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First evidence of rock wall permafrost in the Pyrenees (Southwestern Europe, 42°N)

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Abstract

Permafrost is an important component of the Pyrenean high mountains, including a wide range of geomorphological cryogenic processes. While there has been an increase in frozen ground studies in the Pyrenees, there are no specific studies about rock wall permafrost, its presence, distribution, regime or historical evolution. This work combines measured rock surface temperatures along an elevation profile of the north face wall of the Vignemale peak (main divide of Central Pyrenees) and temperature modelling for this mountain, in order to ascertain the presence of permafrost and to analyze its evolution since the mid-XX century. Results reveal that the entire rock face was affected by warm permafrost (> - 2ºC), as low as 2600 m a.s.l from 1961 to 1990. By 1981-2010, the limit of close to 0ºC permafrost rose to around 2800 m a.s.l and it has reached 3000 m a.s.l by present day. Conditions permit cold (< -2°C) permafrost on north faces above 3100-3200 m a.s.l. The large expansion of warm permafrost suggests an imminent disappearance of permafrost in the Vignemale and in most of the peaks of the Pyrenees.

Key words: Rock wall permafrost, temperature measurements, temperature modelling, climate warming, Vignemale peak, Pyrenees.

1 Introduction

High mountain permafrost plays an important role in the precipitation of rock falls and other mass movements and has become an emerging field of research over the past decade [1-3]. Rock wall permafrost distribution is mainly determined by elevation (air temperature) and slope-shading (incoming short-wave solar radiation affected by cast shadows). These permafrost areas are exceptionally sensitive to climate change because of the direct contact with the atmosphere, relatively low ice content and multi-sided heat propagation into sharp and complex topographies [4].

The Pyrenean high mountains occupy around 365 km^2 and hold 132 peaks over 3000 m a.s.l. Steep rock walls and north faces occupy a significant part of this environment such as in the massifs of Balaitous, Monte Perdido or Aneto-Maladeta among others.

Studies have found that the lower limit of discontinuous permafrost in the region is around 2700 m a.s.l, [5-7]- which is generally at a higher elevation than other European mountain ranges [8-10] - and continuous permafrost is only found above 3000 m a.s.l. However, there is a paucity of comprehensive rock wall permafrost studies in one of the lowest-latitude permafrost affected mountain ranges of the northern hemisphere [11]. The rapid degradation of permafrost in this mountain range has the potential to trigger large slope and mass wasting processes with important socio-economic impacts [5] as well as risks associated with mountaineering activities [12].

The main aims of this study are 1) to verify the presence or absence of permafrost in the high-elevation north face of the Vignemale and 2) to reconstruct the historical evolution and degradation pathways of rock wall permafrost in this north face.

2 Study Site

The Vignemale Peak (3298 m a.s.l, 42°46'16'' N / 0°08'33'' W) is located in the Vignemale massif (Pyrenees National Park, France; Fig. 1). A north-south oriented fault-system has created strong relief asymmetries, generating a deep glacial valley towards the north, where rock walls of more than 800 m of vertical difference define a unique alpine landscape in this temperate mountain range. The north face of the Vignemale peak was first climbed in 1933 by Henri Barrio and Robert Bellocq, establishing the present-day route known as the North Face Classic route (D+, 800 m).

The Vignemale north face shapes the glacial cirque located at the uppermost section of the Gaube valley. The wall experiences constant geodynamic processes including snow avalanches during winter and spring and rockfalls in the summer season. Local mountain guides and members of the Gendarmerie rescue team have reported an increase in rock falls during the last decade [13].

In the Pyrenees, mean temperature has increased by 1.3 ºC since 1955, with no significant changes in precipitation [14], accelerating the shrinkage of remaining glaciers, which are currently in a critical situation and likely to completely disappear [15-17]. Mean annual temperature recorded at the summit of nearby Midi de Bigorre peak (2877 m a.s.l.) -0.13ºC, very close to the 0°C isotherm. No direct observations of precipitation are available for the study area, but annual precipitation is estimated to exceed 2,000 mm yr^{-1} [18]. Most of the Vignemale massif is covered by snow for seven to nine months (from October-November to the following late May-early July), although climate warming has reduced the duration of cover [19]. However, the north face of the Vignemale peak remains mostly free of snow due to the steep (mean slope of 70º) topography of the alpine rock walls.

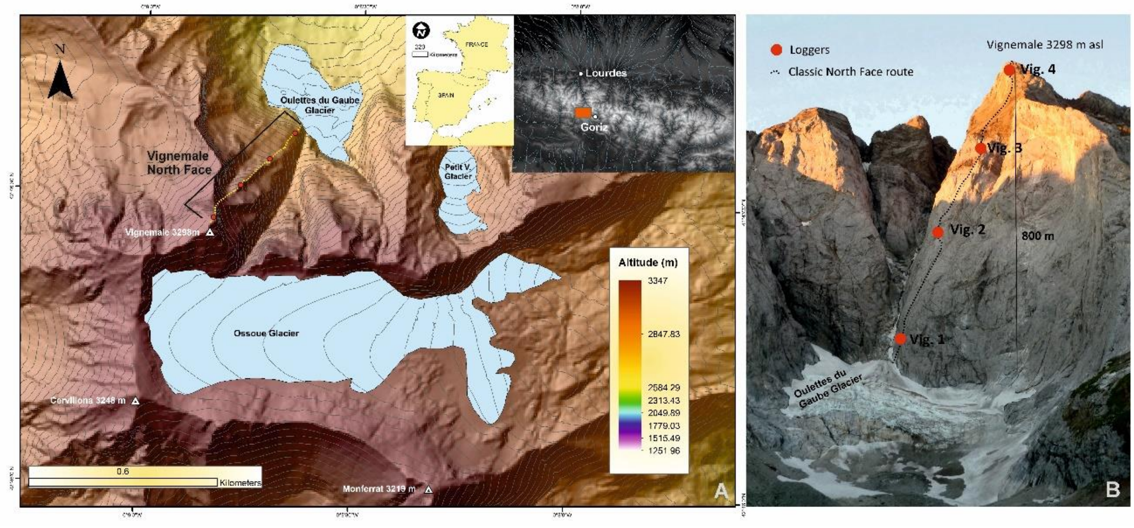

Figure 1. *Study area (A) and the Vignemale North Face with the location of temperature loggers (B).*

3 Material and Methods

3.1 Rock Surface Temperature time series

In September 2013, we equipped the north face of the Vignemale (3298 m a.s.l.) with four temperature loggers following an altitudinal profile spanning 2617-3196 m a.s.l (Tab.1). We placed Ibutton DS1923 temperature and humidity loggers at approximately 5 cm depth and sealed the borehole with synthetic silicone. These loggers have a temperature measuring range from -20 to + 85 ºC and a technical precision of ± 0.5 ºC [20]. Temperature data were recorded every four hours (Tab. 1). Sensors were replaced in September 2014 and finally retrieved in October 2016.

Logger name	Vig_1	Vig_2	Vig_3	Vig_4
Time frame 1 (dd.mm.yyyy)	08/09/2013 - 26/07/2014	08/09/2013 - 26/07/2014	08/09/2013 - 25/04/2014	08/09/2013 - 25/04/2014
Time frame 2	-	-	02/09/2014 -l 02/04/2016	02/09/2014 - 02/04/2016
Coordinates	42° 46.604'N 0° 8.596'W	42° 46.551'N 0° 8.697'W	42° 46.511'N 0° 8.770'W	42° 46.470'N 0° 8.850'W
Elevation	2617 m a.s.l	2803 m a.s.l	2983 m a.s.l	3196 m a.s.l
Aspect	NE (45º)	NE (45º)	NE (45º)	N (0º)

Table 1. *Operational time frame and description of location of the installed loggers.*

Loggers Vig_1, Vig_2, and Vig_3 were place at a maximum elevation of 2983 m a.s.l and below the elevation of the Ossoue glacier plateau on the opposite south side of the massif. Vig_4 is located at 3196 m a.s.l on the summit ridge and well above the Ossoue glacier plateau. The two lowest loggers (Vig_1 and Vig_2) registered data for 11 months (failure due to exposure to extreme conditions) and the highest two sensors (Vig_3 and Vig_3) covered 2.5 years including a gap of 1.5 months (Tab. 1; Fig. S1).

1.1 Prediction of rock surface temperature evolution with air temperature

In the absence or limited accumulation of debris or snow, rock surface temperature (RST) is closely coupled with air temperature (AT), particularly on north faces where the effect of incoming shortwave solar radiations is negligible. Therefore, it is possible to model RST history based on AT time series [4,21] .These predictions can then be used to evaluate whether past conditions were favorable to the formation of permafrost. We formulated three linear regression models per sensor to predict RST time series using temperature data from nearby Lourdes (Météo France 420 m a.s.l) and Goriz (2200 m a.s.l.) weather stations (Tab.S2):

- *All year Lourdes:* calibrated with the Lourdes AT and all RST measurements:
- *Winter Lourdes:* calibrated with Lourdes AT from mid-September to mid-May and corresponding RST
- *Summer Goriz:* calibrated with Goriz AT from mid-May to mid-September and corresponding RST

The *Winter Lourdes* and *Summer Goriz* linear models were combined (hereafter called the *Lourdes-Goriz (L-G)* regression) to predict year-round RST and better represent measured RST during summer (Fig. S2). However, for Vig_2 the regression with Goriz was insignificant (Tab. S2) and was thus ignored for the following data processing.

Summary statistics of models' errors at various time aggregations (daily, monthly, and annual) given in Table S3 show that bias between predicted and measured mean annual RST (MARST) is lower for Vig_3 and Vig_4 when considering the *Lourdes-Goriz* regression. Standard deviations for daily and monthly values are also improved.

Two RST time series were formulated per logger for Vig_1, Vig_3 and Vig_4 using the *All year Lourdes* regression from 1950 to 2018 and the *Lourdes-Goriz* regression from July 1981 to 2018 (Fig. 2). For Vig_2, only one time series was formulated with the *All year Lourdes* regression (the regression with Goriz was insignificant). All RST time series began in 1950 and ended in 2018, except the times series predicted with the *Lourdes-Goriz* regression, which began in 1981 when the Goriz station started recording. Measured RST replaced reconstructed RST when available in each of these time series.

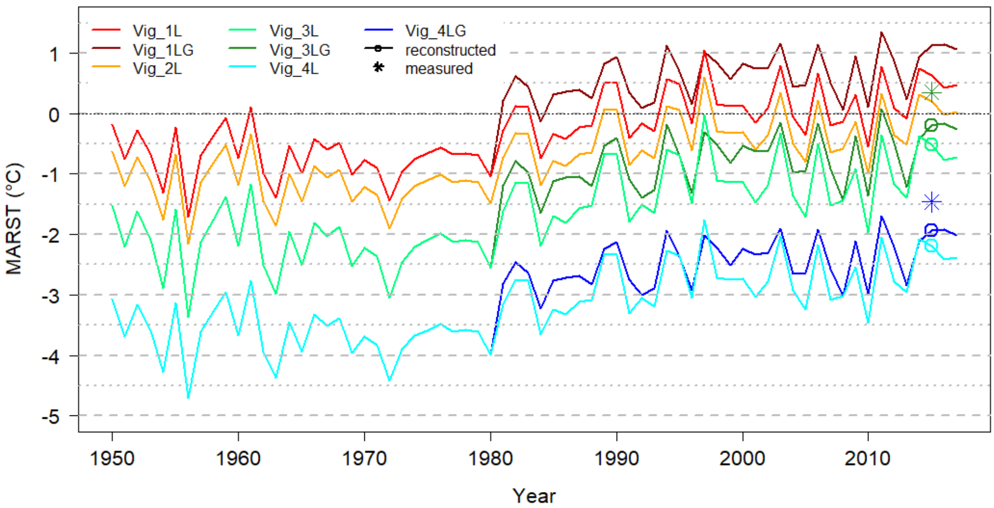

Figure 2. *Evolution of the mean annual RST as predicted with the different regressions. "L" after Vig_x is the time series reconstructed with Lourdes AT, while "LG" is the time series reconstructed with the Lourdes-Goriz regression. The "reconstructed" and "measured" symbols represent the mean annual rock surface temperature (MARST) for the full hydrological year that is available with measurements.*

1.2 Thermal modelling

We use the CryoGRID2 model [22] to asses permafrost evolution and characteristics at depth. We forced the top of the profile with the RST time series and at each time step, the profile at time *n-1* is used as an input for calculating the temperature profile at time *n*. We applied a thermal conductivity of 2.5 W $m^{-1}K^{-1}$, which is a standard value for limestone [23] (main Vignemale massif´s material). We ran simulations with different porosity values to test the sensitivity of our model to this poorly known parameter: 1% and 5% along the entire bedrock profile. While the former value is standard for compact limestone, the latter accounts for bedding that could increase the bulk porosity. Similar characteristics are considered for Vig_4 that lay in the Devonian schist combining carbonate and pelitic rock.

The temperature-depth profile of alpine rock wall is partly controlled by lateral heat fluxes resulting from variable energy balances between opposite faces [4]. For Vig_1, Vig_2 and Vig_3, no bottom heat flux was included in run simulations. However, Vig_4, the opposite south slope corresponds to a gently inclined plateau that is approximately 200 m away and is suspected to have a significant influence on the near surface thermal regime. In the absence of measurements on the south face (due to sensors failure), we determined a bottom heat flux based on assumptions formulated from previous studies on rock wall permafrost [21,24,25]. We thus perform several runs for Vig_4 accounting for no basal heat flux and a heat flux corresponding to an 8°C difference with the opposite south face (0.1 W. m^2) to provide a range of possible extreme values.

Before each simulation, the 10 first years predicted using the Lourdes regression (1950-1960) were run to initialize the thermal profiles. The spatial resolution of the simulated thermal profile was 0.1 m between the surface and 1 m depth, 0.2 m between 1 and 5 m depth, 0.5 m between 5 and 10 m depth and 1 m down to 30 m depth.

2 Results

2.1 Permafrost evolution since the 1950s

The predicted MARST for the period 1961-1990 shows that permafrost may have been present within the entire rock face and mostly characterized by warm permafrost (> -2°C), except at the extreme elevations (above 3100 m a.s.l) where cold permafrost (<-2ºC) is suggested (Tab. 2; Fig. 3). At Vig_2 and Vig_3, heat transfer simulations suggest that the coldest conditions were between 1970-1980. During the period 1981-2010, predicted MARST suggests that permafrost was no longer present at Vig_1 and simulated temperature profiles show a deepening of positive temperature (> 0ºC) from the 2000s, reaching a depth of > 20 m at present (Fig. 3). However, simulations using higher ice content value (5% porosity) or other RST predictions (Fig. S3) suggest that close to 0°C permafrost still persists (Fig. S3). At the elevations of Vig_2 and Vig_3, MARST was close to 0°C during the last period and simulations show that close to 0°C permafrost subsists down to 30 m depth at Vig_2, independent of the simulation forcing data or ice content. At Vig_3, close to 0°C temperature goes deeper since the years 2010s. Permafrost is present at location of Vig_4 (Tab. 2; Fig 3.) but is substantially affected by the incoming heat flux from the opposite south face, which induces rather warm permafrost conditions. Without this incoming heat flux, the conditions would likely favor cold permafrost. (Fig. S3).

		Vig_1	Vig_2	Vig_3	Vig_4
MARST 1961-1990 (°C)	Lourdes	-0.5	-1	-1.95	-3.6
	Lourdes -Goriz	-0.4	×	-1.8	-3.35
MARST 1981-2010 (°C)	Lourdes	0.03	-0.4	-1.25	-2.8
	Lourdes -Goriz	0.5	×	-0.85	-2.5
MARST 2014-2015	Measurement	×	×	0.21	-1.56

Table 2. *MARST during two periods and the measurement year 2014-2015.*

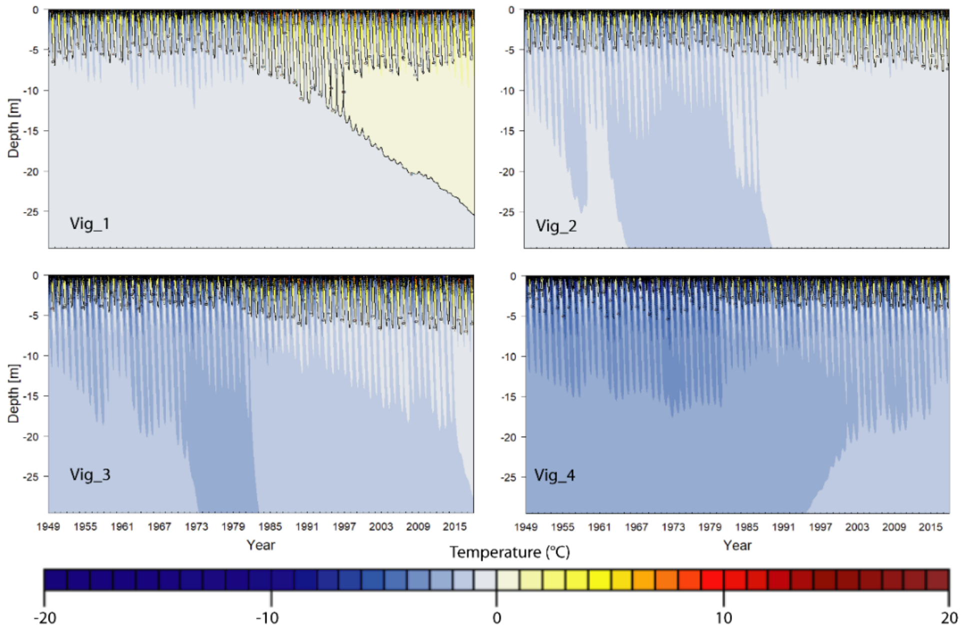

Figure 3. Bedrock temperature predicted with the best-fitted RST (with the Lourdes-Goriz regression for Vig_1, Vig_3 and Vig_4 and with the Lourdes regression for Vig_2), with a 1% porosity value and with a 0.1 W.m^{-1} bottom heat flux for Vig_4.

2.2 Active layer patterns

The active layer thicknesses (ALT) at Vig_3 (5.5 ± 1.2 m depth) and Vig_4 (3 ± 0.2 m depth) during summer 2015 are the only ALT values reported because they were forced with measured RST. The ice content (porosity value) causes the greater differences in the active layer thickness value at the relatively warm Vig_3, where latent heat processes strongly affect the thermal dynamics (Fig. S4).

3 Discussion

Results of this study present the first evidence of rock wall permafrost in the Pyrenees at 42°N. Rock wall permafrost distribution during the period 1961-1990 was similar to that which was found in north faces of the Mont Blanc massif (45°N) where the lowest occurrence on the north face was about 2400 m a.s.l. [21]. ALT in 2015 for Vig_3 and Vig_4 sensors (2983 m a.s.l and 3196 m a.s.l) showed similar values to the Aiguille du Midi site in the Mont Blanc massif [26].

Overall, our results are consistent with the classification described by Serrano et al. [6,7] .Our data show that permafrost may subsist at lower elevation (2600 m a.s.l) in fractured areas with higher ice content bedrock (MARST value of -0.5°C) coinciding with the upper limit of the infraperiglacial belt. Currently, close to 0°C permafrost has been identified on the Vignemale North face at 2800 m a.s.l, and up to 3000-3100 m a.s.l (periglacial belt). The upper section of the Vignemale north face, above 3100-3200 m a.s.l, has favorable climate conditions that enable the occurrence of cold (< -2°C) permafrost on the north face where no heat flux from a surrounding sun-exposed face significantly warms the subsurface. The main limitations in the interpretation of results are related to the temperature sensor quality (± 0.5 ºC), errors in RST reconstruction, which does not account for local and complex meteorological processes, as well as structural and thermal parameters used for thermal modelling.

The distribution of permafrost since the 1960s on the rock face has shown profound changes. During the 1961-1990 period, the entire rock face may have been affected by permafrost. By 2010, there was no longer permafrost up to 2600 m a.s.l and close to 0 ºC permafrost had receded up to 2800 m a.s.l. Since 2010, close to 0 ºC permafrost has receded to at least 3000 m a.s.l and cold (< -2°C) permafrost is only found in shaded areas above 3100 m a.s.l. These results confirm a progressive degradation of permafrost during the last decades as a consequence of increasing air temperatures [14] .Additionally, the rapid wastage and thinning of the Ossoue glacier [18],could potentially impact the energy balance of the south and east face and increasing the heat flux reaching the north face and intensifying permafrost degradation in the upper sections. The warm character of permafrost (> -2ºC up to 3000 m a.s.l) suggests an imminent disappearance of permafrost in the Vignemale, as well as in most of the peaks of the Pyrenees where elevations are lower than 3100 m a.s.l. These findings highlight the need to systematically study rock wall permafrost in the Pyrenees, as this would be an effective baseline for assessing climate change impacts in a relatively low-latitude, but still permafrost-affected mountain range, including hazards assessment, geotechnical and land planning concerns. Land planning in the high elevation areas of the Pyrenees must incorporate the current state of rock wall permafrost state and its future evolution in order to implement mitigation measures.

Conclusions

This study combines RST measurements, meteorological records, statistical analysis, and numerical thermal modelling to provide the first evidence of rock wall permafrost in the Pyrenees at 42 °N and the recent thermal evolution of an emblematic north face wall of the Pyrenees. During the late XX century, permafrost may have affected the entire Vignemale north face (as low as 2600 m a.s.l.) and it has progressively degraded and disappeared as consequence of an increase in air temperature of almost 1.5ºC since 1950. The lower limit of close to 0°C permafrost is currently likely between 2800 m a.s.l to 3000-3100 m a.s.l, while permafrost may subsist at lower elevations (2600 m a.s.l) in fractured areas with higher ice content bedrock. Climate conditions allow for the occurrence of cold (< -2°C) permafrost above 3100-3200 m a.s.l. but warmer conditions may be found near the top (3298 m a.s.l) due to warm heat fluxes coming from the south face.

This study is a preliminary step in demonstrating the interest to more systematically investigate rock wall permafrost in the Pyrenees with the aid of a robust and complete temperature sensor network. More robust monitoring would enable investigations of past and recent thermal dynamics in various topographical settings, permafrost distribution mapping, and determination of potential permafrost evolution in the near future according to available temperature projections.

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References

1. Haeberli W, Wegmann M, Mühll D. Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps. *Eclogae Geol Helv*. 1997;90:407-414.

2. Deline P, Gruber S, Delaloye R, et al. Chapter 15 - Ice Loss and Slope Stability in High-Mountain Regions. In: Shroder JF, Haeberli W, Whiteman Risks and Disasters CBT-S and I-RH, eds. Academic Press; 2015:521-561. doi:https://doi.org/10.1016/B978-0-12-394849-6.00015-9

3. Ravanel L, Magnin F, Deline P. Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. *Sci Total Environ*. 2017;609:132-143. doi:https://doi.org/10.1016/j.scitotenv.2017.07.055

4. Noetzli J, Gruber S, Kohl T, Salzmann N, Haeberli W. Three-dimensional distribution and evolution of permafrost temperatures in idealized high-mountain topography. *J Geophys Res Earth Surf*. 2007;112(F2). doi:10.1029/2006JF000545

5. Oliva M, Žebre M, Guglielmin M, et al. Permafrost conditions in the Mediterranean region since the Last Glaciation. *Earth-Science Rev*. 2018;185:397-436. doi:https://doi.org/10.1016/j.earscirev.2018.06.018

6. Serrano E, de Sanjosé-Blasco JJ, Gómez-Lende M, López-Moreno JI, Pisabarro A, Martínez-Fernández A. Periglacial environments and frozen ground in the central

Pyrenean high mountain area: Ground thermal regime and distribution of landforms and processes. *Permafr Periglac Process*. 2019;30(4):292-309. doi:10.1002/ppp.2032

7. Serrano E, López-Moreno JI, Gómez-Lende M, et al. Frozen ground and periglacial processes relationship in temperate high mountains: a case study at Monte Perdido-Tucarroya area (The Pyrenees, Spain). *J Mt Sci*. 2020;17(5):1013-1031. doi:10.1007/s11629-019-5614-5

8. Colucci R, Boccali C, Žebre M, Guglielmin M. Rock glaciers, protalus ramparts and pronival ramparts in the south-eastern Alps. *Geomorphology*. 2016;269. doi:10.1016/j.geomorph.2016.06.039

9. Westermann S, Schuler T V, Gisnås K, Etzelmüller B. Transient thermal modeling of permafrost conditions in Southern Norway. *Cryosph*. 2013;7(2):719-739. doi:10.5194/tc-7-719-2013

10. Magnin F, Etzelmüller B, Westermann S, Isaksen K, Hilger P, Hermanns R. Permafrost distribution in steep rock slopes in Norway: measurements, statistical modelling and implications for geomorphological processes. *Earth Surf Dyn*. 2019;7:1019-1040. doi:10.5194/esurf-7-1019-2019

11. Grunewald K, Scheithauer J. Europe's southernmost glaciers: response and adaptation to climate change. *J Glaciol*. 2010;56(195):129-142. doi:10.3189/002214310791190947

12. Rico I, Magnin F, López-Moreno JI, Alonso E, Revuelto J, Serrano E. First evidence of permafrost occurrence in a steep rock wall in the Pyrenees: The Vignemale North Face. . In: *VI Iberian Congress of the International Permafrost Association, Mieres (Spain).* ; 2017.

13. Desnivel. Diedro amarillo del Vignemale, en cuarentena por derrumbe. *https//www.desnivel.com/escalada-roca/diedro-amarillo-del-vignemale-en-cuarentena-por-derrumbe Accessed October, 26, 2020* . Published online 2012.

14. Cuadrat JM, Valero Garcés B, González-Sampériz P, et al. Clima y Variabilidad Climática en los Pirineos. In: Terraez J, Arauzo I, eds. *1º Informe Cambio Climático Pirineos OPCC - CTP 2018*. ; 2018:6-16.

15. Rico I, Izagirre E, Serrano E, López-Moreno J. Superficie glaciar actual en los Pirineos: Una actualización para 2016. *Pirineos*. 2017;172:029. doi:10.3989/Pirineos.2017.172004

16. Rico I. Los glaciares de los Pirineos. Estudio glaciológico y dinámica actual en el contexto del cambio global. . Published online 2019.

17. López-moreno JI, Alonso-González E, Monserrat o, et al. Ground-based remote-sensing techniques for diagnosis of the current state and recent evolution of the Monte Perdido Glacier, Spanish Pyrenees. *J Glaciol*. 2019;65(249):85-100. doi:DOI: 10.1017/jog.2018.96

18. Marti R, Gascoin S, Houet T, et al. Evolution of Ossoue Glacier (French Pyrenees) since the end of the Little Ice Age. *Cryosph Discuss*. 2015;9:2431-2494. doi:10.5194/tcd-9-2431-2015

19. López-Moreno JI, Soubeyroux J-M, Gascoin S, et al. Long-term trends (1958–2017) in snow cover duration and depth in the Pyrenees. *Int J Climatol*. Published online March 29, 2020. doi:10.1002/joc.6571

20. Navarro-Serrano F, López-Moreno JI, Azorin-Molina C, et al. Air temperature measurements using autonomous self-recording dataloggers in mountainous and snow covered areas. *Atmos Res*. 2019;224:168-179. doi:https://doi.org/10.1016/j.atmosres.2019.03.034

21. Magnin F, Brenning A, Bodin X, Deline P, Ravanel L. Statistical modelling of rock wall permafrost distribution: Application to the Mont Blanc massif. *Géomorphologie*. Published online January 1, 2015.

22. Westermann S, Schuler T V, Gisnås K, Etzelmüller B. Transient thermal modeling of permafrost conditions in Southern Norway. *Cryosph*. 2013;7(2):719-739. doi:10.5194/tc-7-719-2013

23. Kukkonen IT, Šafanda J. Numerical modelling of permafrost in bedrock in northern Fennoscandia during the Holocene. *Glob Planet Change*. 2001;29(3):259-273. doi:https://doi.org/10.1016/S0921-8181(01)00094-7

24. Magnin F, Westermann S, Pogliotti P, Ravanel L, Deline P, Malet E. Snow control on active layer thickness in steep alpine rock walls (Aiguille du Midi, 3842ma.s.l., Mont Blanc massif). *CATENA*. 2017;149:648-662. doi:https://doi.org/10.1016/j.catena.2016.06.006

25. Beutel J, Delaloye R, Hilbich C, et al. *PERMOS 2019. Permafrost in Switzerland 2014/2015 to 2017/2018*. Vol 16-19. (Nötzli J, Pellet C, Staub B, eds.). Cryospheric Commission of the Swiss Academy of Sciences (SCNAT); 2019. doi:10.13093/permos-rep-2019-16-19

26. Magnin F, Deline P, Ravanel L, Noetzli J, Pogliotti P. Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l). *Cryosph*. 2015;9(1):109-121. doi:10.5194/tc-9-109-2015

Supplement

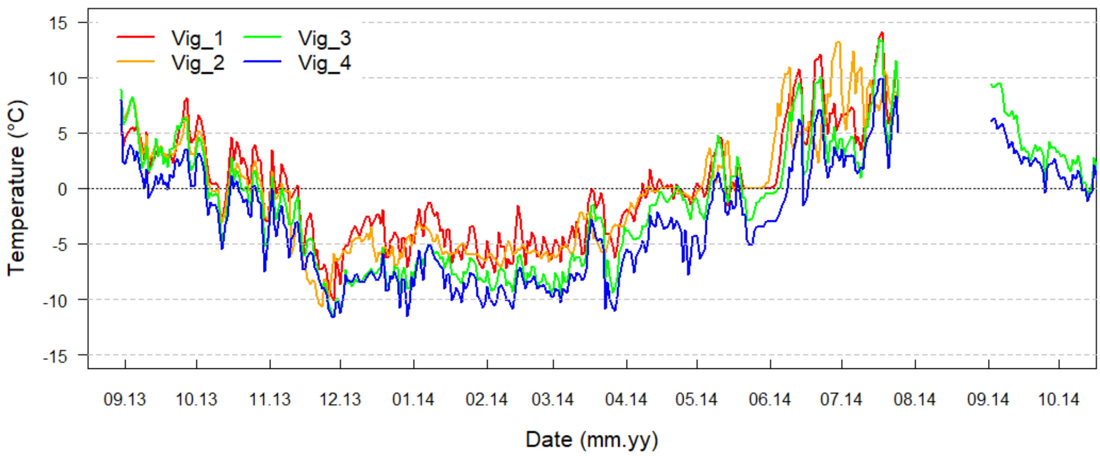

Figure S1. *Measured rock surface temperature time series aggregated in daily values*

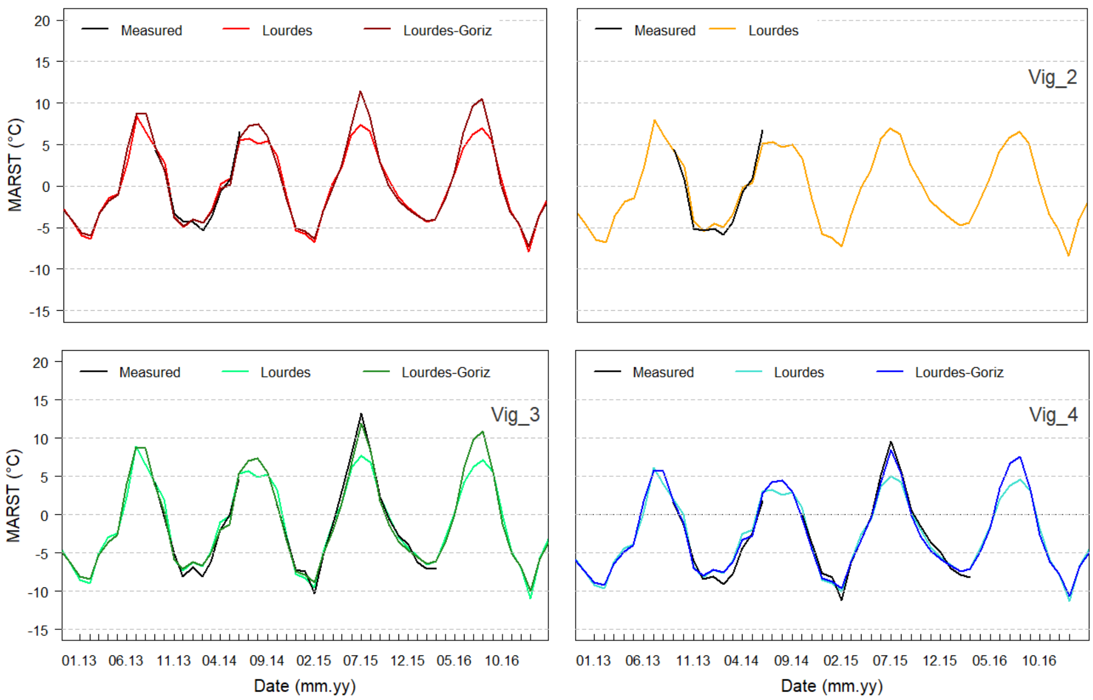

Figure S2. *Measured against predicted RST time series (monthly means). « Lourdes » is the linear regression fitted with all daily values of RST while « Lourdes-Goriz » are times series combining a linear regression with Lourdes data from mid-September to mid-May and a regression with Goriz from mid-May to mid-September.*

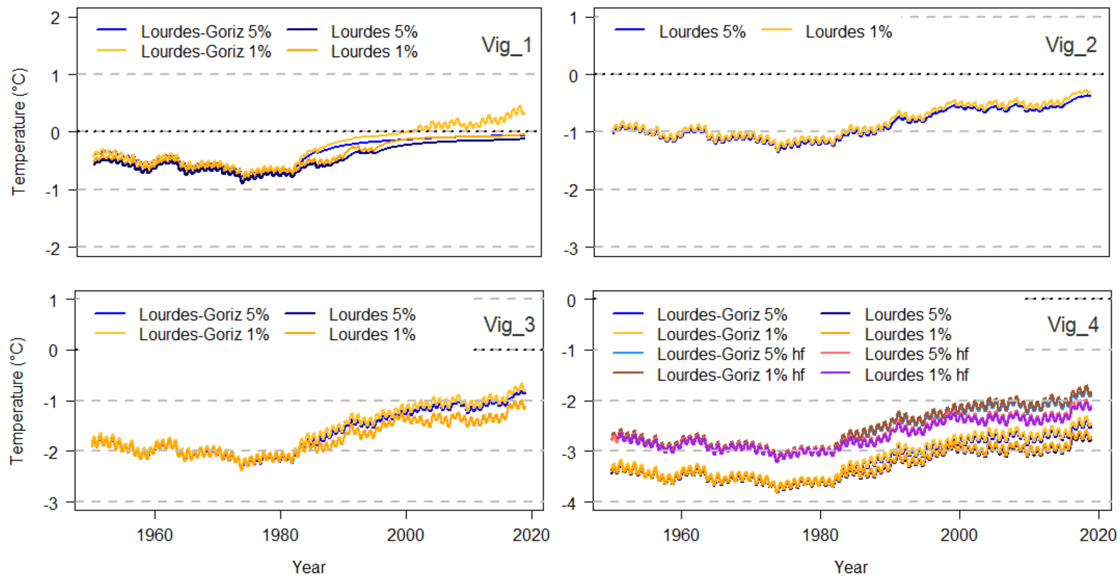

***Figure S3**: Modelled temperature at 15 m depth of each logger according to the various regressions and porosity value (5 and 1%) as well as without or with heat flux (hf).*

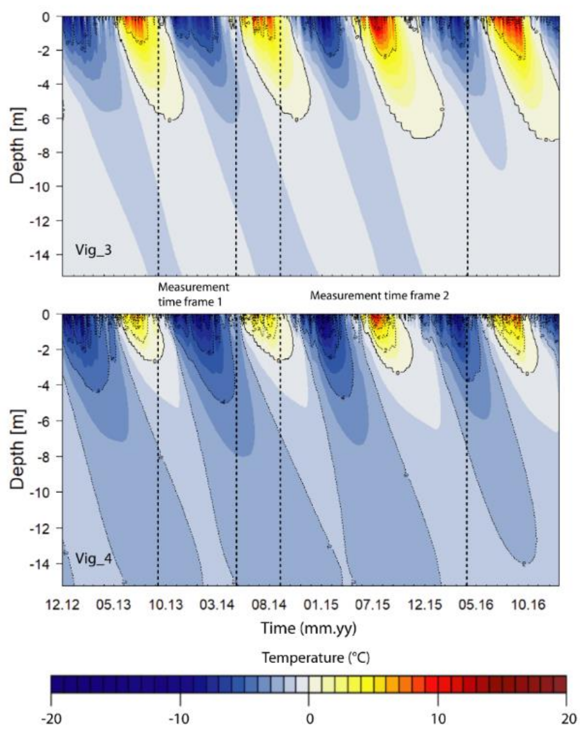

***Figure S4.** Focus on active layer thickness during years of RST measurements at Vig_3 and Vig_4.*

	Vig_3	Vig_4
Measured (2014-2015)	0.21	-1.56
Lourdes regression	-0.5	-2.2
Lourdes-Goriz regression	-0.17	-1.9

Table S1. *Comparison between measured and predicted mean annual RST for the hydrological year 2014-2015.*

		Vig_1	**Vig_2**	**Vig_3**	**Vig_4**
All year Lourdes	***R^2***	0.86	0.76	0.85	0.85
	Regression	0.8274x – 10.38	0.8314x – 10.875	1.0041x – 13.888	0.8837x – 13.962
	Obs. pts*	332	332	942	942
Winter Lourdes	***R^2***	0.84	0.75	0.81	0.80
	Regression	0.7072x – 9.4018	0.6608x – 9.7221	0.8097x – 12.383	0.7396x – 12.85
	Obs. pts*	242	242	683	683
Summer Goriz	***R^2***	0.75	0.32	0.88	0.83
	Regression	0.8621x – 2.5535	0.5595x + 0.6494	1.0053 – 4.4072	0.8635x – 5.5722
	Obs. pts*	90	90	266	266

Table S2. *Regression values between RST and AT. *Obs. pts is the number of available daily RST measurements for regression calibration.*

		Vig_1		Vig_2		Vig_3		Vig_4	
		Lourdes	L-G	Lourdes	L-G	Lourdes	L-G	Lourdes	L-G
MARST difference between measure and prediction		×	×	×	×	0.71	0.38	0.64	0.34
R^2	Month	0.97	0.98	0.96	×	0.95	0.98	0.94	0.97
	Day	0.86	0.9	0.76	×	0.85	0.92	0.85	0.9
Mean error (°C)	Month	0.19	0.02	0.29	×	0.39	0.33	0.9	0.58
	Day	0	-0.02	0	×	0	-0.03	0	-0.02
Standard deviation (°C)	Month	0.7	0.57	0.94	×	0.6	0.86	0.79	0.78
	Day	1.8	1.6	2.58	×	2.48	1.83	2.19	1.74

Table S3. *Summary of predicted RST errors.*