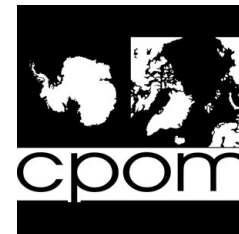


Uncertainty in East Antarctic firn thickness constrained using a model ensemble approach

V. Verjans, A. A. Leeson, M. McMillan, C. M. Stevens, J. M. van Wessem, W. J. van de Berg, M. R. van den Broeke, C. Kittel, C. Amory, X. Fettweis, N. Hansen, F. Boberg and R. Mottram



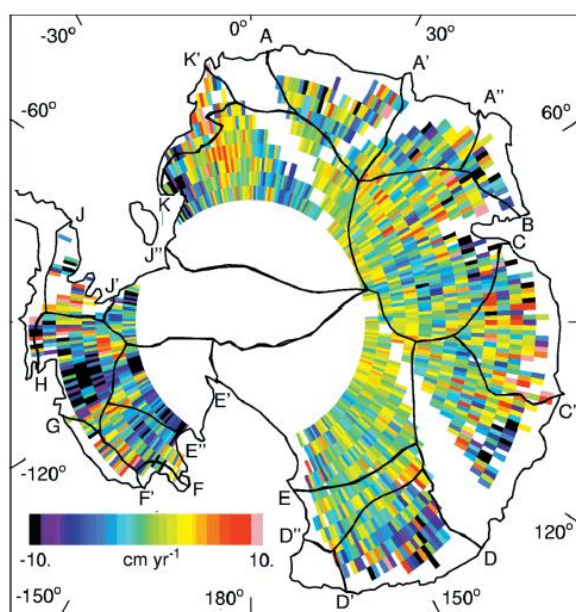
Universiteit Utrecht



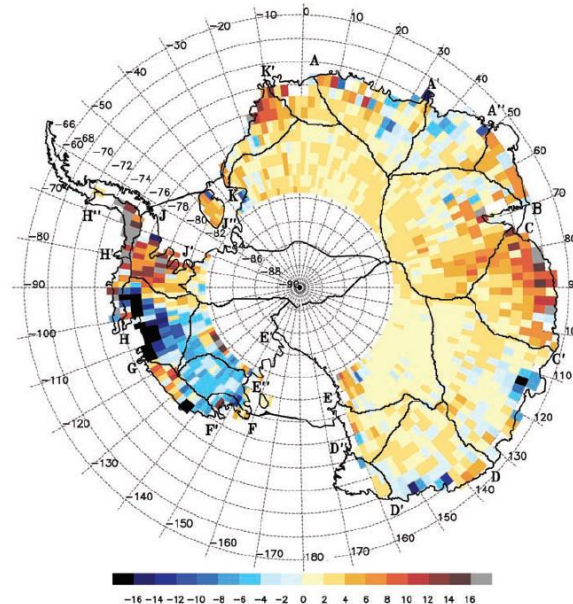
Motivation (1): Firn and altimetry

Since 1992, satellite-based measurements of elevation changes across Antarctica are performed, allowing altimetry-based mass balance assessments.

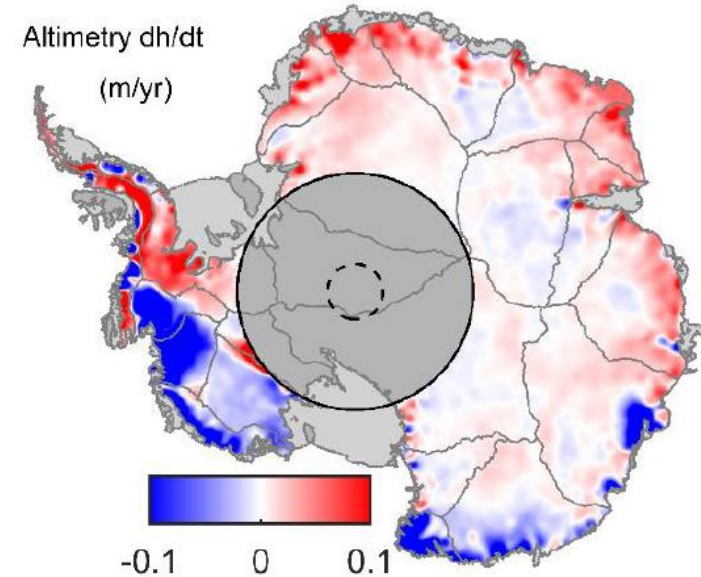
As measurements become more precise, the importance of process understanding increases.



Wingham et al. (1998)



Davis et al. (2005)



Shepherd et al. (2019)

A key step is the **volume-to-mass conversion**; the signal must be partitioned in:

- Firn change
- Ice dynamical change

Firn covers 99% of the Antarctic ice sheet → firn modelling is key to mass balance accuracy

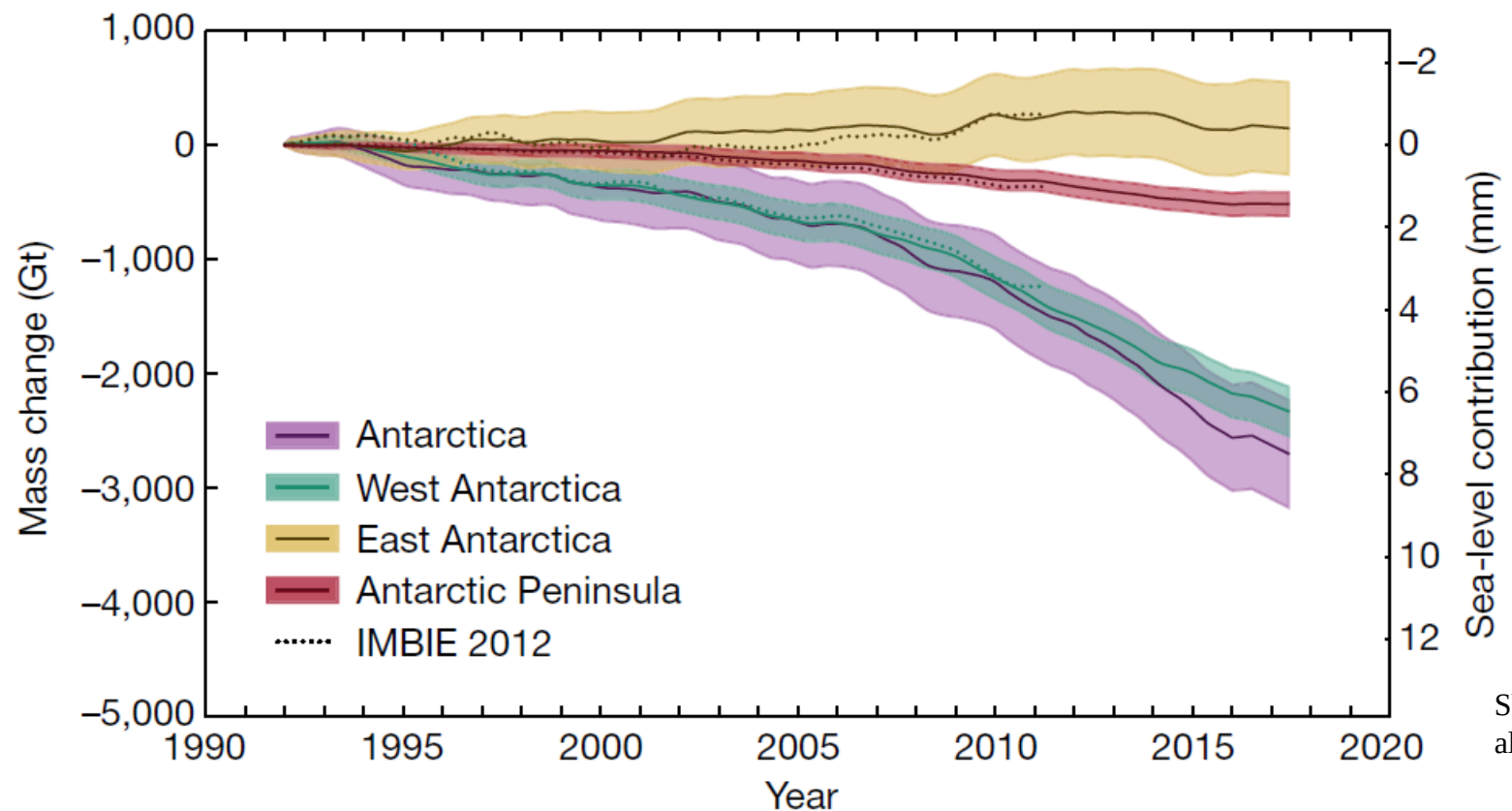
Motivation (2): Firm on the East Antarctic Ice Sheet (EAIS)

EAIS mass balance assessments are highly sensitive to firn thickness change because:

- Magnitudes of elevation change signals are small
- Elevation changes are assumed driven by snowfall and firn compaction fluctuations

In this context, it is unclear whether some ice dynamical imbalance may be at play

Although considered dynamically more stable, EAIS presents highest uncertainty concerning recent mass trends.

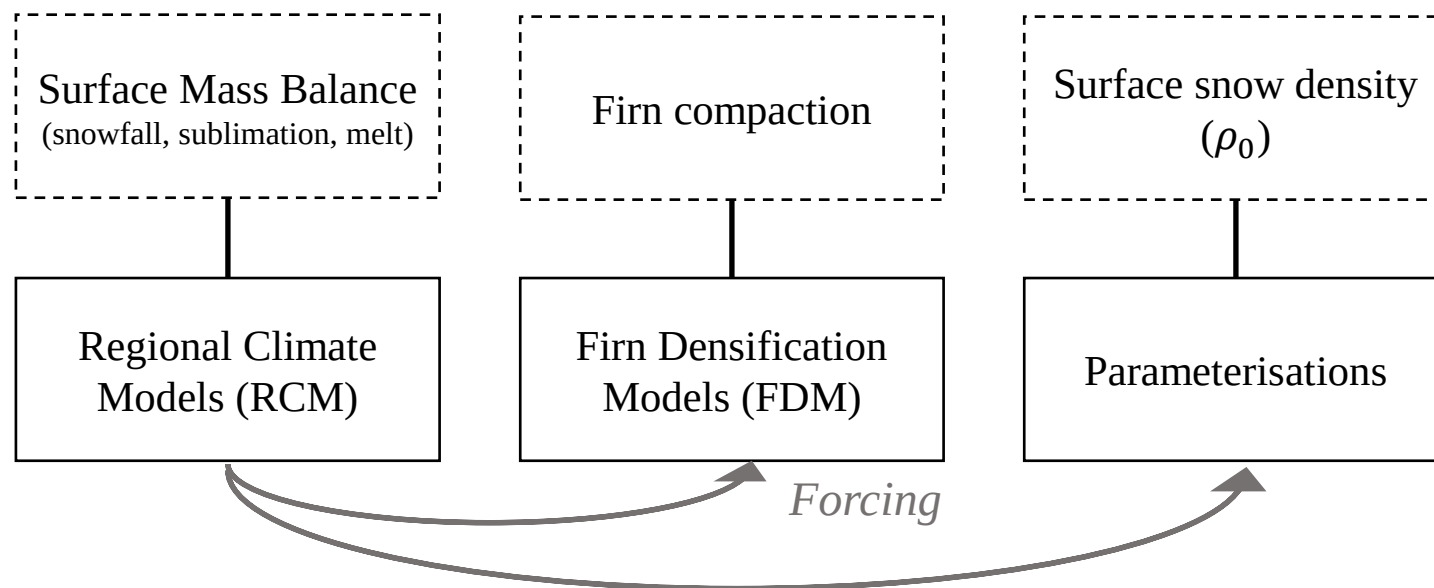


Shepherd et al. (2018)

Methodology: Model-Ensemble

Goal: Better constrain firn thickness change uncertainty over 1992-2017
(period choice allows comparison with a long-term altimetry record (Shepherd et al., 2019))

Approach: Ensemble of model combinations to capture all the processes underlying firn thickness variations



3 RCMs (RACMO2, MAR, HIRHAM) --- 9 FDMs --- 2 ρ_0 parameterisations

All possible model combinations → Ensemble of 54 scenarios

~ 10×10^6 km² domain
Multi-decadal simulations
54 model combinations

Computational challenge is overcome via
statistical emulation of the FDMs

Methodology: Overview of statistical emulation

Goal is to emulate firn compaction (dh_c) of the nine different FDMs

We select 50 calibration sites in a representative range of EAIS climate

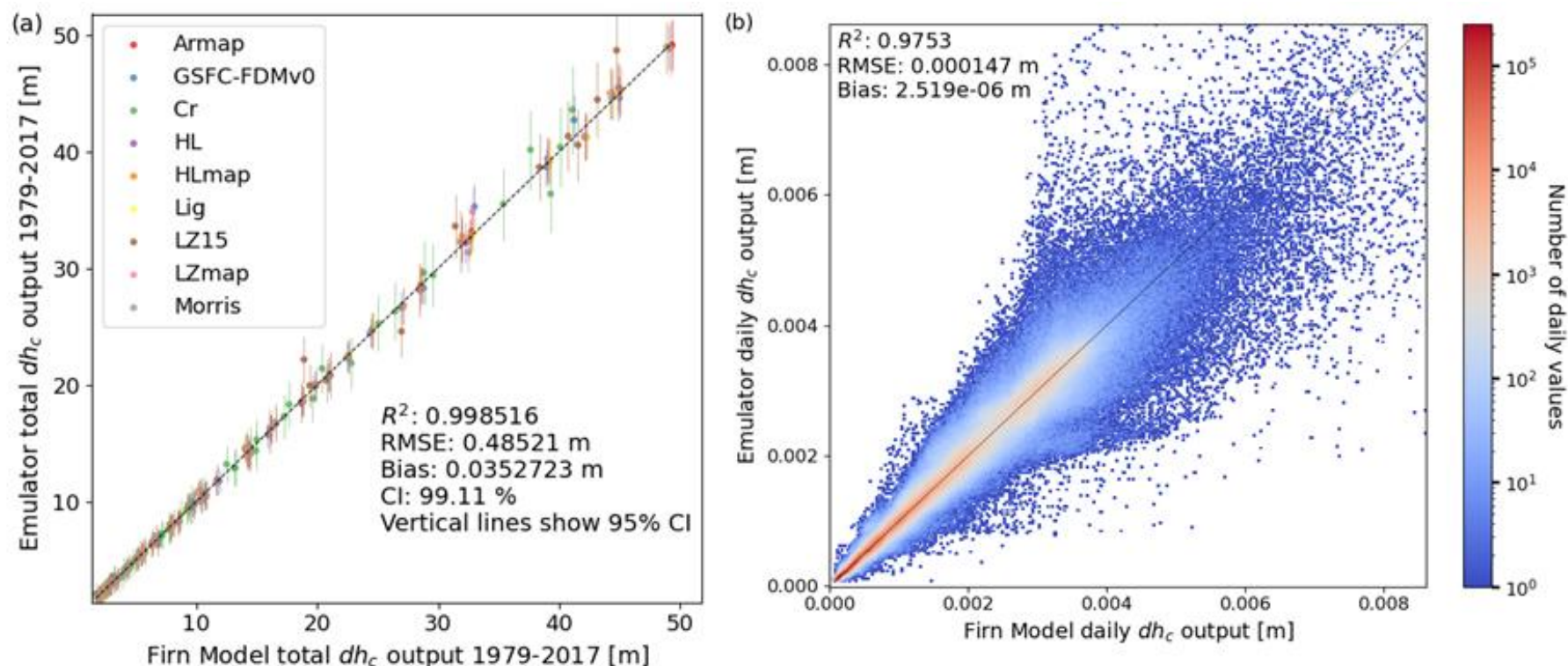
The emulators are calibrated to their respective FDM by combining linear and Gaussian process regression

Emulators only rely on RCM input (accumulation, temperature, melt) and $\rho_0 \rightarrow$ predict firn compaction

Leave-one-out cross-validation for long-term trends and short-term variability (match emulator-FDM)

see all details in the Supplementary slides at the end of this presentation

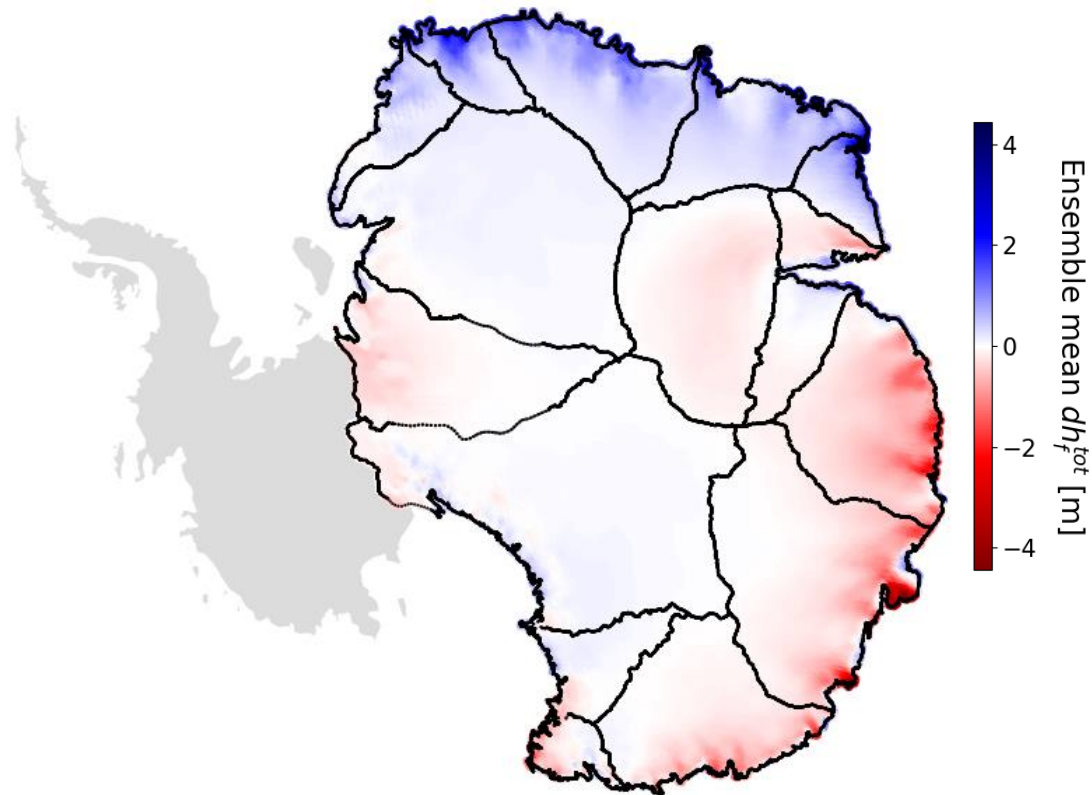
For our simulations: we can use the emulators over the entire EAIS



Evaluation of the emulators: match of the emulated firn compaction results with the corresponding FDM results.

Left: total compaction over 1979-2017. Right: every daily compaction value. Note: 50 sites and 9 FDM-emulator pairs

Ensemble mean of 1992-2017 firn thickness change (dh_f^{tot})



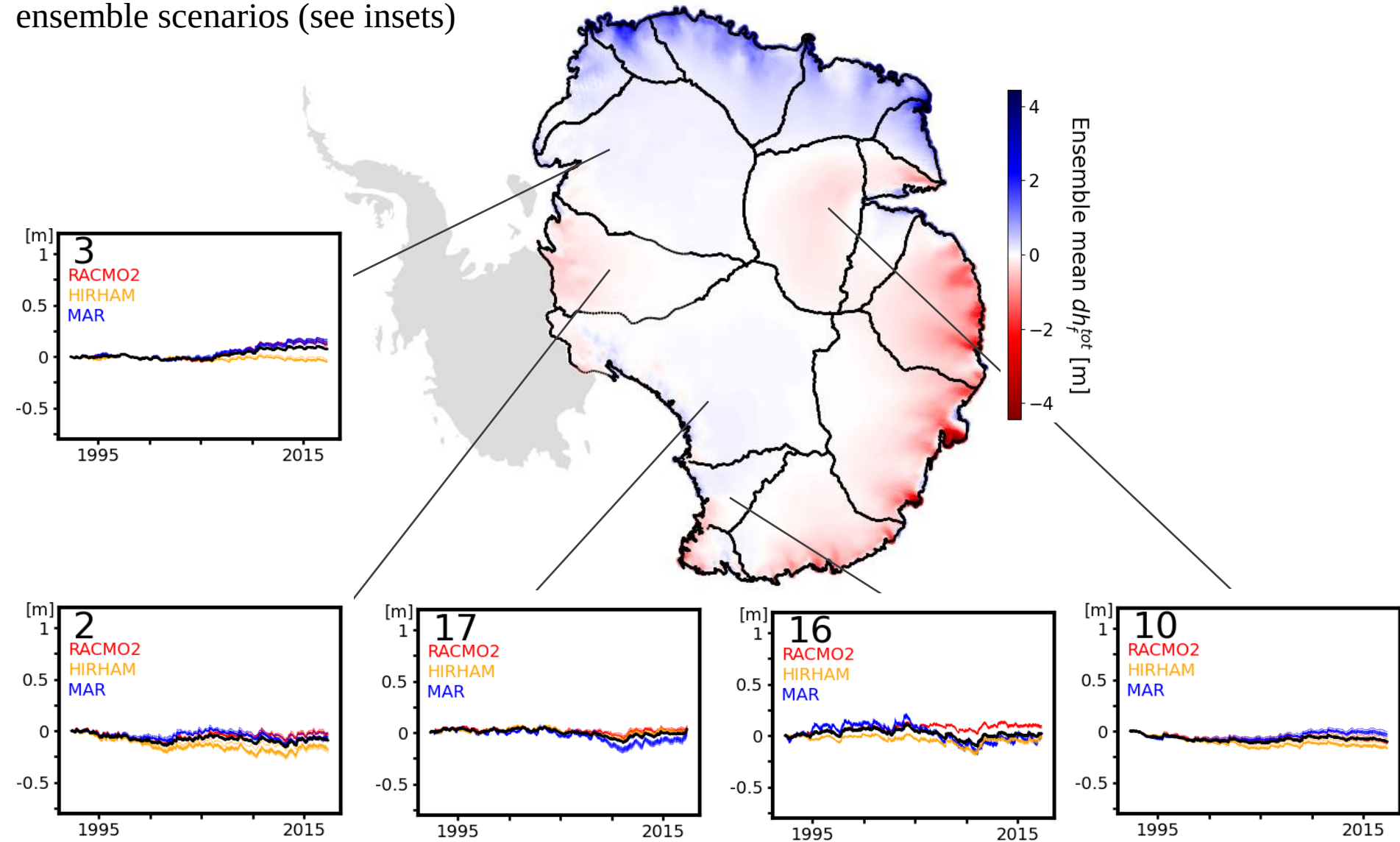
Next slides focus on regional patterns in the Ensemble results.

Guide to the insets shown in the next slides:

Each inset shows the basin-averaged modelled time series of all the 54 model scenarios. Red, yellow and blue curves represent scenarios forced with RACMO2, HIRHAM and MAR respectively. Each curve represents a particular RCM-FDM- ρ_0 combination. The thick black curve represents the ensemble mean. Basin numbers are displayed within the insets. Frame colours show whether dh_f^{tot} is significantly positive (blue), negative (red) or not significantly different from zero (black) (at $\pm 2\sigma$).

Ensemble mean of firn thickness change (dh_f^{tot})

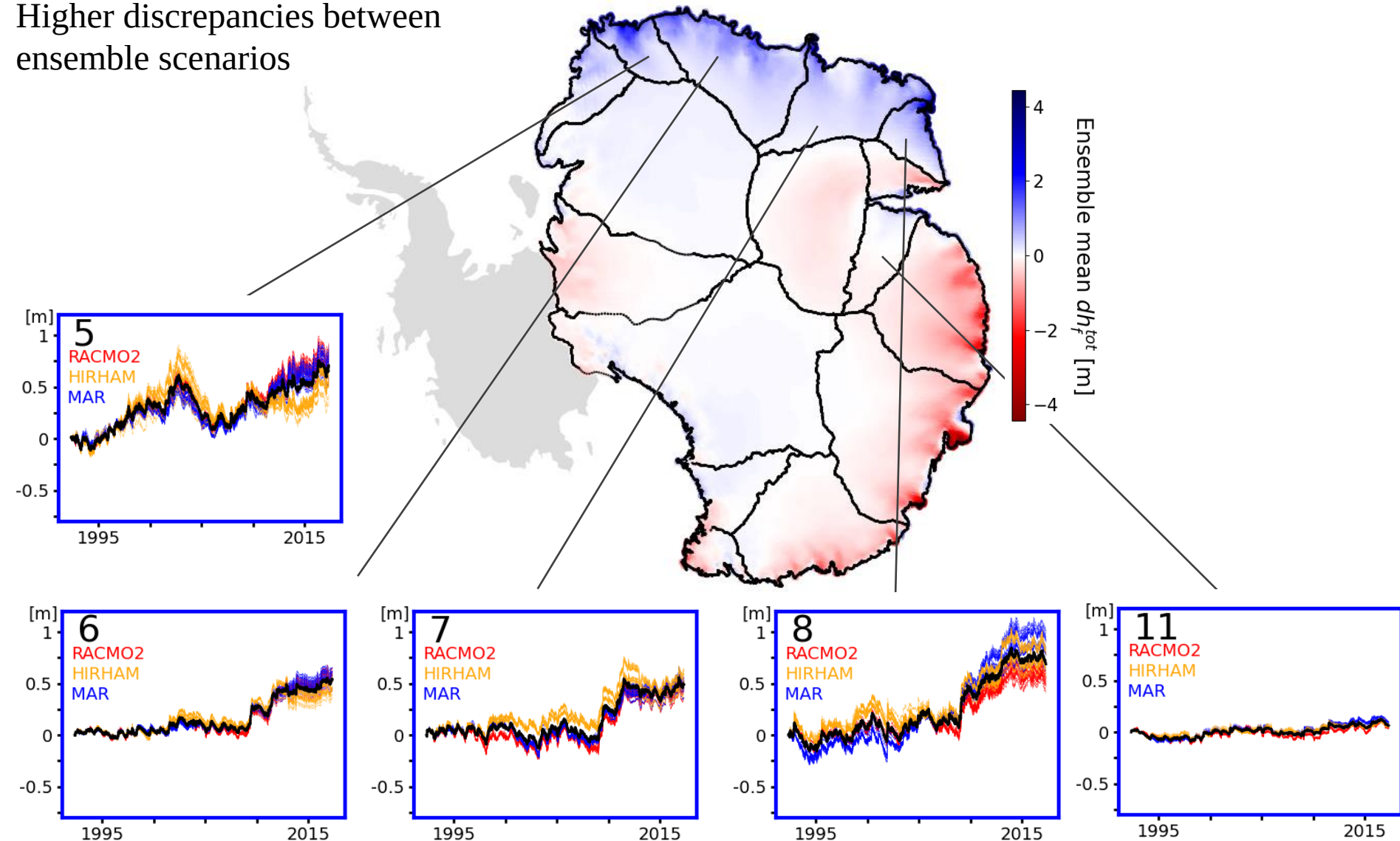
- 1) Cold interior basins show stable firn layer thickness: no significant change
Good agreement between the different ensemble scenarios (see insets)



Ensemble mean of firn thickness change (dh_f^{tot})

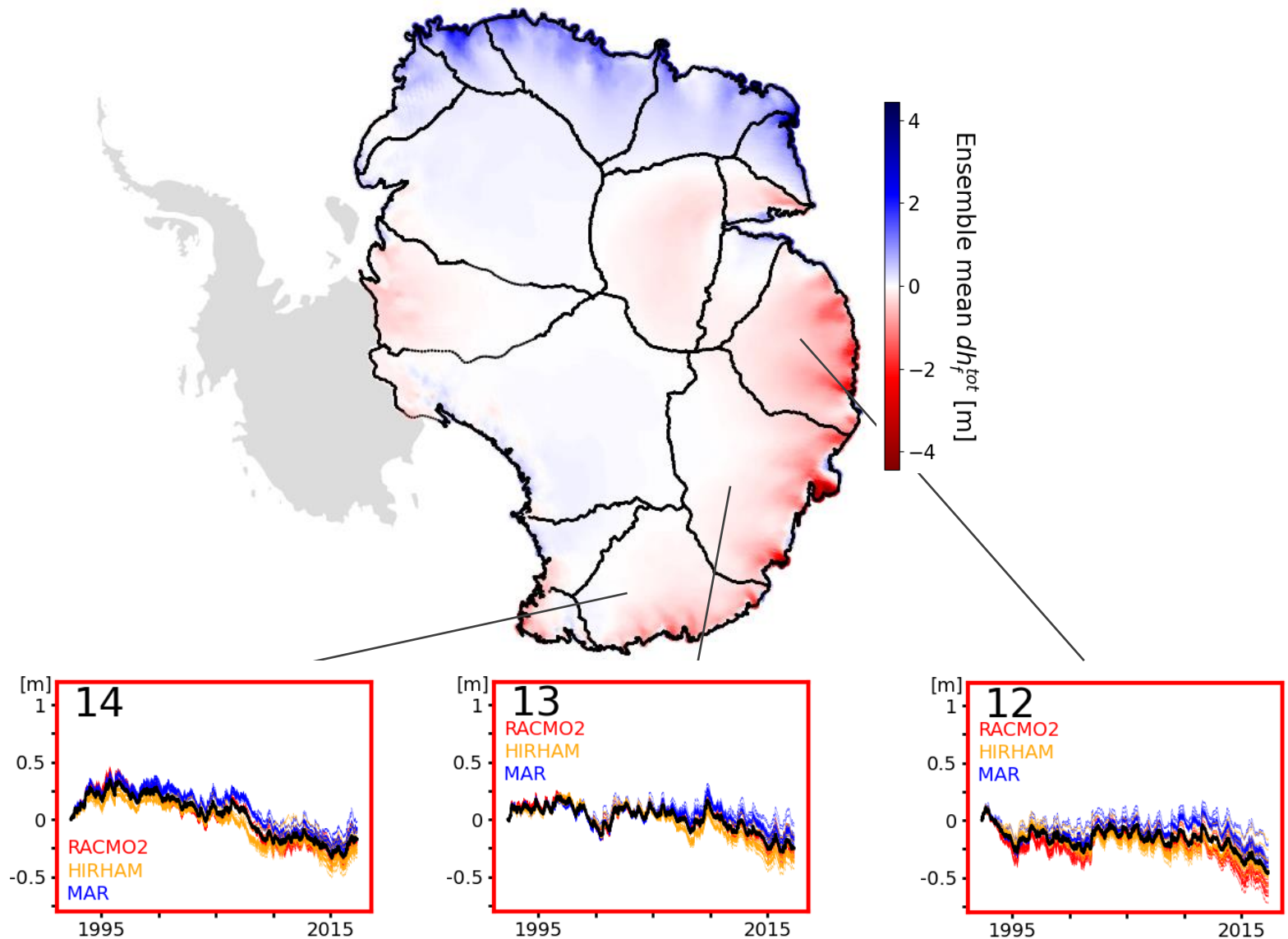
2) Pronounced and significant thickening of basins in Dronning Maud Land driven by higher snowfall

Higher discrepancies between ensemble scenarios



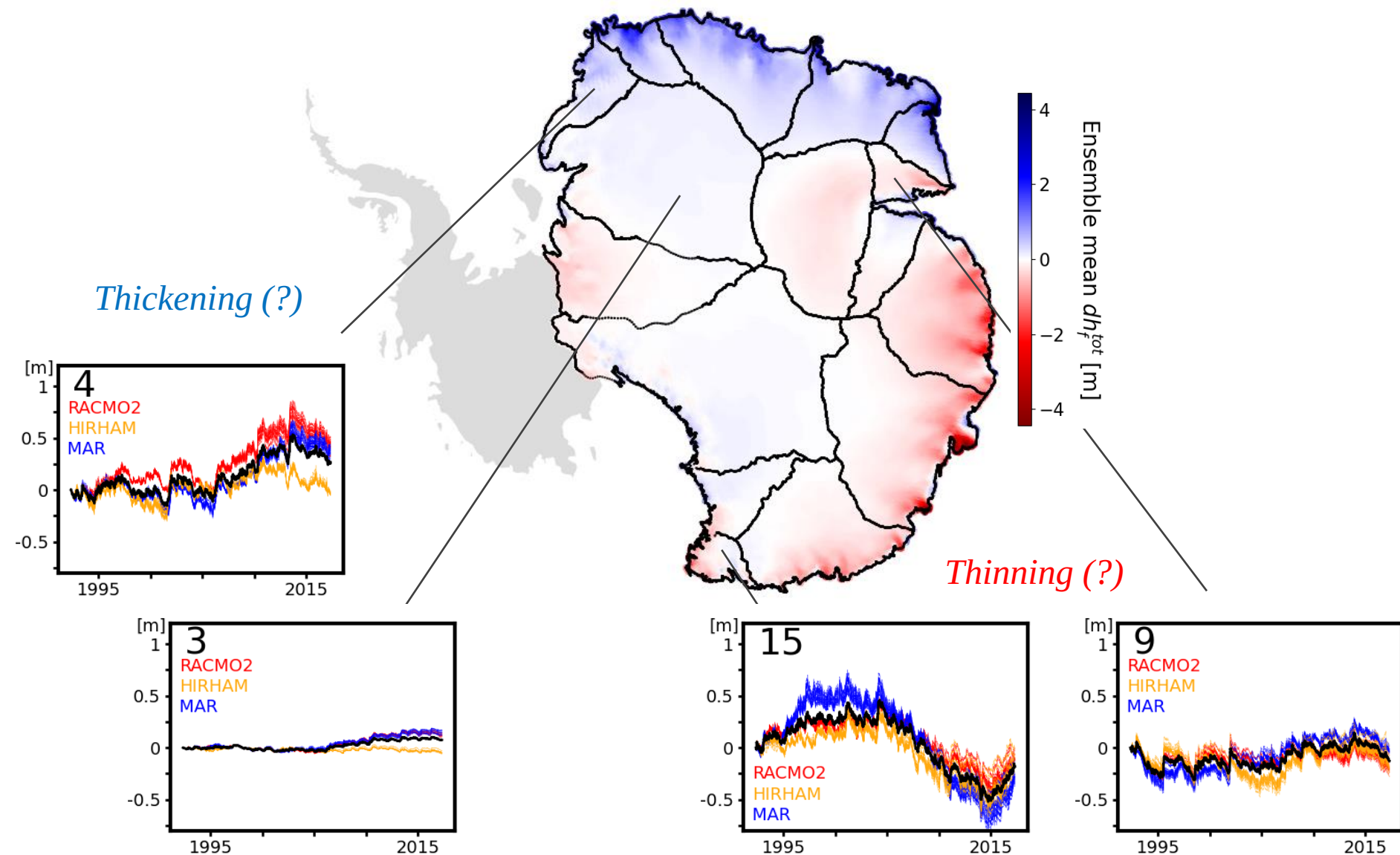
Ensemble mean of firn thickness change (dh_f^{tot})

3) Significant thinning in areas of Shackleton ice shelf, Totten glacier and Victoria Land

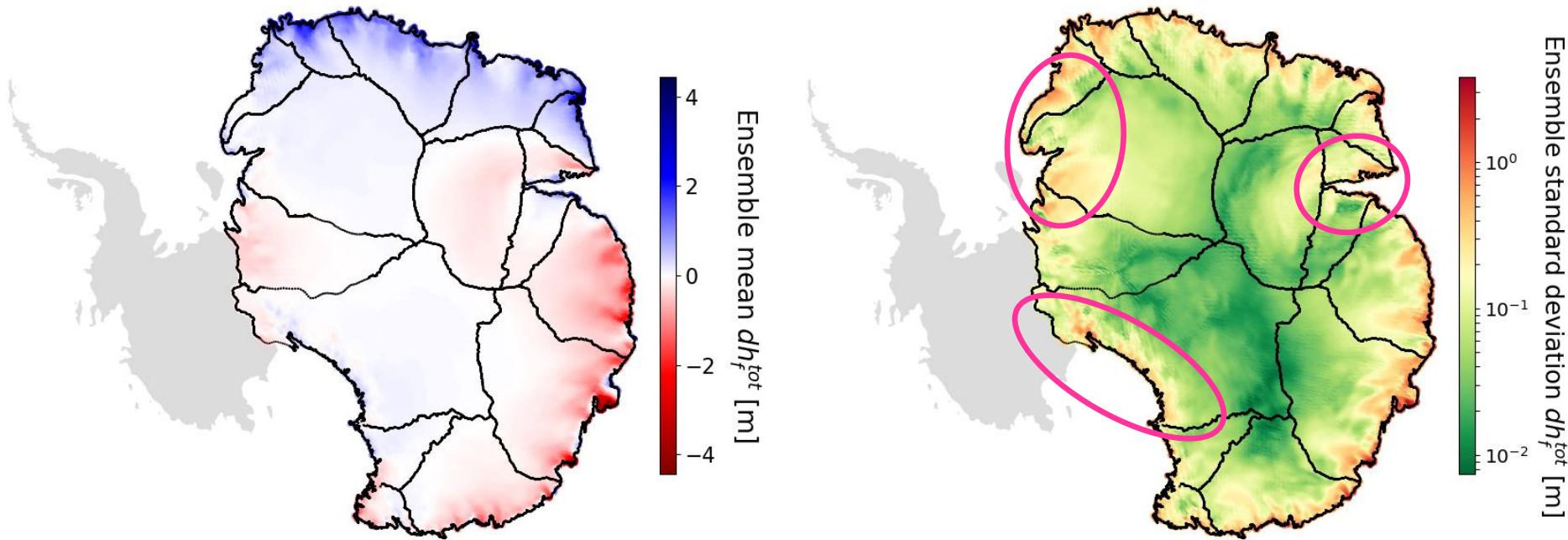


Ensemble mean of firn thickness change (dh_f^{tot})

4) Some basins show thinning/thickening patterns, but relative model spread is high



Ensemble uncertainty



- Using the standard deviation as a measure of model uncertainty
- Good model agreement in areas of stable firn thickness
- Higher disagreements in areas of substantial thinning/thickening
- Still, specific areas show minor change but high uncertainty (highlighted in pink)

At basin level: uncertainties on trend in firn thickness changes range between
 $[0.2 - 1.0] \text{ cm yr}^{-1} \leftrightarrow [15 - 300] \%$

Uncertainty decomposition by Analysis of Variance: dh_f^{tot}

RCM factor
 ρ_0 factor

FDM factor
interaction effects

Pie-diagrams show the uncertainty contributions.
Red circles are proportional to the basin-specific total uncertainty.

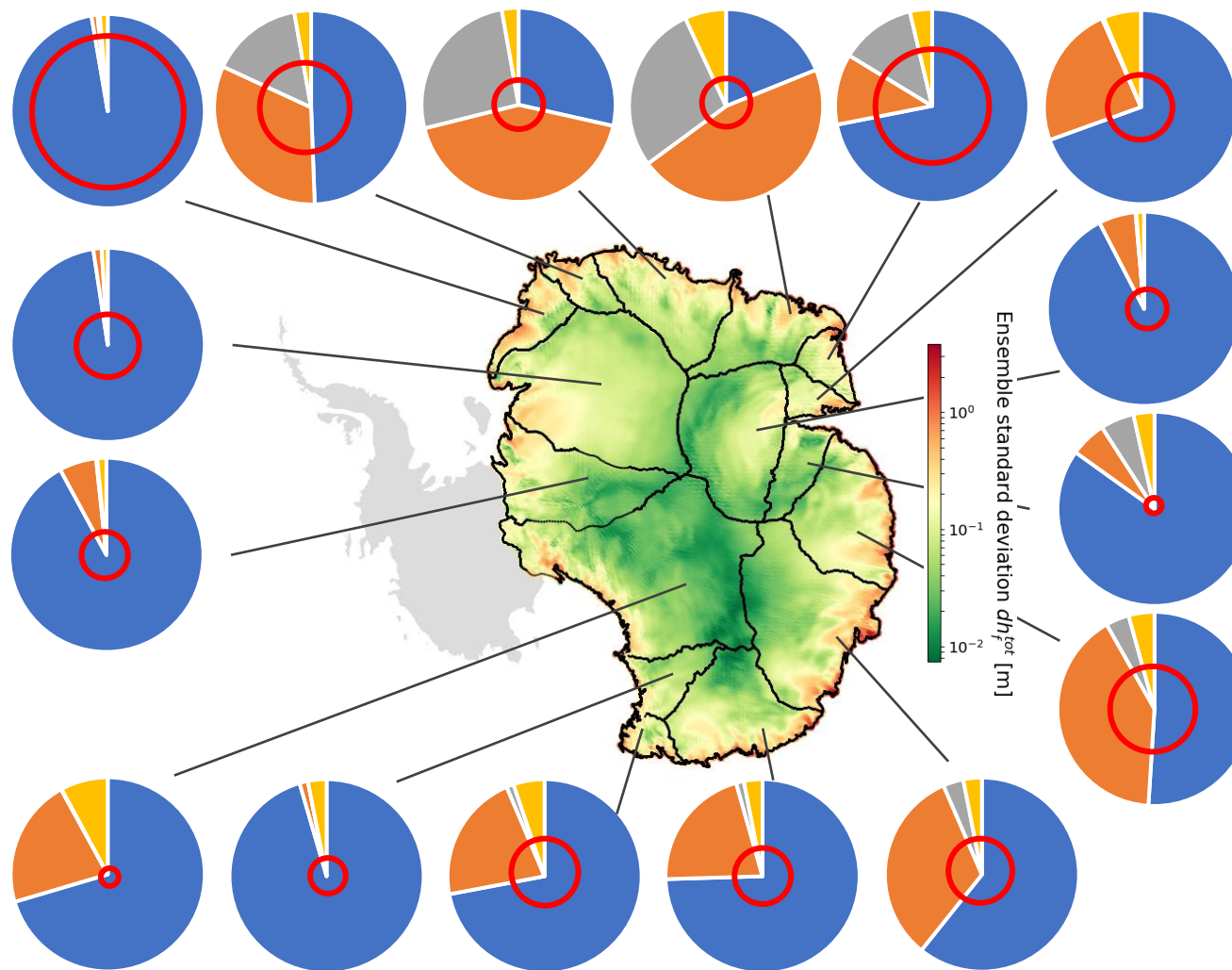
RCM factor dominates (~70%) the ensemble uncertainty.
And most strongly in cold, low snowfall basins (>90%)

FDM factor increases (up to 46%) in basins of:

- Warmer temperatures
- Higher snowfall

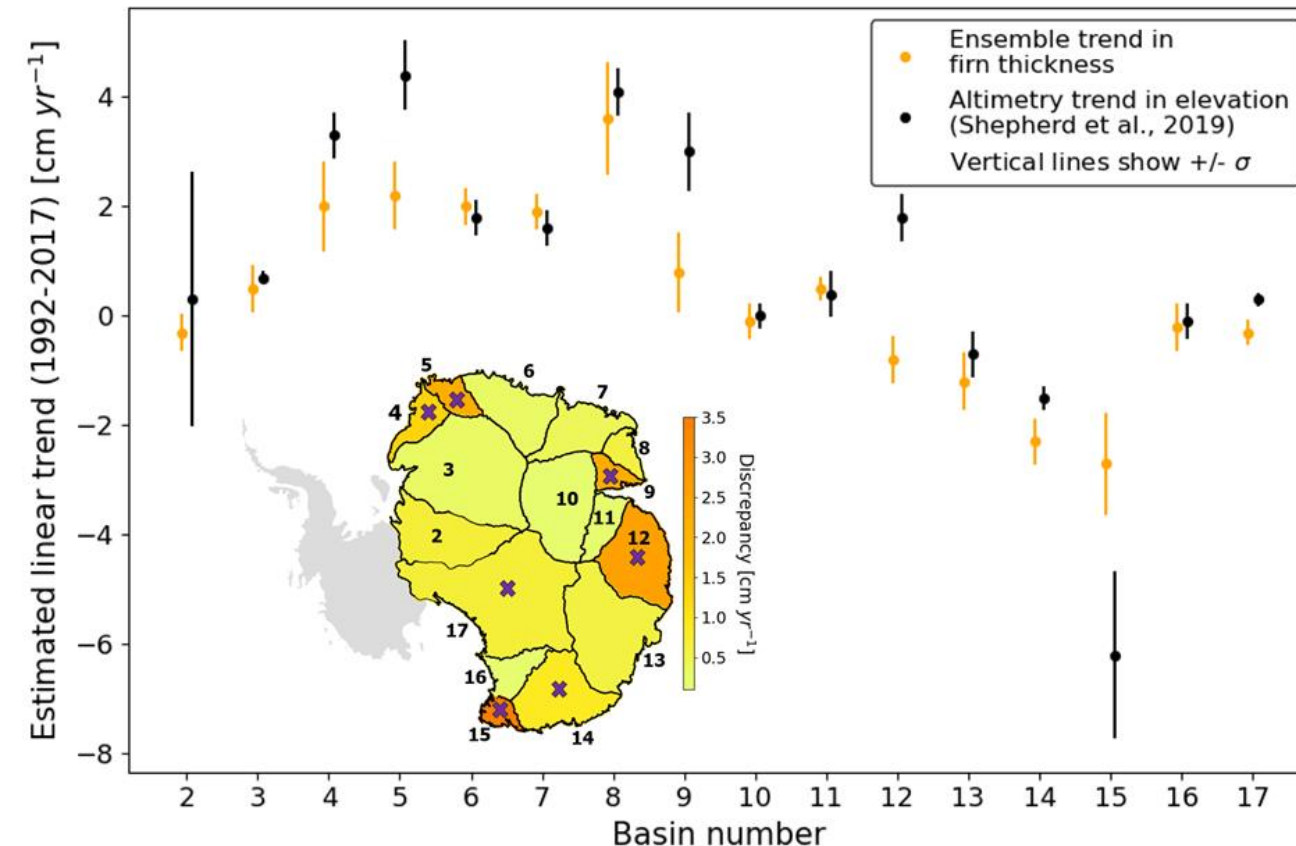
ρ_0 contribution is highest (up to 28%) in basins with substantial snowfall increase

Interaction terms are non negligible across EAIS (1-8%)
These stem from the nonlinear behaviour of the three uncertainty sources (RCM, FDM, ρ_0) when combined in model experiments.



Comparison with altimetry

Ensemble results of firn thickness change can be compared with measured elevation change signal



! Not the same variables !

$$\frac{dh}{dt} = \frac{dh_f}{dt} + \frac{dh_{ice}}{dt}$$

i.e. measurements from altimetry capture both firn thickness change and ice flow imbalance

✕ basins with non-overlapping uncertainty intervals

Conclusions

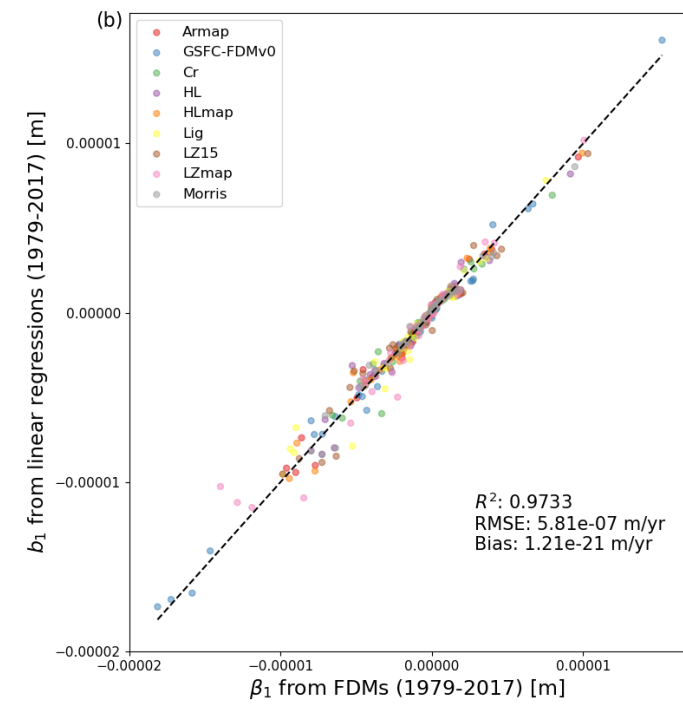
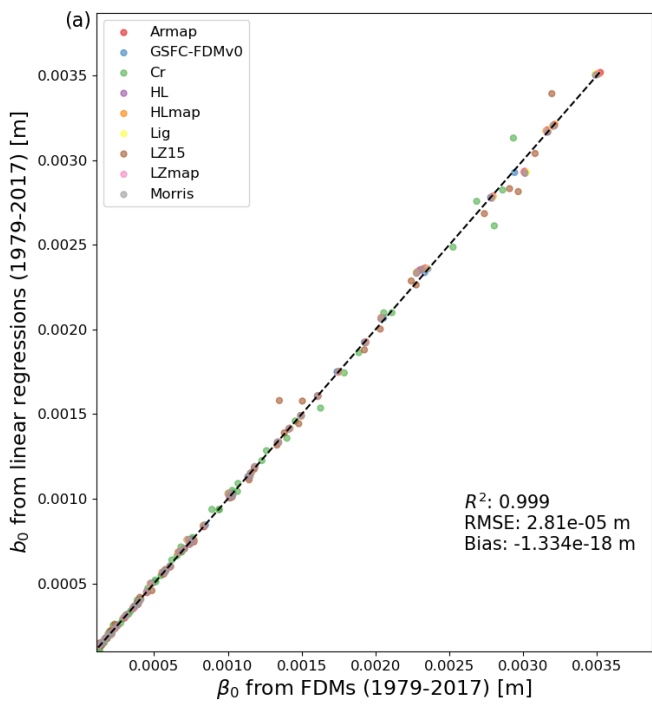
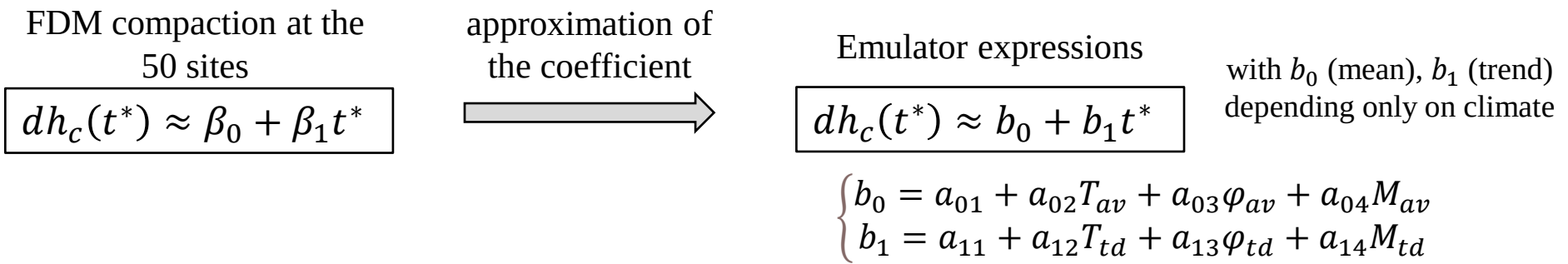
- Using statistical emulation of firm models, we develop and compute a comprehensive range of 54 model scenarios of EAIS firm thickness change.
 - At basin-level, model uncertainties range between $[0.2 - 1.0]$ cm yr⁻¹ (15 – 300 %).
 - Contributions of RCM, FDM, ρ_0 to the model spread vary in space, but RCM-related uncertainty tends to predominate.
 - Modelled firm thickness change and altimetry agree within 1σ uncertainty ranges in a majority of basins.
 - But several basins show significant Model-Altitude discrepancies, highlighting the need to:
 - (1) Understand cause of the disagreement
 - (2) Further improve model performance
 - (3) Investigate possible inadequacies in uncertainty characterisation (models and altimetry)
- Our results do not allow to identify the exact causes of discrepancies...
- But they highlight areas where more focus is needed and show that further work is required.

Supplementary slides: statistical emulation (1)

Construction of statistical emulators of the 9 FDMs

1) Calibration in representative range of EAIS long-term (1979-2017) climate → 50 sites

Mean (β_0) and trend (β_1) in firn compaction (dh_c) are represented by linear regressions on climatic input



- T Temperature
- φ Accumulation
- M Melt
- av Long-term average
- td Long-term trend

Agreement between FDM means (β_0) and trends (β_1) in firn compaction and the corresponding emulator means (b_0) and trends (b_1)

Note: 50 calibration sites and 9 FDM-emulator pairs → 450 points

Supplementary slides: statistical emulation (2)

The long term linearised compaction time series are well represented by the linear regressions...

Shorter term variability in compaction (seasonality, daily spikes, etc.) captured by GP regression

$$\widehat{dh_c(t^*)} = b_0 + b_1 t^* + \varepsilon(t^*)$$

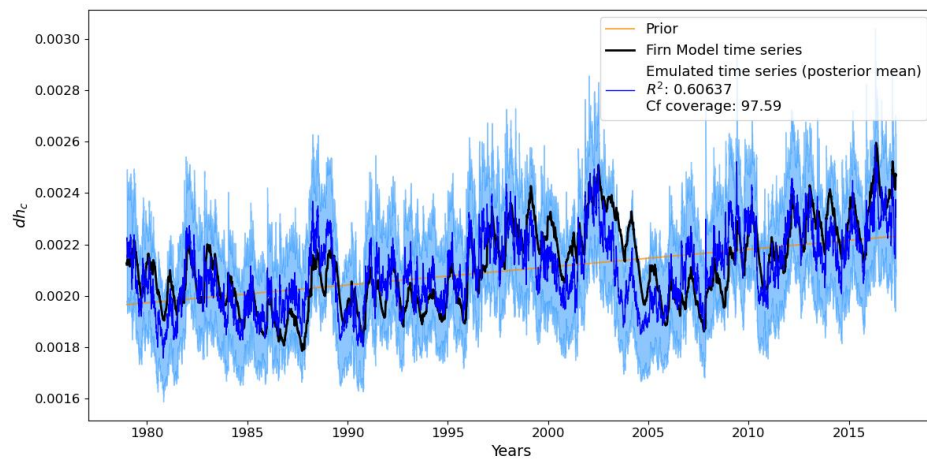
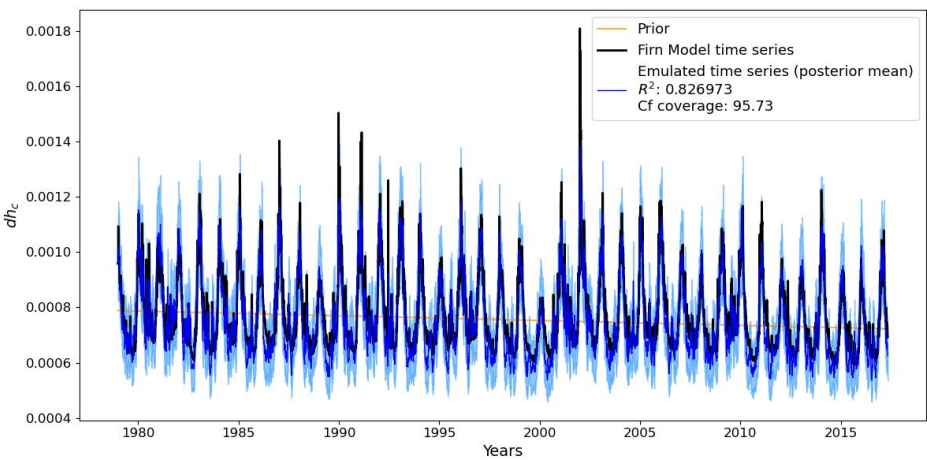
$$\varepsilon \sim GP(0, K(\mathbf{x}, \mathbf{x}'))$$

Stochastic term

with

$$K(\mathbf{x}, \mathbf{x}') = \underbrace{\sigma_f^2 \exp[(\mathbf{x} - \mathbf{x}')^T D^{-1}(\mathbf{x} - \mathbf{x}')] }_{\text{Squared exponential covariance function}} + \underbrace{\nu \delta(\mathbf{x}, \mathbf{x}')}_{\text{Nugget term (prevents overfitting)}}$$

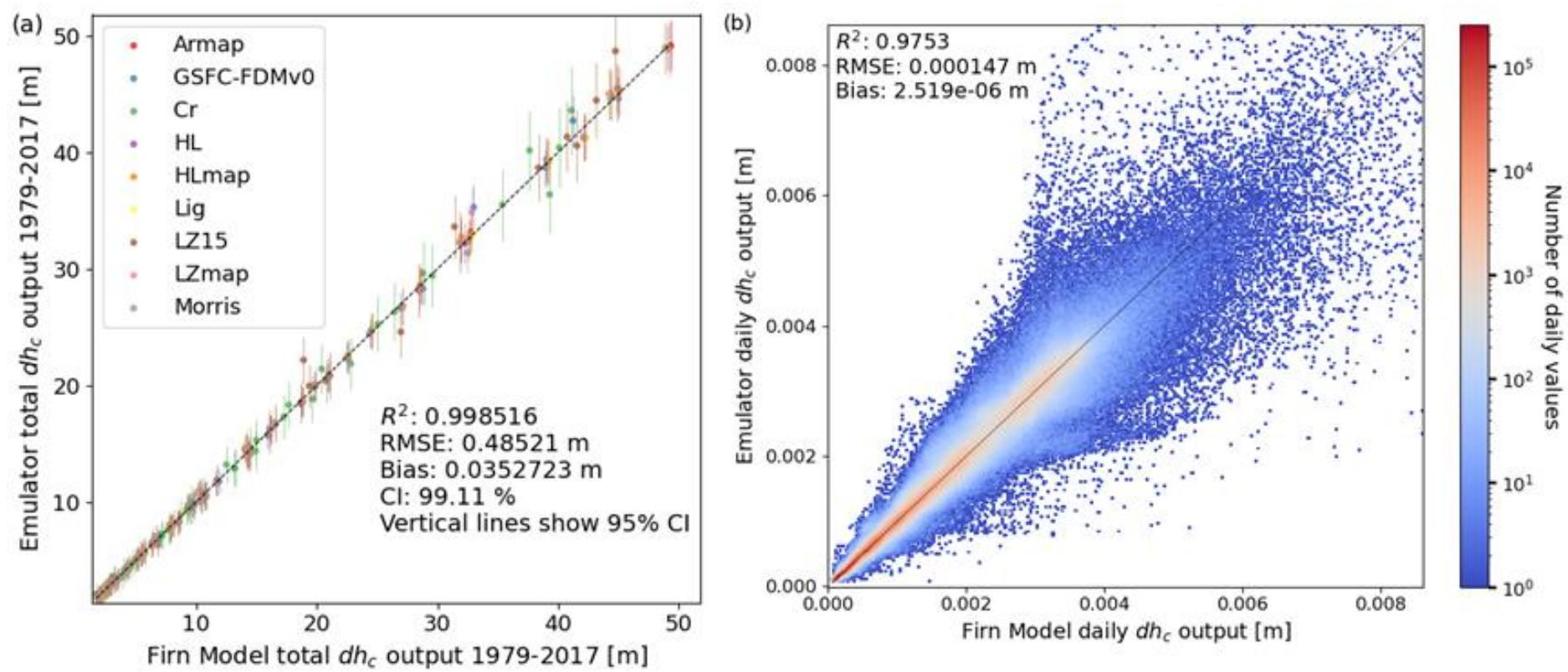
Examples of firm compaction time series emulation



Supplementary slides: statistical emulation (3)

Evaluation by Leave-One-Out Cross Validation:

- (1) One of the 50 calibration sites is left-out of the calibration process
- (2) The emulators are calibrated at the 49 remaining sites
- (3) The results are evaluated at the site left-out
- (4) Go back to (1) for another site left-out and repeat for the 50 sites



Evaluation of the emulators: match of the emulated firn compaction results with the corresponding FDM results. Left: total compaction over 1979-2017. Right: every daily compaction value.

Supplementary slides: List of FDMs, RCMs, ρ_0 used in the Ensemble

	References
FDM	
Armap	Arthern et al. (2010); Verjans et al. (2020)
GSFC-FDMv0	Smith et al. (2020)
Cr	Vionnet et al. (2012); van Kampenhout et al. (2017)
HL	Herron and Langway (1980)
HLmap	Herron and Langway (1980); Verjans et al. (2020)
Lig	Ligtenberg et al. (2011)
LZ15	Li and Zwally (2015)
LZmap	Li and Zwally (2011); Verjans et al. (2020)
Morris	Morris and Wingham (2014)
RCM	
RACMO2.3p2 (27 km)	van Wessem et al. (2018)
MARv3.11 (35 km)	Agosta et al. (2019); Kittel et al. (2020)
HIRHAM5 (12.5 km)	Christensen et al. (2007)
ρ_0	
L11	Ligtenberg et al. (2011)
fixed-350	Smith et al. (2020)