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Temperatures in the Life Zones of the Tyrolean Alps

By

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Abstract

The bioclimatic temperatures that mountain plants experience are very different from the macroclimatic temperatures and vary according to the exposition, relief, and growth form. This is shown in the example of boundary layer temperatures recorded in the Tyrolean Alps between the timberline and the nival zone over several years. Microsite temperatures were compared to the air temperatures provided by meteorological stations of the official weather service nearby.

In winter plant temperatures below the snow are largely uncoupled from the free air temperatures. During the growing season, across all zones, plant temperatures diverge to differing degrees from free air temperatures depending on the growth form of plants and the canopy structure. In *Vaccinietum* communities and in closed grassland, average temperature differences between the free air and plant canopy were 0.5 K in July and August. Prostrate mats of the *Loiseleuria* heath, rosette and cushion plants, however, heat up much more than erect plants during sunny periods, and mean plant temperatures were about 2–3 K warmer than the free air temperatures. As a result, the adiabatic lapse-rate for bioclimatic temperatures of the life zones in the Alps does not parallel the adiabatic lapse rate of free air temperatures.

1. Introduction

The elevational zonation of the vegetation in high mountains reflects the different growth limits of plant species. The decrease of diversity and density of species mirror the adverse life conditions [17, 33]. The high mountain climate is defined by a small-scale, terrain-dependent and short-term changeability [1, 42]. Sunny slopes and windy ridges are fairly dry and show rather little snow in winter whereas sheltered depressions are relatively wet in summer and permanently covered with snow during winter. Above the timberline, the duration of snow cover not only depends on the altitude but also on topography. With incomplete snow cover, characteristic patterns of snow patches and snowmelt areas develop for a given terrain. In these patches, which can be covered by winter snow as late as mid June and August, the growing season is very short and thus unfavourable for growth and development of high mountain plants.

The bioclimate, which is the microclimate from the upper surface of the vegetation down to the deepest roots in the soil is more balanced, warmer and wetter than the surrounding air [31]. Among the different climatic factors, temperature is of crucial importance to the life processes of plants. The thermal climate that mountain plants experience is very different from free-air temperatures. The boundary layer temperatures in micro-habitats demonstrate that weather services data are unable or not relevant [37]. In the night, plant temperatures are similar to the free-air temperatures or, due to radiation cooling, are even lower. During the daytime hours, plants can considerably heat up above the air temperature on clear days with low wind, whereas in periods with clouds, wind and precipitation plant temperatures approximate to the air temperatures [4, 24].

Plant architecture and thus the canopy structure additionally affects the thermal bioclimate. Generally, prostrate growing plants as prostrate dwarf shrubs, rosettes and cushions decouple their climate stronger from the ambient than erect plant forms in that they accumulate more heat during daytime at high irradiation, but may also lose more heat by thermal re-radiation at clear sky during the night [17].

In the last 50 years of mountain research in the Tyrolean Alps comprehensive microclimatic and ecological studies have been carried out. In this contribution, representative examples of plant temperatures in diverse habitats between timberline (1950 m a.s.l.) and glacier regions (subnival and nival zone up to 3450 m a.s.l.) are presented and compared to the air temperatures recorded by the nearest meteorological stations of the official weather service. Study sites were in a treeline ecotone [2, 41, 46], in dwarf-shrub communities of the lower alpine zone [4, 23], in closed alpine grassland (e.g. [6, 40]), in open alpine vegetation and in the alpine-nival ecotone (e.g. [22, 30, 35]), and in a nival area with scant patchy vegetation [32, 44].

2. Air Temperatures Beyond of the Timberline

Air temperatures steadily decrease with increasing elevation. In the Alps, the temperatures of the free atmosphere are reduced, according to the adiabatic lapse rate, which amounts to 0.55–0.62 °C (annual mean) and 0.60–0.65 °C (in summer) per 100 m from the bottom of the valley to the high mountain regions [11]. In the Tyrolean Central Alps (period 1995–2009), the annual mean adiabatic lapse rate amounts to 0.59 °C/ 100 m between the timberline (1950 m a.s.l.) and the glacier foreland (2850 m a.s.l.), and to 0.46 °C/100 m between the upper alpine zone (2247 m a.s.l.) and the glacier foreland.

In the Central Alps, the annual mean air temperatures were 3.0 °C at the timberline (Mt Patscherkofel; 1950 m a.s.l.), 0.5 °C in the alpine zone (summit of Mt Patscherkofel; 2247 m a.s.l.), –2.3 °C at the glacier foreland (Mittelbergferner, Ötztal Alps; 2850 m a.s.l.) and –5.8 °C in the nival zone (Mt Brunnenkogel, Ötztal Alps; 3440 m a.s.l.). Mean temperatures during summer were 10.6 °C in July and 10.7 °C in August at the timberline, 8.5 °C in the upper alpine zone in both months, 5.6 and 5.7 °C in the glacier foreland, and only 1.6 °C and 1.9 °C in the nival zone (Tables 1–4). The long-time temperatures in the alpine zone calculated for the climate normal period 1961–1990 on the

Table 1. Air temperatures at 2 m height at the timberline of Mt Patscherkofel (1950 m a.s.l.; 11°27′02″E–47°12′22″N) provided by the Federal Office and Research Centre for Forests (G. WIESER; unpubl. data). (*Tm*) mean air temperature; (*Max abs*) absolute maximum; (*Min abs*) absolute minimum. *Frost-free*: number of days with >0 °C

1995–2009	Tm	Max abs	Min abs	Day with frost-free
January	–3.9	14.4	–20.0	8
February	–4.0	12.6	–19.0	8
March	–2.3	13.9	–19.6	11
April	1.0	17.3	–16.4	15
May	6.3	23.0	–8.1	28
June	9.4	25.1	–4.5	25
July	10.6	25.0	–2.6	29
August	10.7	*25.8*	–0.9	30
September	7.1	22.9	–5.2	22
October	4.9	21.2	–11.2	23
November	–0.8	14.4	–22.4	13
December	–3.5	11.4	*–22.9*	9
Year	**3.0**			220
Extreme		*25.8 (2003)*	*–22.9 (2001)*	

Table 2. Air temperatures at 2 m height at the summit of Mt Patscherkofel (2247 m a.s.l.; 11°27′39″E–47°12′31″N) provided by Central Institute for Meteorology and Geodynamics, Regional Center for the Tyrol and Vorarlberg. (*Tm*) mean air temperature; (*Max abs*) absolute maximum; (*Min abs*) absolute minimum. *Frost-free*: number of days with >0 °C

1995–2009	Tm	Max abs	Min abs	Day with frost-free
January	–6.1	9.0	–21.8	1
February	–6.5	8.6	*–23.8*	1
March	–5.0	9.7	–22.5	2
April	–1.9	11.5	–18.8	6
May	3.6	18.3	–8.6	19
June	6.9	21.5	–6.9	24
July	8.5	20.2	–2.8	29
August	8.5	*21.8*	–3.8	30
September	4.8	18.8	–6.4	22
October	2.6	15.7	–12.9	18
November	–3.2	10.6	–19.4	4
December	–5.7	7.3	–23.4	1
Year	**0.5**			156
Extreme		*21.8 (2003)*	*–23.8 (2005)*	

Table 3. Air temperatures at 2 m height at the Mittelbergferner (Ötztal Alps 2850 m a.s.l.; 10°52′58″E–46°55′33″N) provided by Central Institute for Meteorology and Geodynamics, Regional Center for the Tyrol and Vorarlberg. (*Tm*) mean air temperature; (*Max abs*) absolute maximum; (*Min abs*) absolute minimum. *Frost-free*: number of days with >0 °C

1995–2009	Tm	Max abs	Min abs	Day with frost-free
January	–8.7	5.8	–26.0	0
February	–9.3	6.9	*–29.0*	0
March	–8.0	6.8	–26.3	0
April	–5.0	8.0	–23.4	0
May	0.4	13.0	–14.7	8
June	3.6	15.4	–11.2	16
July	5.6	*17.6*	–6.6	22
August	5.7	17.5	–6.3	25
September	2.2	15.3	–10.1	15
October	0.1	12.6	–19.4	9
November	–5.7	9.5	–21.7	1
December	–8.3	5.3	–25.2	0
Year	**–2.3**			94
Extreme		*17.6 (2005)*	*–29.0 (2005)*	

Table 4. Air temperatures at 2 m height at the summit of Mt Brunnenkogel (Ötztal Alps 3440 m a.s.l.; 10°51′42″E–46°54′46″N) provided by Central Institute for Meteorology and Geodynamics, Regional Center for the Tyrol and Vorarlberg. (*Tm*) mean air temperature; (*Max abs*) absolute maximum; (*Min abs*) absolute minimum. *Frost-free*: number of days with >0 °C

2003–2009*	Tm	Max abs	Min abs	Day with frost-free
January	–12.5	0.0	–29.1	0
February	–13.5	1.0	*–30.8*	0
March	–12.3	1.7	–28.4	0
April	–7.7	0.9	–20.0	0
May	–3.9	8.8	–18.6	2
June	–0.5	11.0	–14.7	7
July	1.9	12.3	–9.0	15
August	1.6	*12.7*	–10.5	13
September	–0.1	11.9	–12.3	8
October	–3.3	8.7	–22.2	3
November	–8.2	3.2	–24.1	0
December	–11.5	1.1	–30.0	0
Year	**–5.8**			48
Extreme		*12.7 (2003)*	*–30.8 (2005)*	

* In operation since 2003

basis of 2 m air temperature on Mt Patscherkofel amounts to 0.2 °C for the annual mean, and 8.0 and 8.1 °C for the summer months July and August.

The number of frost-free days per year declines from 220 days at the timberline to 156 days in the upper alpine zone, to 94 days in the glacier foreland and to 48 days in the nival zone. During midsummer (July to August) freezing temperatures from –3 °C in the alpine zone to –7 °C in the subnival zone and –10 °C in the nival zone can occur. During winter, absolute minima of the air temperature of the free atmosphere ranged from –23 to –24 °C in the treeline ecotone and alpine zone, and reached as low as –29 and –31 °C in glacier regions. However, most high mountain plants are hardly affected by these low temperatures as they are protected by a layer of snow.

3. Temperatures in the Alpine Dwarf-shrub Heath

In the Central Alps the alpine dwarf shrub heath covers the treeline ecotone and the lower alpine zone [14]. *Rhododendron ferrugineum* grows beyond the timberline (ca. 1900–2000 m a.s.l.) followed by the Rhododendro-Vaccinietum community with *Vaccinium myrtillus*,

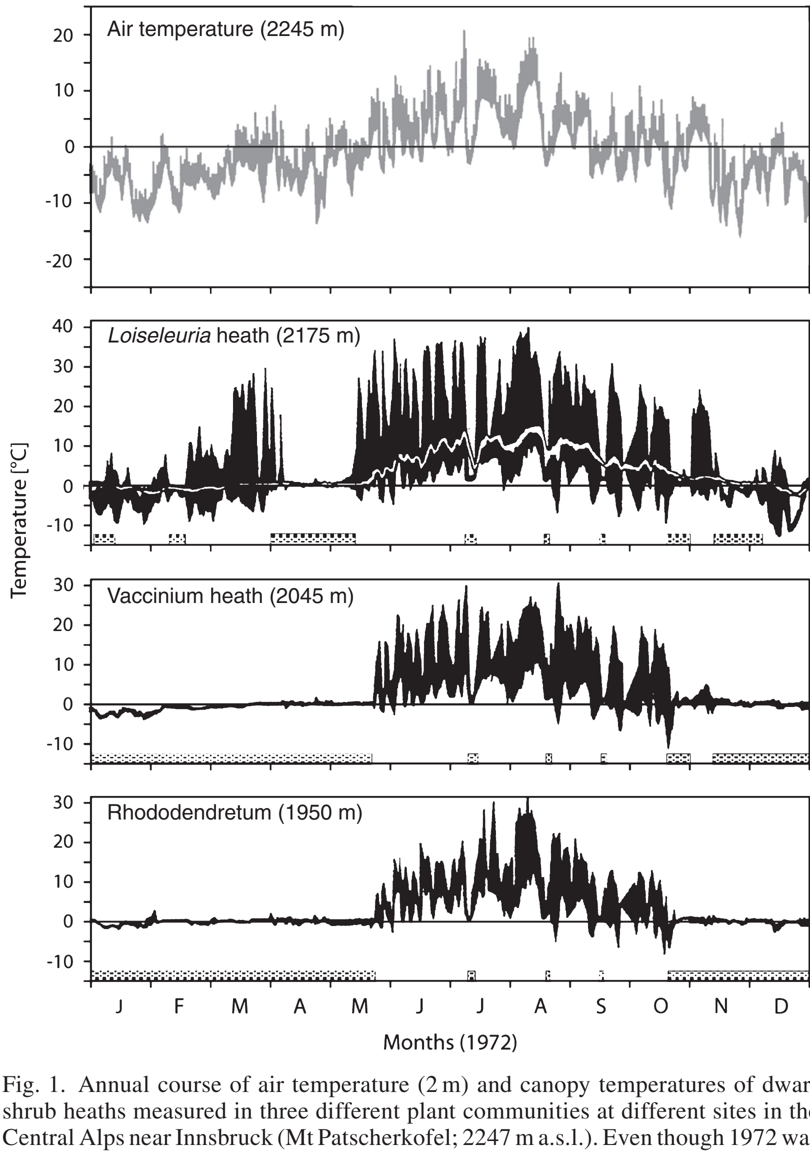

Fig. 1. Annual course of air temperature (2 m) and canopy temperatures of dwarf shrub heaths measured in three different plant communities at different sites in the Central Alps near Innsbruck (Mt Patscherkofel; 2247 m a.s.l.). Even though 1972 was a cool year, the absolute minimum temperatures were not very low during winter. Black area: daily minimum and maximum temperatures. White strip: soil temperature at 10 cm depth in *Loiseleuria* heath. Grey bars: snow cover. Temperatures were recorded with mobile meteorological equipment using platinum thermometers ([4], modified)

V. uliginosum and *Calluna vulgaris*. The limit of the dwarf shrub belt is reached at ca. 2200–2400 m a.s.l. Here, prostrate mats of Loiseleurio-Cetrarietum (*Loiseleuria procumbens* and lichens) are found. Figure 1 shows annual time courses of canopy temperatures in three different dwarf shrub heaths and air temperatures at 2 m on Mt Patscherkofel near Innsbruck. In 1972 the annual means of canopy temperatures were 2.8 °C within the 60 cm high *Rhododendron* shrubs, 3.4 °C in the 1.5 cm high prostrate mats of *Loiseleuria* and 2.7 °C in the 20–26 cm high *Vaccinium* heaths.

In winter, *Rhododendron* shrubs and *Vaccinium* heaths are usually protected from low temperatures by a snow cover which lasts for 6 months. In early winter, however, lower temperatures can occur due to thin layers of snow. The generally wind-blown *Loiseleuria* heath is only covered by snow for 4–5 months because of snow drift. Under sunny conditions and in the absence of snow cover above-ground plant parts can warm up considerably at noon. On a clear winter day in 1972, for example, air temperatures of –5 °C were measured, while temperatures of +15 °C and +20 °C occurred in the prostrate mats of *Loiseleuria* and +10 °C and +13 °C in low *Calluna*-shrubs [23].

In summer, the temperatures very seldom dropped below –3 °C in the dwarf-shrub heaths. During the climatically potential growing season the average mean temperatures were about 7–8 °C in *Rhododendron* shrubs at the treeline [27]. A frequency distribution was calculated for the same habitat (Fig. 2); temperatures of 0–5 °C occurred most

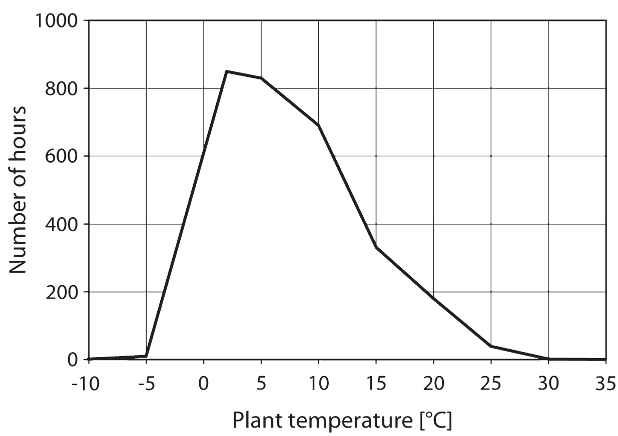

Fig. 2. Frequency distribution of shrub temperatures measured in *Rhododendron ferrugineum* (at 45 cm height) at the timberline (1950 m a.s.l.) from May 1 to September 15, 1982. Recorded by platinum thermometers. Data by SIEGWOLF [38]

frequently (35% of the hours measured) and temperatures of 5–10 °C were second most frequent (32% of the hours measured). Frosty temperatures as low as –6 to –7 °C occurred with a frequency of 13% in May and from September to October.

In the low prostrate mats of *Loiseleuria* mean maximum temperatures of 20–30 °C were recorded in the summer. Short-term temperatures of 30–32 °C were repeatedly measured on south exposed slopes, maximum temperatures were as high as 35–38 °C. On summer days with strong incoming radiation absolute maximum leaf temperatures of 40–42 °C and boundary layer temperatures of up to 50 °C occurred. When skies are clear, soil is dry and there is little wind the patches of bare humic soil in the vegetation gaps can even reach surface temperatures as high as 50–55 °C [20].

4. Temperatures in the Alpine Grassland

Closed vegetation with plant growth forms characteristic of alpine grasslands cover the broad transect from the timberline to about 2500 m a.s.l. In the Central Alps, Sieversio-Nardetum strictae and

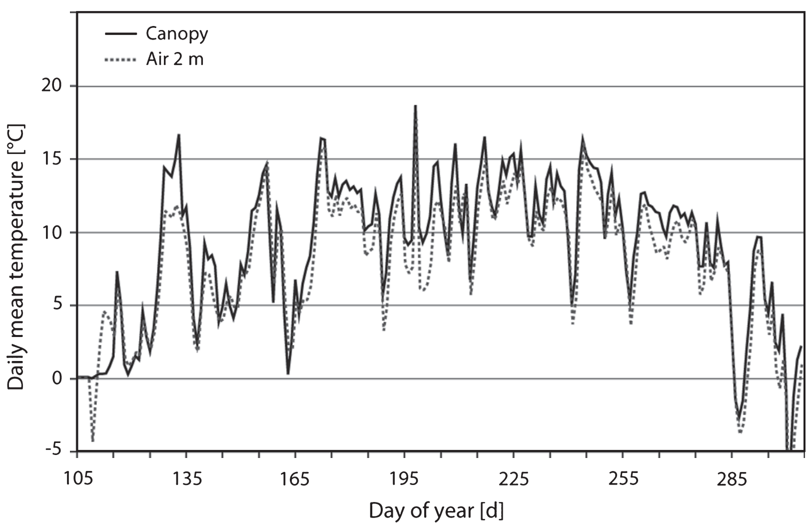

Fig. 3. Variation in daily mean canopy and free atmosphere temperatures during the growing season on a S-facing slope at 2000 m a.s.l. in the Passeier valley (Stubai Alps; 11°15′50″E–46°49′56″N). Solid line: canopy temperature; thin line: air temperature at 2 m height. Temperatures were recorded using small data loggers with a NTC-pearl sensor. Data by E. Tasser [40]

Caricetum curvulae (Curvuletum) form the upper alpine grassland plant communities while in the Calcareous Alps Seslerio-Caricetum sempervirentis (Seslerio-Semperviretum) and *Festuca*-communities are found [13]. These alpine grasslands occur on S- or SW-facing slopes which benefit from the steep radiation angle and are therefore warmer and drier than the shady N-facing slopes or depressions.

On a sunny slope at 2000 m a.s.l. in the Stubai Alps variations in daily mean temperatures were measured in a community of Caricetum-sempervirentis and Nardetum strictae during the climatically potential growing season from mid April until the end of October (Fig. 3). During the investigated growing season the daily mean air temperatures were 9.3 ± 4.5 °C, and 8.3 ± 4.1 °C within the canopy [40]. The highest daily mean temperatures were 18.6 °C (canopy) and 17.7 °C (at 2 m); the lowest were –2.6 °C (canopy) and –3.9 °C (at 2 m).

In the canopy, the +5 °C daily mean temperature threshold was passed in the first week of May (day of year 127) and stayed above this level until October 1997 (day of year 296). This base temperature of 5 ± 2 °C is enough for sedges and grasses to maintain continuous growth [25]. In May, heading and anthesis (threshold 10–12 °C) occur. Between June (day of year 170) and September (day of year 254) fluctuating daily mean temperatures of between 10–15 °C were recorded. Metabolism, storage and reproduction peak during these 12 weeks [36, 43].

At the same altitude considerable differences in canopy temperatures between SW-facing and NE-facing slopes were observed. Two temperature loggers were positioned on the summit of Mt Patscherkofel (southern slope: 2200 m a.s.l., 25 ° inclination; northern slope: 2230 m a.s.l., 35 ° inclination) to record the temperatures in the Curvuletum (Table 5).

Table 5. Canopy temperatures and dates of different sites of upper alpine grassland during the snow free-period during the climatically normal year in 2000

Characteristics	North-east site 2230 m a.s.l.	Southwest site 2200 m a.s.l.
Mean plant temperatures during the snow-free period	6.4 °C	8.5 °C
Most frequent temperature range	0–5 °C	5–10 °C
Absolute maximum	29.4 °C	34.3 °C
Absolute minimum	–3.5 °C	–2.7 °C
Length of the snow-free period	145 d	154 d
Days with ≤ 0 °C	52 d	32 d
Days with >0 °C	93 d	112 d

The mean boundary layer temperatures on the sunnier SW-facing slope were higher by 2 K than on the cooler NE-facing slope throughout the whole growing season.

Throughout the whole measuring period temperatures ranging from 5 to 10 °C were most common on the SW-facing slope. On the NE-facing slope temperatures between 0 and 5 °C were most common. In addition, for the SW-facing slope, the frequency of the daylight and night hours was calculated separately. During the night, temperatures between 0 and 5 °C as well as 5 and 10 °C were most frequent. During daylight hours the range of the frequency distribution was much broader, namely 0–20 °C. In the snow free period (May until June) there were 32 days of night frost (absolute minimum –2.7 °C) on the SW-facing slope and 52 days of frost (absolute minimum –3.5 °C) on the NE-facing slope. The monthly means of the daily maximum were 17 °C (July) and 24 °C (August) on the SW-slope and 15 °C (July) and 18 °C (August) on the NE-slope.

CERNUSCA and SEEBER [7] investigated the vertical profiles of temperature, of a Curvuletum in the Hohe Tauern at an altitude of

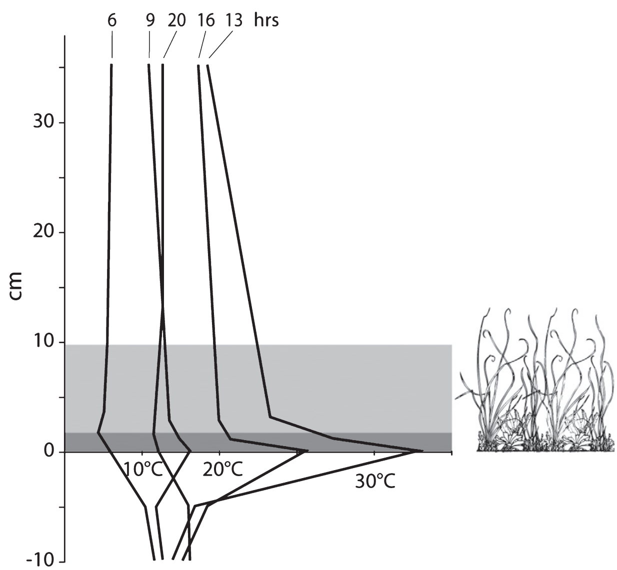

Fig. 4. Vertical distribution of air and soil temperatures (T) measured on a clear day in the Curvuletum at 2300 m a.s.l. Canopy structure: shaded light area: graminoids growth form (mostly *Carex curvula*), dark area: layer of rosettes (e.g. *Primula minima*). Temperatures were recorded with mobile meteorological equipment using platinum thermometers [5]

2300–2400 m a.s.l. The average height of the canopy is 6–12 cm and shows a two layer structure: the top layer is mostly made up of *Carex curvula* and other grasses, whereas the underlying layer consists of prostrate herbaceous vascular plants, mosses and lichens. The top layer is more often exposed to wind with extensive heat transfer and little overheating under conditions of intensive solar radiation. The bottom layer (0 °C to 2 cm) is not only wind protected but also warmer (ca. 10–15 K).

On a bright summer day in August the daily fluctuations of temperatures were 9.5 K at 2 m, 19 K at the average canopy height of the Curvuletum and 36 K at the boundary layer. During the night canopy temperatures dropped considerably due to thermal re-radiation. In the morning, canopy temperatures were below the temperatures at 2 m. With increasing incoming radiation the canopy heated up. A clear overheating of the canopy can also be detected in the daily mean temperatures. Thus, on a clear sunny day, daily means of boundary layer temperatures were 5 K higher than the daily mean temperature at 2 m. Temperatures at 3 cm were only higher than the daily mean temperature at 2 m by 1 K (Fig. 4). On cloudy days the heating effect is only half as big.

5. Temperatures in Open Alpine Vegetation

Beyond the closed alpine grassland the sparse vegetation of the upper alpine life zone begins. The prostrate plant life forms like dwarf shrubs, short graminoids, rosettes and cushion plants inhabit the micro-habitats. Figure 5 shows examples of the annual course of boundary layer temperatures at two contrasting sites.

In winter, prostrate plants growing at microsites sheltered from the wind are mostly covered with snow. Until the end of May these plants experience temperatures between 0 and –3 °C. Pioneer plants and cushion plants growing at sites exposed to the wind, however, have to endure free atmosphere temperatures. On south exposed slopes, snow-melt starts in the first and second week of May. Between 2300 and 2500 m a.s.l. the duration of the growing season (until September) is normally 100–120 days.

In the summers of 2001 and 2002 – climatically normal years – the monthly means of boundary layer temperatures (July and August) were about 9–11 °C; in 2003 – with an exceptionally long, warm and dry summer – mean temperatures were 11.7 °C in July and 13.0 °C in August [21]. The daily minimum temperatures during the summer were

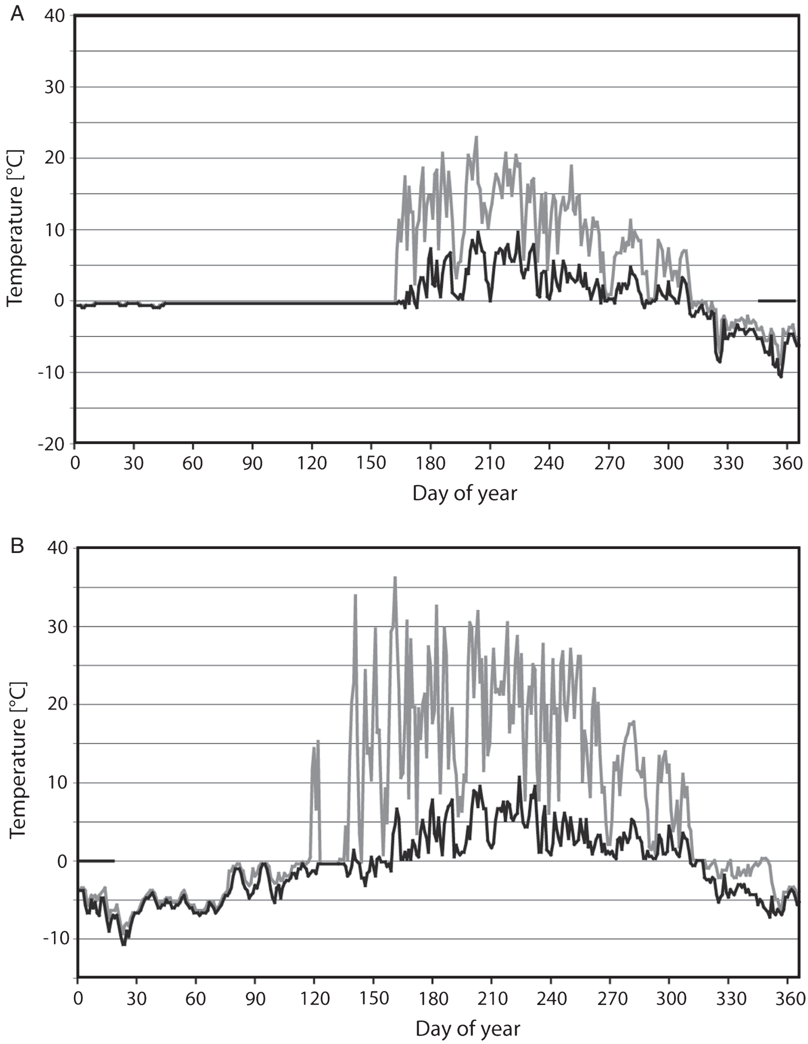

Fig. 5. Annual course of plant temperatures on a Northern Calcareous Mountain range (Hafelekar; 11°23′11″E–47°18′46″N) in the climatically normal year of 2004; (A) a snow-rich northern site (2324 m a.s.l.); (B) a windy western ridge (2314 m a.s.l.). Upper line: daily maximum, lower line: daily minimum. Temperatures were recorded using small data loggers with a NTC-pearl sensor; loggers were protected from direct radiation [29]

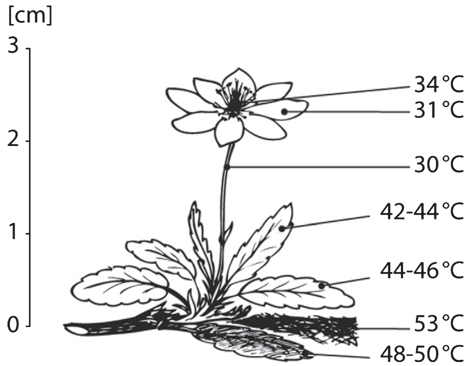

Fig. 6. *Dryas octopetala* in rocky habitats at 2300 m a.s.l. in midsummer with clear skies, dry soil and little wind. Living leaves were 42–46 °C, dead leaves 48–50 °C, and litter and black humus on the soil surface were 53 °C. Measurements by W. LARCHER using thermocouples

3–10 °C, daily maximum temperatures on a N-slope about 20–25 °C and on a W-slope 25–30 °C. In July and August temperatures between 5 and 10 °C were most common (38% (N) and 31% (W) of total hours). The warmer temperature classes (above 10 °C) together added up to 37% (N) and 39% (W) of total hours.

Heat stress in high mountain regions is brought about by intensive incoming radiation, shelter from the wind and dry soil surface on S and SW facing slopes. During summer, prostrate plants of the alpine zone repeatedly reach maximum noon temperatures of 30–35 °C. On rocky sites plants can reach such high temperatures that some plant parts are prone to heat threat [3]. Small layering shrubs, e.g. *Dryas octopetala*, reached temperatures of more than 40 °C (Fig. 6). Even higher temperatures were found on *Sempervivum* rosettes; on midsummer days we repeatedly measured leaf temperatures of about 50 °C [26].

Cushion plants, especially on south exposed slopes, can also heat up considerably. On a clear day in midsummer *Silene acaulis*, *Saxifraga oppositifolia* and *Carex firma* were measured with an infrared pyrometer (PRT-10 L, Barnes, Stamford, USA) at sites 2300 m a.s.l. in the Northern Calcareous Alps [29]: maximum temperatures of 35 °C were recorded in *Silene* and *Saxifraga*, and the dry cushions of *Carex firma* heated up to 46 °C. Even higher temperature maxima (above 40 °C) were measured in cushions of *Silene acaulis* by NEUNER et al. [34] at a subalpine site, resulting in maximum air to leaf temperature differences up to 22 K. Dome-shaped cushions often show large differences in temperature between the sunny and the shady side. For *Silene acaulis* could be shown that the temperature gradient across the cushion reaches a maximum at 10 a.m. (9 K) and at 4 p.m. (12 K) and is smaller during the midday hours, when the angle of incidence of the solar radiation is higher [19].

6. Temperatures in Pioneer Plants in the Glacier Region

In the Central Alps, the microclimatic temperatures show marked differences between the subnival ecotone ("transition from the upper alpine to the nival zone"; [33]) and the nival zone. Temperatures were measured in the subnival ecotone in the glacier foreland of the Schaufelferner (2880 m a.s.l.; Stubai Alps) at a windy and rocky plateau with scattered vegetation and little snow cover in winter (Fig. 7A). Cushion species and isolated rosette plants were most commonly found in this scant patchy vegetation. Microclimatic temperatures in the nival zone were recorded on Mt Brunnenkogel (3440 m a.s.l.) in the Ötztal Alps. This mountain rises like a nunatak from the glacier area and is fully glaciated on the northern side. Small temperature loggers were placed on the soil surface between *Ranunculus glacialis* individuals (Fig. 7B).

During winter below the snow, temperatures were between –5 and –10 °C at both sites. However, during periods with a sparse snow cover plants experienced temperatures of down to ca. –25 °C. At both localities, the snow melted between the end of June and the beginning of July in 2004. In autumn snow cover was complete at the beginning of September on Mt Brunnenkogel or at the end of September in the glacier foreland of the Schaufelferner. Thus, the duration of the snow-free period was 93 days at the subnival sites and 74 days on the summit of Mt Brunnenkogel.

During the growing season frosty temperatures were regularly measured in the sparse vegetation and at the soil surface. In midsummer (July and August) temperature minima between –2 and –3 °C were recorded on about 20 days in the subnival ecotone and temperature minima down to –5 °C were recorded on about 50 days on the nival summit. Abrupt changes in weather patterns are characteristic of high mountain climate. After a cold wave, plants at these altitudes can be suddenly snowed in for several days (Fig. 8).

On the other hand, due to high irradiation, high boundary layer temperatures can also occur in the glacier region on clear days. From July until mid-August temperature maxima of about 25 °C were

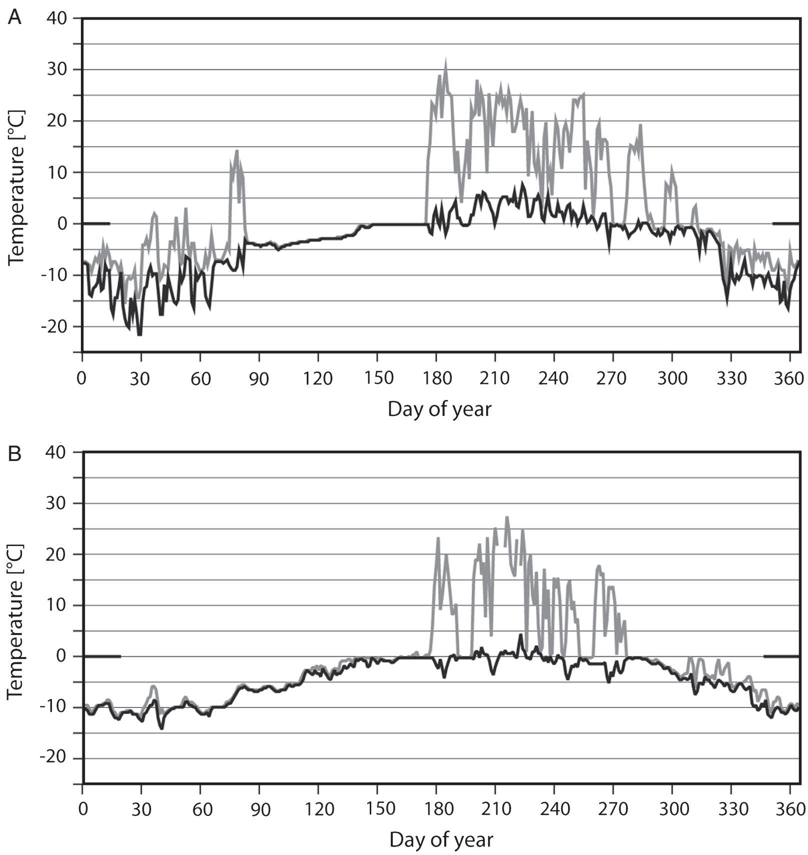

Fig. 7. (A) Annual course of boundary layer temperatures at a subnival site in the glacier foreland of the Schaufelferner in the Stubai Alps (2880 m a.s.l.; 11°06′56″E–46°59′14″N) in the climatically normal year of 2004. A small temperature logger ("StowAway Tidbit") was installed in a cushion of *Saxifraga bryoides*. Upper line: daily maximum, lower line: daily minimum [29]. (B) Annual course of boundary layer temperatures at the nival site on Mt Brunnenkogel in the Ötztal Alps (3440 m a.s.l.; 10°51′42″E–46°54′46″N) during the year 2004. The temperature logger was placed in the shade of *R. glacialis* leaves. Upper line: daily maximum, lower line: daily minimum [28]

recorded at both sites. Overall boundary layer mean temperatures during the growing season were 8.2 °C at 2880 m a.s.l. and 3.6 °C at 3440 m a.s.l.

The difference between the subnival ecotone and nival zone is most clearly seen when comparing the frequency distribution of the number of hourly temperatures. During the snow-free period 33% of hours

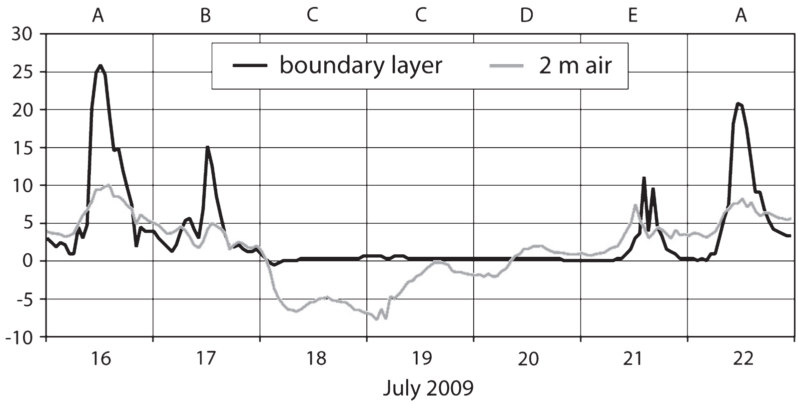

Fig. 8. Diurnal course of boundary layer temperatures and air temperatures at 2 m height on Mt Brunnenkogel (3440 m a.s.l.) during a cold wave in summer. (A) Clear skies at noon bring about overheating on the soil surface; clear nights can induce low temperatures in the morning due to re-radiation. (B) Beginning of cold front; (C) cold wave and snow fall; (D) snow covered sites; (E) snow melt. Temperatures were recorded by data loggers placed on the soil surface; air temperatures of the free atmosphere were provided by the Regional Centre for Meteorology (zamg.ac.at)

were between 0 and 5 °C (Schaufelferner) in contrast to 43% on Mt Brunnenkogel. Furthermore, on Mt Brunnenkogel, 31% of all hours showed temperatures of less than 0 °C. At 2880 m a.s.l. almost half of the night hours are between 0 and +5 °C whereas the temperatures of the daylight hours are more evenly distributed with about 20–25% of the hours in all temperature ranges between 0 and 20 °C. Subzero temperatures (absolute minimum –4 to –4.5 °C) were measured in 6% of all hours at the subnival site and in 31% of all hours on the nival summit site. That means that in contrast to the subnival ecotone, boundary layer temperatures on summits in the nival zone frequently show subzero temperatures.

7. Temperatures in the Phytosphere and Free Atmosphere Across the Altitude Zones

Plant temperatures across the alpine and the nival zone in the Alps differ from free air temperatures provided by the weather services (Table 6). The vegetation cover under full solar radiation heats up so that the elevational gradient of the canopy temperatures is lower than that of the air temperatures. In dense canopies of Rhododendro-Vaccinietum communities the mean temperatures during the climatically potential

Table 6. Bioclimatic temperatures of the different life zones in the Alps. All microclimatic temperature data were measured on sunny slopes. The data of the bioclimatic temperatures and free atmosphere were collected at the same time of years. Mean temperature during the climatically potential growing season (*Tm CPGS:* the period from snowmelt in spring to daily mean temperatures below subzero in autumn); (T_{plant}) mean plant temperatures in open vegetation or canopy temperatures (alpine grassland and dwarf-shrubs heath) and (T_{air}) mean free air temperatures during July and August

Vegetation	Altitude [m]	Sites CPGS [d]	Tm CPGS [°C]	T_{plant} July+Aug [°C]	T_{air} July+Aug [°C]	T_{plant}–T_{air} [K]*
Glacier area	>3000	85	ca. 4	4.5	ca. 2	2.5
Ranunculus glacialis		(60–100)				
Glacier foreland	2650–2880	105	ca. 8.5	9.0–9.5	5.5–6.0	3.5
cushions		(65–120)				
Alpine patchy vegetation	2200–2400	120–140	ca. 9	ca. 9–10	7–8	2
cushion and rosette plants						
Alpine grassland	1900–2200	140–150	9–11	ca. 11	ca. 10.5	0.5
canopy						
Alpine dwarf-shrubs	2000–2200	175	10	ca. 11	ca. 8	3
Loiseleuria		(120–200)	8	ca. 9	ca. 8.5	0.5
Vaccinium sp.						
Rhododendretum	1900–2100	ca. 150	8–10	10–11	10	1

* Temperatures are presented in K, as differences of degrees centigrade

growing season (i.e. the period from snowmelt in spring to daily mean temperatures below subzero in autumn; [39]) were 8–10 °C; in the prostrate growing dwarf shrub communities (*Loiseleuria* heath) and in the sunny alpine grasslands they were between 9 and 11 °C; during the summer (July and August) canopy temperatures of about 11 °C were measured. Beyond 2200–2300 m a.s.l. the mean plant temperatures did not pass the threshold of 9–10 °C at any time during the growing season. In the upper alpine life zone and in the glacier foreland individual plants e.g. cushion and rosette plants and short graminoids had mean temperatures of 8–9 °C. At the nival microsites near the glacier mean temperatures were only 4.5 °C during the active period of the plants. In the present study the adiabatic lapse rate of plant temperatures was 0.23 °C per 100 m (2000–2880 m a.s.l.) for July and August.

Mean differences between plant temperatures and the free air temperatures amounted to 0.5–1 K in Vaccinietum communities mainly composed of erect plant forms. Mean temperature difference was 3 K in prostrate mats of the *Loiseleuria* heath, both for the canopy (see Table 5) and for shoot meristems 3–5 K [16]. Temperature difference was 2 K in rosette plants and 3 K in cushion plants.

8. Conclusions

Diversity in plants is reflected in the diversity of bioclimatic temperatures. The different plants architectures have an important influence on the different temperatures [18]. Measurements in different habitats at different elevations have shown that, under high irradiation, prostrate plants are thermally favoured and can accumulate more heat than erect forms. Thus, prostrate growth forms lessen the impact of the rough high mountain climate and allow alpine plants to successfully survive and reproduce. Most high mountain plants show a broad temperature amplitude for metabolism, growth and stress resistance [17]. Those plant species that stay in their habitat and show broad acclimatisation amplitudes or physiologically contrasting ecotypes [8–10] survive successfully. Under climate change conditions less acclimatised species have to migrate to adequate small-scale microsites [12, 15, 45].

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