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Supplement of

Seasonal glacier motion variations and underlying hydro-mechanical processes at Glacier d'Argentière, French Alps

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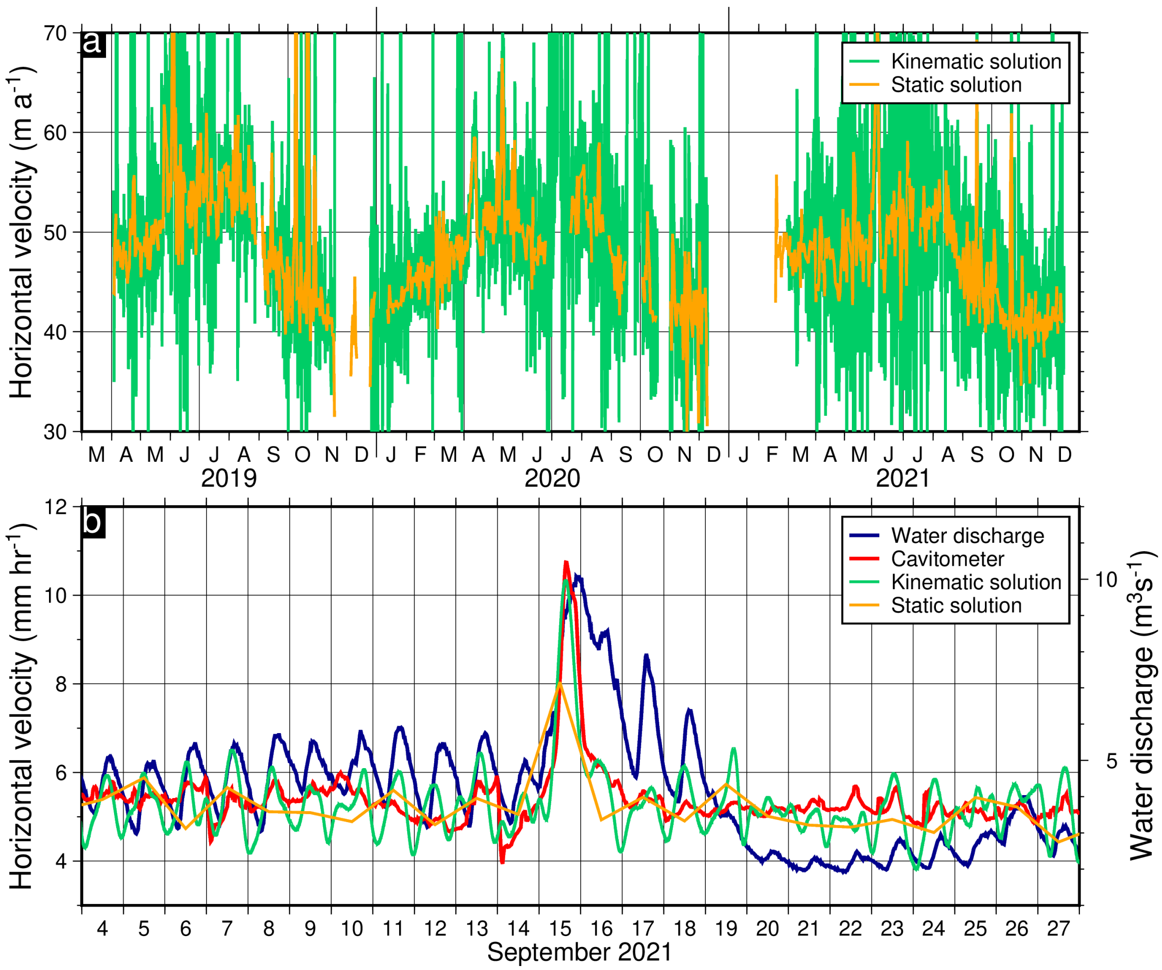

Figure S1: Comparison of static and kinematic GNSS solutions for site ARG1. (a) Multi-year horizontal velocty time series from 2019 to 2021. (b) High-resolution comparison over a shorter observational window in September 2021.

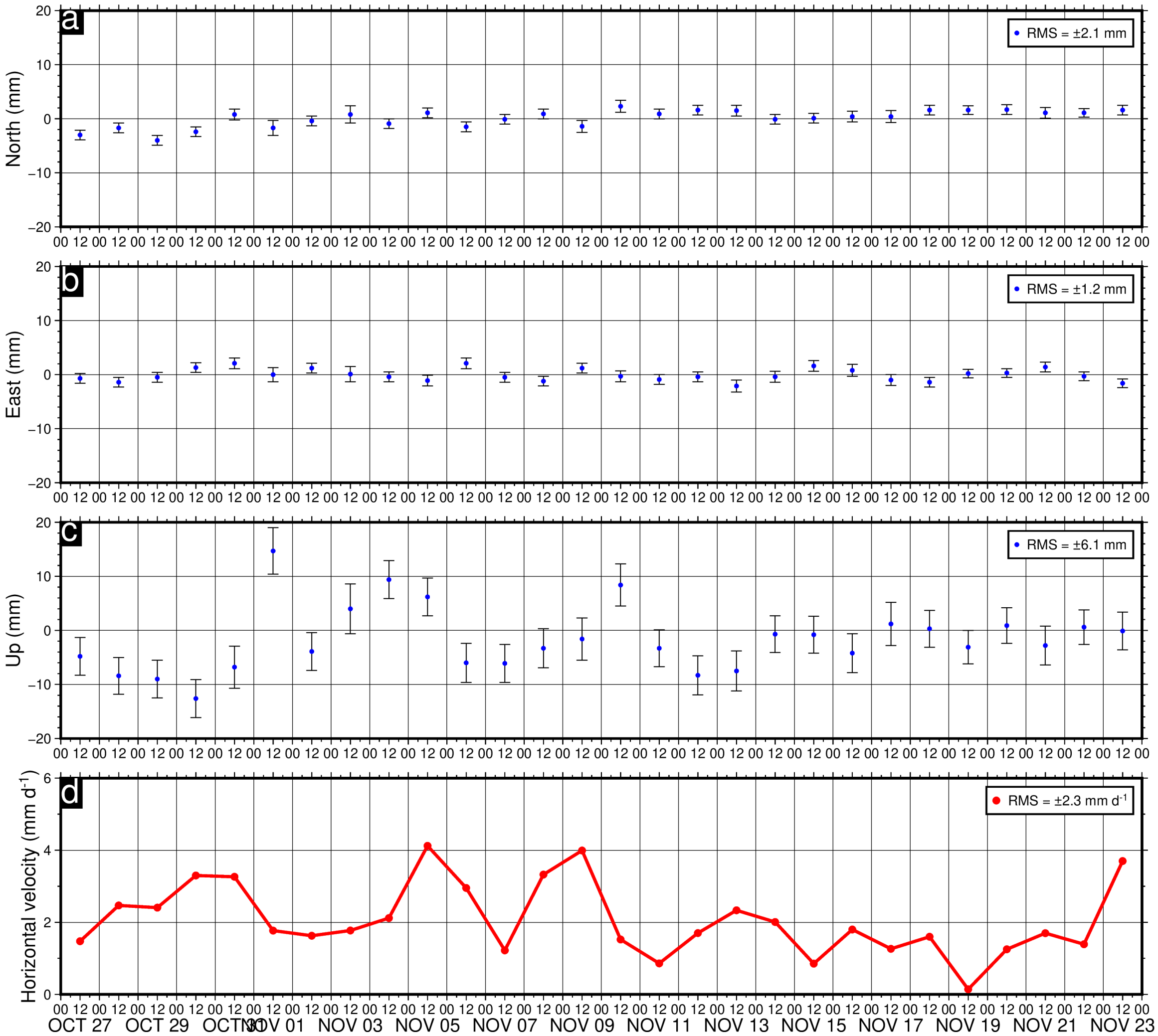

Figure S2: The noise level in (a-c) position estimates and (d) horizontal velocity determined at the stationary site ARGB.

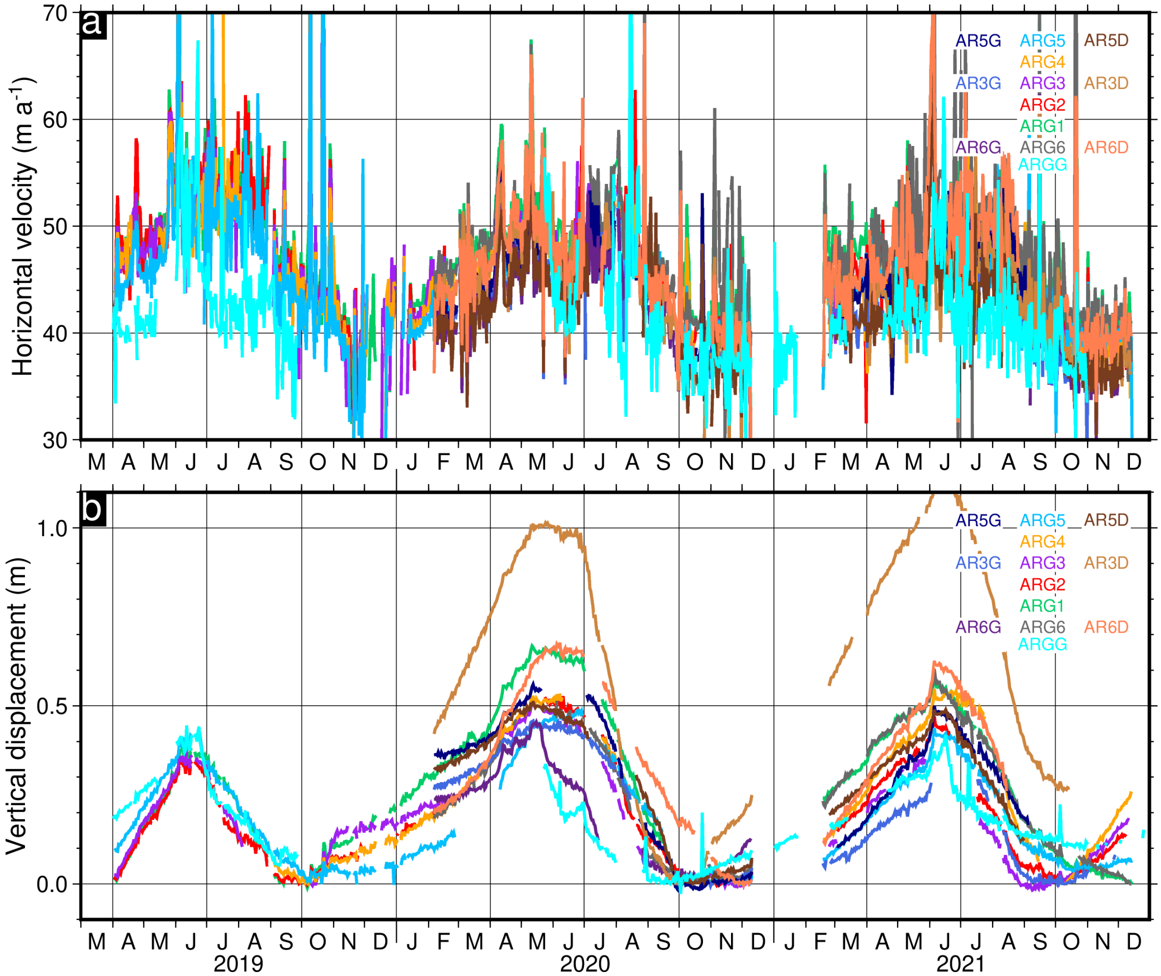

Figure S3: Seasonal variations in (a) horizontal velocity and (b) vertical displacement for 13 GPS stations.

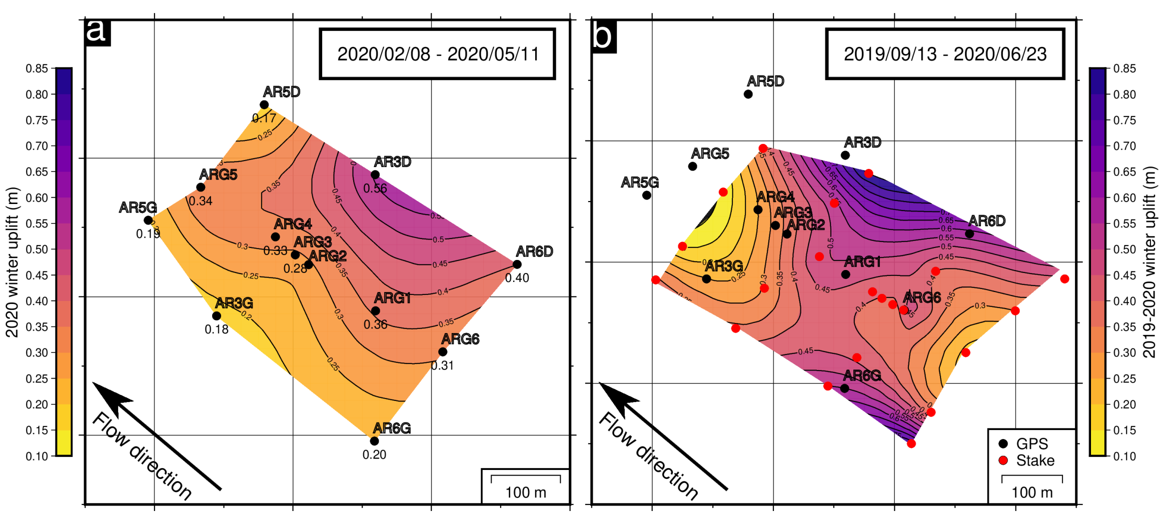

Figure S4: Comparison of spatial patterns of winter uplift in 2019-2020 derived from (a) GPS and (b) ablation stakes.

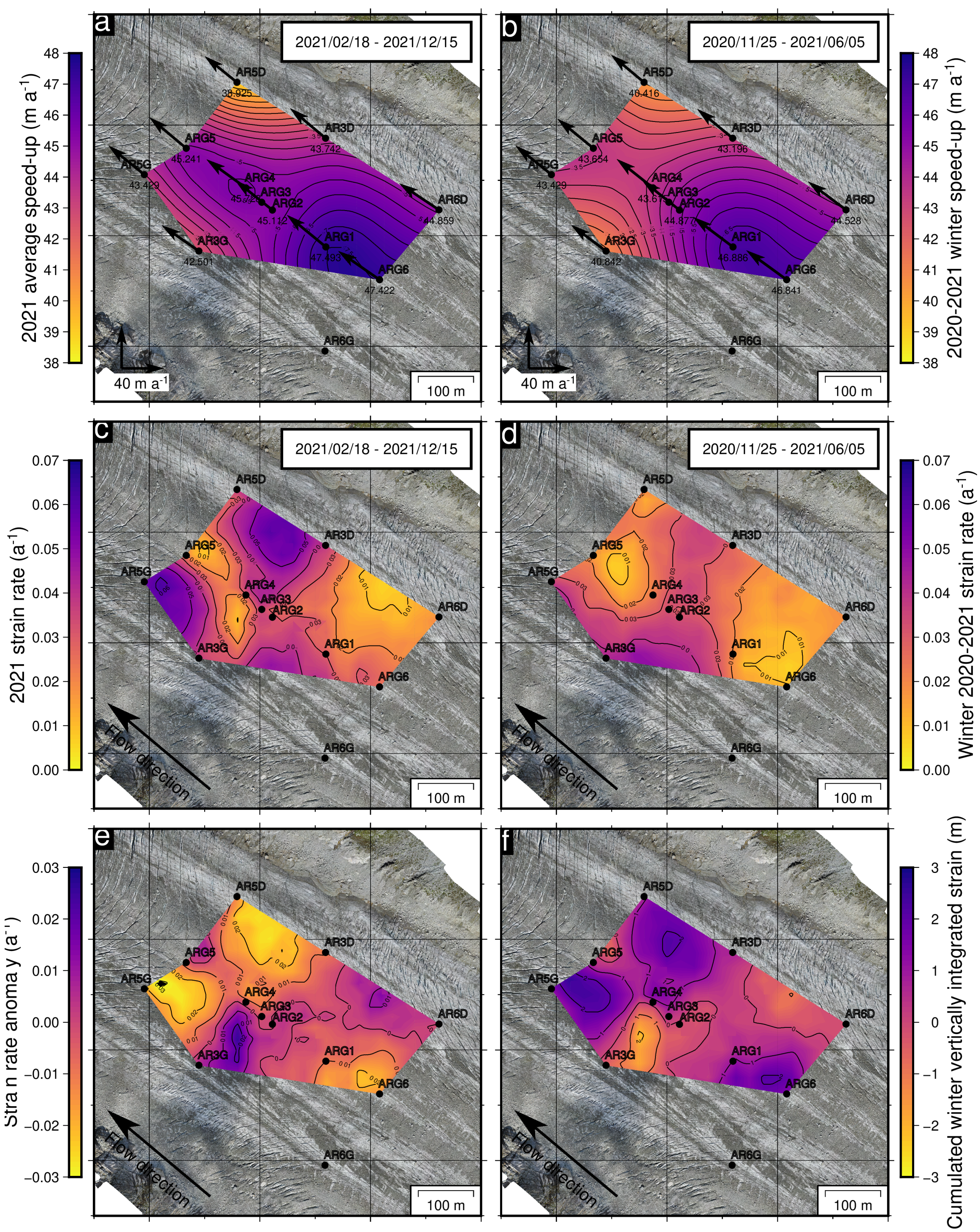

Figure S5: Progress of calculating cumulated winter vertically integrated strain in winter 2020-2021. Spatial pattern of (a) absolute speed-up, (b) horizontal velocity anomaly, (c) observed uplift, and (d) cumulated vertically integrated strain in winter 2020-2021.

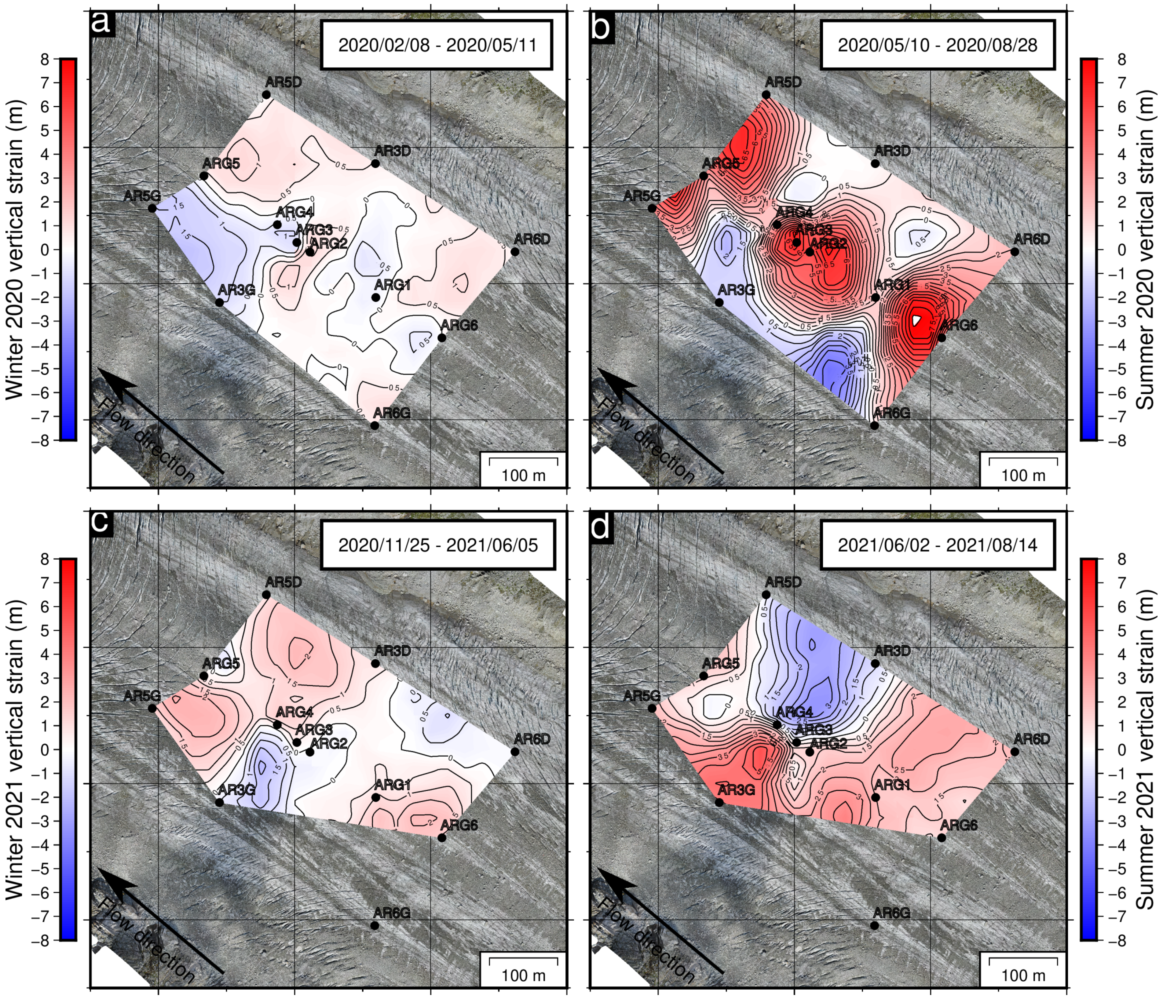

Figure S6: Spatial patterns of cumulated vertically integrated strain in chronological order during (a,c) winter and (b,d) summer in 2020-2021.

S1. Calculation of the contour integrals

The ice deformation rate was calculated for a grid spaced every 20 m based on a GPS-derived horizontal velocity field, following Rampal et al. (2019). To obtain sets of polygons, we perform successive Delaunay triangulation through the grid points. Then for each triangle, the total deformation rate is calculated as follows:

$$\dot{\varepsilon}_{\text{total}} = \sqrt{\dot{\varepsilon}^2_{\text{shear}} + \dot{\varepsilon}^2_{\text{div}}} \tag{S1}$$

where $\dot{\varepsilon}_{\text{shear}}$ and $\dot{\varepsilon}_{\text{div}}$ are the two invariant, shear and divergence, respectively, of the deformation rate. Measures of ice deformation are divergence rate and shear rate computed at each triangle as follows:

$$\dot{\varepsilon}_{\text{shear}} = u_x - v_y + u_y + v_x \tag{S2}$$

$$\dot{\varepsilon}_{\text{div}} = u_x + v_y \tag{S3}$$

where u_x, u_y, v_x, and v_y are the spatial gradients in ice motion computed using a line integral around the boundary of the area A, following (Kwok et al., 2008):

$$u_x = \frac{1}{A}\oint u\ dy, \tag{S4}$$

$$u_y = -\frac{1}{A}\oint u\ dx, \tag{S5}$$

$$v_x = \frac{1}{A}\oint v\ dy, \tag{S6}$$

$$v_y = -\frac{1}{A}\oint x\ dx, \tag{S7}$$

Then, for example, u_x is approximated by:

$$u_x = \frac{1}{A}\sum_{i=1}^{n}\frac{1}{2}\left(u_{1+i} + u_i\right)\left(y_{1+i} + y_i\right) \tag{S8}$$

where n is 3, the number of vertices in a triangle. Analogous formulas can be written down for the other partial derivatives.

Strain rate anomaly is calculated for the period of interest by subtracting annual mean strain rate. The conservative strain rate error between two dates is $\pm 0.0002\ \text{yr}^{-1}$, calculated by doubling the GPS horizontal position error of 0.005 m and dividing by the shortest distance in the GPS network, which is 50 m. Then we calculate uplift from vertical strain ΔZ over time Δt by assuming a homogeneous vertical strain rate with depth H and ice incompressibility:

$$\Delta Z = \dot{\varepsilon}_{\text{total}} H \Delta t \tag{S9}$$

References

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Rampal, P., Dansereau, V., Olason, E., Bouillon, S., Williams, T., Korosov, A., and Samaké, A.: On the multi-fractal scaling properties of sea ice deformation, Cryosphere, 13, 2457–2474, https://doi.org/10.5194/tc-13-2457-2019, 2019.