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

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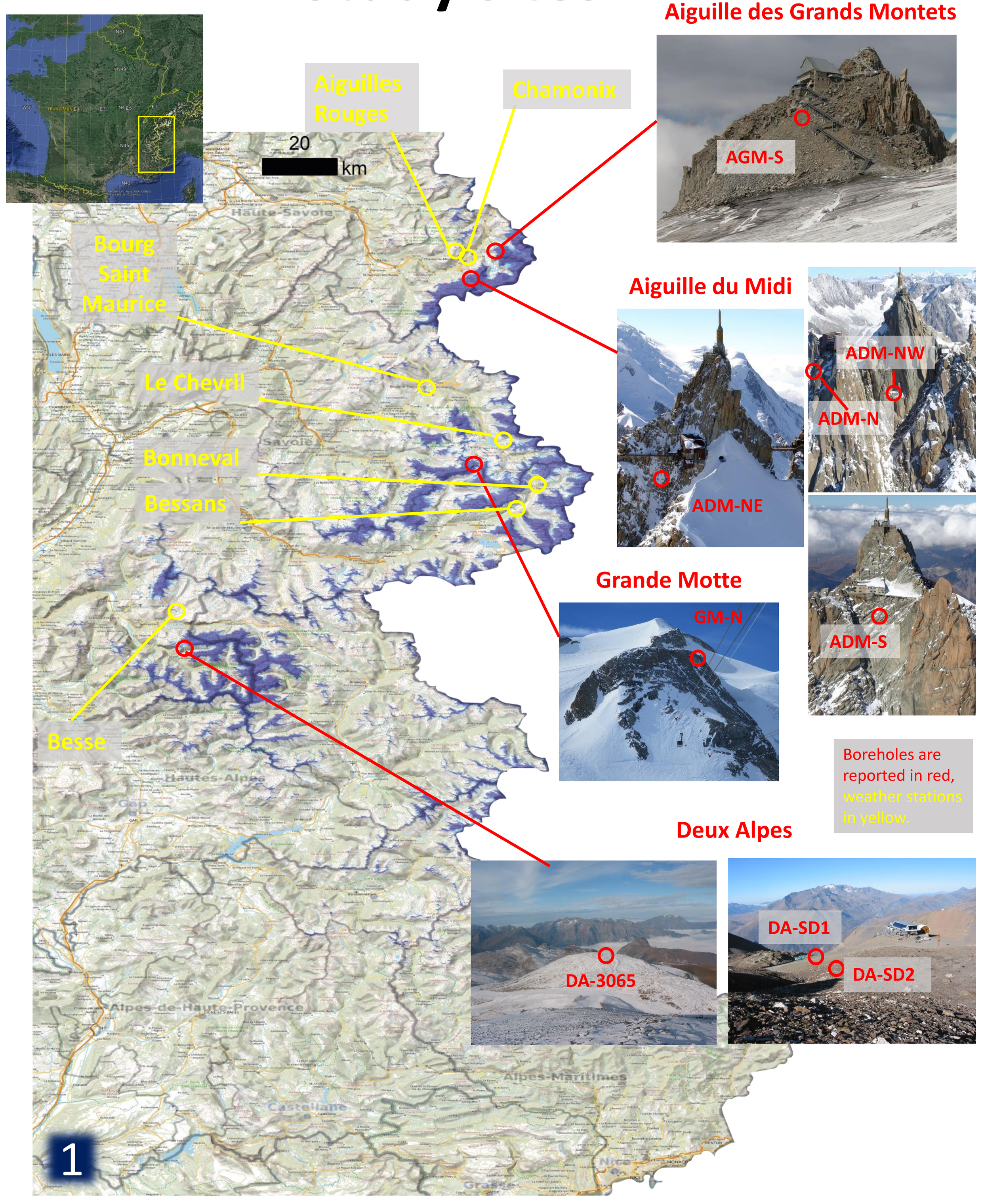
Study sites



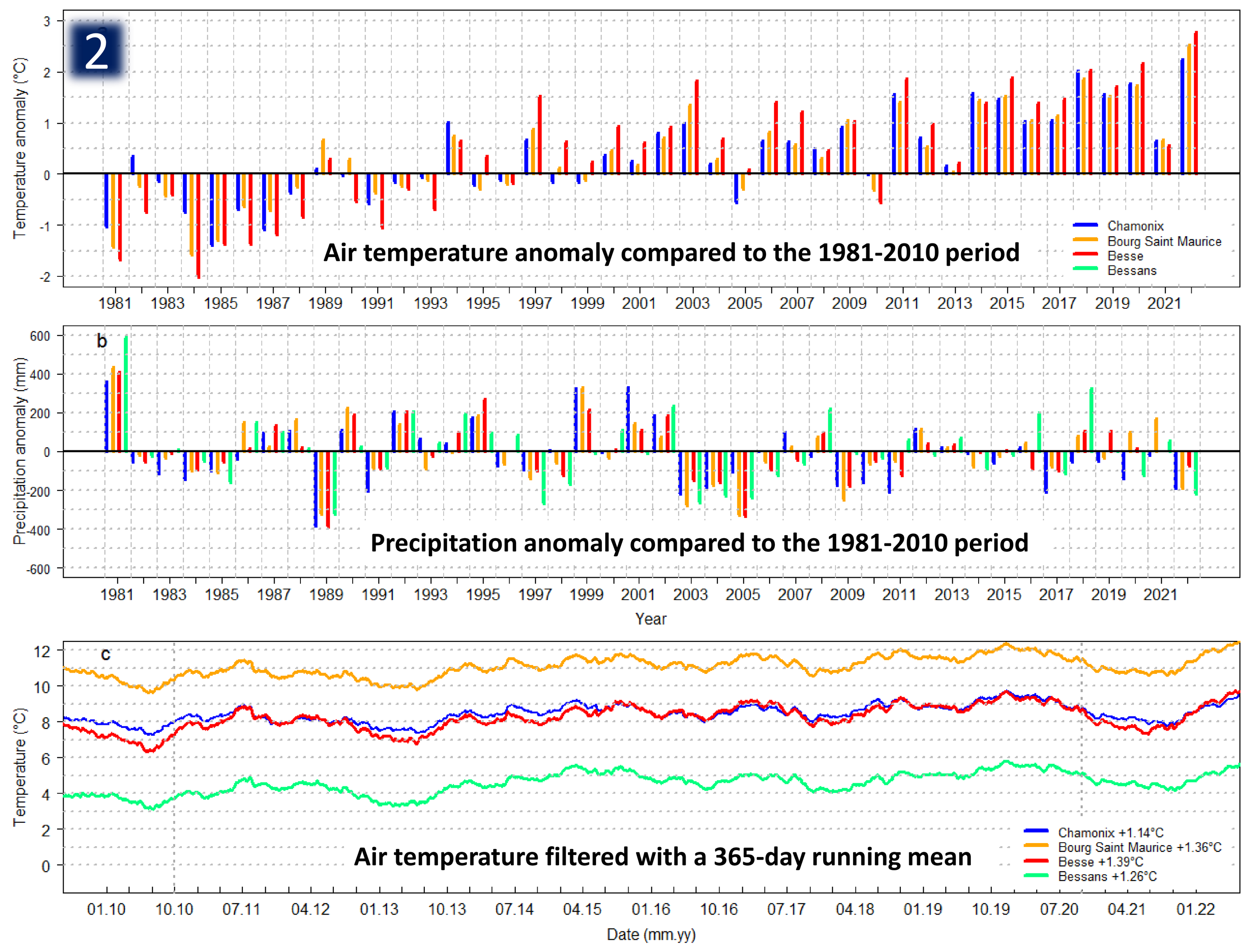
In between 2009 and 2021, 9 boreholes (**Fig. 1**) whose depth ranges between 10 and 100 m were drilled and equipped with thermistor chains in the French Alps in various ground conditions.
DA-3065 (100 m depth) is also equipped with a distributed temperature sensing fibre optic cable.

Borehole settings and climate conditions

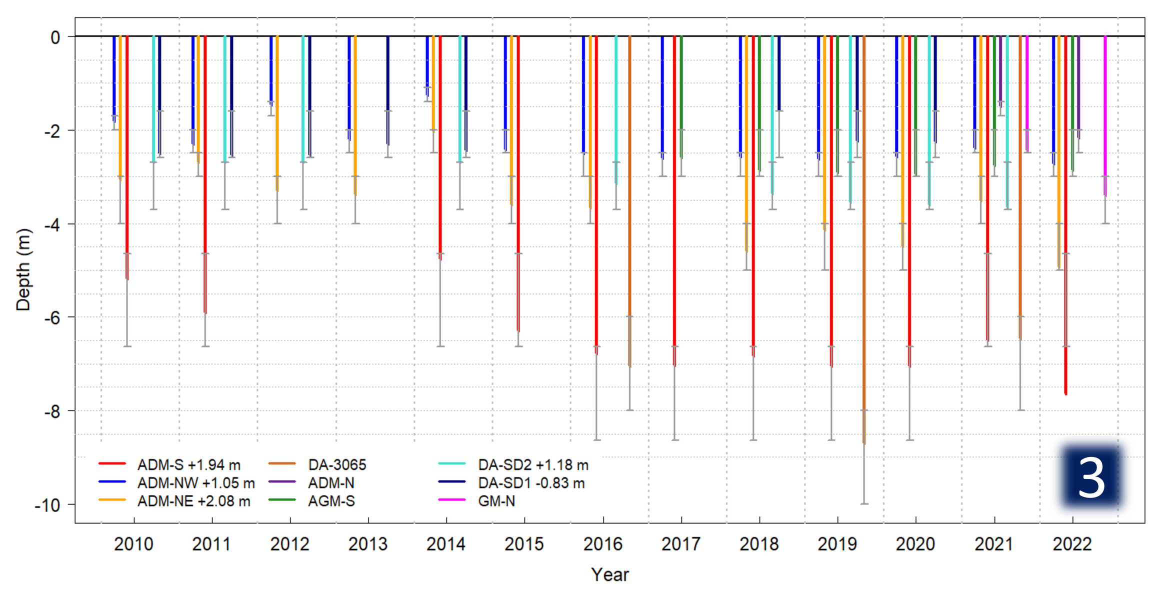
ID	Massif	Ground type (surface)	Elevation (m a.s.l.)	Aspect (°)	Slope (°)	Borehole depth and inclination	Comments
ADM-S	Mont Blanc (MBM)	Bedrock	3753	185	55	10 m, normal to slope	Fractured and rugged bedrock, heterogeneous snow accumulation
ADM-NE			3738	75	65	10 m, normal to slope	Fractured rock with 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			3754	345	77	10 m, normal to slope	Homogeneous and very little fractured bedrock
AGM-S		Bedrock	3242	183	42	17 m, normal to slope	Coarse blocks in the shallowest meters, bedrock at depth, snow.
DA-SD1	Ecrins	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			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.

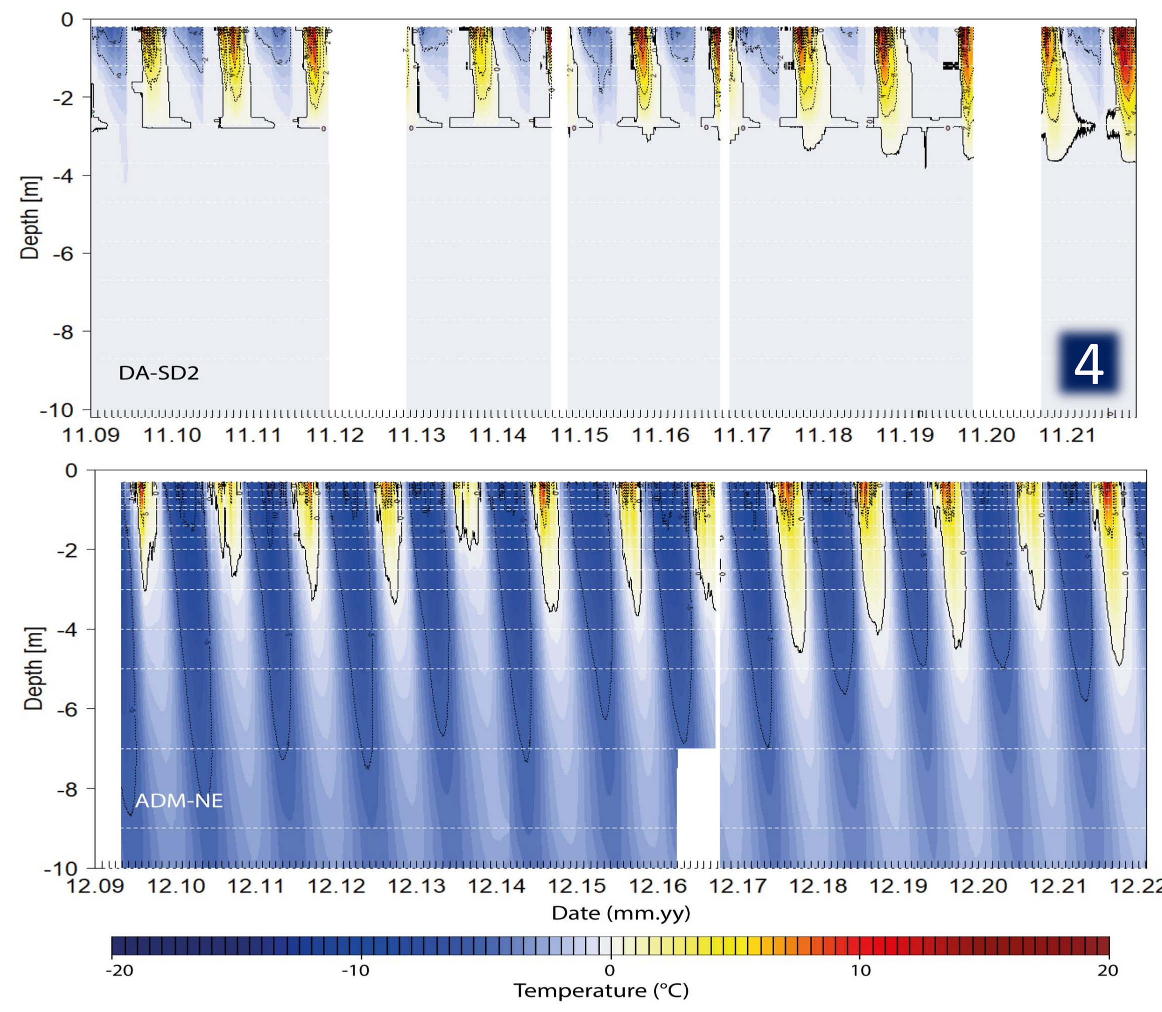
The GM-N borehole is located in a climate divide (between Atlantic and Mediterranéean influences) and two weather stations are considered to caracterise its precipitation regime (Bessans and Bourg Saint Maurice). Air temperature records at Bessans start in 1984 and the anomaly is thus not displayed for 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.



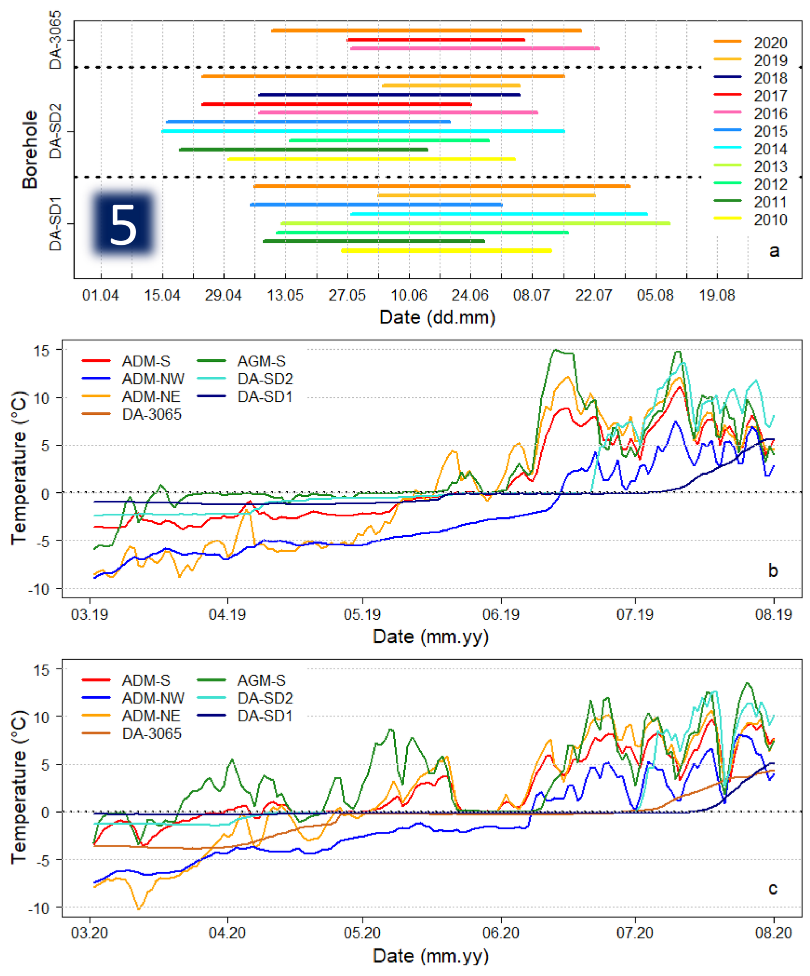
Active layer



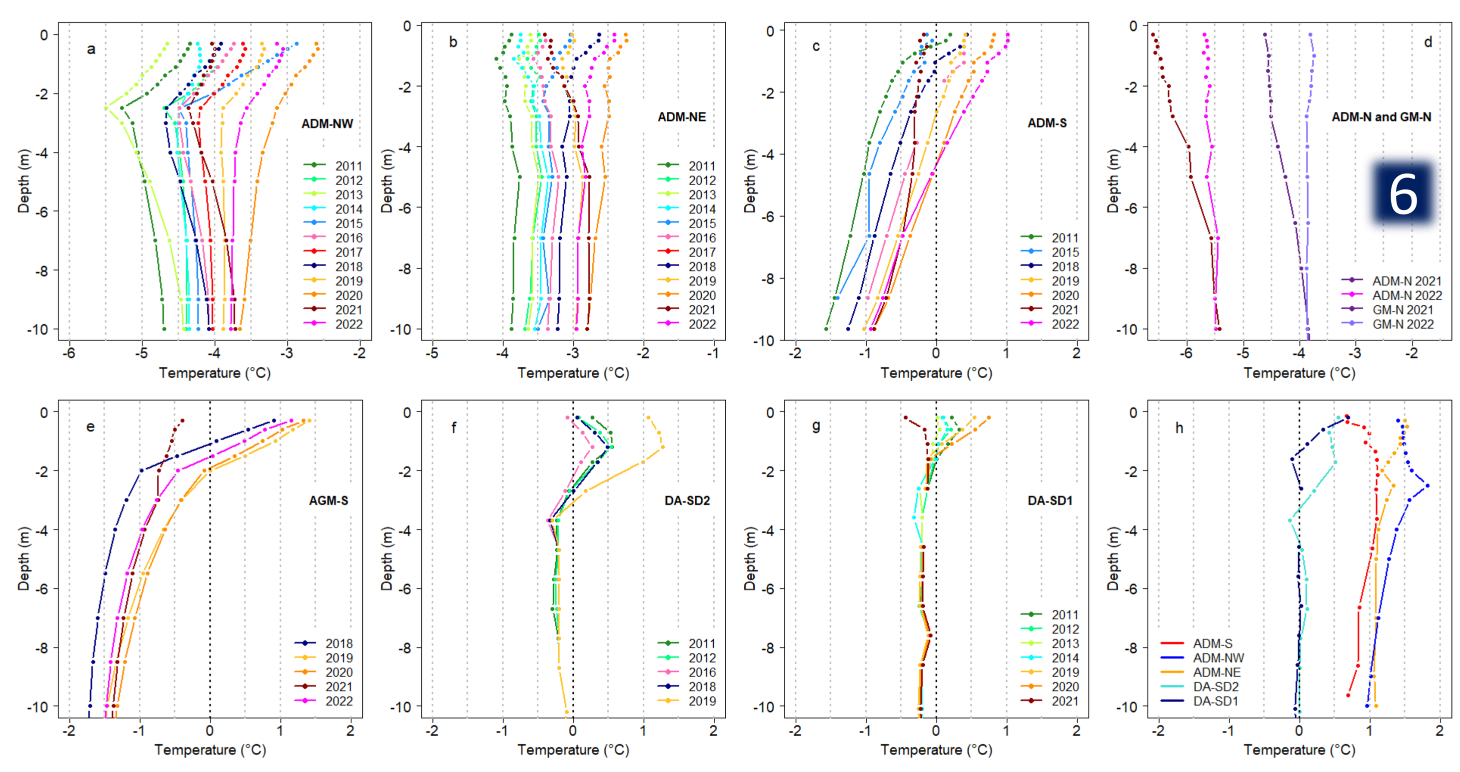


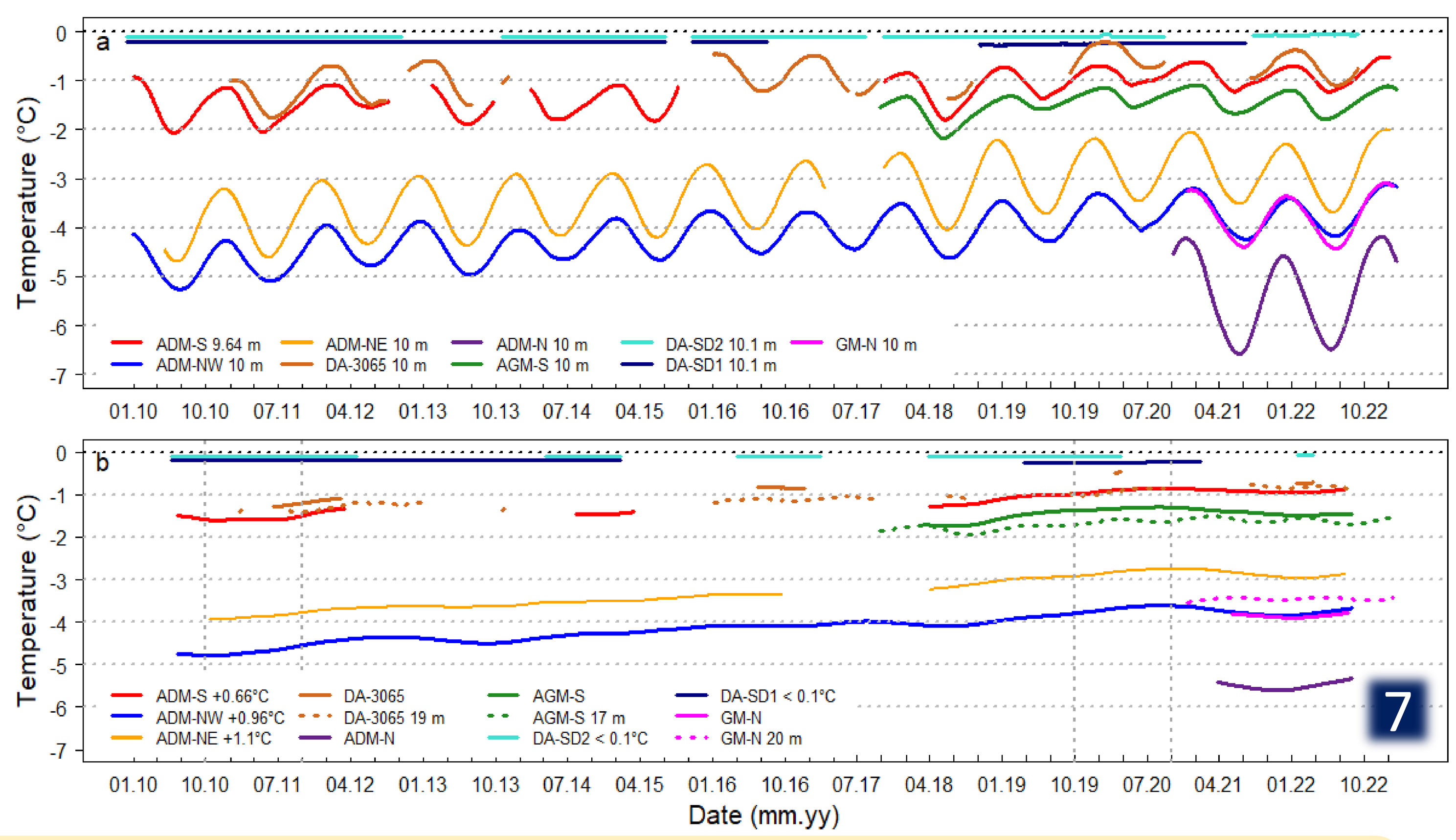
Maximum active layer thickness (ALT, **Fig. 3**) is interpolated between the deepest sensor recording positive temperature and the following sensor that registered only negative values (showed through error bars). Decadal trends (°C/decade) are calculated from linear regressions.
Interpolated daily values 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 (Tz) profiles are calculated for available hydrological years at and 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 Tz profiles while an open fracture at ADM-NW strongly affects the Tz 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.