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Observation of transient meltwater accumulation in Greenland with GRACE satellite gravity data

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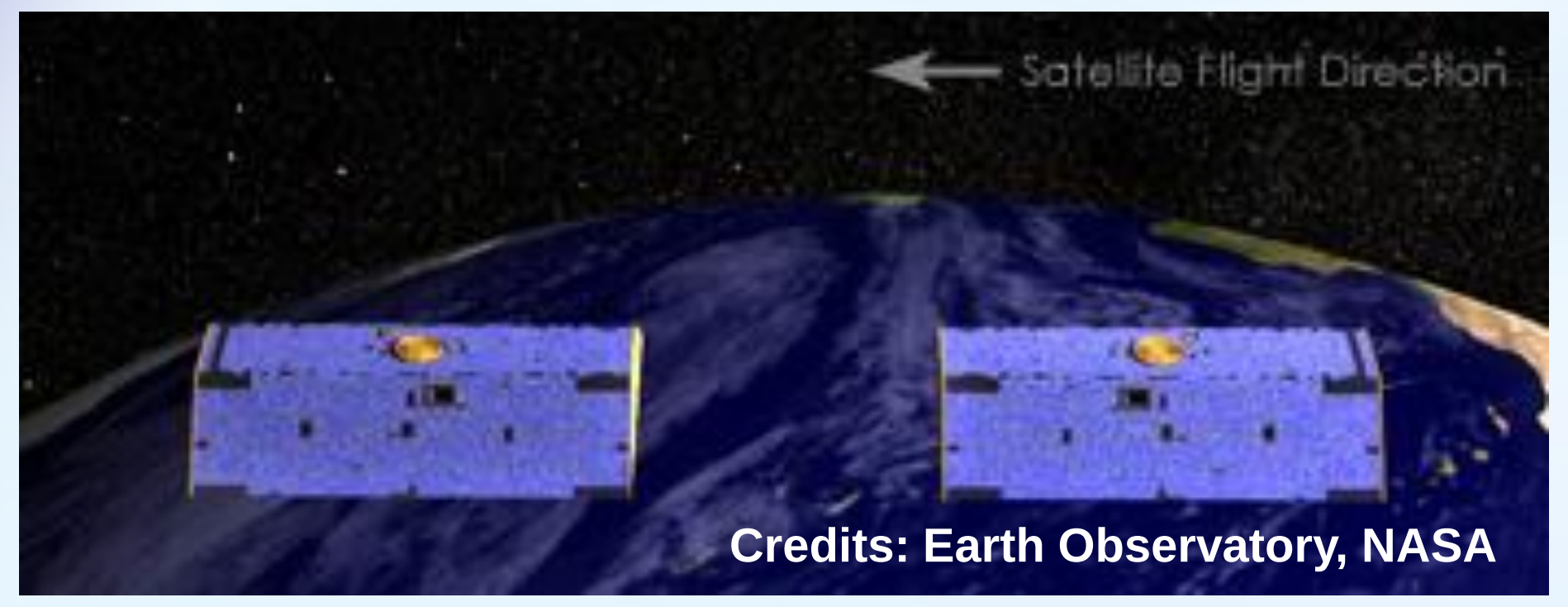
Abstract

A unique feature of satellite gravimetry is its sensitivity to processes not only at the Earth's surface, but also inside the Earth. We apply data from the GRACE satellite gravimetry mission to analyse the mean annual cycle of mass anomalies in Greenland. We reveal systematic discrepancies with respect to the surface mass anomalies based on the Regional Atmospheric Climate Model RACMO.2.3. Our analysis shows that ice discharge, as well as model and data errors are not the likely explanation of those discrepancies. We suggest that they reflect a transient supra-, en-, and sub-glacial accumulation of meltwater. The maximum accumulation integrated over entire Greenland is observed in July (80 – 120 Gt). The largest contributors are the North-West (NW) and South-East (SE) drainage systems (accumulating up to 40 Gt of meltwater each). This is consistent with the largest amount of meltwater produced in these drainage systems based on RACMO2.3.

1. GRACE satellite mission



Credits: Earth Observatory, NASA

The DLR/NASA satellite gravimetry mission GRACE was operational between 2002 and 2017. It delivered global maps of the Earth's gravity field with a temporal sampling of one month. This information allows mass re-distribution in the Earth's system to be monitored. A unique feature of satellite gravimetry is its sensitivity to processes below the Earth's surface.

2. Data processing

We use monthly maps of the Earth's gravity field provided in the spectral representation (in the form of spherical harmonic coefficients). After applying commonly-used corrections (including the subtraction of the Glacial Isostatic Adjustment signal), we convert those data into mass anomalies using the "mascon approach". The major data processing steps are:

- Computation of gravity disturbances at satellite altitude above Greenland and a buffer zone and computation of their full error covariance matrices.
- Subtraction of gravity disturbances associated with surface mass variations.
- Inversion of gravity disturbances into mass anomalies in homogeneous patches ("mascons") tiling the territory of Greenland (inversion is performed both with and without the data weighting based on the error covariance matrices).
- Aggregation of individual mascons to obtain mass anomalies per drainage system or for entire Greenland
- Computation of the mean mass anomalies per calendar month (i.e., the mean annual cycle of mass anomalies).

3. Primary data

- GRACE data: CSR RL5 monthly solutions + their full error covariance matrices
- Glacial Isostatic Adjustment model: A et al (GJI, 2013)
- Surface mass variations: Regional Atmospheric Climate Model RACMO2.3.

4. Geometry of mascons and drainage systems

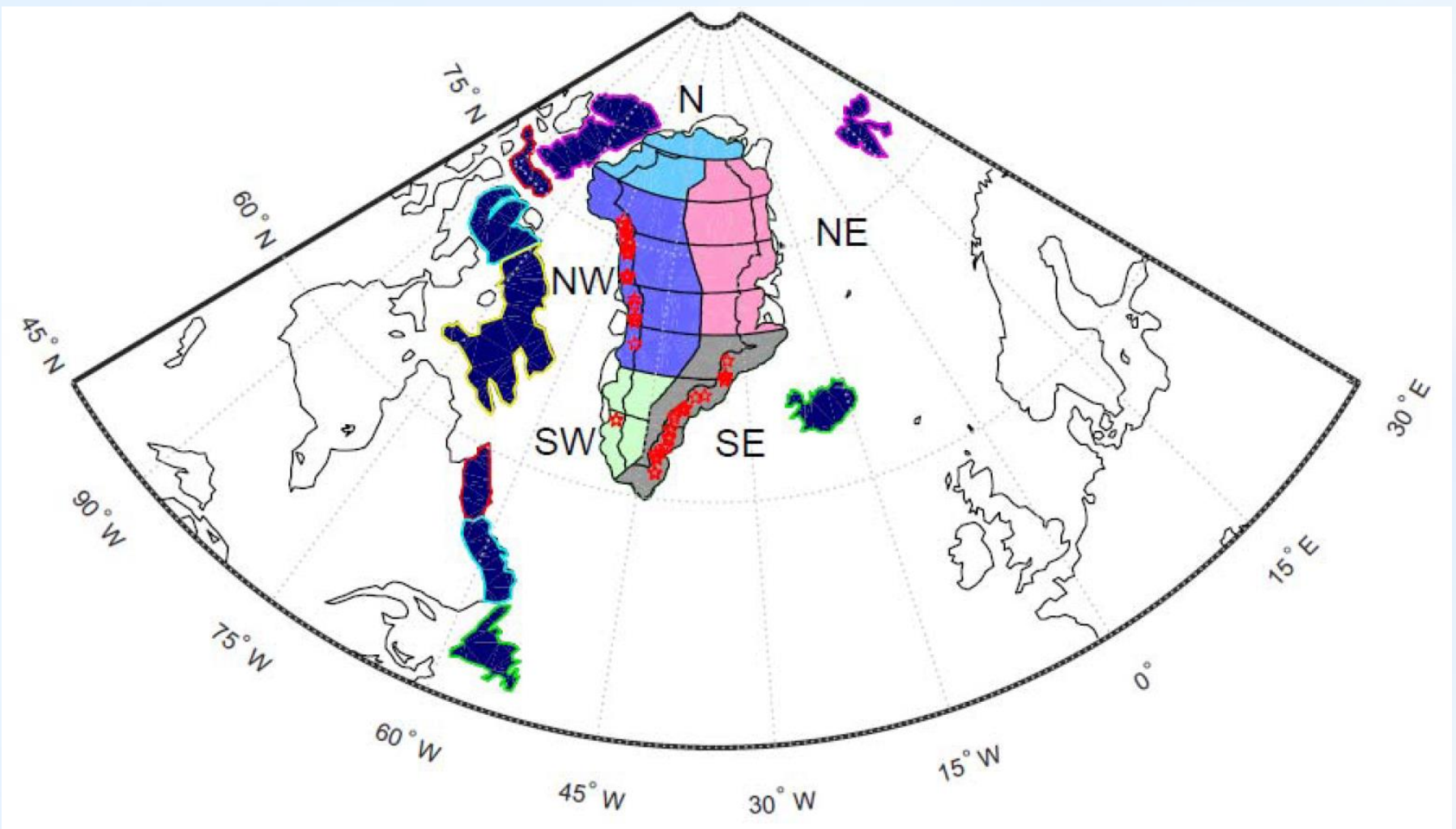


Fig.1 The territory of Greenland is panelized into 28 mascons, which are aggregated into five drainage systems. In addition, 9 mascons outside Greenland are defined to account for possible mass variations there. Red stars denote the glaciers considered in the estimation of ice discharge (see Sect. 8)

5. Mean annual cycle of mass anomalies integrated over entire Greenland

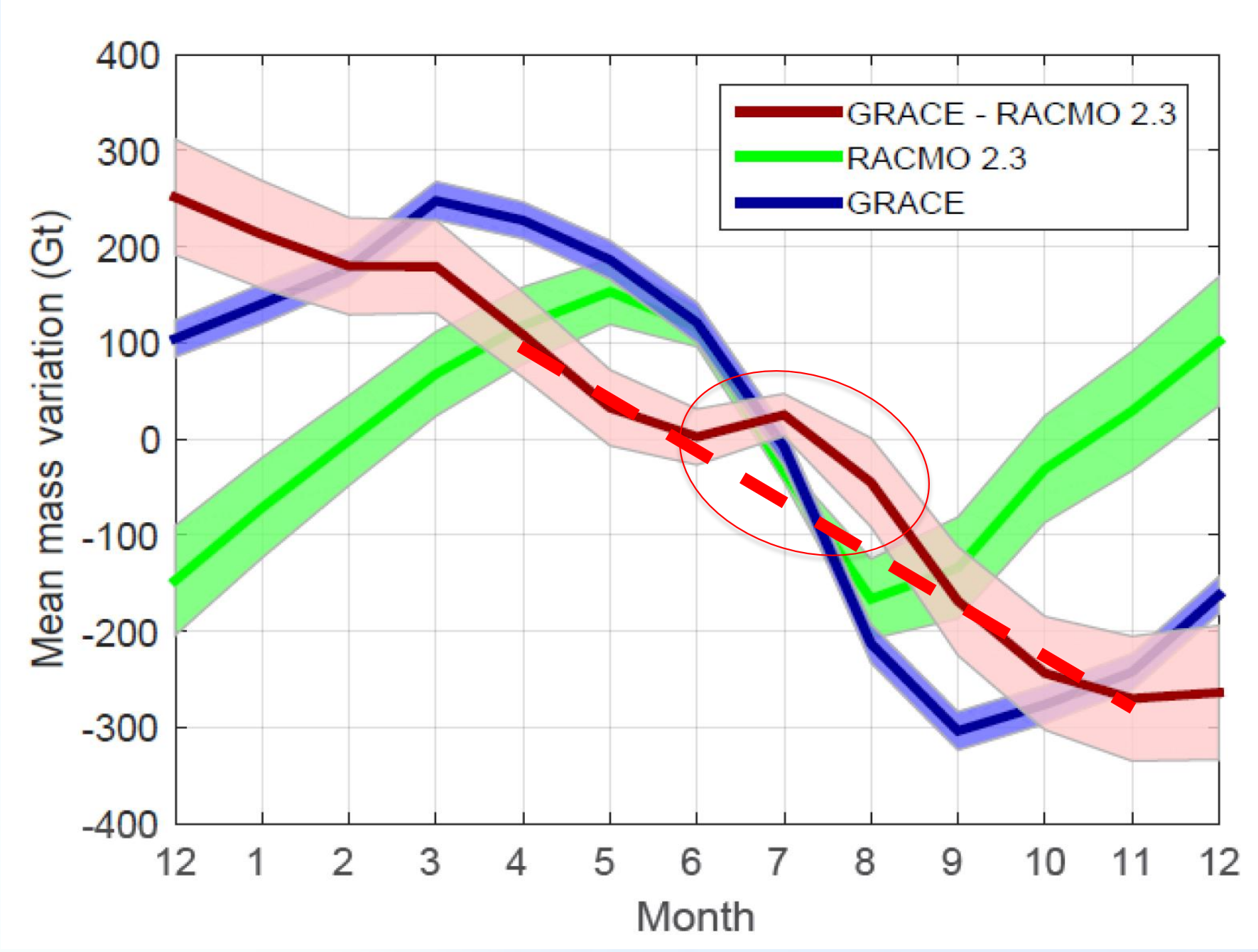


Fig.2 Mean annual cycle of: total mass anomalies observed with GRACE (blue); surface mass anomalies from RACMO2.3 (green); and residual mass anomalies (brown). The shaded areas indicate the 1-σ error bars. Data weighting in the data inversion procedure is switched on. The positive variation of residual mass anomalies in July-August (enclosed in a red oval) is likely evidence of a transient meltwater accumulation.

6. Isolation of the transient meltwater storage signal

To eliminate the effect of ice discharge and isolate the transient meltwater storage signal, we fit a regression line to the annual cycle of residual mass anomalies in April-May and September-November (dashed red line in Fig.2).

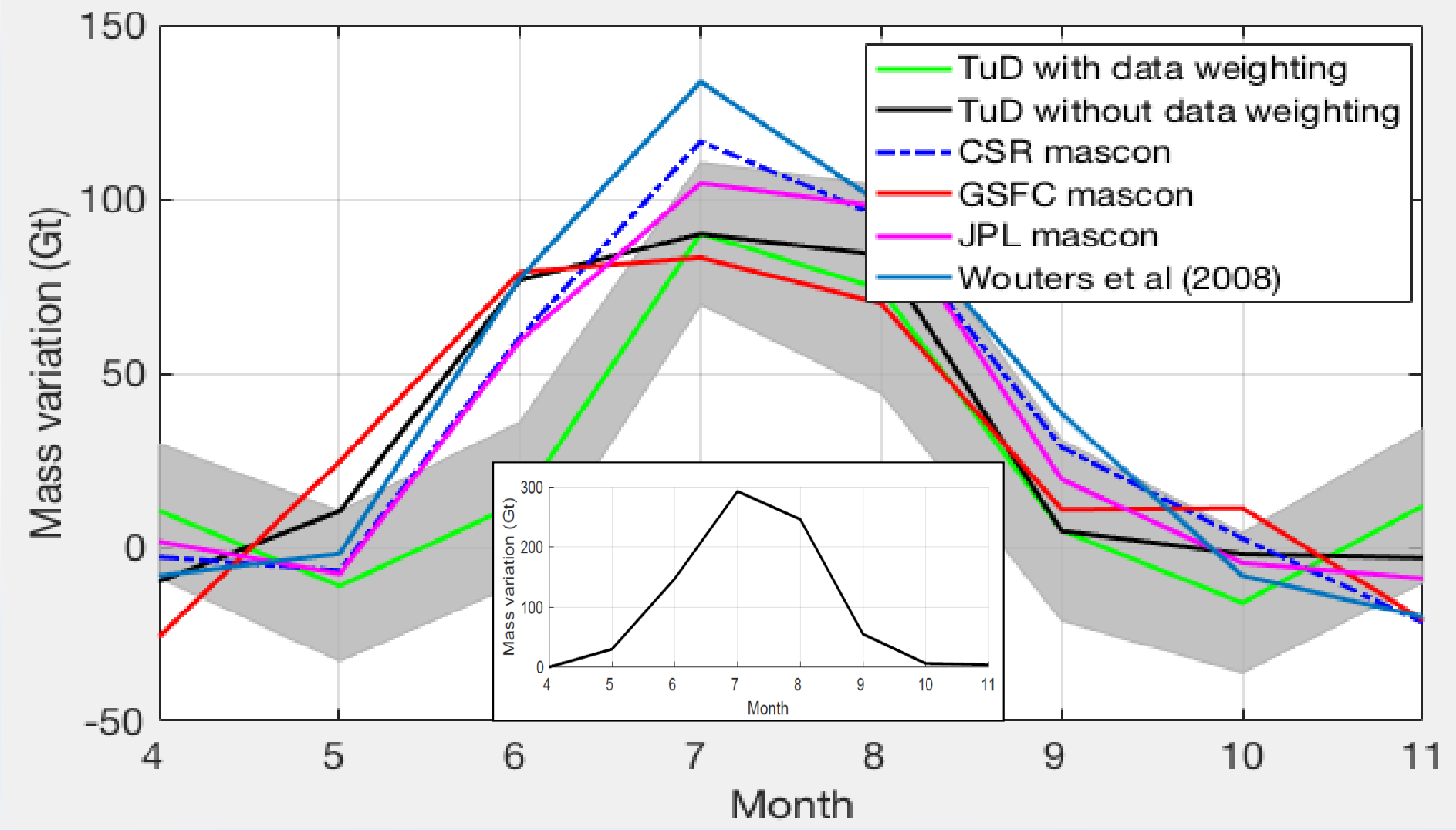


Fig.3 Annual cycle of mass anomalies associated with the hypothesized transient meltwater storage obtained by subtracting the estimated linear function from the annual cycle of residual mass anomalies. A strong peak (of 80–120 Gt) in summer months is observed both in the TUD mascon solutions (this study) and in other mascon solutions – from CSR, GSFC, JPL, and Wouters et al (2008) – though the amplitude and timing from these solutions are somewhat different. The observed signal also shows a good correlation with the monthly meltwater production from RACMO2.3 (inset).

7. Robustness with respect to modelling the surface mass anomalies

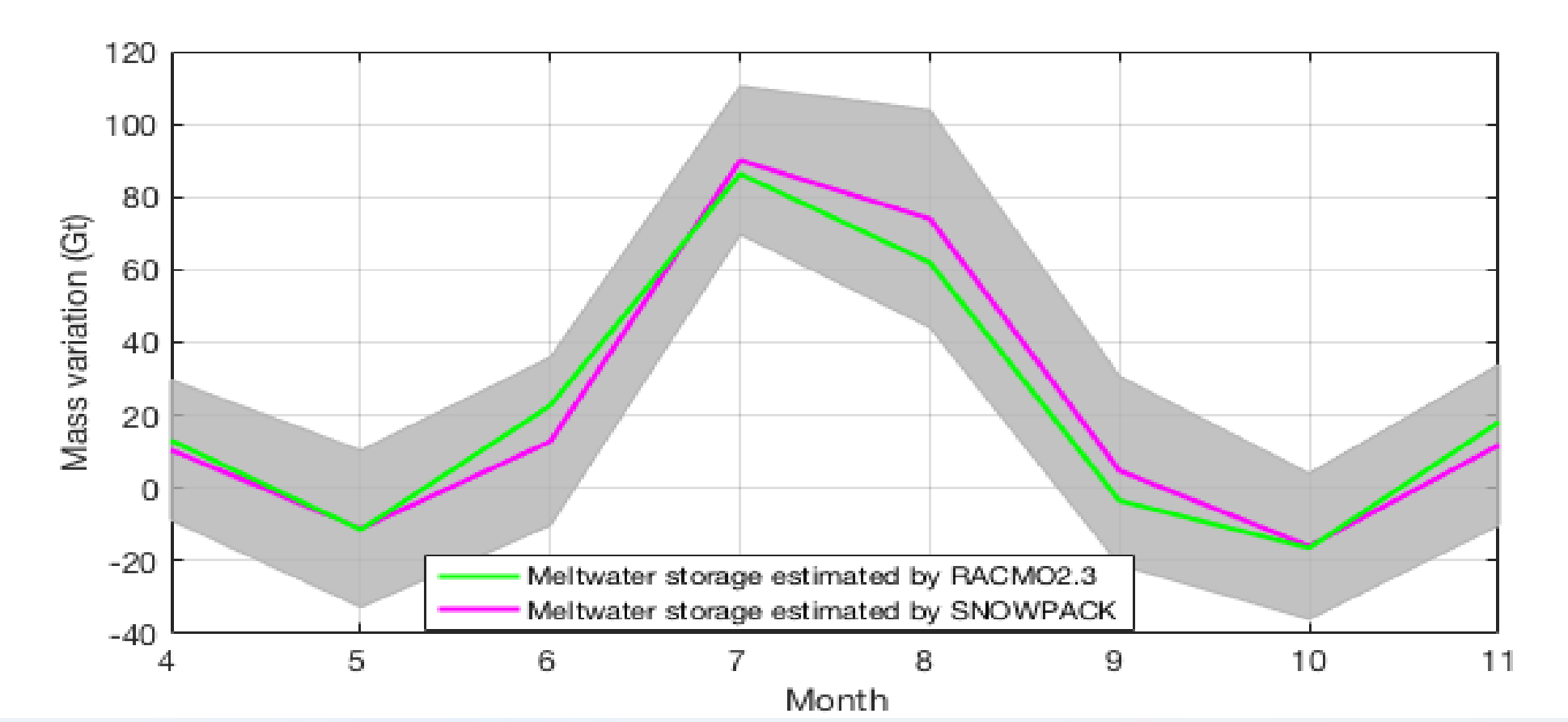


Fig.4 Annual cycle of mass anomalies presumably associated with the transient meltwater storage. The estimates are based on surface mass anomalies from RACMO2.3 and the SNOWPACK model respectively. The differences do not exceed 12 Gt.

8. Contribution of temporal variations in ice discharge

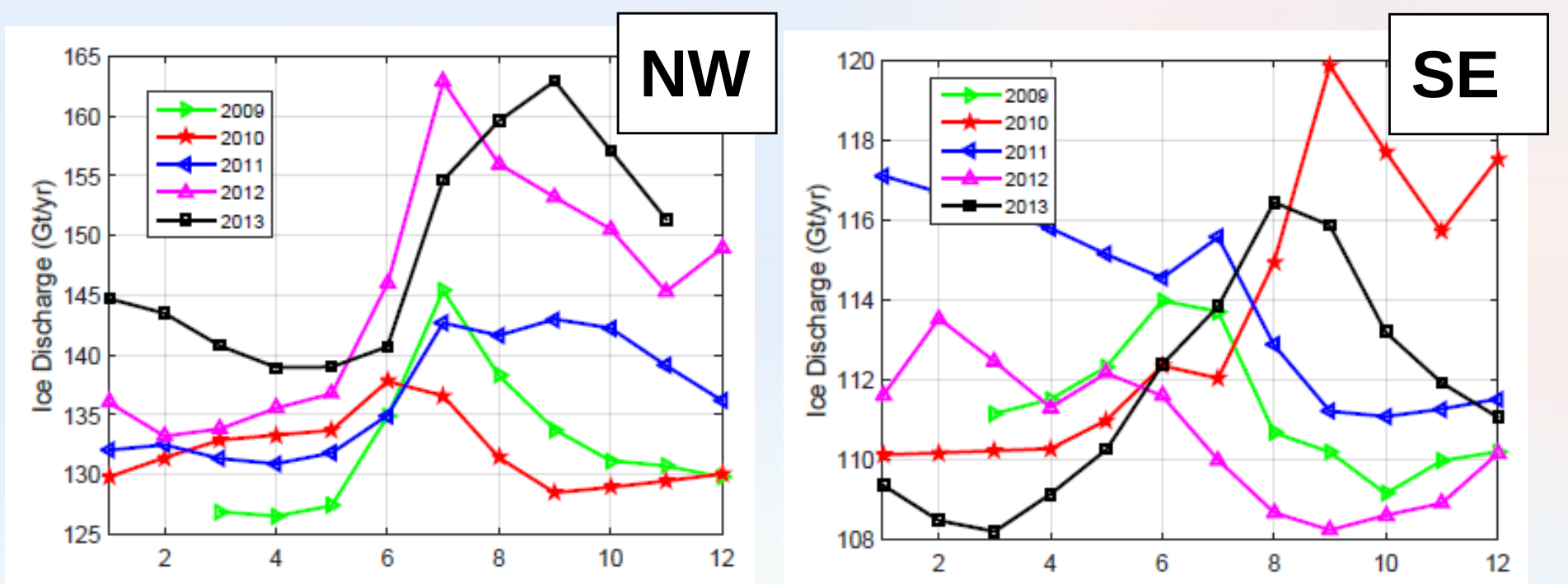


Fig.5. Temporal variations in ice discharge in 2009–2013 obtained by the summation of estimates for individual marine-terminating glaciers located in the NW (left) and SE (right) drainage system. Locations of the considered glaciers are depicted with red dots in Fig.1 (55 glaciers in total). The observed variations stay within 10-20%.

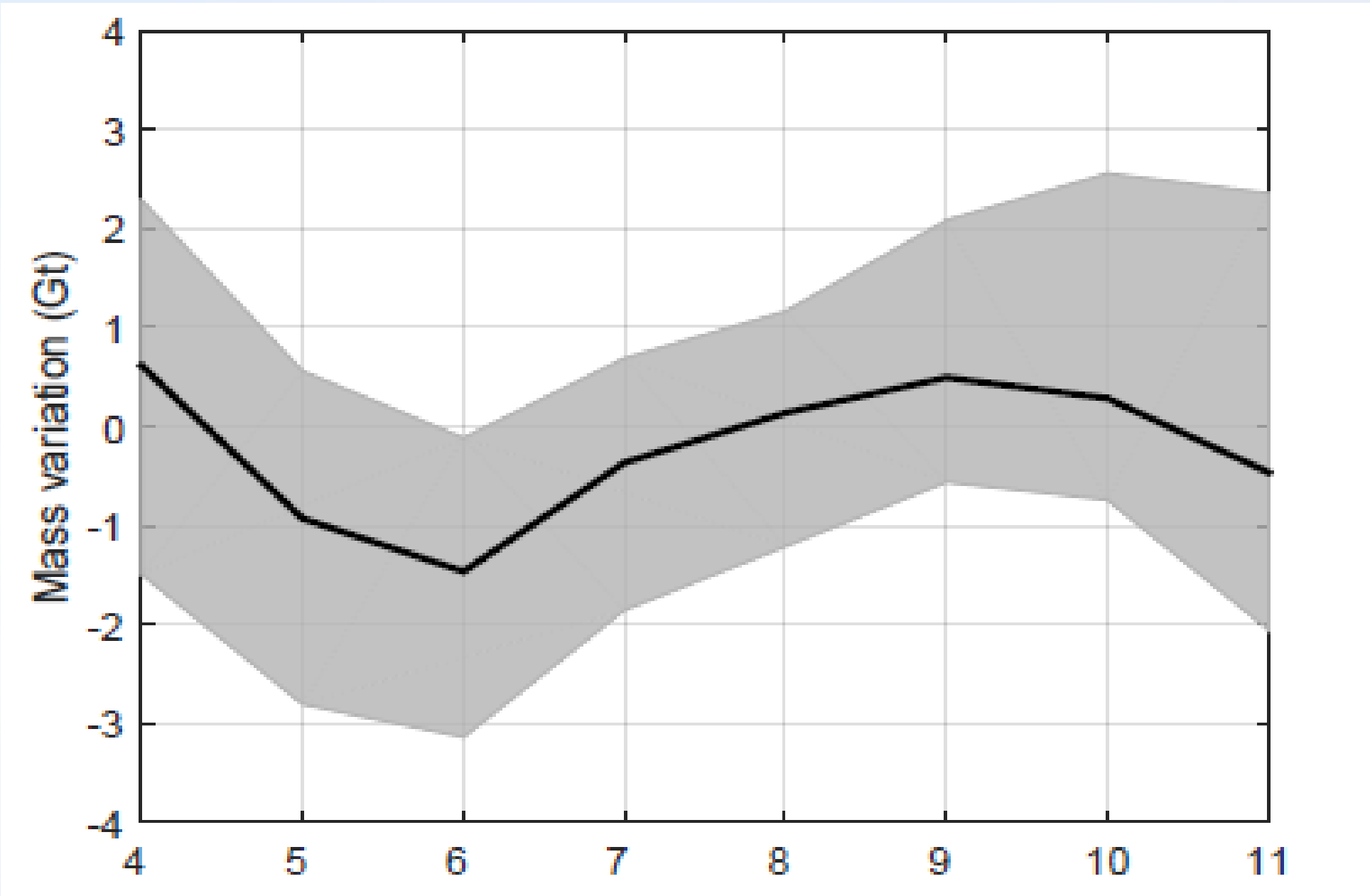


Fig.6. Contribution of ice discharge to the annual cycle of mass anomalies associated with the transient meltwater storage. The values are obtained by (i) the summation of ice discharge estimates over the 55 considered glaciers; (ii) up-scaling to match the long-term discharge-related trend estimated for the entire Greenland (Enderlin et al., 2014); (iii) converting into the mean mass anomalies per calendar month; (iv) subtracting a linear function fitting the values from the annual cycle in April-May and September-November. The results show that the contribution of ice discharge to the residual mass anomalies amounts to only a few Gt (i.e., is negligible).

9. Transient meltwater storage in NW and SE drainage systems

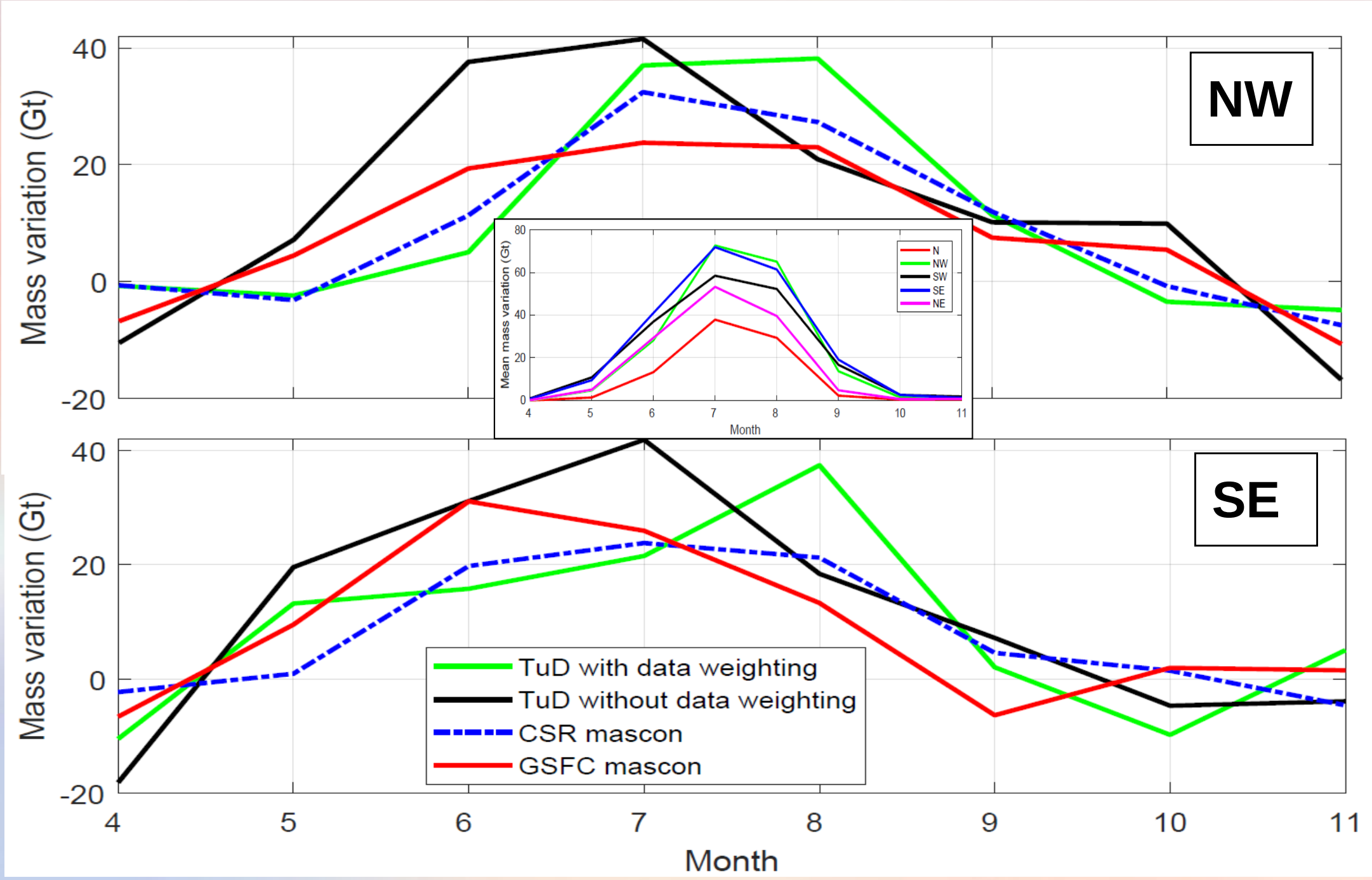


Fig.7 Annual cycle of mass anomalies associated with the transient meltwater storage in the NW (top) and SW (bottom) drainage systems. These drainage systems are the largest contributors (up to 40 Gt each) to the integrated values for the entire Greenland. This is consistent with the largest meltwater production in these drainage systems from RACMO2.3 (inset in the top plot).

10. Conclusions

- Annual cycles of GRACE-based total mass anomalies in Greenland and model-based surface mass anomalies show large discrepancies in summer that cannot be explained by ice discharge, model errors or data errors.
- The most likely explanation of the observed discrepancies is a transient accumulation of meltwater (supra-, en-, and sub-glacial). It attains values of 80-120 Gt in July for the entire Greenland.
- The largest contributors are the NW and SE drainage systems (up to 40 Gt each), which is consistent with the largest meltwater production from RACMO2.3.
- For more information, see (Ran et al., 2018).

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