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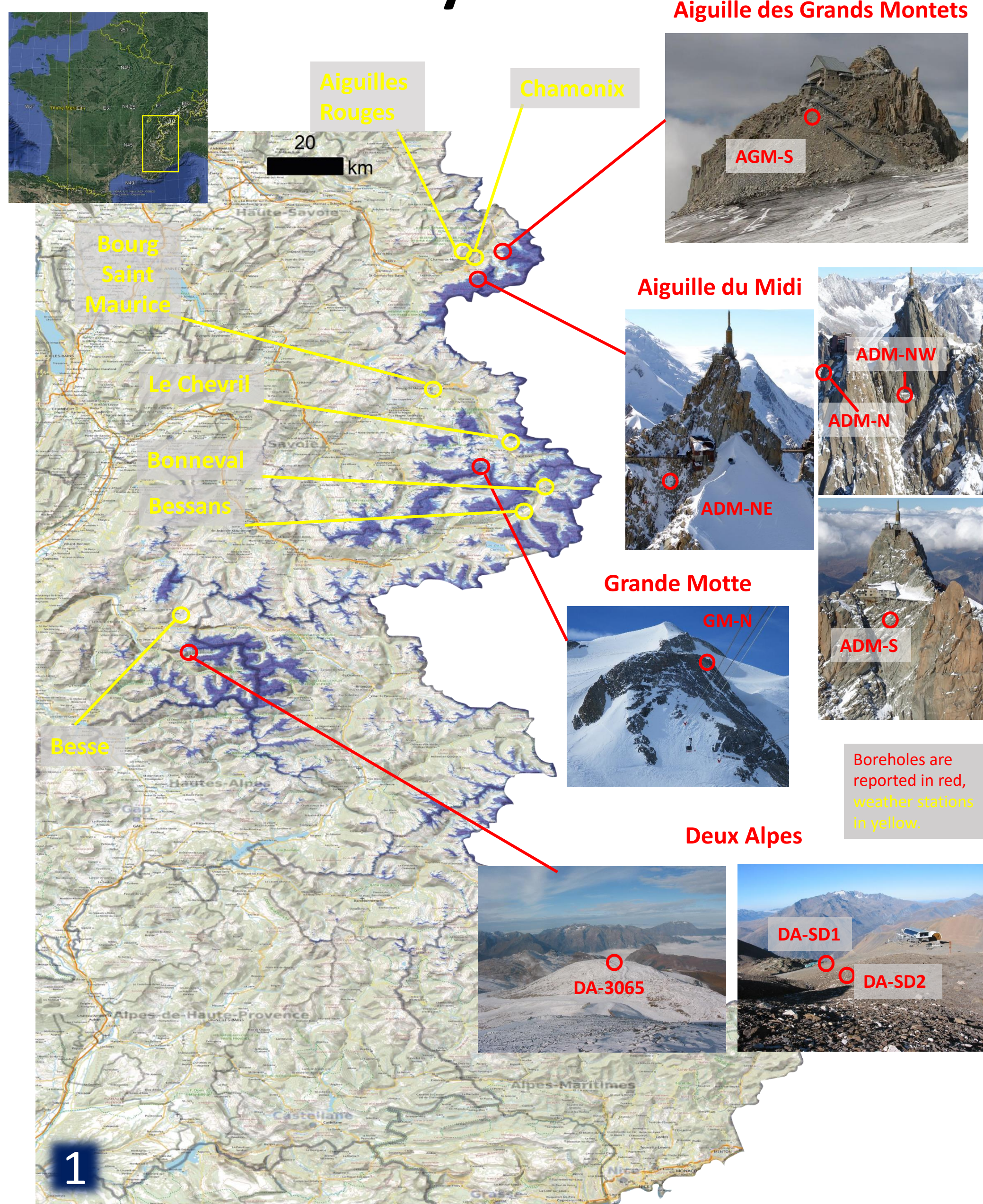
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A decade of mountain permafrost monitoring in the French Alps from the *PermaFrance* network: results of the 2010-2022 period



F. Magnin¹, L. Ravanel¹, X. Bodin¹, P. Deline¹, E. Malet¹, J-M. Krysiecki², P. Schoeneich³

Study sites



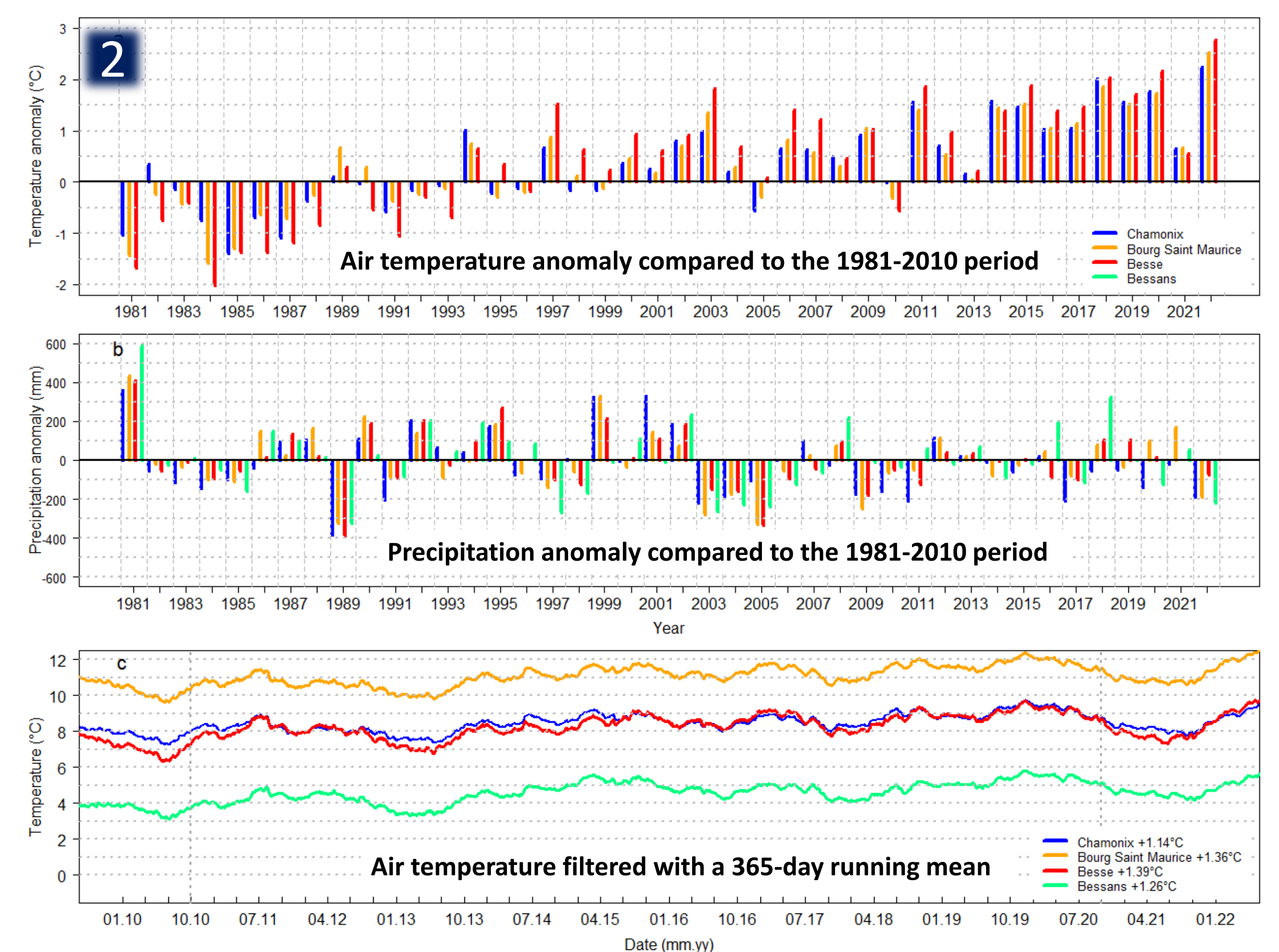
In between 2009 and 2021, 9 boreholes (Fig. 1) whose depth ranges between 10 and 100 m were drilled and equipped with thermistor chains in the French Alps in various ground conditions. DA-3065 (100 m depth) is also equipped with a distributed temperature sensing fibre optic cable.

Borehole settings and climate conditions

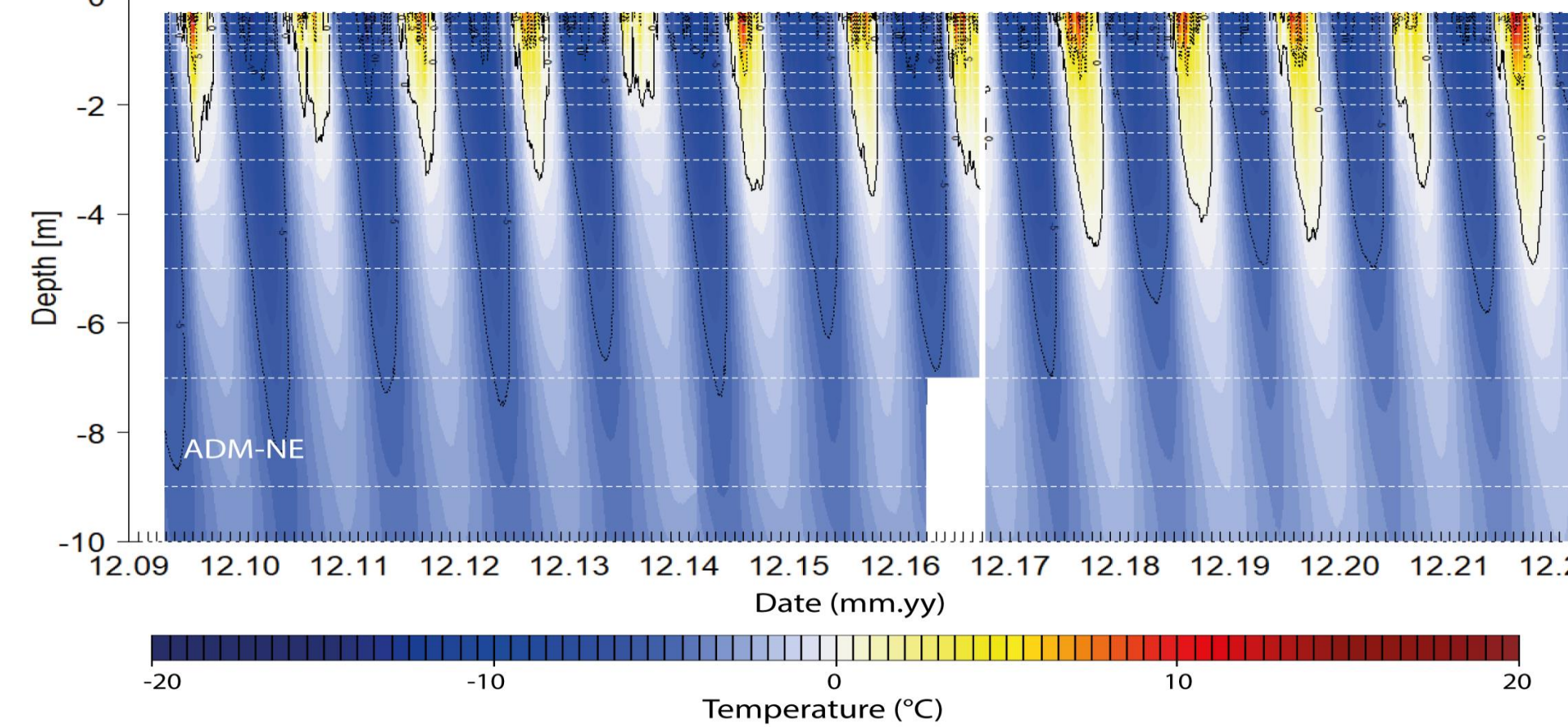
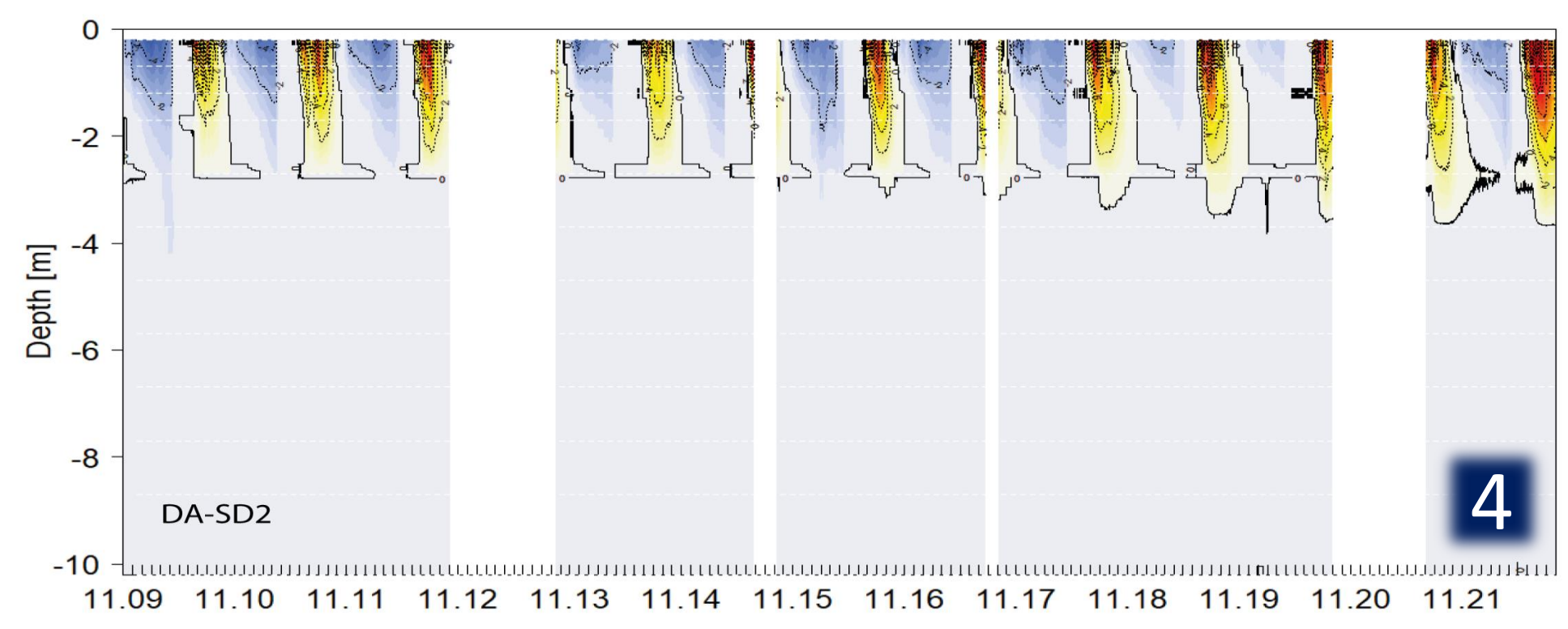
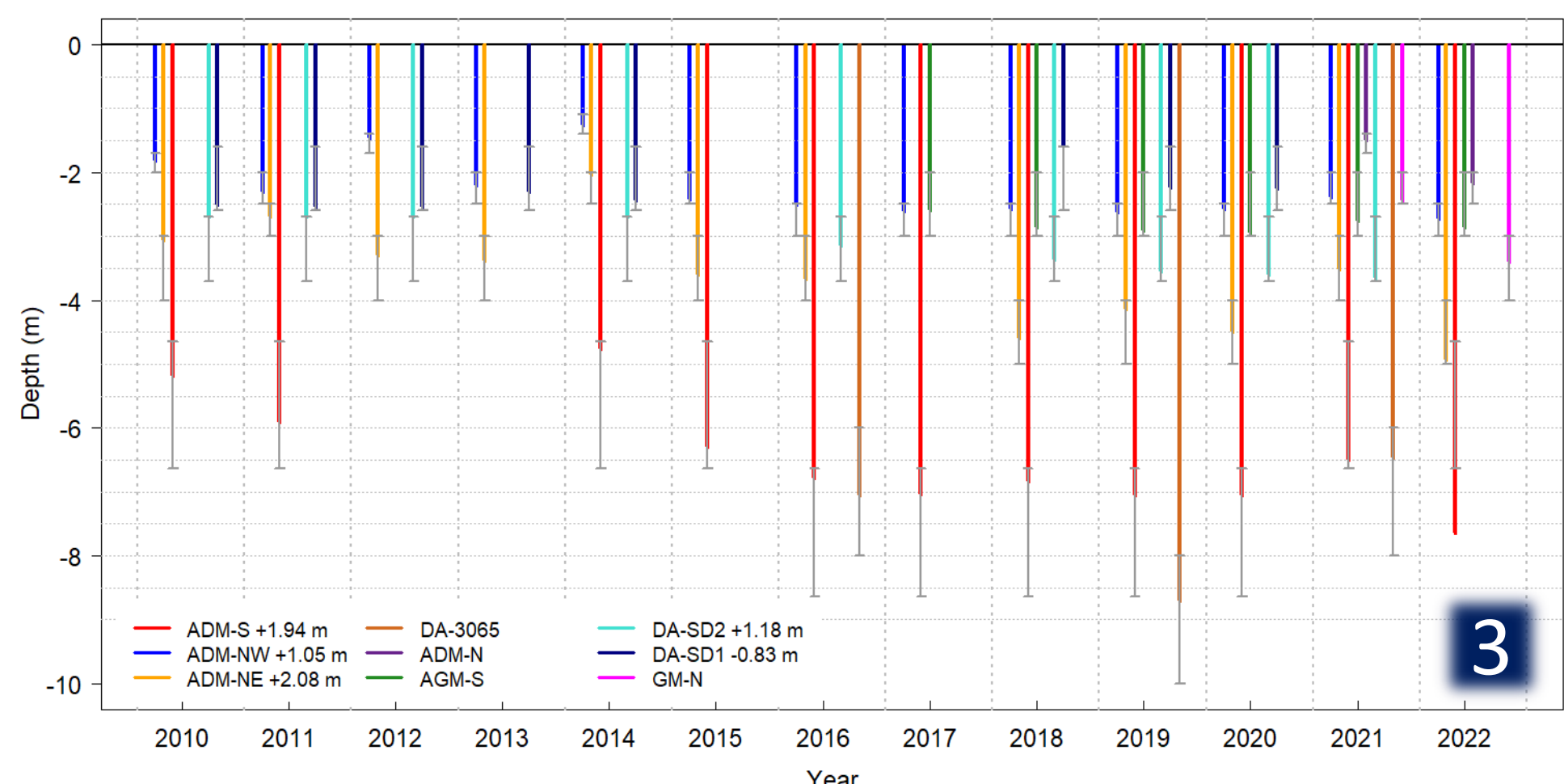
| ID | Massif | Ground type (surface) | Elevation (m a.s.l.) | Aspect (°) | Slope (°) | Borehole depth and inclination | Comments |
|---------|------------------|-----------------------|----------------------|------------|-----------------------|---|---|
| ADM-S | Mont Blanc (MBM) | Bedrock | 3753 | 185 | 55 | 10 m, normal to slope | Fractured and rugged bedrock, heterogeneous snow accumulation |
| ADM-NE | | | 3738 | 75 | 65 | 10 m, normal to slope | Fractured rock with heterogeneous snow deposits |
| ADM-NW | | | 3745 | 270 | 90 | 10 m, normal to slope | Rockwall, crosses an open fracture at c. 2.5 m depth, right above a ledge with locally thick snow deposit |
| ADM-N | Bedrock | 3754 | 345 | 77 | 10 m, normal to slope | Homogeneous and very little fractured bedrock | |
| AGM-S | | 3242 | 183 | 42 | 17 m, normal to slope | Coarse blocks in the shallowest meters, bedrock at depth, snow. | |
| DA-SD1 | Rock glacier | 2710 | 340 | 10 | 15 m, vertical | Unfrozen coarse debris to 1.7 m, unfrozen fine debris to 2.3 m, ice-rich debris to 4.8 m, ice and stones to 9.7 m, bedrock below, snow. | |
| DA-SD2 | Ecrins | 2725 | 340 | 5 | 15 m, vertical | Debris to 2.2 m, ice-rich debris to 9.5 m, bedrock below, snow. | |
| DA-3065 | | Bedrock | 3065 | - | 0 | 100 m vertical | Frost shattered bedrock up to 2 m thick, moderately fractured bedrock deeper, windblown. |
| GM-N | Vanoise | Bedrock | 3355 | 345 | 58 | 20 m, normal to slope | Fractured bedrock, mostly snow free. |

The GM-N borehole is located in a climate divide (between Atlantic and Méditerranéenne influences) and two weather stations are considered to characterise its precipitation regime (Bessans and Bourg Saint Maurice). Air temperature records at Bessans start in 1984 and the anomaly is thus not displayed for this variable. All weather stations recorded an air temperature increase > 1°C (fitted with linear regression, Fig. 2) over the 2011-2020 reference decade.

→ Permafrost monitoring has been so far conducted during the hottest period ever recorded since the 1980s.

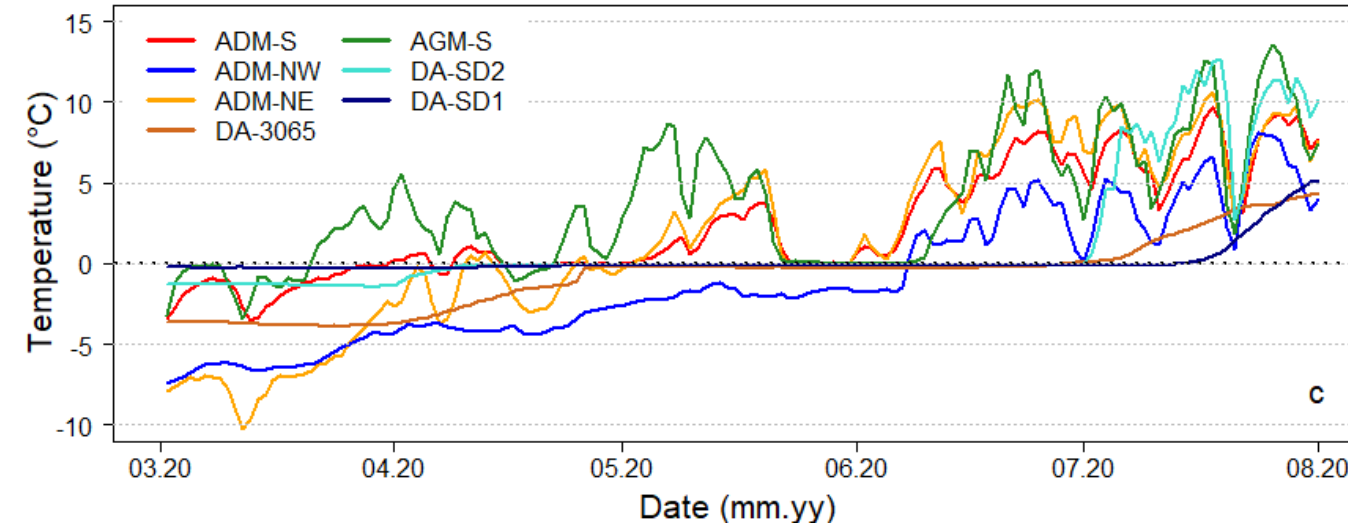
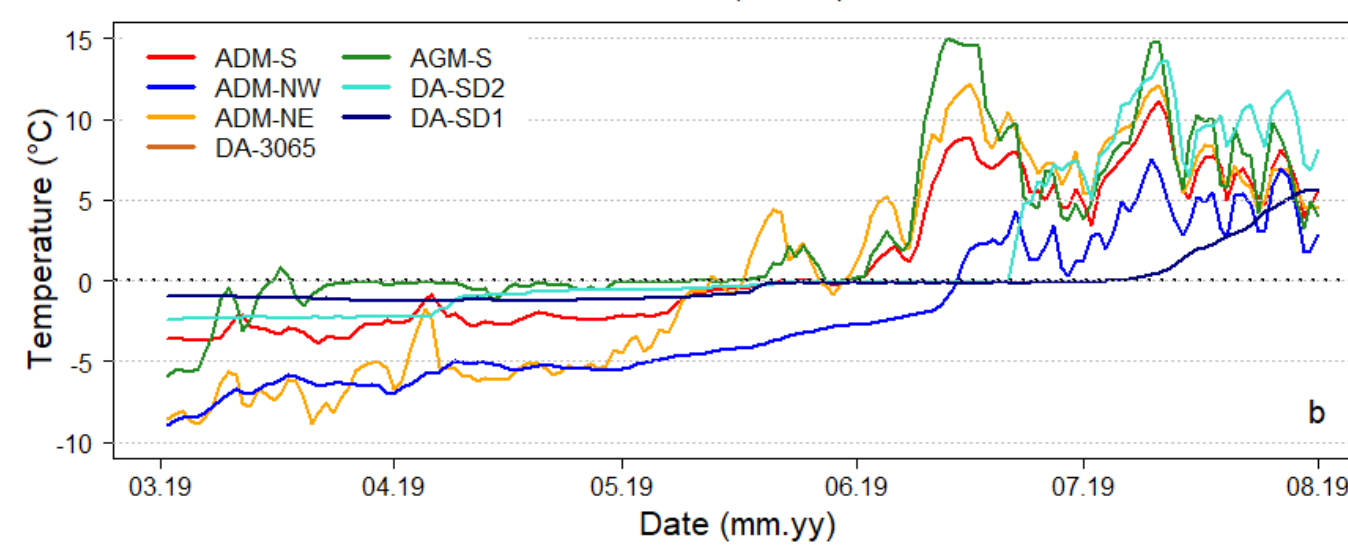
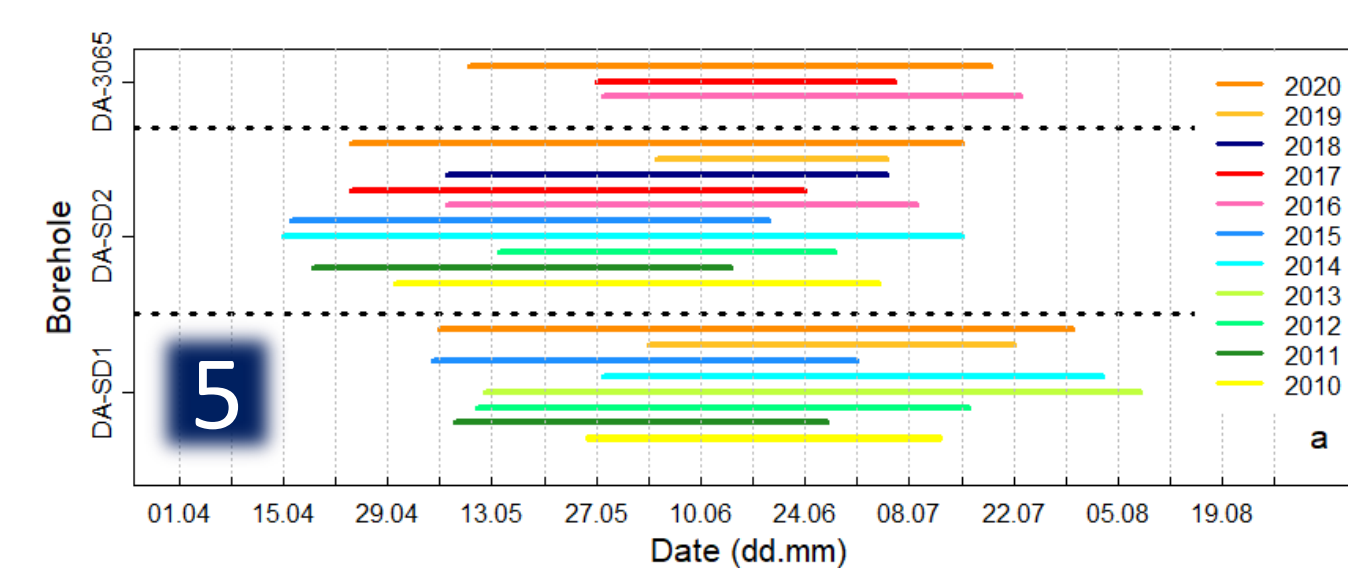


Active layer

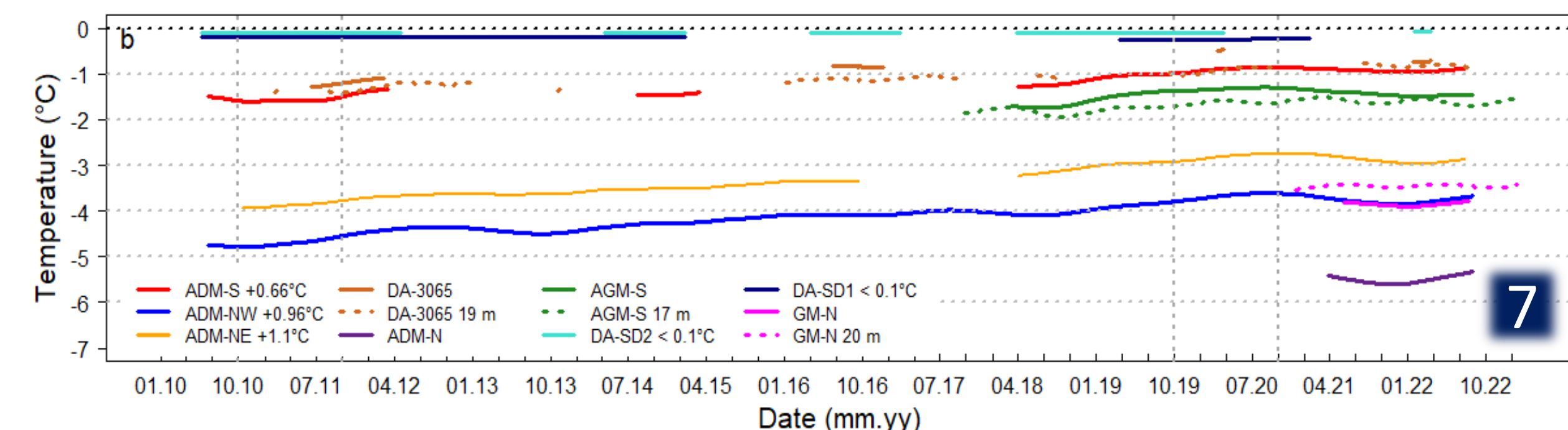
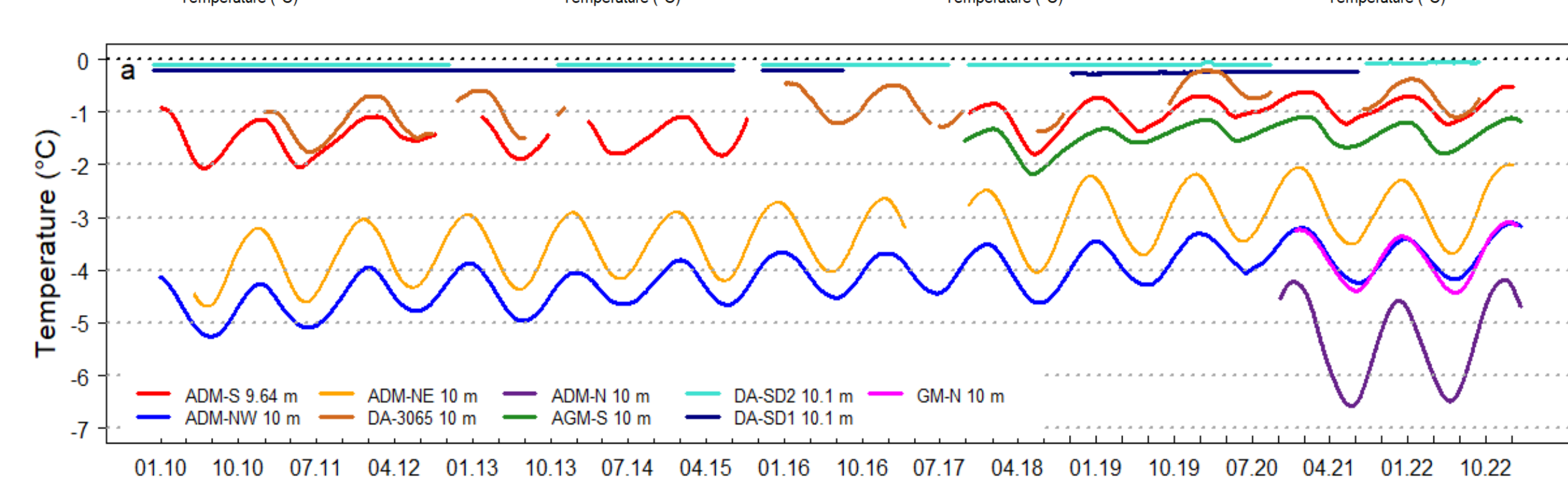
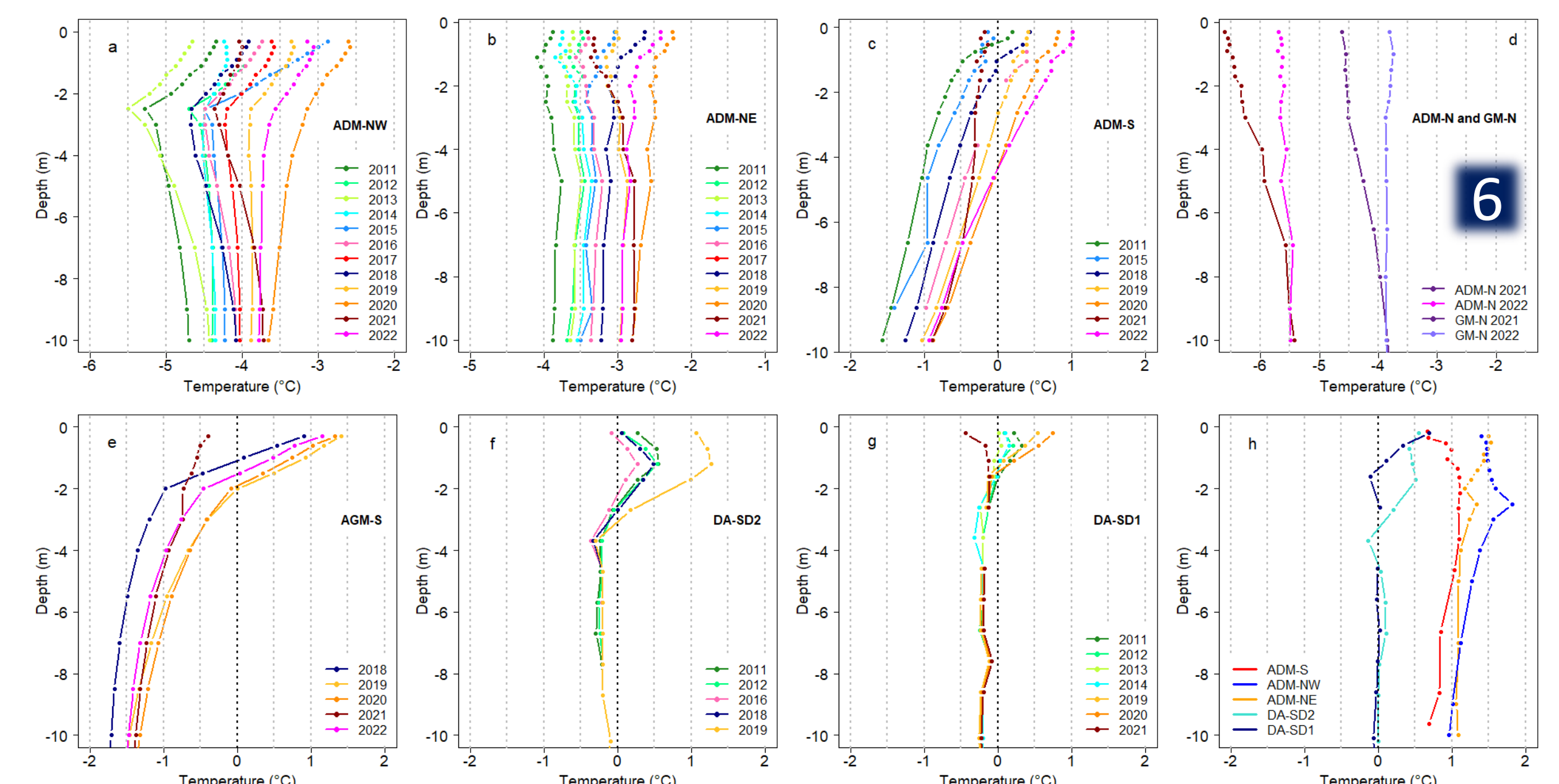


Maximum active layer thickness (ALT, Fig. 3) is interpolated between the deepest sensor recording positive temperature and the following sensor that registered only negative values (shown through error bars). Decadal trends (°C/decade) are calculated from linear regressions. Interpolated daily values are given for two contrasted boreholes (Fig. 4): DA-SD2 in a rock glacier and ADM-NE in sub-vertical bedrock. Snow effect is visible through length of surface zero curtain (sustained near-0°C temperature at the surface, Fig. 5a) and daily surface temperature in spring (Fig. 5bc).

→ ALT trends and reversibility are strongly controlled by ice-richness and snow lasting during spring



Permafrost temperature



Mean annual Temperature-depth (T_z) profiles are calculated for available hydrological years at each borehole (Fig. 6 a-g) and decadal trends (2011-2020) are calculated with linear regression from annual means (Fig. 6h). Daily temperature at 10 m depth and deepest sensor when available is displayed with a 31-day running mean (Fig. 7a) and a 365 running mean (Fig. 7b). Decadal trends are calculated from linear regressions.

→ Rockwall sites show stronger interannual variability down to 10 m depth and stronger warming than ice-rich sites whose ZAA is found at c. 4 m depth. At AGM-S the cooling effect of a coarse block layer is visible through the T_z profiles while an open fracture at ADM-NW strongly affects the T_z profile shape. Dampened warming of warm permafrost is also visible at ADM-S.

Ice-poor and cold permafrost (high-elevated north-facing rock walls) has registered permafrost warming of up to > 1°C/decade at 10 m depth during the 2010-2022 period, **among the highest permafrost temperature increase reported at the global scale**, while ice-rich permafrost (rock glaciers) registered stable sub-zero temperature. ALT has increased at all boreholes except one, especially since summer 2015: up to 50% since the first year of measurement for ice-poor permafrost, and by 34% in ice-rich permafrost. Linear trends suggest active layer thickening of + 2 m in 10 years for some ice-poor rock walls, independently of their thermal state (cold or warm permafrost). The presented data show a large variety of permafrost patterns and evolution with significant intraregional and local differences. Peculiar responses are mostly attributed to snow effects, but also buffer layers of coarse blocks, with evidence of favourable conditions for active layer thickening under early snow melting in spring and dampened effect of hot summers on bedrock site covered with coarse blocks.