New observations indicate the possible presence of permafrost in North Africa (Djebel Toubkal, High Atlas, Morocco)

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Abstract. Relict and present-day periglacial activity have been reported in the literature for the upper reaches of the High Atlas mountains, the highest range in North Africa (Djebel Toubkal – 4,167 m a.s.l.). Lobate features in the Irhzer Ikbi South at 3,800 m a.s.l. have been previously interpreted as an active rock glacier, but no measurements of ground or air temperatures are known to exist for the area. In order to assess on the possible presence of permafrost, we analyse data from June 2015 to June 2016 from two air temperature sites at 2,370 and 3,200 m a.s.l., and from four ground surface temperature (GST) sites at 3,200, 3,815, 3,980 and 4,160 m a.s.l. allowing to characterize conditions along an altitudinal gradient along the Oued Ihghyghaye valley to the summit of the Djebel Toubkal. GST were collected at 1-hour intervals and the presence of snow cover at the monitoring sites was validated using Landsat-8 and Sentinel-2 imagery. Two field visits allowed for logger installation and collection and for assessing the geomorphological features in the area. The results show that snow plays a major role on the thermal regime of the shallow ground, inducing important spatial variability. The lowest site at 3,210 m showed a regime characterized by frequent freeze-thaw cycles during the cold season but with a small number of days of snow. When snow settled, the ground remained isothermal at 0 ºC, the thermal regime indicating the absence of permafrost. The highest sites at 3,980 and 4,160 m a.s.l. showed very frequent freeze-thaw cycles and a small influence of the snow cover on GST, reflecting the lack of snow accumulation due to the wind-exposed settings in a ridge and in the summit plateau. The site located at 3,815 m in the Irhzer Ikbi South valley showed a stable thermal regime from December to March with GST varying from -4.5 to -6 ºC, under a continuous snow cover. The site's location in a concave setting favours wind-driven snow accumulation and lower incoming solar radiation due to the shadowing effect of a southwards ridge, favouring the maintenance of a thick snow pack. The stable and low GST are interpreted as a strong indicator of the probable presence of permafrost at this site, an interpretation supported by the presence of lobate and arcuate features in the talus deposits. These results are still a first approach and observations through geophysics and boreholes are foreseen. This is the first time that probable permafrost is reported from temperature observations in the mountains of North Africa.

1. Introduction

Permafrost occurrence in arid and semi-arid mountains plays a significant environmental role due to its influence on hydrology. Frozen ground induces refreezing of rain and snowmelt and acts as a subsurface water reservoir able to support streamflow even during the dry season. Its influence can therefore be significant for ecosystems and biodiversity, and in some mountain areas, permafrost may show impacts for agriculture and grazing. However, permafrost research in high remote mountain regions is still in its early stages (see Rangecroft et al., 2013). In fast changing and sensitive mountain environments, permafrost niches can also provide special conditions allowing for the occurrence of biological refugia, which may include endemisms and extremophiles of scientific significance (Hu et al., 2015; Jansson and Taş, 2014). Ice-rich permafrost and ground ice may also allow for environmental reconstruction (Lacelle and Vasil'chuk, 2013). Permafrost also plays a significant role for geomorphological dynamics in mountains, with a number of specific associated landforms and hazards linked to its warming and consequent thaw, such as rock falls and landslides (Haeberli et al., 2010).

The climatic importance of permafrost and the active layer has lead to their classification as Essential Climate Variable (ECV 9) by the Global Climate Observing System of the World Meteorological Organization (Smith and Brown, 2009). The International Permafrost Association maintains the Global Terrestrial Network for Permafrost (GTN-P), which includes over 1074 boreholes, but with only 31 sites in mountain permafrost settings (Biskaborn et al., 2015), which are still poorly assessed regions (Gruber and Haeberli, 2009).

Contemporary permafrost occurrence is known in the Western Mediterranean region but is mostly constrained to small areas at high altitude or shady sites. In the Pyrenees, several active rock glaciers are present and their distribution suggests that the lower limit of permafrost is at about 2,630-2,700 m a.s.l. (Oliva et al., 2016b; Serrano et al., 2009). Geophysical and temperature observations compiled from several authors by Serrano et al. (2009) suggest that continuous permafrost occurs above 3,000-3,100 m a.s.l. In the Sierra Nevada (37º 03' N, 03º 19' W) an isolated patch of permafrost and a very small rock glacier lobe occurs in the Veleta cirque in a north facing cirque at 3,150 m a.s.l., protected by a steep rockwall and reflecting relict conditions associated with buried ice (Tanarro et al., 2001). The mean annual ground temperature for 1998/99-2008/09 in a shallow borehole in the rock glacier was 0.6 ºC at 0.05 m depth and -1.4 ºC at 1.5 m (Salvador Franch et al., 2011). A deep borehole in the summit area at the Veleta Peak (3,380 m a.s.l.) shows that permafrost is absent and mean annual ground temperatures were 3.2 ºC at 0.6 m and 2 ºC at 20 m depth (Oliva et al., 2016a).

Periglacial features are widespread in the High Atlas (Hughes et al., 2011) having been described for the Central High Atlas by Couvreur (1966), who has reported active solifluction above 2,200 m a.s.l. The same author states that permafrost is absent in that part of the High Atlas and notes that there is a strong lithological control on the types of periglacial features that occur. For the Western High Atlas, Chardon and Riser (1981) have pushed the limit of frost activity towards 2,500 m and consider that frost action dominates the morphogenesis above 3,000 m. Robinson and Williams (1992) on a study on sandstone weathering report frequent air temperature minima from -10 to 0 ºC in winter and as low as -20 ºC, at 2,000 m a.s.l. The only landforms supporting a permafrost-related morphogenesis described in the literature are rock glaciers reported for the High

Atlas by Dresch (1941), Wilche (1953) and Chardon and Riser (1981). Most of them are relict features and at least one case, the Arroumd rock mass near Imlil, has been recently re-interpreted as a very large rock slide (Hughes et al., 2014). The only reference that we have found for active permafrost-related landforms is Chardon and Riser (1981), who interpret lobate features in the Irhzer Ikbi South at 3,800 m a.s.l. as an active rock glacier. However, recent studies are missing and the literature lacks direct observations and quantitative data supporting the presence of permafrost. The only direct thermal observation of permafrost in the whole Africa, known to the authors, is from Mount Kilimanjaro, where permafrost has been reported at 5,785 m a.s.l. with temperatures of -0.03 ºC at 3 m depth (Yoshikawa, 2013).

Given the climate change scenarios that the Mediterranean regions face, marked by warming and precipitation decrease (Giorgi and Lionello, 2007; Montanari, 2013; Simonneaux et al., 2015), permafrost should be close to the threshold of disappearance in most Mediterranean mountains. The subsurface nature of permafrost and the presence of a thawed surface layer in the warmer season (the active layer) strongly limit its identification, characterization and mapping, especially in remote mountain areas (Gruber and Haeberli, 2009).

The present research aims at contributing to solve the question of the presence of permafrost in North Africa and is an exploratory step towards an in-depth assessment aiming at the characterization and modelling of permafrost in the High Atlas. For such an initial assessment, we have installed a set of ground surface temperature (GST) and air temperature data loggers across an altitudinal gradient from 3,200 m to the summit of the Djebel Toubkal in order to characterize the ground temperature regime and heat exchange at the ground-atmosphere interface. The detailed analysis of the GST provides a good insight on the atmosphere-soil interaction, as one of the major controlling factors on the ground thermal regime.

2. Study Area

The Djebel Toubkal is located in the Western High Atlas (31º 4' N, 7º 55' W) and is the highest mountain in North Africa with 4,167 m a.s.l. (Figure 1). The Atlas Mountains comprise a series of ranges and plateaus extending from southwest Morocco to northern Tunisia across more than 2,400 km (Mark and Osmaston, 2008). In Morocco, the Atlas Mountains comprise, from north to south: the Middle Atlas (Djebel Bou Naceur, 3,340 m), the High Atlas (Djebel Toubkal, 4,167 m) and the Anti-Atlas (Djebel Sirwa, 3,304 m). The High and Middle Atlas are intracontinental fold-thrust belts located in the foreland of the Rif (Arboleya et al., 2004). The three major massifs in the High Atlas are, from west to east: the Djebel Toubkal Massif, the Irhil M'Goun Massif (4,071 m) and the Djebel Ayachi (3,751 m).

The climate in the High Atlas is marked by the influence of the Atlantic Ocean to the West, the Mediterranean Sea to the North and the Sahara Desert to the South, resulting in a semi-arid to arid climate (Knippertz et al., 2003; Marchane et al., 2015). The rainy season lasts from November to April and the dry season coincides with the summer, reflecting the Mediterranean style of the climate (N'da et al., 2016). Annual rainfall exceeds 600 mm above 700 m, with summer precipitation being mostly convective. Boudhar et al. (2014) report an average of 520 mm of annual precipitation for the period of 1989 to 2010 in Oukaimeden at 3,200 m elevation. Snow is present from November to April/May in the highest parts of the mountains, but with irregular regimes (Badri et al., 1994; Peyron, 1980) and is rarely continuous at mid-altitude, with events of snowfall and subsequent melt sometimes happening within one week. However, in the highest reaches, snow cover lasts for several weeks to months (Boudhar et al., 2009). Snowmelt contributes to 15-50% of the stream flow in the Tensift catchment, playing a significant role for irrigation (Boudhar et al., 2009). The low atmospheric humidity and typically subfreezing temperatures above 3,000 m favour losses by sublimation, which can account up to 44% of snow ablation, while at lower altitudes melting prevails (Schulz and de Jong, 2004). Seemingly, the only perennial snow patch in North Africa, occurs in the northern cliffs of the Tazaghart plateau (3,980 m a.s.l.), close to the Toubkal. This feature is described in various recent papers and was identified by Dresch (1941) together with other periglacial features (see Hughes, 2014). Its presence may be related to the high snow feeding area in the plateau above, together with the shelter effect of the steep north-exposed cliff face.

The present study was conducted in the upper reaches of the Oued Ihghyghaye valley, between the marabout of Sidi-Chamharouch and the summit of Djebel Toubkal (Figure 1). The lithology of the study area is composed by Precambrian volcanics, such as Piroxene-bearing doleritic basalts and megaporphyric basalts of the Sidi Chamharouch formation (Zahour et al., 2016) and andesites in the Djebel Toubkal (Cheggour, 2008; Rauh, 1952; Ros et al., 2000). The area shows a typical alpine relief with sharp crests rising above 3,500 m and long deep valleys, with the upper catchments showing evidence of Late Pleistocene glaciation with frequent landforms such as roches mouttounées and moraines (Chardon and Riser, 1981; Hannah et al., 2016; Hughes et al., 2011; Hughes and Woodward, 2008; Mark and Osmaston, 2008; de Martonne, 1924). Extensive talus slopes and debris cones, together with widespread evidence of frost shattering mark the landscape above 3,000 m.

The detailed study area for ground surface temperatures develops between the Neltner refuge and the Toubkal summit along the Irhzer Ikhibi-South valley, which is the main climbing route. The valley with about 1,400 m in length is a hanging tributary of the Oued Ihghyghayene valley and rises southeastwards of the Neltner refuge above a rock knob with glacier polished outcrops at 3,350-3,400 m. Up valley from the knob, the floor shows a steep longitudinal gradient and is filled by accumulations of large boulders, passing towards the east into the distal parts of talus slopes, which are matrix-supported accumulations of decimetric to metric angular clasts (figure 2). At ci. 3,800 m the deposits show small lobate forms and incipient arcuate ramparts supporting an active periglacial dynamics, either by solifluction or permafrost creep. Chardon & Riser (1981) interpret this sector as an active rock glacier, but no steep front occurs and no debris body is clearly defined and therefore we do not support this interpretation. No water springs have been observed near the talus slope. The valley shows dissimetric slopes, with 15-25º prevailing in the north slope and 20 to 40º prevailing in the south slope, valley headwalls showing 30-40º, with scarps and free faces occurying at 3,800-3,900 m, except in the north slope. Above the scarps, slope angle is 15-30º and the surfaces are mantled with angular clasts and boulders, with a similar situation in the north slope of the Irhzer Ikhibi-South. The south ridge rises above 3,900 m shadowing the valley floor in winter. A snow patch occurs frequently until June in the valley, especially in the Toubkal slope and may be partly responsible for the debris ramparts described above. Oral information from local guides confirms that during the cold season snow accumulates due to wind redistribution from the col and that avalanches do not occur at the site. Google Earth imagery allows identifying around the Toubkal numerous debris-mantled slopes and taluses with flow-like lineaments, suggesting creep, and small rock glacier-like features are also identifiable. At the col of the Irhzer Ikhibi Nord, north of the Toubkal, at 3,900 m, solifluction lobes are present.

3. Methods

3.1 Air and ground surface temperature monitoring

Air temperature, relative humidity and ground surface temperature data loggers were installed in June 2015 from Sidi Chamharouch (2, 370 m) to Djebel Toubkal (4,160 m a.s.l.) across an altitudinal transect aiming at an hourly characterization of the soil and air climate for 2015-16. For air temperature and relative humidity, we used Hobo ProV2 loggers, with an accuracy of ±0.2 ºC, installed in radiation shields at ci. 2 m height. One was installed close to a shop in Sidi Chamharouch (2,370 m) and the other near the Neltner refuge of the Club Alpin Français de Casablanca (3,210 m). Both sites were surveyed by local partners. A minilogger ibutton DS-1922L was installed at the summit of Djebel Toubkal (4,167 m), hidden in a shaddy location in the iron trig that stands at the top. However, this logger disappeared and data was lost.

For GST, single channel miniloggers Hobo TidBit with an accuracy of ±0.2 ºC were glued to the lower face of a 15x15x0.2 cm high diffusivity steel plate that maximizes contact with the soil particles, when buried at 2-3 cm depth (see Ferreira et al. 2016). To check for drifts on temperature accuracy after retrieval, the loggers were tested under various temperature settings (-20 ºC to 39 ºC) and showed average differences under 0.1 ºC, which is well within sensor error. The data was corrected using the freezing zero-curtain, having resulted in correction from -0.02 to -0.08 ºC. Four of such plates were used between the Neltner refuge and the summit of Djebel Toubkal. The sites were selected to characterize the altitude control on GST and were installed along the main climbing route. All sites were installed in stony silty-sandy soils, matrix-supported, in gentle slope positions, but where locally the terrain was relatively flat. Neltner (NLT) was installed above the refuge in a boulderly diamicton. Toubkal 3 (T3) was installed in boulderly diamicton in a valley position, where snow accumulation is favoured. Toubkal 2 (T2) was installed in a debris-mantled slope, a few meters below a ridge crest. Toubkal 1 (T1) was installed in the debris-mantled surface of the Djbel Toubkal summit plateau, about 100 m from the summit, to avoid the proximity of climbers. Given the known high spatial variability of GST in complex mountain settings (see Gubler et al., 2011) the interpretation of the results must be conducted with care and this is also the reason why we tried to limit the soil differences between sites. Details are provided in Table 1 and figure 3.

Temperatures were recorded hourly from 16 June 2015 to 16 July 2016 with the objective of having a whole year of data, centered in the cold season. All measures presented are derived from hourly data.

3.2 Potential solar radiation modelling

Slope angle and potential solar radiation was modelled using the algorithms of SAGA GIS 4.0, using a standard lumped atmospheric transmittance effect of 70% and the ASTER Global Digital Elevation Model version 2 from NASA, with a pixel size of 30 m. The total potential solar radiation (direct + diffuse) was used for the whole year and also for July in order to assess the influence of solar input in the ground temperature maxima.

3.3 Remote sensing characterization of the snow cover

Although ground surface temperature regimes allow for identifying the presence of snow cover with high degree of confidence, for this study it was essential to demonstrate that snow played a major role on GST and that it was present at some of the sites. For characterizing snow cover we used 18 scenes from Landsat 8 OLI and 2 scenes from Sentinel 2-A from 16/09/2015 to 14/06/2016. Landsat scenes were obtained at 16-day intervals, at 10 AM local time (USGS, 2016) and only one scene showed partial cloud cover. Sentinel-2 scenes at 10:30 AM complement the series and allow confirming the results obtained with Landsat. Pixel size is 30 m for Landsat 8 and 10 m for Sentinel 2 (ESA, 2015). We have used full resolution georeferenced visible colour composites provided by USGS at EarthExplorer. The images allowed to identify the general snow cover conditions at the monitoring sites. For the interpretation, caution was necessary since the spatial resolution of the imagery is much larger than the microscale variability that may affect the monitoring sites. The snow conditions at each site were classified by visual inspection of the imagery as « no snow », « possible snow/snow margin », « snow » and « significant snow ». The later showed a homogeneous spectral signal of the snow surface across the areas surrounding the sensor sites, while the “snow” class showed still some spectral mixture, but clearly the presence of snow cover. The classification was done on-screen in QGIS using an overlay of elevation contours and the coordinates of the monitoring sites for better accuracy. Differences between snow and cloud cover were easily identifiable and clouds were rare.

3.4 Climate series and extrapolation

To assess the climatic representativity of the period of June 2015 to July 2016, a long-term climate series of temperature and precipitation from a nearby meteorological station is needed. This allows comparing monthly records with the reference series and better frame the study period and discussing the results. However, the High Atlas has no long-term meteorological stations and the regional network is very sparse. The only long-term meteorological data available are from Marrakesh (Menara) in the plains north of the mountain range at 468 m a.s.l. and about 65 km from the study site, or from Ouarzazate, in the southern piedmont, at 1,153 m a.s.l, but in a very dry setting. Middelt, located 350 km to the east of the Toubkal Massif at 1,515 m a.s.l. shows very incomplete data. Given the more complete data series of Menara we used it for framing the climate characteristics of the study period in a time series. The data was obtained from the Custom Monthly Summaries of the Global Historical Climate Network (NCDC) for 1977-2016. Before 1977 there are several gaps in the series.

4. Results

4.1 Climate characteristics of the study period

Climate records from Marrakesh (Menara – Figure 4) for June 2015 to March 2016 (no data available afterwards) show that mean monthly temperature from June to December was close to the median, but January was extremely warm, with a value (15.2 ºC) close to the maximum (15.5 ºC) of the period 1977-2015 and well above the 3rd quartile (13.4 ºC). February with 14.9 ºC was between the median and the 3rd quartile and March showed a mean monthly temperature close to the 1st quartile, with 15.4 ºC. Precipitation showed very high values in August and September (close to the maximum), decreasing afterwards, with November to January as very dry months, below the 1st quartile and close to the minimum. February showed precipitation close to the median and March, close to the 3rd quartile. The study period was therefore initially characterized by a wet summer, followed by a dry autumn and early winter, which coincided with a very warm January, followed by a very cold and wet March.

The mean monthly air temperatures measured at Sidi Chamharouch and Neltner showed similar variation as Menara, with the exceptions of February and March, which were colder in the mountain massif (figure 5). The lowest mean air temperature was recorded at Neltner with -1.2 ºC in February 2016 (3.8 ºC in Sidi Chamharouch) and the highest was July 2015 with 14.0 ºC in Neltner (20.9 ºC in Sidi Chamharouch). The mean annual air temperature (MAAT) for July 2015 to June 2016 was 6.2 ºC at Neltner and 11.1 ºC at Sidi Chamharouch, which results in a lapse rate of -0.59 ºC.100 m^{-1}, a value close to the -0.56 ºC.100 m^{-1} calculated by Boudhar et al. (2009) from weather station data from Saada (411 m) and Oukaimeden (2,760 m) for 1998-2005. The extrapolation of the lapse rate obtained for our two stations to the summit results in a MAAT of 0.6 ºC.

Reports from local guides indicate that the winter of 2015/16 was anomalous for snow conditions, with a very late onset of the snow pack in mid-February. This is confirmed by the remote sensing data (figure 6), which shows snow in early October 2015 affecting the Toubkal massif with a peak in the scene of 18/10/2015, then decreasing progressively until early January when a short duration cover shows up, then melting again until 7 February. It was only between 7 and 23 February that significant snowfall occurred covering the whole study area. The snow cover remained in the valley floors and concave areas until 11 April, but quickly melted from the ridges and south facing slopes. In mid-May another large snow fall event took place, but snow melted quickly in two weeks and by mid-June was completely gone from the study area.

4.2 Ground Surface Temperatures

Mean monthly ground surface temperatures at the Toubkal massif showed a similar annual regime at the 4 sites (figure 7), with the warmest month in June 2016 showing values from 13.5 ºC at T2 to 17.7 ºC at NLT. The cold season showed mean monthly temperatures below 0 ºC from November to March at the 3 higher sites, with NLT still showing a positive average in November. T3 showed stable mean GST below -5 ºC from December to March, while T1 showed the minimum in February with -4.5 ºC.

The daily absolute temperature maxima and minima follow in general the regime of the monthly means, except at T3 and evidence very high amplitudes. A plateau in the curve for the daily maxima is observable from April to September, with T3 showing the highest values reaching 39.3 and 40.5 ºC in June and July 2016, respectively. At the same site, the stabilization of the absolute maxima below -4.4 ºC in January and February 2016, as well as the sudden rise from 0 ºC in March to 31.3 ºC in April, are noteworthy. The mean annual GST (MAGST) showed a decrease with altitude with values of 6.0 ºC at NLT, 3.2 ºC at T3, 3.3 ºC at T2 and 2.8 ºC at T1, the summit of Toubkal (figure 8 and table 2). Degree-days of freezing were extremely varied, with the minimum at NLT with 110, the maximum at T3 with 779, and 325 and 499 at T2 and T1 respectively (table 2). Degree-days of thawing showed very high values, ranging from 1536 at T1 to 2317 at NLT, with a general decrease with altitude. Annual potential incoming solar radiation (figure 9) showed much higher values at the interfluve sites (T1 – 2432 and T2 – 2631 $kWh.m^{-2}$) than at the valley sites (NLT – 1703 and T3 – 1892 $kWh.m^{-2}$), while July values were much more homogeneous ranging from 223 $kWh.m^{-2}$ at NLT to 262 $kWh.m^{-2}$ at T1.

Four altitudinal patterns of mean monthly GST occurred in the study period (figure 10). Group 1 includes the warm season, with June, July and August and shows decreasing GST with altitude, with T2 slightly colder than T1. Group 2 integrates the transition months, with May, September and October showing a similar continuous decrease of GST with altitude and a rate of ci. -0.47 $ºC.100\ m^{-1}$. Group 3 includes the cold season, with January, February, March, November and December and shows a general decreasing of GST with altitude, but with T3 being the coldest site. Finally, April 2016 shows up as an outlier, with an inverted rate with altitude, but with T3 as the warmest site (Group 4).

The hourly records of GST allow for a more accurate analysis of the conditions influencing the monthly means and to assess the environmental controls on the ground thermal regime (figure 11). The first striking characteristic of the GST at the 4 sites is the large diurnal thermal amplitude range, especially from May to September with averages of 11.4 to 12 ºC, except at T3, with 19.7 ºC. Maximum amplitudes were from 19.2 to 22.5 ºC, except at T3, with 35 ºC.

The cold season is clearly defined in the GST, lasting from mid-October to the end of April, with May being a transition month. Differences in GST regimes are clear during the cold season. NLT showed a long period from mid-October to mid-February with small thermal amplitude and numerous freeze-thaw cycles. Afterwards, temperatures remained stable just below freezing until mid-April. At T3 the cold season was marked by subfreezing temperatures from mid-October to mid-April, with temperatures decreasing regularly until mid-December after a zero-curtain effect lasting about 2 weeks in late-October. Then, a stable value starting at around -4.5 ºC and decreasing irregularly to about -6 ºC occurred, as situation which lasted until late March, when temperatures increased quickly and then stabilized for about 10 days with a zero-curtain effect. During this period the diurnal amplitudes of GST at T3 were typically between 0.4 and 1.0 ºC, with an average of 0.8 ºC. The GST regime is especially significant in this paper and will be analysed in more detail below. The two upper sites, T2 and T1, show very similar GST regimes during the cold season, with the main differences being the number of freeze-thaw cycles which is larger at T2, with lower maxima during the cold season at T1. Both sites show a short zero-curtain effect in late-October, simultaneously to T1. GST daily amplitudes from mid-December to mid-March averaged 5.2 ºC at T2 and 4.8 ºC at T1 and were variable at NLT.

After an increase in GST in April 2016, May showed a significant cooling that lasted for 8 days in NLT and 19 days at T3. This cold event resulted in a stabilization of GST at 0.5 ºC at NLT, at 0.2 ºC at T3 and at 0 ºC at T1 and in a cold but unstable regime at T2.

5. Discussion

MAGST in the study area varied between 6.0 and 2.8 ºC, values which are high when compared to mid-latitude mountains with permafrost. There is a clear altitudinal control on the MAGST but site specific factors, such as high snow accumulation and lower annual potential solar radiation, affect the spatial pattern and lower the temperatures as occurs at T3. Consequently, this site showed 779 degree-days of freezing (DDf) in contrast with 325 and 499 DDf at the ridge and summit sites. The effect of increased solar radiation at ridge and summit sites, which show very high values of potential radiation, together with the wind exposition and lack of snow, are also causes for the freeze-thaw regimes observed even during the cold season. The low cloudiness of the mountain range, as demonstrated by the high number of cloudfree remote sensing scenes, emphasises this effect. Potential solar radiation in the summer is high, but homogeneous between sites and do not explain the differences in diurnal thermal regimes, with very high maxima, especially at T3. This fact is noteworthy it the extreme value of 1,936 thawing degree-days (DDt) at the later site, when compared to 1,536-1,542 DDt at the ridge and summit sites. The cause to this difference must be in ground thermophysical properties, as well as to the concave and wind sheltered location at T3, receiving increased radiation from the valley slopes.

The hourly GST data allow for a first insight into the ground thermal regime of the High Atlas periglacial zone. The comparison of the snow cover at different altitudes derived from the remote sensing imagery with the GST regimes confirms that the presence of the snow pack is the cause for stable temperatures close or below 0 ºC during the cold season at the different sites (figure 6). This fact is clear both for the period from late October to mid-April, but also for the short cooling event in May. The effect is well known and has been shown for different regions. While a thin and compacted snow layer a few centimeters thick allows for fast heat transfer between the ground and the atmosphere, and in some cases, even to an increase in ground cooling due to high albedo and high ice thermal diffusivity, a thick snow pack acts as buffer between the ground and the atmosphere. If snow is thick enough, the thermal wave will be delayed in the ground (Goodrich, 1982; Staub and Delaloye, 2016; Williams and Smith, 1989). If the ground is unfrozen at depth, heat will flow towards the snow pack and the ground surface temperature will be controlled by phase change at the snow interface, generating near 0 ºC isothermal regimes (Vieira et al., 2003) - the so-called zero-curtain effect (Outcalt et al., 1990). On the other hand, if the ground is colder than the snow pack, it will generate a heat sink at depth, inducing a decrease in GST, which are function of the insulating capacity of the snow pack, that also depends on forcing induced by the atmosphere at the snow-air interface (see Haeberli and Patzelt, 1982; Ishikawa, 2002).

From the four monitored sites, T3 shows a remarkable regime with relatively stable GST at ci. -5.8 ºC from December 2015 to March 2016. The small temperature range reflects the insulating effect of snow cover, but still a small diurnal wave is identifiable in the GST with daily amplitudes of up to 1 ºC. As an example, the detailed examination of the hourly temperatures at T3 from 4 to 20 December 2015 shows GST consistently below estimated air temperatures, except for a few hours in 11 and 12 December (figure 12). This situation occurred all over the snow cover period. Data also shows that the thermal wave is delayed in the snowpack for about 5-6 hours with the resulting GST curve being much smoother than air temperatures.

Ishikawa (2003) reports two sites with GST regimes very close to the one of T3 in the Hidaka Mountains (Hokkaido, Japan), located in low altitude openwork boulder deposits, favouring cold air drainage and funneling in winter. The author has classified this type of settings as the extrazonal permafrost zone. Lambiel and Pieracci (2008) also report a similar thermal regime to T3 at the base of a talus slope at low altitude in the Western Swiss Alps, reporting GST in the end of the winter below -5 ºC as an indicator of the probable presence of permafrost. Values of spring GST below thick snow covers under -3 ºC are frequently used in the literature as an indication of the probable presence of permafrost, an approach derived from the widely used Bottom Temperature of Snow (BTS) method (Hoelzle, 1992; Lewkowicz and Ednie, 2004). Numerous cases with sporadic permafrost developing in talus slopes have been reported and the cooling process below coarse debris is well-known (e.g. Delaloye et al., 2003; Delaloye and Lambiel, 2005; Gadek, 2012; Sawada et al., 2003). Gądek and Kędzia (2008) in a study for the Tatra Mountains (Poland and Slovakia), where different GST regimes were analysed, associated sites with steadily decreasing temperatures during the winter to increasing snow cover, and where GST dropped to below about -5 ºC, permafrost was found. Such sites were not open work, which limited cold air flow through the boulders, a situation similar to T3 in the Toubkal. Furthermore, small variations in GST through the cold season indicated that the snow insulation was not perfect. In those situations, ground cooling was attributed to the concave locations with cold air flowing over the surface, which cooled the snow and ground. This process acted together with the low summer solar irradiation to promote cooling, with a larger influence on low GST than snow thickness or elevation. Other authors have indicated snow redistribution by avalanches as an important factor promoting cooler ground and permafrost formation at the base of slopes, since snow lasts longer at those localities, mitigating ground surface warming (Haeberli, 1975). Onaca et al. (2015) indicate this as an important effect for the maintenance of permafrost in the Retezat Mountains (Romania), where permafrost occurs at sites with MAGST below 0 ºC, BTS lower than -3 ºC and ground freezing index higher than 600 degree-days. Snow avalanche and rock and debris fall events have also been shown to be responsible for burial of snow and ice at the base of talus slopes, even at low altitude (see for example Scapozza et al. 2011). Such buried-ice may be preserved outside the climate boundary of permafrost and act as heat sinks promoting lower GST and are therefore another hypothesis for the conditions observed at T3.

Following the literature synthesis made above, the low and stable GST measured at T3 (3,815 m) is a strong indicator of probable permafrost occurrence. However, MAGST is relatively high, with 3.2 ºC resulting from the very high summer GST, likely caused by the concave setting and thermophysical properties of the soil. At the site, the surface material is a boulderly matrix-supported deposit, with a pebbly-sandy matrix and no visible voids. This limits the interpretation of a talus-ventilation related origin for the low GST and suggests conditions close to those described by Gądek and Kędzia (2008) in the Tatra Mountains and also by Onaca et al. (2015) to the Tatras. Further supporting the importance of the effect of the long lasting snow cover, the area at T3 has shown to be one of the latest sites with snow melt. Local guides also indicate that wind redeposition of snow is an important mechanism for snow accumulation at the site. The geomorphic setting at the lower part of a talus favours the possibility of the presence of ice burial by rockfall and avalanching, an hypothesis than should be tested, for example, by Electrical Resistivity Tomography surveying and/or refraction seismics (see Hauck et al., 2007). The possibility of the deposit to be open work at depth, which could help explain the low temperatures, cannot be excluded, but lacks verification.

The GST regimes measured at Neltner (3,200 m) show clearly that permafrost is absent at the site. The snow pack settled only in mid-February and temperatures become very stable close to 0 ºC, which shows that there is no heat sink at depth, but rather a warmer unfrozen ground. Snow lasted about a week longer than at T3, possibly due to local effects, such as shadowing or thicker snow accumulation associated with snow drift.

The upper sites at the ridge (T2 – 3,980 m) and summit of Toubkal (T3 – 4,160 m) show small events of stable GST as a reaction to the scarce number of snow fall episodes, but long lasting zero-curtains are not visible after the initial one in late October, which was synchronous at T1, T2 and T3 (figure 11). After that episode, GST shows irregular curves with ranges of ~1 to 8 ºC reflecting an absent or very thin and compact snow layer with high conductivity. The lack of zero-curtain effects and the frequent freeze-thaw cycles at T2 indicate the absence of snow and a very dry soil. At both sites, the data suggest that the ground remains frozen below the surface during the cold season, however the GST regime analysis does not allow assessing on the presence of permafrost.

The very high daily GST ranges during the warm season are explained by the high insolation of the Mediterranean high mountain, together with the scarce moisture and rocky nature of the soil. We have no data to explain with safety the very high GST at T3, but they should be function of local differences in soil thermophysical properties, together with the concave setting of the site, receiving more reflected and emitted radiation from the surrounding slopes and also due to a wind shelter effect. Both T2 and T1 are convex and very wind exposed sites, which may explain lower maxima than at T3.

The probable presence of permafrost at site T3 is not unexpected, since the valley shows landforms typical of mountain permafrost, such as lobate deposits and poorly developed transverse ridges and furrows in the lower part of the scree slope (figure 13). The high altitude and sheltered location favouring wind driven snow accumulation and longer lasting snow cover, together with the talus setting, also favours ice-burial either by snow deposition (dry snow into the debris voids) or rockfalls. This would led to the formation of intersticial ice that would facilitate the creep of the frozen talus and the formation of solifluction and creep features Amplified cooling over the snow surface due to the concave setting and cold air drainage, as shown for the Tatra mountains, may also be a controlling process in ground cooling. The longer lasting snow can also provide moisture that would refreeze at depth when percolating in the debris.

The extrapolation of the long-terms records from Menara to the summit of Djebel Toubkal using a lapse rate of -0.59 ºC.100 m^{-1}, a similar approach to Hannah et al. (2016) for paleoequilibrium line altitude estimation in the region allows for an insight into the climate sensitivity of the high reaches of the Toubkal Massif. The results should be interpreted with care, but it is worth noting that the extrapolation of the warming trend observed in Marrakesh, represents a gradual shift towards positive

MAAT at the summit (Figure 14). This suggests that the probable permafrost sites in the High Atlas are possibly at risk of disappearing if the trend is to be continued.

6. Conclusions

The analysis of GST from June 2015 to July 2016 across an altitudinal transect in the Toubkal Massif provided, for the first time, data for the high altitude periglacial domain of the High Atlas. The period was marked by high temperatures in December and January, with very low precipitation from November to January, causing the late onset of the winter snow cover. GST from 3,210 to 4,160 m a.s.l. showed two contrasted periods: a hot season from late-May to late-September, and a long cold season, from mid-October to mid-April. The former showed positive air temperatures at all sites and was marked by very high daily temperature amplitudes, with maxima reaching 40.1 ºC at Toubkal 3. This regime was controlled by the high solar radiation inputs and by the dryness of the soil. The cold season was marked by either subfreezing GST or by frequent freeze-thaw cycles, depending on snow conditions. Neltner in a valley floor at 3,210 m showed frequent freeze-thaw cycles during the start of the cold season, until a heavy snow fall event in mid-February, inducing GST to stabilize close to 0 ºC. The high altitude sites (T2 - 3,964 and T1 - 4,160 m) located in wind swept areas showed subfreezing temperatures with frequent freeze-thaw cycles illustrating the lack of an insulating snow cover. These conditions prevailed during the whole cold season, with mean monthly GST below 0 ºC from November to March.

The Toubkal 3 minilogger located in Irhzer Ikhibi-South valley at 3,820 m a.s.l. showed a remarkable GST regime. After an early onset of a stable snow pack in mid-October, GST decreased regularly until mid-December and then showed minor oscillations around ci. -5.8 ºC. These conditions were only interrupted in late-March with snow melt. The GST regime at the site supports the likely presence of permafrost, which agrees with the presence of poorly developed arcuate ridges and furrows in the area. The site is in a valley section with long lasting snow cover due to wind accumulation and moderate potential incoming solar radiation and in the distal part of a talus, a setting which is known to favour lower ground temperatures. The data and observations are still scarce and do not allow for conclusions on the origin of the lower temperatures at the site, nor at assessing their spatial significance. Possibly, the low GST are a result of the joint effects of snow, cold air flow within the talus and over the snow surface, as well as from the presence of intersticial/buried ice derived from rockfall events.

These results should be interpreted with care and although the data suggests the presence of permafrost, for a more accurate assessment, more observations are needed. The possible presence of permafrost at 3,800 m in the Djebel Toubkal massif, to be confirmed, could become spatially significant, since such altitudes are frequent in the High Atlas, not only in the Toubkal region, but also further east, in the M’Goun massif.

7. Outlook

For the continuation of this research, forthcoming studies should target at: i. Electrical resistivity surveying to identify the presence of ice, ii. Installing a larger number of GST loggers at different settings around T3, iii) Installing an air temperature logger at T3 to assess the possible shadowing effect on air temperature and GST cooling, and iv) installation of a borehole for monitoring temperatures.

The presence of permafrost would also need to be assessed for: ice-content and consequent impacts for hydrology (at least at a local level), thermal state and spatial distribution at the regional scale, ecological significance (vegetation communities, endemisms, refugia), possible presence of extremophiles and possible analysis of permafrost ice as a paleoenvironmental archive. Given the warming trend as shown by the Menara data-series, future climate scenarios and the very sensitive setting of the upper reaches of the High Atlas, just above 0 ºC MAAT, further research at an interdisciplinary level is needed, since the possible permafrost remnants could quickly disappear facing climate change. And this can be the last permafrost remnant in North Africa.

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Sites	Alt (m)	Model	Variables	Interval (h)
Sidi Chamharouch	2,370	Hobo Prov2	AT, HR	1
Neltner (NLT)	3,200	Hobo Prov2, TidBit	AT, HR, GST	1
Toubkal 3 (T3)	3,815	TidBit	GST	1
Toubkal 2 (T2)	3,980	TidBit	GST	1
Toubkal 1 (T1)	4,160	Ibutton, TidBit	AT, GST	4,1

Table 1 – Temperature data loggers installed in the High Atlas. Variables: GST -Ground surface temperature, AT - Air temperature, HR - Relative humidity.

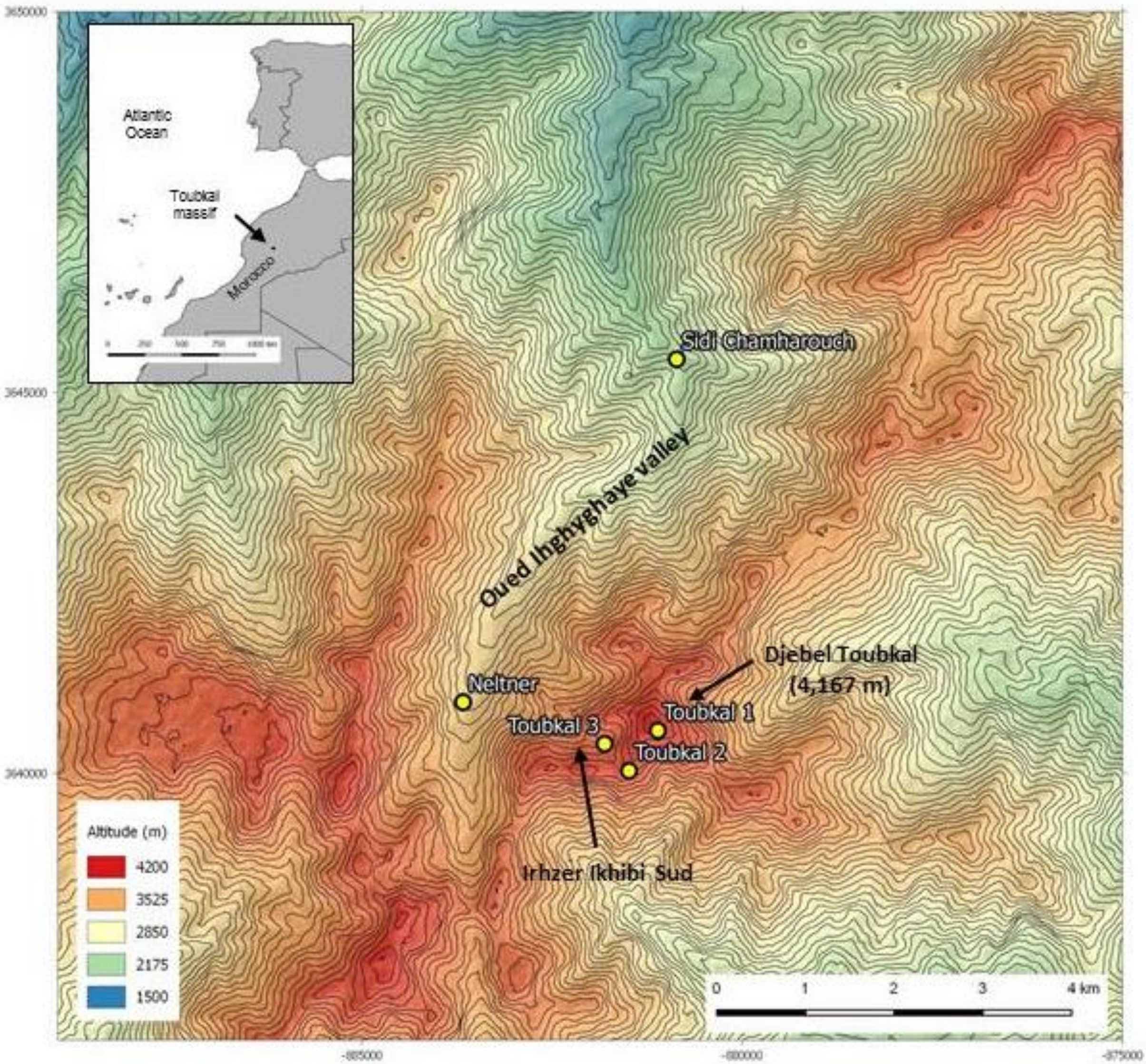

Figure 1 – Location and topography of the Toubkal Massif study area. Yellow circles are the sites of the data loggers. Contour equidistance is 50 m.

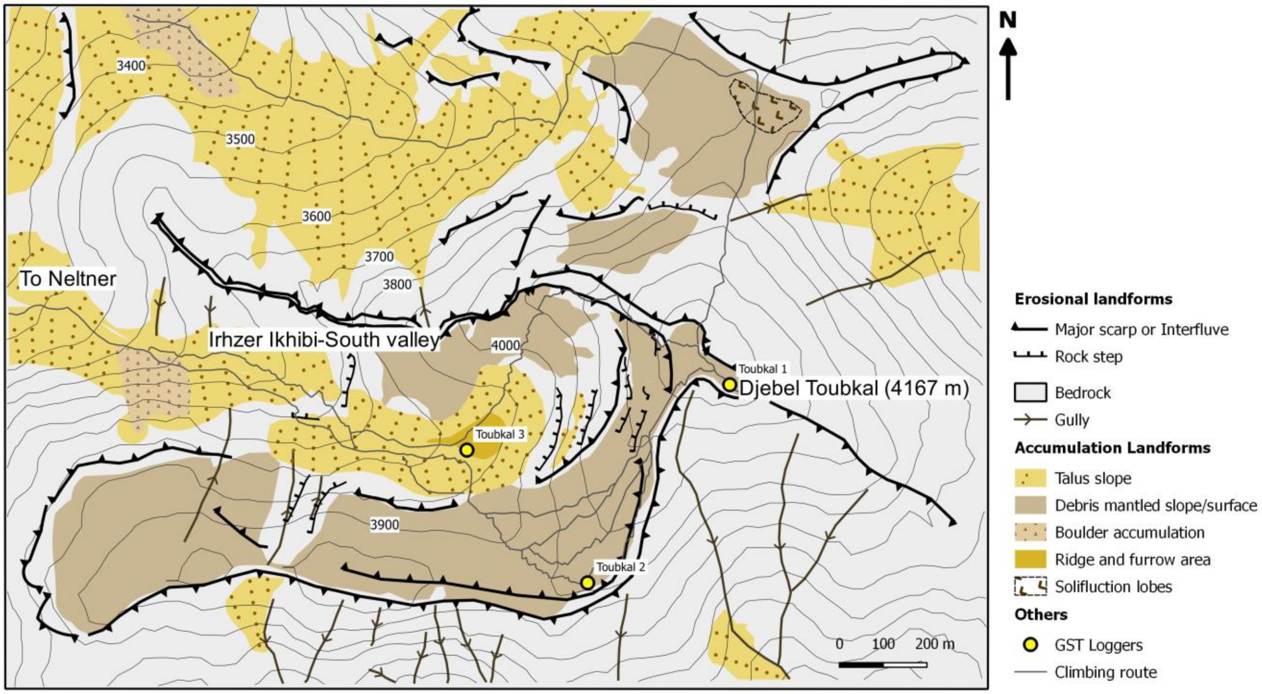

Figure 2: Geomorphological sketch map of the Toubkal Massif.

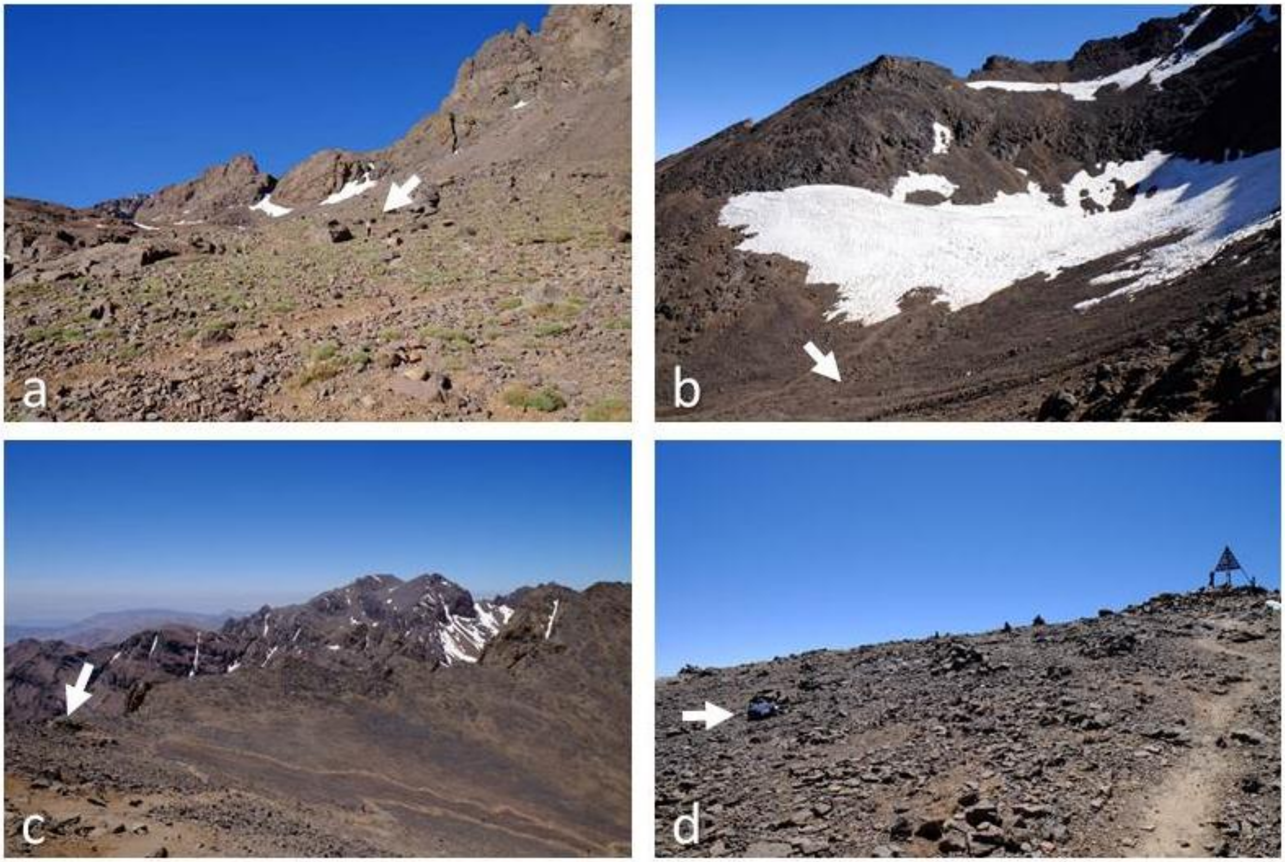

Figure 3: Location of the ground surface temperature loggers: a. Neltner (3,200 m), b. Toubkal 3 (3,815 m), c. Toubkal 2 (3,980 m), d. Toubkal 1 (4,160 m).

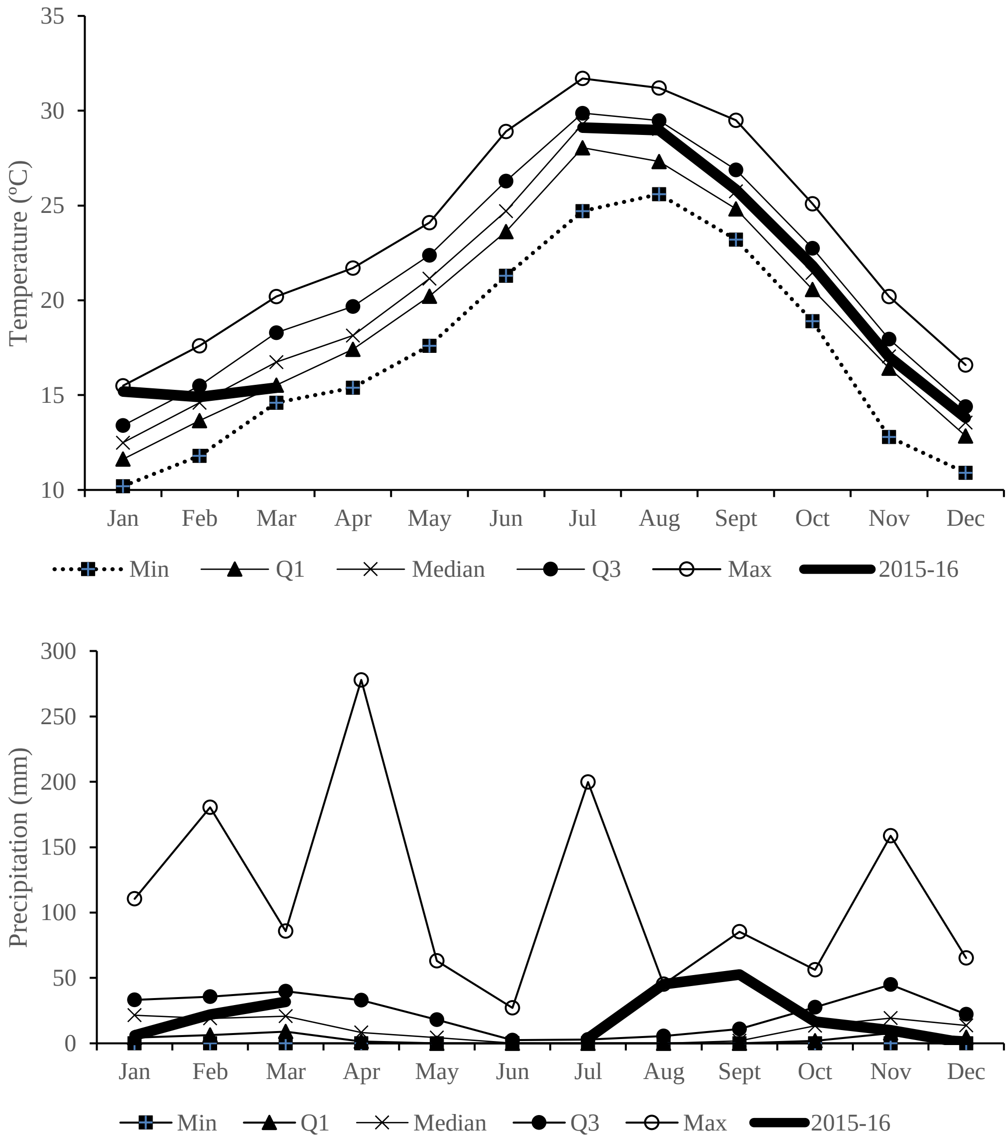

Figure 4: Statistics of monthly temperature and precipitation at Menara (Marrakesh) from 1977 to 2015 and records of the study period (July 2015 – March 2016). Source: NCDC/GHCN.

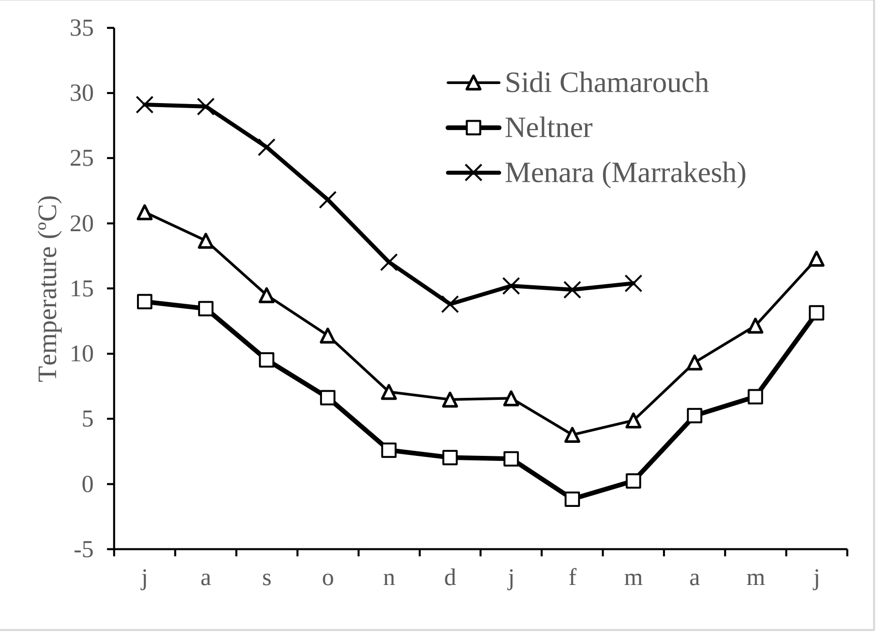

Figure 5: Mean monthly air temperatures from July 2015 to June 2016 in Marrakesh (Menara) and in Sidi Chamharouch (2,370 m) and Neltner (3,210 m).

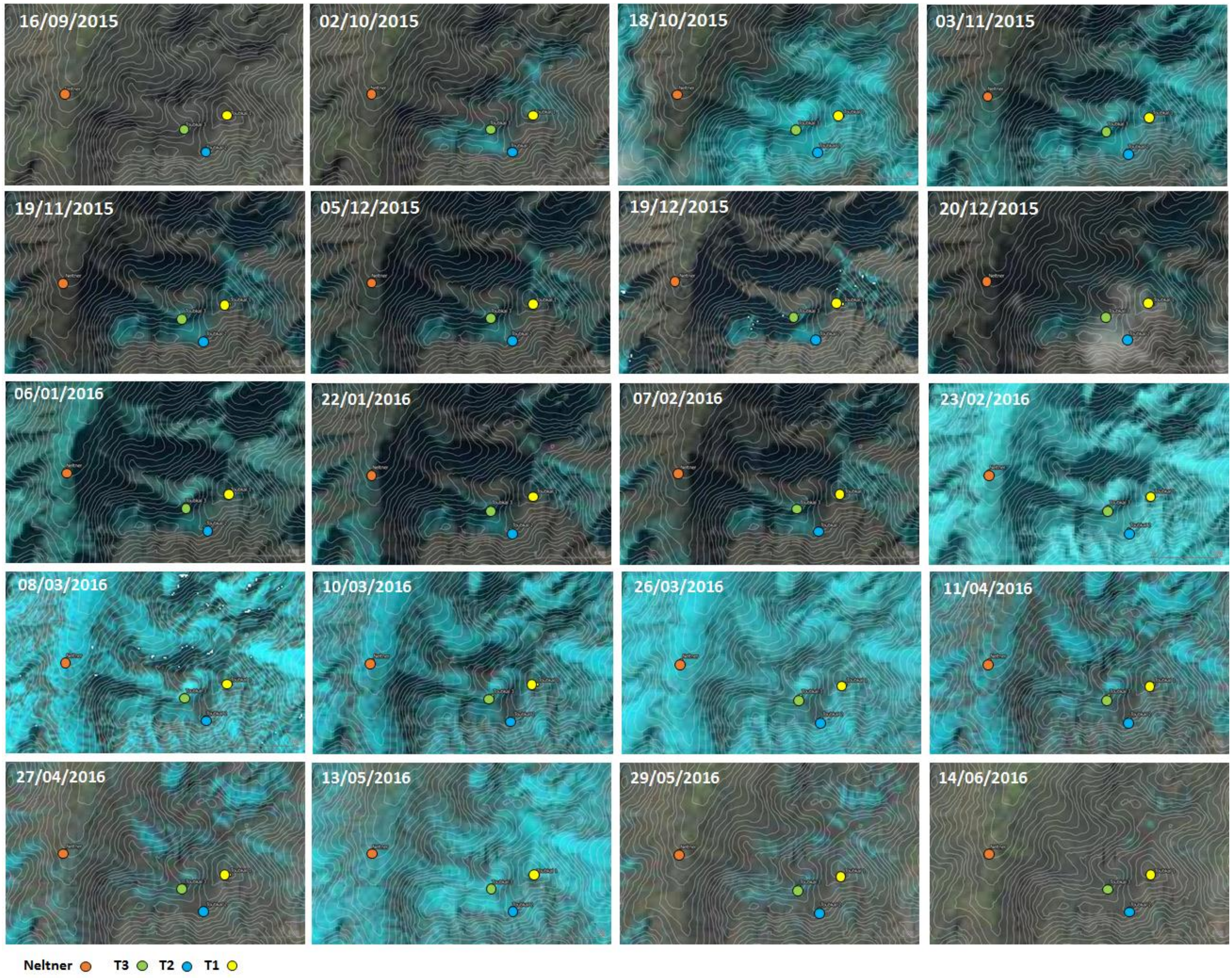

Figure 6: Satellite true colour composite scenes from Landsat-8 (USGS) and Sentinel-2 (ESA) used for assessing the snow cover at the monitoring sites from September 2015 to June 2016. Light blue indicates snow cover and brown and green indicate snow free terrain. Satellite imagery obtained from USGS EarthExplorer.

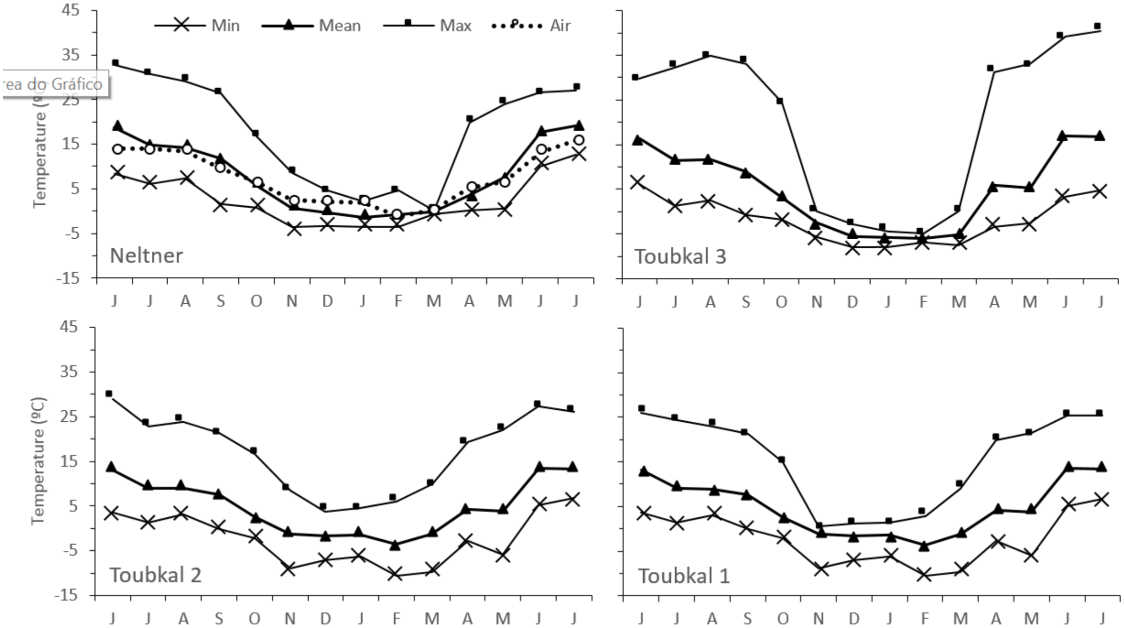

Figure 7: Monthly ground surface and air temperatures in the Djebel Toubkal massif from June 2015 to July 2016. Extremes are absolute monthly maximum and minimum temperatures.

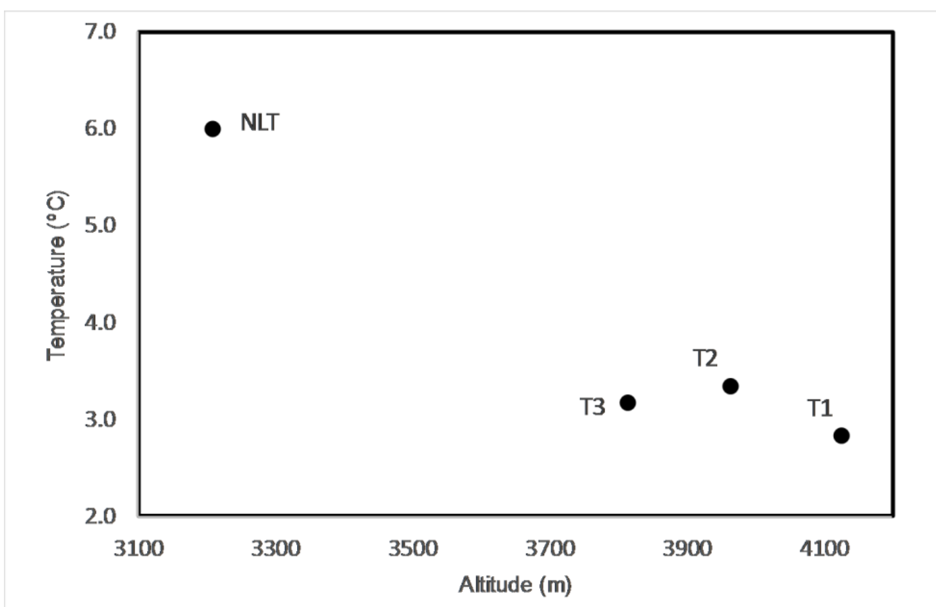

Figure 8: Mean annual ground surface temperatures vs altitude for the 4 monitored sites in the Djebel Toubkal massif.

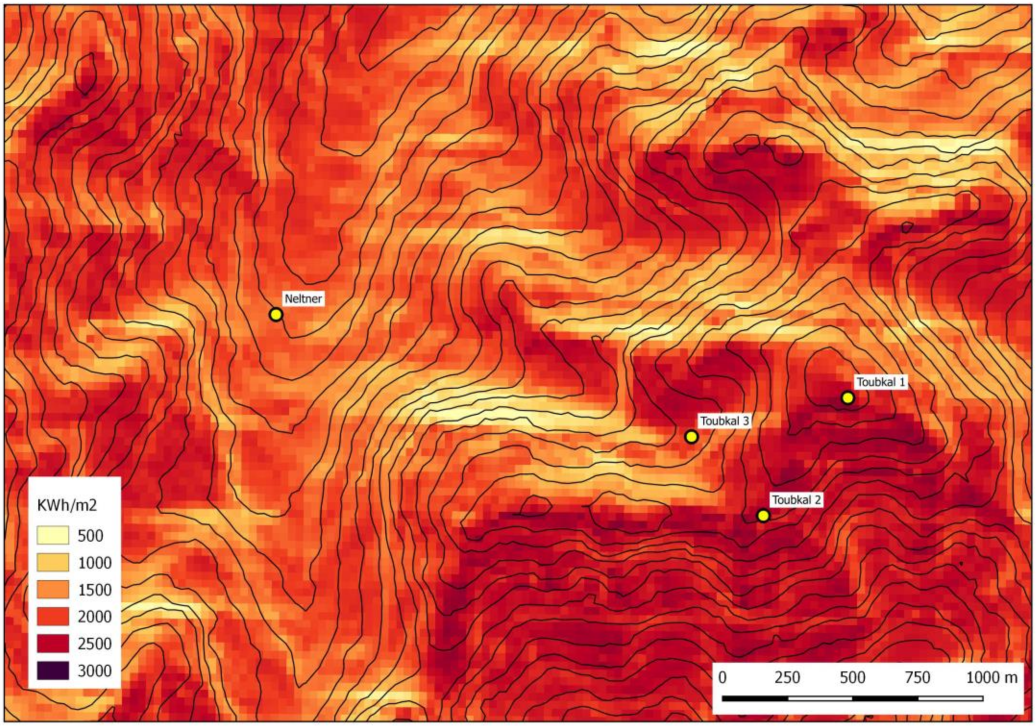

Figure 9: Distribution of annual potential solar radiation in the Toubkal massif, with indication of the ground surface temperature monitoring sites.

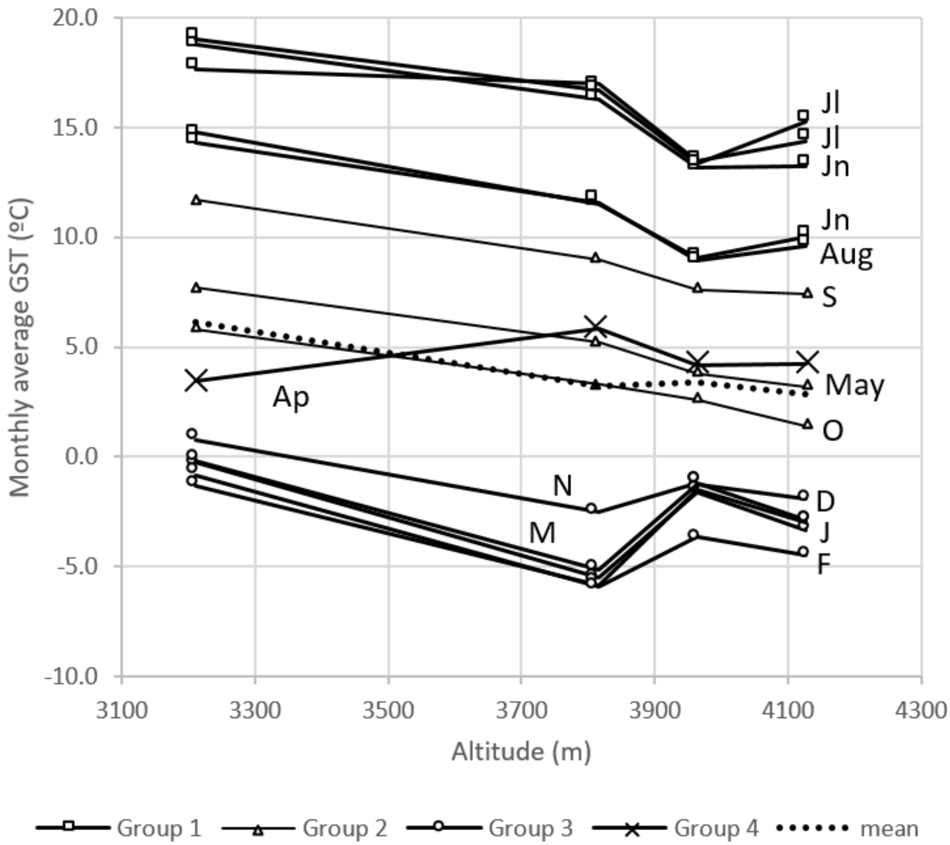

Figure 10: Mean monthly ground surface temperatures at the 4 study sites in the Toubkal Massif from July 2015 to June 2016.

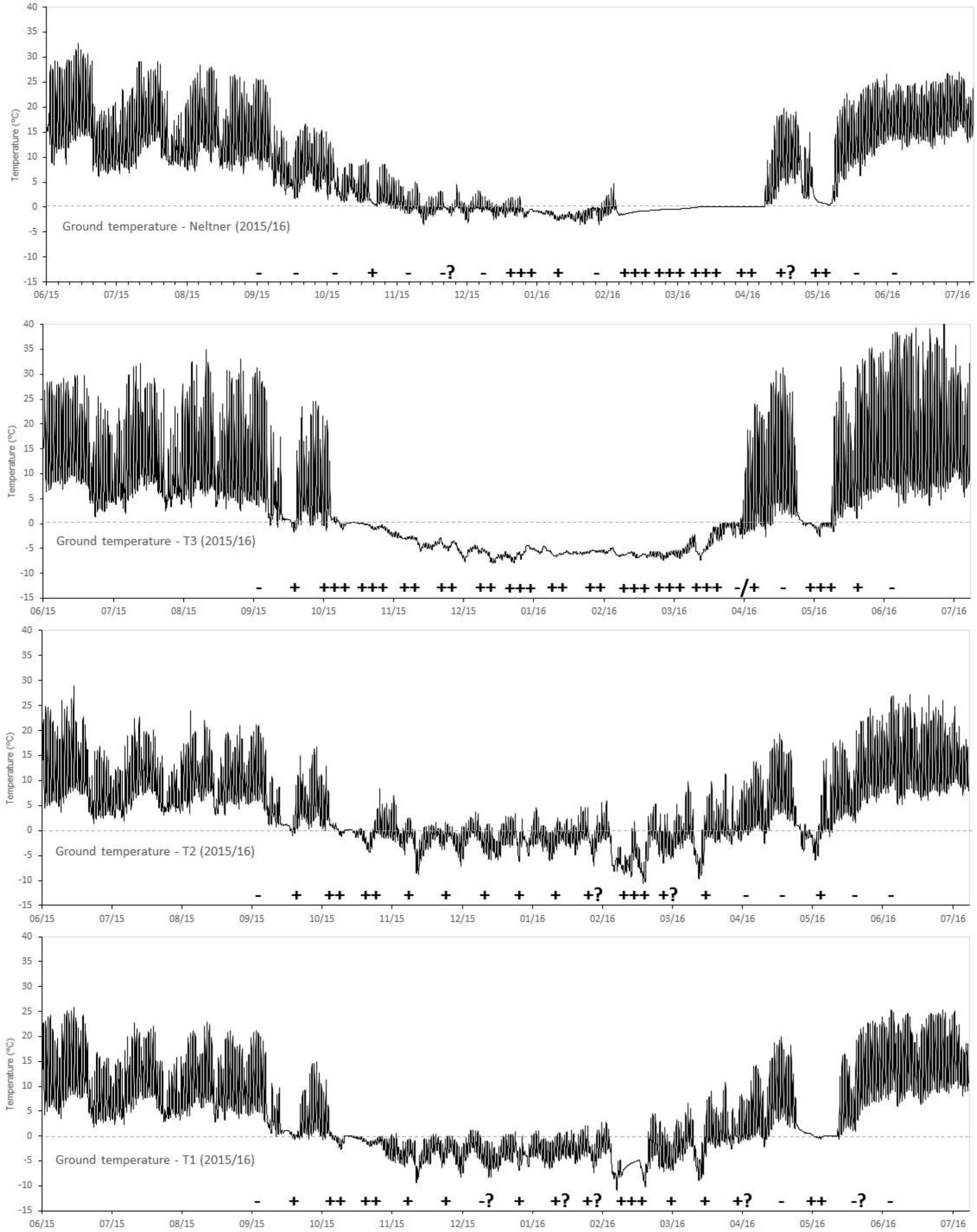

Figure 11: Ground surface temperature regimes at the 4 sites in the Toubkal Massif. The plot shows hourly data. Symbols indicate the snow cover conditions at the date of satellite scenes: - no snow, + possible snow/snow margin, ++ - snow, +++ - significant snow, ? – Uncertainty in classification.

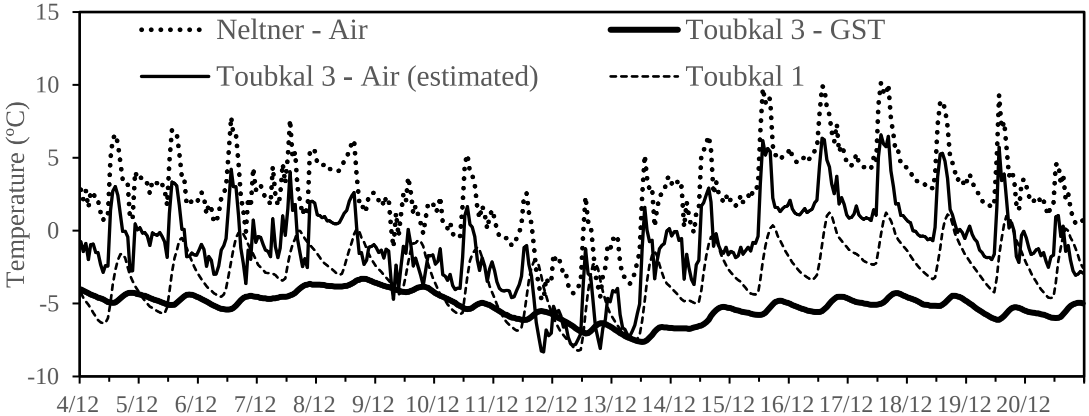

Figure 12: Example of the hourly GST regime at Toubkal 3 and comparison with air temperatures measured at Neltner and extrapolated to T3 using the observed lapse rate of -0.59 ºC.100 m^{-1}.

Figure 13: The Irhzer Ikhibi south valley, where the datalogger Toubkal 3 was installed. The arrows indicate arcuate boulder ridges and furrows in the talus slope.

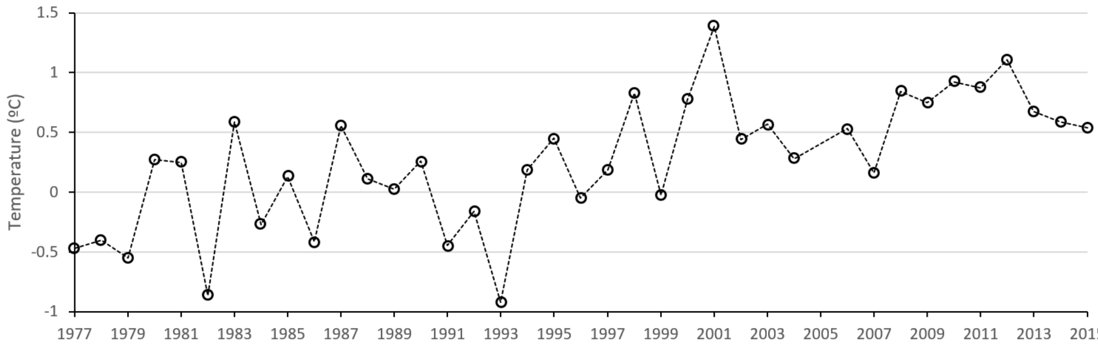

Figure 14: Estimated mean annual air temperatures at the Djebel Toubkal (4,167 m asl) obtained from extrapolation of temperatures from Menara (Marrakesh) using a lapse rate of -0.59 ºC.100 m^{-1}.