Increase in SMB
- Above +2°C: more runoff production
 - Significant decrease in SMB
 - Potential irreversible damages over ice shelf surfaces
 - High risk of hydrofracturing
- Above +7.5°C: snowfall is not increasing anymore
 - All the increase in precipitation as rainfall
 - More liquid water in the snowpack => stronger saturation and runoff



For the individual links between SMB components and warming, see 

Statistical projections for the CMIP5 and CMIP6 ensemble

Anomalies in Antarctic SMB and its driving components (precipitation and run-off) are strongly explained by near-surface ESM temperature anomalies between 90–60° S

- The reconstruction with the forcing ESMs we used is reliable compared to SMB anomalies as modelled by MAR forced by the 4 ESMs

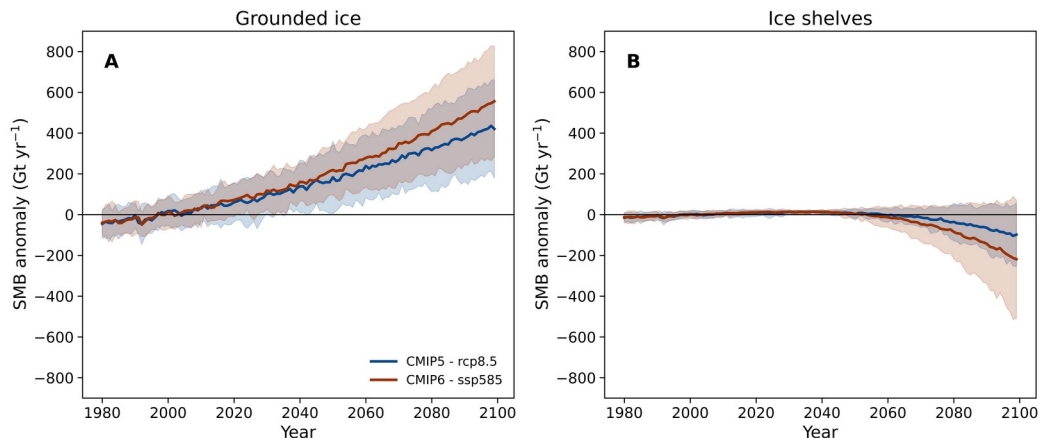
$$\begin{aligned}\Delta \text{SMB}_{\text{grd}} &\approx -1.3 \Delta \text{TAS}_{90-60\text{S}}^2 \\ &\quad + 115.4 \Delta \text{TAS}_{90-60\text{S}} - 11.1, \\ \Delta \text{SMB}_{\text{shf}} &\approx -12.7 \Delta \text{TAS}_{90-60\text{S}}^2 \\ &\quad + 32.1 \Delta \text{TAS}_{90-60\text{S}} - 3.1,\end{aligned}$$

- We can then use the statistical regression to reconstruct the SMB projections for the CMIP5/6 ensemble
 - No extrapolation even for the strongest warmings as our anomalies are made including the warmest projected temperature changes by 2100
 - But strong hypotheses as no circulations changes and fixed topography

Reconstructed SMB changes: CMIP5 vs CMIP6

Reconstruction of the annual Antarctic SMB for all the CMIP5 (RCP8.5) and CMIP6 (ssp585)

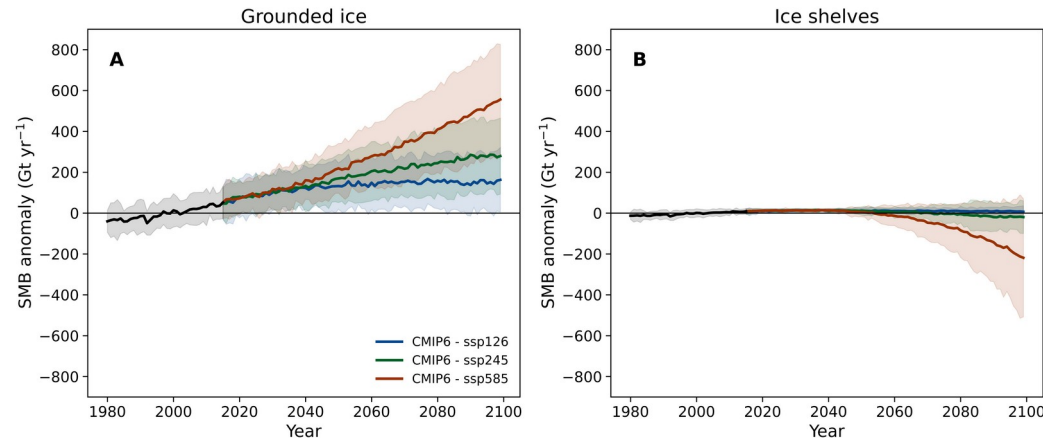
- Increase over the grounded ice vs decrease over the ice shelves for both ensemble
- **Larger changes for the CMIP6 reconstruction** (similar up to 2045 and then diverge)
- Grounded
 - -6.3 ± 2.0 cm SLE in CMIP6-ssp585 vs -5.1 ± 1.9 cm SLE in CMIP5-RCP8.5
- Ice shelves
 - Multi-model mean difference of 65Gt/yr
 - Large uncertainties in CMIP6 (up to -600 Gt/yr and close-to-equilibrium)



Reconstructed SMB changes: CMIP6 scenarios

Reconstruction of the annual Antarctic SMB for CMIP6 (ssp126, ssp245, ssp585)

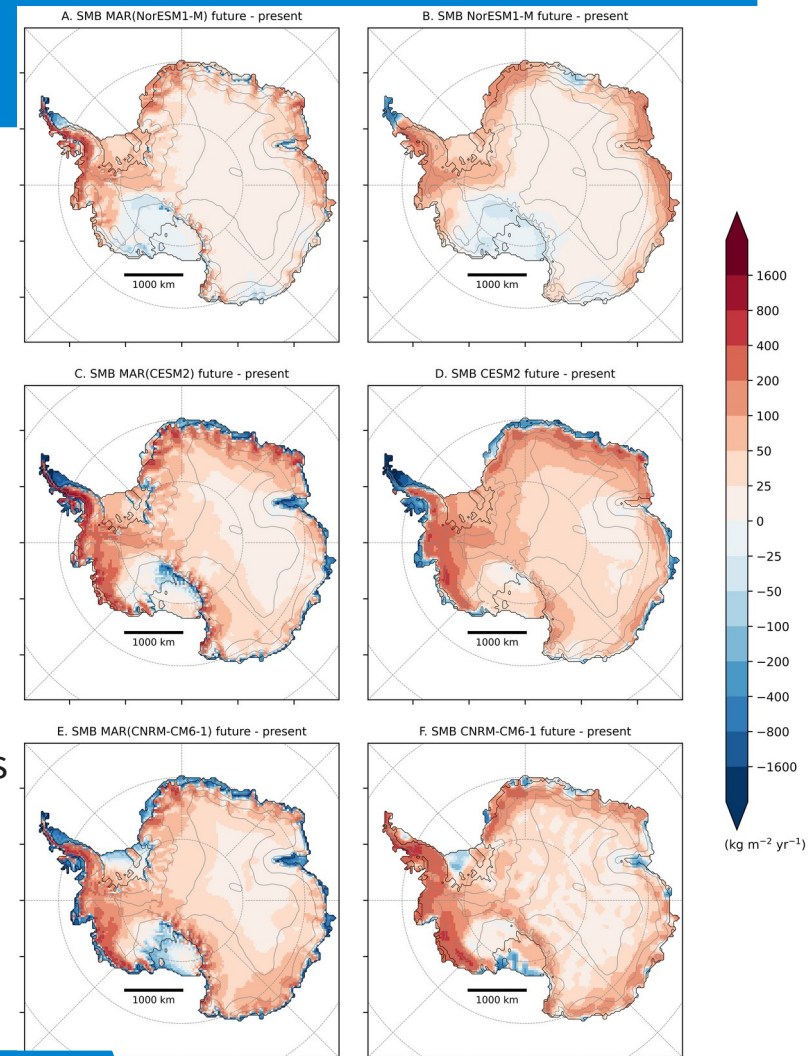
- Increase over the grounded ice vs decrease over the ice shelves
- **Larger changes for the high-emission scenario**
- Grounded
 - -6.3 ± 2.0 cm SLE in CMIP6-ssp585 vs -3.0 ± 1.4 cm SLE for CMIP6-ssp126 and -4.2 ± 1.6 cm SLE for CMIP6-ssp245 with stabilization for ssp126 and ssp245
- Ice shelves
 - **Close-to-equilibrium for ssp126 and ssp254**, should then limit risk of hydrofracturing and surface damages!



Comparison with the ISMIP6-derived SMB

Due to time constraints and computational demands faced by ISMIP6, future Antarctic projections for forcing ice sheet models were derived directly from ESMs

- Comparison of ESMs SMB anomalies with MAR anomalies (same forcing) between 2081–2100 and 1995–2014
 - Impact of the higher resolution of MAR (see peninsula or ice shelves)
 - differences unrelated to the resolution
 - For instance CNRM-CM6-1 projects a strong warming but almost no melt resulting in positive SMB changes

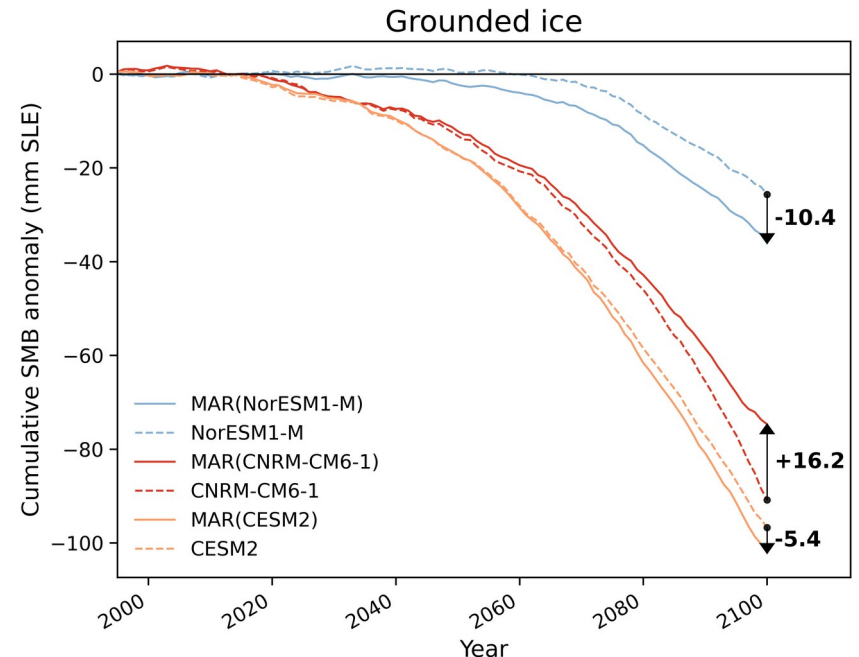


Comparison with the ISMIP6-derived SMB

Integrated over the whole grounded ice, **MAR-ESM differences in SMB can be even larger than reconstructed differences** between CMIP5-RCP8.5 and CMIP6-ssp585 or between CMIP6-ssp126 and CMIP6-ssp245

- Also large differences over the ice shelves (see )

Raise the question of the sensitivity to the forcing of ISMIP6 projections



Limitations: missing fundamental processes

Run-off

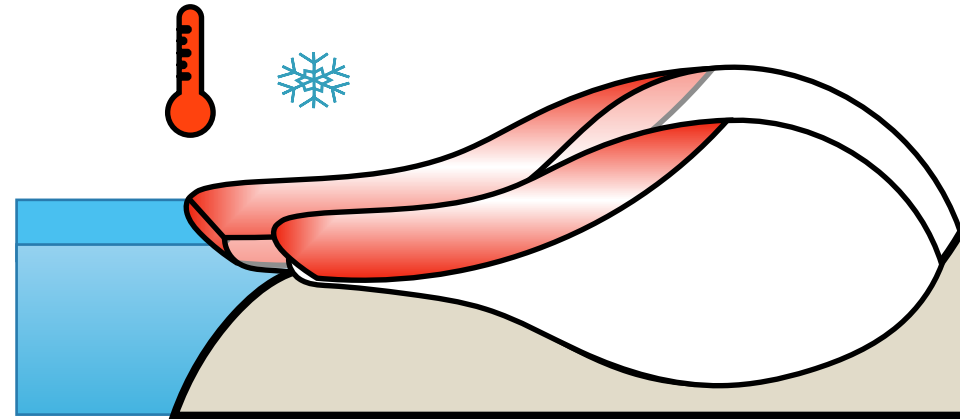
- No water-routing scheme in MAR
 - Liquid surface water should refreeze further or run-off into the ocean?
 - Strong influence on the ice shelf SMB and potentially on ice shelf collapse due to hydrofracturing

Fixed ice sheet geometry

- It should evolve according to (surface) mass balance changes
 - No temperature-elevation neither precipitation-elevation feedbacks
- Underestimation or overestimation of the SMB sensitivity to warming temperatures?

Blowing snow

- Not activated in our experiment while present main ablation component
- But the future of blowing snow while melt should promote stronger cohesion of the snowpack is an open question?



Take home message

In this study, we use the regional atmospheric model MAR forced by 4 carefully selected ESMs to study the future the Antarctic SMB.

Diverging future SMB changes between Antarctic grounded ice and ice shelves

- Suggested by both MAR simulations and CMIP5/6 reconstructions

Significant differences between MAR projections and ESM-derived projections used in ISMIP6

Identification of a warming threshold ($+2.5^{\circ}\text{C}$) where ice shelves should “survive” from a atmospheric perspective

Do not miss the associated publication in The Cryosphere  and MAR SMB outputs until 2100 

References

Gilbert, E. and Kittel, C.: Surface melt and runoff on Antarctic ice shelves at 1.5°C, 2°C and 4°C of future warming. *Geophysical Research Letters*, 48, e2020GL091733, 2021.

Gorte, et al.: Scoring Antarctic surface mass balance in climate models to refine future projections, *The Cryosphere*, 14, 4719–4733, 2020.

IMBIE Team: Mass balance of the Antarctic Ice Sheet from 1992 to 2017, *Nature*, 558, 219–222, 2018.

Kim, et al.: Antarctic ice mass variations from 1979 to 2017 driven by anomalous precipitation accumulation, *Scientific reports*, 10, 1–9, 2020.

Medley, B. and Thomas, E.: Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise, *Nature Climate Change*, 9, 34–39, 2019.

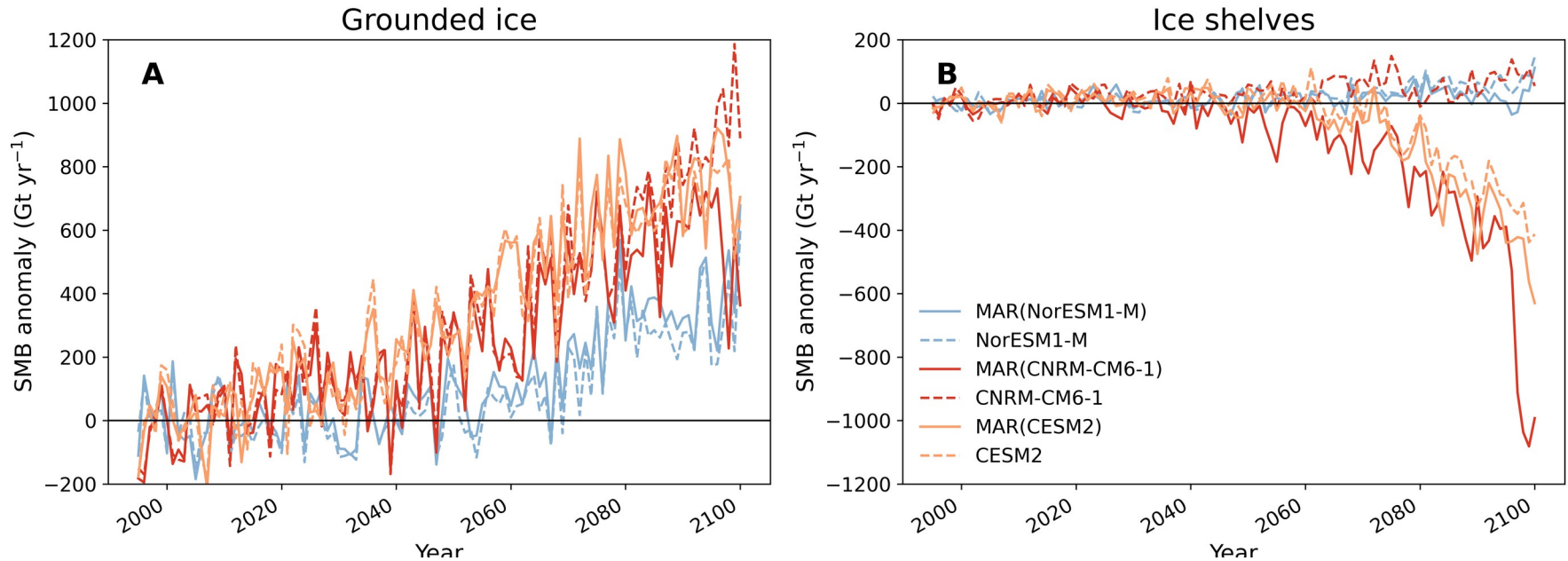
Mottram, et al.: What is the Surface Mass Balance of Antarctica? An Intercomparison of Regional Climate Model Estimates, *The Cryosphere Discussions*, pp. 1–42, 2020.

Palerme, et al.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, *Climate dynamics*, 48, 225–239, 2017.

Previdi, M. and Polvani, L. M.: Anthropogenic impact on Antarctic surface mass balance, currently masked by natural variability, to emerge by mid-century, *Environmental Research Letters*, 11, 094 001, 2016.

Velicogna, et al.: Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, *Geophysical Research Letters*, 41, 8130–8137, 2014.

Comparison with the ISMIP6-derived SMB (extra)



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