THE CLIMATOLOGIC SIGNIFICANCE OF TOPOGRAPHY, ALTITUDE AND REGION IN HIGH MOUNTAINS – A SURVEY OF OCEANIC-CONTINENTAL DIFFERENTIATIONS OF THE SCANDES

With 3 figures, 3 tables and 1 supplement (I)

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Zusammenfassung: Die klimatologische Signifikanz von Topographie, Höhenstufe und Region im Hochgebirge – Eine Untersuchung der ozeanisch-kontinentalen Differenzierung der Skanden.

Die Heterogenität der untersuchten norwegischen Gebirgslandschaft führte zu einem multi-skaligen Ansatz, der die kleinräumige Differenzierung innerhalb von Einzugsgebieten (Mikro-Skala), den höhenwärtigen Wandel innerhalb jeweils eines ozeanischen und kontinentalen Gebirgssystems (Meso-Skala) sowie den ozeanisch-kontinentalen Wandel zwischen den beiden klimatischen Regionen (Makro-Skala) miteinander verknüpfte. Die Unterschiede der mikroklimatischen Standortverhältnisse wurden auf den o.g. Raumskalen untersucht. Wir erwarteten, dass sich verschiedene übergeordnete meteorologische Phänomene entlang von Höhen- und regionalen Gradienten in den standörtlichen Temperaturverhältnissen widerspiegeln. Es stellte sich heraus, dass die kleinräumige topographische Differenzierung die bedeutendste Steuerungsgröße des Temperaturwandels entlang von großräumigen Höhenstufen- und Ozeanitäts-Kontinentalitäts-Gradienten darstellt. Der adiabatische Koeffizient zeigte keine deutlichen Korrelationen mit den standörtlichen Temperaturgradienten. Die regionalen klimatischen Unterschiede zwischen ozeanischen (westlichen) und kontinentalen (östlichen) Gebirgen waren auf der Basis lokaler und höhenwärtiger Temperaturgradienten signifikant. Um diese übergeordneten Phänomene zu quantifizieren, wurden Thermoisoplethendiagramme mit korrespondierenden Histogrammen für den paarweisen Vergleich der Standorte, Höhenstufen und Regionen erzeugt. Im Ergebnis liefert die Arbeit auf der Basis der gefundenen komplexen Temperaturdifferenzierungen eine Quantifizierung der klimatologischen Signifikanz von Topographie, Höhenstufe und Region im Hochgebirge. Diese kann künftigen Extrapolationen und Modellierungen der mikroklimatischen Verhältnisse in Hochgebirgslandschaften als Basis dienen.

Summary: The heterogeneity of the Norwegian mountain landscape under investigation led to a multi-scale approach. We combined micro-spatial differentiations within small catchments (micro-scale), altitudinal changes of an oceanic and a continental mountain system (meso-scale), and oceanic-continental alteration between these two mountain regions (macro-scale). We analysed differences between micro-climatic site conditions at the spatial scales given above. It was assumed that different superior meteorological phenomena along altitudinal and regional gradients find their expression in local temperature conditions. It turned out that micro-topographic site conditions were superiorly determining thermal changes along altitudinal and oceanic-continental broad-scale gradients. The adiabatic lapse rate did not show high correlations with local temperature gradients. Regional climatic differences between the oceanic western and the continental eastern mountains were significant by means of local and altitudinal temperature gradients. We used isopleth-diagrams of temperature differences and corresponding histograms between each, site–site, low alpine–middle alpine, and oceanic mountain–continental mountain couples to quantify these over-laying phenomena. As a result we quantified the significance of complex differences of temperature gradients across topography, altitude and region in order to enable micro-climate extrapolation and modelling in high mountain landscapes.

1 Aims and hypotheses

Within the discussion of climate change (HOUGHTON et al. 1990; OSTENDORF et al. 1999; WALTHER et al. 2002) the sensitive high mountain ecosystems could act as indicators for ecosystem response to global warming (BENISTON a. INNES 1998; ELIASSEN a. GRAMMELTVEDT 1990). This may induce a change of species distribution and biodiversity in high mountain landscapes (CALLAGHAN et al. 1993; CHAPIN et al. 2000) and finally lead to a replacement of alpine by sub-alpine ecosystems (AAS a. FAARLUND 1995; CRAMER 1997), respectively. To understand possible mountain ecosystem response to global warming, the climate system itself must be analysed at different spatio-temporal scales (ACIA 2004).

High mountain climate is most decisively differentiated by topography (BARRY 1992; BECKER a. BUGMANN 1997). On a broad scale, superior circulation systems are modified by means of mountain chains located within the climate zones (FØRLAND et al. 2000; RUMMUKAINEN et al. 2001). As such, the Scandes mountain chain stretching orthogonally to the westerlies is clearly differentiated into most oceanic and continental regions over a relatively short distance (MOEN 1999). Since most official meteorological stations are located in the valleys (PRICE a. BARRY 1997), common approaches of spatial data interpolation (HUTCHINSON 1995; FLEMING et al. 2000) are critical, due to the general lack of data from higher elevations. Simple but common approaches to assess altitudinal gradients are based on the mean adiabatic lapse rate of temperature (WHITEWAY et al. 1995) using the standard (mean) air temperature at a height of two metres above ground (BENDIX 2003). Its ecological relevance was questioned and micro-climatologic variations were analysed using one continental mountain system in Norway. The heterogeneity of the landscape investigated led to an across-scale procedure that combined vertical interactions at single locations, micro-spatial differentiations within small catchments, and altitudinal changes of the entire continental mountain system. Correlations between general meteorological trends and local climatic differentiations were analysed. It turned out that the micro-spatial conditions resulted in complex principles of thermal changes along broad-scale altitudinal gradients. So, the adiabatic lapse rate, commonly used to describe the altitudinal zonation, did not explain the different mosaics of ecosystems. Biases between measurements and common assumptions were illustrated by means of correlation matrices. Complex differences of temperature gradients were achieved from across-scale multiple-regression analysis (LÖFFLER a. PAPE 2004).

Within this paper we used the results from the above study and additional parallel measurements in an oceanic mountain system to analyse differences between mountain climates on the oceanic and continental slopes of the Scandes. We followed the aims and hypotheses given below:

a) Which spatial scale is characterised by the most decisive temperature difference? The assumption was that regional differences are most significant and will find their expression in local conditions in areas with complex topography, as stated as the principle basis for data extrapolation and regional model implementation (BENISTON 2003; DIRNBÖCK et al. 2003).

b) How do altitudinal gradients vary over regional and local scales? The assumption was that these gradients are constant over regional distances (DIRNBÖCK et al. 2003). These gradients were supposed to be independent of local site conditions, as used to model future climate change to mountain plant response (SÆTERSDAL a. BIRKS 1997; KLANDERUD a. BIRKS 2003).

c) How do micro-scale regularities of temperature variability differ between oceanic and continental mountain conditions, and how do these gradients correspond to general assumptions and meteorological trends? The assumption was that high mountain microclimate in oceanic and continental regions is most significantly determined by superior meteorological conditions (JÄGER 1968; WALLÉN 1970; MOEN 1999).

2 Study areas

Central Norway shows a clearly defined oceanic-continental gradient represented by the western and eastern slopes of the mountain chain. The study area Geiranger/Møre og Romsdal (62°03′ N; 7°15′ E) within the inner fjords region of western Norway is climatically characterised as sub-oceanic with annual precipitation sums of 1,500–2,000 mm in the valleys (MOEN 1999). The most continental climate is found only 150 km east off the coast in the Vågå/Oppland region (61°53′N; 9°15′E). The study area situated within this climatic region is characterized by a lowest annual precipitation of about 300–400 mm per year (in the valleys), i.e. showing the highest aridity found in Norway (MOEN 1999). The alpine altitudinal zonation in both areas is differentiated into a low alpine belt, dominated by shrub and heather communities, and a middle alpine belt, dominated by patchy grassy vegetation (DAHL 1986). It reaches from the tree-line at about 840–880 m a.s.l. (Geiranger) or 1,000–1,050 m a.s.l. (Vågå), to the highest peaks, i.e. the Dalsnibba (1,476 m a.s.l.) in Geiranger, and the Blåhø (1,618 m a.s.l.) in Vågå. The transition zone between low- and middle-alpine belts is found at around 1,150 (Geiranger) or 1,350 m a.s.l. (Vågå). Four investigation areas are chosen as representative mountain catchments of central Norway and delimited in each altitudinal belt so as to represent the conditions within a large-scale (Fig. 1).

3 Materials and methods

Micro-climatologic investigations of near-surface temperature conditions were applied to the main relief positions of ridge, depression and mid-slopes both in northern and southern exposure within each of the four representative small watersheds. Within this study we used the ridges and south-facing slopes to evaluate the significance of topography (Fig. 1).

One meteorological station at ridge positions registered the dynamics of air (+100/+15 cm) and soil (–1/–15/–30 cm) temperatures, precipitation, solar radiation, air humidity, barometric pressure, wind direction, and wind speed throughout the year as hourly means and sums. Temperature data from the south-facing slopes were achieved by data loggers at +15, –1 and –15 cm, providing the same temporal resolution. The temperature measurements were based upon pt100-sensors with an accuracy of ± 0.1 K.

Data analysis in the frame of this paper was based on the period from August, 1st 2002 until July, 31st 2003, but restricted a) to ridge and south-exposed slope, representing the most pronounced differences, and b) to temperatures at +15 cm (hereafter referred to as T+15) and –15 cm (hereafter referred to as T–15). Due to the formation of snow-cover at south-exposed slopes, T+15 refers to snow temperatures during winter.

Hourly means of temperature data were used to create thermoisopleth-diagrams. By use of overlay operations within a GIS (IDRISI 1999), distinctions between sites at different scales were calculated: a) micro-scale

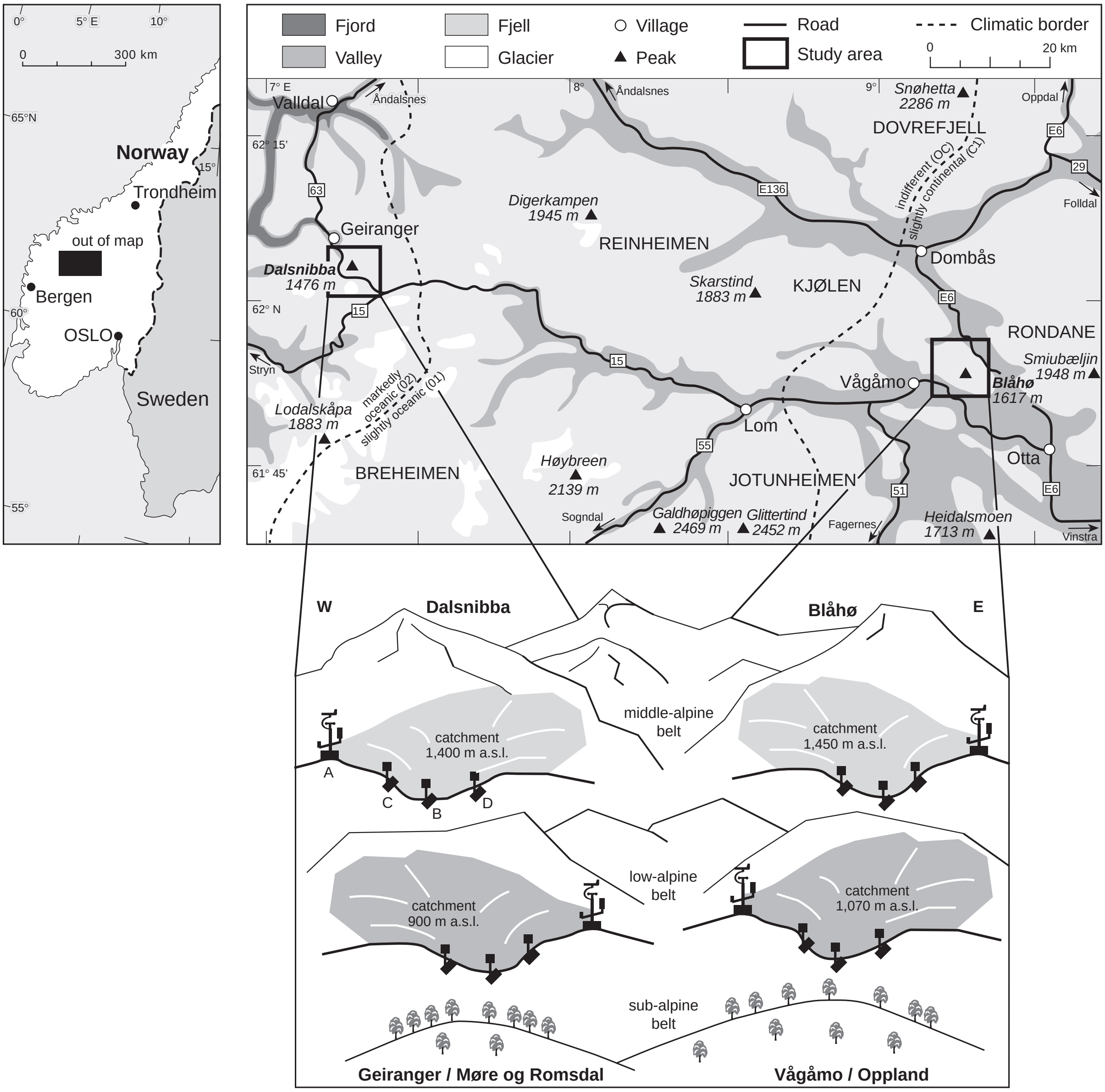

Fig. 1: Location of study areas in Central Norway and scheme of investigated catchments. Investigations were conducted along the transect ridge (A, with meteorological station), south-exposed mid-slope (C), north-exposed mid-slope (D) and depression (B, as C and D with temperature loggers).

Die Lage der Untersuchungsgebiete in Mittelnorwegen mit einem Schema der untersuchten Einzugsgebiete. Die Untersuchungen wurden entlang eines Transekts Kuppe (A, mit Klimastation), süd-exponierter Mittelhang (C), nord-exponierter Mittelhang (D) und Muldenlage (B, sowie C und D mit Temperaturdataloggern) differences among ridge and slope within each catchment, b) meso-scale distinctions among the same relief positions in different altitudinal belts, and c) macro-scale differences among oceanic and continental conditions for the same relief positions within the same altitudinal belt. Thermal differences were visualized using the resulting isopleth-diagrams and corresponding histograms.

The concept of multiple scales (micro-, meso-, and macro-scale) was adopted for the northern mountain areas (LÖFFLER 2002a) using landscape ecological terminology (BASTIAN a. STEINHARDT 2002) derived from the theory of geographical dimensions (NEEF 1967). Landscape complexes were used in a hierarchical order combined with corresponding scale terms, principally based on a transition of emergence, moving from one spatial level of abstraction to another (LÖFFLER 2002b).

Due to different altitudes of the western and eastern low alpine catchment, temperatures of the western catchment were recalculated for 1,100 m a.s.l. using dynamic lapse rates given by hourly temperature differences between the western low and middle alpine watershed.

To prevent a comparison of singularities between western and eastern Norway, the time period under consideration was compared with long-term mean data (1961–1990) provided by two meteorological stations of the NORWEGIAN METEOROLOGICAL INSTITUTE (Fokstua II, Nr. 16610 [1968] for eastern Norway at 972 m a.s.l., and Tafjord, Nr. 60500 [1925] for western Norway at 15 m a.s.l.). Moreover, the solar analyst (FU a. RICH 1999) was used to calculate the possible maximum of global radiation for each catchment to quantify relief-induced shading-effects especially in the western low alpine catchment.

4 Results

The following description of our outcomes is structured according to three spatial scales: micro-scale (topography), meso-scale (altitude), and macro-scale (region). Prior to any analyses within these scales, monthly means of air temperature during the time period under consideration were compared to long term means (1961–1990) within the western and eastern investigation area. This approach enabled the estimation of a), the representativeness of the time period in question, and b), the legitimacy of a macro-scaled oceanic-continental comparison. In both investigation areas the mean temperature during the period from August 2002 to July 2003 was 0.8 K above the long-term mean. A temporally differentiated view showed a warmer period until September, with a significant maximum during summer (>4 K in August), but a cooler close of the year (–4 K in October). However, the deviation of the monthly average temperatures from the normal period in both investigation areas ran nearly synchronously.

The major results of this study are presented in supplement I. Temperature differences are demonstrated between a), ridge and south-exposed slope within each investigated catchment (micro-scale, to be found in the middle of Suppl. I), b), low alpine and middle alpine within each region for sites with similar relief position (meso-scale, to be found at the left and the right of Suppl. I), and c), west and east for sites located within the same altitudinal belt at similar position within the relief (macro-scale, to be found at the bottom and top of Suppl. I). In each case the comparison covered near-surface temperatures at 15 cm above ground, as well as soil temperatures at a depth of 15 cm below the surface. The diurnal and seasonal variability of temperature differences between the respective locations is presented by isopleth-diagrams and histograms within supplement I.

4.1 The significance of topography (micro-scale)

The small-scale temperature differences near the surface as a function of the local site variability were found to be subject to the same characteristic regularities in all investigation areas. Compared to ridges, air and soil temperatures at south-exposed slopes were generally found to be warmer during winter (1–4). Within the continental eastern low alpine catchment (4), as well as the oceanic western middle alpine catchment (1), temperature differences at T+15 exceeded 15 K. In spring, clearly higher daily maxima of air temperatures appeared in ridge positions, middle alpine (1, 3) even until end of June, before the air at south-facing slopes turned warmer during summer. During summery nights, ridges and slopes were almost isothermally in the air, or the slopes were even found to be cooler than the ridges. Proceeding in the course of the year, an autumnal isothermal phase led up to the already mentioned winter conditions. Regarding the soil temperatures, they were found to be isothermal during spring and autumn but dedicated lower at the slopes during summer.

The histogram representation of the temperature difference between south-facing slopes and ridges clarifies the generally warmer conditions at the slopes. Based on the distribution, curves shifted to the right within the histograms and south-exposed slopes proved to be warmer.

The absolute annual temperature amplitude within the air (see Tab. 1a) showed very high values at all locations (40 K ± 5 K). However, the number of days at

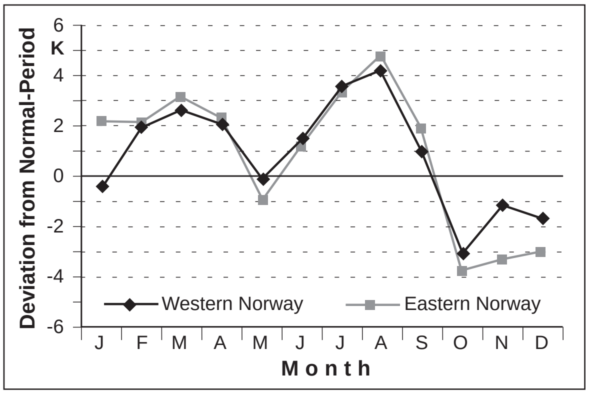

Fig. 2: Deviation of monthly mean temperatures during the investigation period from the normal-period.

Abweichung der monatlichen Mitteltemperaturen während der Untersuchungsperiode von der Normalperiode

ridges with freeze-thaw processes clarifies the more pronounced temperature dynamics of these locations, opposite to south-facing slopes. Everywhere ridges form the most extreme sites, with pronounced daytime air temperature course during all seasons. The average daily amplitudes were found to be 5.5 K (3.5 K standard deviation) in the west and 6.9 K (4.2 K standard deviation) in the east. The average daily amplitude of air temperature at south-facing slopes achieved similar values, as at ridges (5 K low alpine, 3.3 K middle alpine). A high standard deviation (5.7 +/– 1 K) emphasized the seasonal variability, however. In the low alpine belt the mean daily amplitudes of < 0.6 K in the 1st quarter arose to 13.6 K (maximally 23.6 K) in the 3rd quarter and were thereby on average about 2 K higher than in ridge positions.

The soil temperatures showed generally lower absolute amplitudes than the air temperatures (Tab. 1b). The values ranged around 13.9 K at the continental low alpine south-facing slope and 30.1 K at the continental middle alpine ridge, according to local site conditions. Principally, slope positions showed lower mean daily amplitudes of soil temperatures than ridges, with

Table 1a: Characteristic micro-climatic variables of air temperature at different sites

Charakteristische mikro-klimatische Variablen der Lufttemperatur unterschiedlicher Standorte

Air temperatures	Oceanic sites				Continental sites			
	Low alpine		Middle alpine		Low alpine		Middle alpine	
	Ridge	Slope	Ridge	Slope	Ridge	Slope	Ridge	Slope
Mean temperature [°C]	2.3	3.7	–1.0	1.3	0.5	3.6	–0.5	0.1
Absolute max. temperature [°C]	30.8	32.4	25.1	26.6	27.6	28.7	28.4	26.3
Absolute min. temperature [°C]	–16.8	–14.3	–20.0	–14.3	–19.0	–12.2	–18.7	–9.6
Absolute amplitude [K]	47.6	46.7	45.1	40.9	46.5	40.9	47.1	35.9
Annual mean daily amplitude [K]	5.3	5.0	5.7	3.5	7.6	5.0	6.3	3.2
1st quarter mean daily amplitude [K]	4.6	0.6	0.3	0.1	6.1	0.0	4.9	0.5
3rd quarter mean daily amplitude [K]	5.7	13.4	5.6	9.8	11.5	13.6	9.5	10.7
No. of days with freeze-thaw processes	30	19	41	18	48	15	46	13

Table 1b: Characteristic micro-climatic variables of soil temperature at different sites

Charakteristische mikro-klimatische Variablen der Bodentemperatur unterschiedlicher Standorte

Soil temperatures	Oceanic sites				Continental sites			
	Low alpine		Middle alpine		Low alpine		Middle alpine	
	Ridge	Slope	Ridge	Slope	Ridge	Slope	Ridge	Slope
Mean temperature [°C]	2.5	3.6	0.3	2.4	2.0	3.6	0.2	0.4
Absolute max. temperature [°C]	16.1	16.0	15.2	22.9	22.4	13.8	18.6	15.2
Absolute min. temperature [°C]	–9.2	–4.1	–8.3	–6.0	–7.6	–0.2	–11.5	–6.3
Absolute amplitude [K]	25.3	20.1	23.5	28.9	30.0	13.9	30.1	21.5
Annual mean daily amplitude [K]	0.8	0.6	0.9	1.5	2.4	0.5	1.7	0.7
1st quarter mean daily amplitude [K]	0.8	0.1	0.3	0.1	0.6	0.0	0.8	0.1
3rd quarter mean daily amplitude [K]	4.4	0.9	2.1	5.6	5.2	1.4	3.4	2.0
No. of days with freeze-thaw processes	0	0	0	1	0	0	0	0

the exception of the oceanic middle alpine slope. Seasonal variability of air temperature amplitudes at south-facing slopes (see above, Tab. 1a) found their equivalent in the soil temperature amplitudes: mean daily amplitudes of 0.1 K in the 1st quarter increased up to 5.6 K in the 3rd quarter.

4.2 The significance of altitude (meso-scale)

Histograms of temperature differences between low and middle alpine sites at similar positions of both the oceanic and continental study areas showed generally warmer conditions in the low alpine belt (Suppl. I). Histogram peaks illustrate that, compared with the middle alpine belt, most time of the year the low alpine belt was about 2 K warmer in the western region, while it was about 4 K warmer in the eastern region. This temperature difference matched approximately the general adiabatic lapse rate of 0.6 K per 100 metres.

In contrast, the temporal variability of the temperature difference between the low and the middle alpine belts only became apparent through isopleth-diagram analyses (Suppl. I), as illustrated in the following.

In the western study area the difference of the air temperature between ridges (5) and slopes (6) was characterised by pronounced intraday variations. During daytime, the low alpine belt was clearly warmer than the middle alpine belt, while distinctions levelled off or nearly vanished during the night. Thus, lower radiation input due to relief conditions (Tab. 2) at the low alpine site did not find its expression in lower temperatures there.

During the winter period diurnal variations were superimposed by long-term variations, especially at south-facing slopes. In general, the altitudinal differences between air temperatures at south-facing slopes showed a stronger variability during the course of the year than at ridge positions. They ranged from +17 K in early summer to –7 K in early winter. Altitudinal differences of soil temperatures almost exclusively showed low-level long-term variations, with in general slightly warmer low alpine conditions (see histograms 5 and 6 in Suppl. I). However, temperature differences at south-facing slopes were again characterized by a more pronounced variability than ridges: in summer, soil temperatures at the low alpine slope were higher in the morning, but lower in the afternoon compared to the middle alpine slope. As a result, the altitudinal temperature gradient showed a change of sign: negative until noon and positive afterwards.

In the continental eastern study area (7, 8 in Suppl. I) both the diurnal and seasonal variability of the altitudinal temperature difference were found to be more clearly pronounced than in the oceanic western study area (recognizable also from the broader dispersion of the histograms). But the principles were the same: soil temperature differences showed ranges on a more seasonal scale, while air temperatures on ridges possessed diurnal distinctions all over the year. This phenomenon was restricted to the summer time at slope sites. Sharp air temperature differences up to 23 K during early summer periods between the south-facing slopes were developed in evidence. Additionally, during August a pronounced diurnal cycle of altitudinal temperature differences occurred: at noon the low alpine south-facing slope was up to 11 K warmer than the middle alpine slope, but at night 7 K cooler (8). The altitudinal differences of soil temperatures at ridge positions showed a similar change of sign, but on a seasonal scale: during summer, soil temperatures at low alpine ridges were higher, and during winter lower than at middle alpine ridges (7).

Resulting altitudinal temperature lapse rates are presented in figure 3.

The mean annual lapse rate ranged between –0.2 to –0.9 K per 100 metres, with generally higher values in the continental study area. A more detailed analysis led to a more differentiated characterisation: the altitudinal lapse rate showed extreme diurnal and seasonal deviations from the annual average at all sites. On the one hand, the lapse rate dropped down to –6 K per 100 metres in the continental study area at extreme conditions. On the other, increasing temperatures with height were found, i.e. an inversion of the general lapse rate. Both

Table 2: Relief-induced radiation deficit of western low alpine investigation area compared to middle alpine investigation area. Values are given in percentage of possible radiation

Reliefbedingtes Strahlungsdefizit des westlichen unteralpinen Untersuchungsgebietes gegenüber dem mittelalpinen Untersuchungsgebiet. Die Werte sind in Prozent der möglichen Einstrahlung angegeben

	J	F	M	A	M	J	J	A	S	O	N	D	
Ridge	32	54	71	82	89	91	89	86	74	63	35	34	%
Slope	28	59	79	86	89	89	89	88	82	72	30	29	%

the overall amplitude of observed lapse rates, and the lower amplitude of temperature lapse rates within the soil compared to the air, was similar within the oceanic and continental study area. But a higher standard deviation indicated more frequent deviations from annual means within the continental study area.

4.3 The significance of region (macro-scale)

Within the comparison between the oceanic and continental region the histograms revealed no general trend towards one region being generally warmer than the other (Suppl. I, 9–12). General warmer conditions were restricted to the oceanic middle alpine south-facing slope compared to its continental counterpart (10). On average, differences between the oceanic and continental region were lower than 1 K. Also the standard deviation from this average was lowest compared to observations within the other spatial scales. A more differentiated analysis of distinctions at ridge positions indicated general warmer winter conditions and cooler summer conditions, the latter differentiated in colder days and warmer nights, within the oceanic low alpine catchment (11). This trend was also observed comparing middle alpine sites, but was less clearly pronounced.

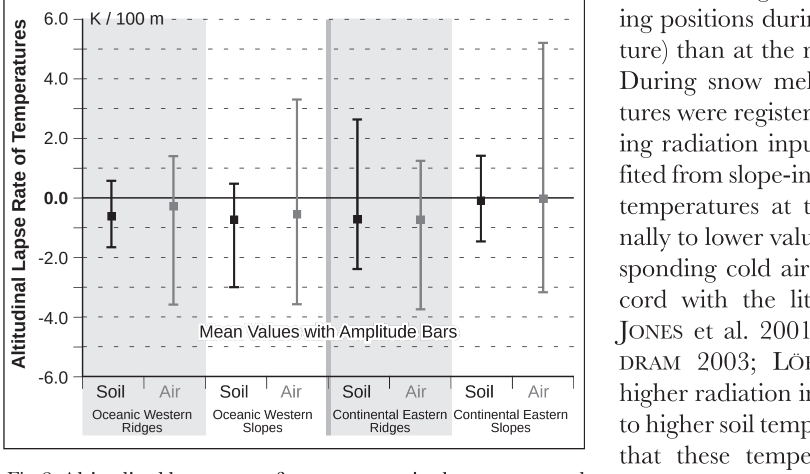

Fig. 3: Altitudinal lapse rate of temperature in the western and eastern investigation areas at ridge positions and south-facing slopes, given separately for soil and air temperatures. Annual means and their range of minimum and maximum values are shown.

Adiabatischer Koeffizient der Boden- und Lufttemperaturen im westlichen und östlichen Untersuchungsgebiet in Kuppen- und Südhangposition. Abgebildet sind die jährlichen Mittel- sowie Minimum- und Maximumwerte

In retrospect to the other scales, further characteristics were observed: neither absolute annual temperature amplitude, nor mean daily amplitude (Tab. 1a, b) revealed significant distinctions between oceanic and continental conditions. Under oceanic conditions micro-scaled temperature differences between ridge and slope position were weakly pronounced, especially during the winter season. For instance, air temperatures at continental south-facing slopes were about 3 K higher than those at the ridges; oceanic conditions proved to be similar, but only 1 K higher. Diurnal and seasonal variability of altitudinal temperature differences was more pronounced in the continental study area.

5 Discussion and conclusions

Temperatures within the time period under consideration showed significant deviations from the long-term mean 1961–1990. The comparability of the data used was proved according to high synchronicity of these deviations in the continental and oceanic study areas.

Micro-scale temperature differences between the ridges and slopes compared were characterised by different snow pack conditions and different solar radiation input. As such, the snow-free period on slopes was much shorter than at the ridges and temperature curves did not show any diurnal dynamics. In all study areas T+15 was higher throughout the day at the south-facing positions during the winter season (snow temperature) than at the ridges (near-surface air temperature). During snow melt, higher daily maximum temperatures were registered at the ridges according to increasing radiation input. During the summer, slopes benefited from slope-induced higher radiation input. In part temperatures at the slope positions dropped nocturnally to lower values, according to inversion and corresponding cold air flows. So far, these phenomena accord with the literature (Dahl 1956; Barry 1992; Jones et al. 2001; Löffler 2003; Löffler a. Wundram 2003; Löffler a. Pape 2004). Interestingly, higher radiation input during the summer did not lead to higher soil temperatures at the south-facing slopes, so that these temperatures were generally lower than those at the ridges. Intensive but short-term diurnal heating of the near-surface substrate only led to heated soil layers up to 5 cm depth (Löffler 2002a; Löffler a. Rößler 2005). Deeper warming effects up to 15 cm depth were restricted to sites where indirect heating was enabled by surface-exposed bedrock that functioned as a heat conductor for the loose substrate from below.

Described temperature amplitudes of up to 35–45 K as well as micro-scale site-specific temperature variability of more than 15 K are well known climatic phenomena of high mountain environments (BARRY 1992; LÖFFLER a. WUNDRAM 2003). But in contrast to assumption a) that regional differences are most significant and will find their expression in local conditions in areas with complex topography, as stated as the principle basis for data extrapolation and regional model implementation (BENISTON 2003): differences of local temperatures were found to be most significant compared to differences at the other spatial scales! In turn, these results reveal that, intrinsically, modelling of ecosystem response to climate change has to consider local site variability. Actually, recent studies are based on low-resolution topography data (GUISAN a. THEURILLANT 2000; DIRNBÖCK et al. 2003).

Contrary to hypothesis b) that altitudinal gradients are constant over regional distances (DIRNBÖCK et al. 2003) and that these gradients are independent of local site conditions, we found altitudinal gradients to be distinguished between oceanic and continental regions. Furthermore, we showed that altitudinal gradients also ranged extremely in diurnal and seasonal terms. We proved both that temporal and spatial variations were always due to local site conditions. As described above, snow cover, radiation input, and cold air flows were most decisive in distinguishing between local temperatures. Thus, mean temperature values were identified as unsuitable for representing the altitudinal changes of high mountain climate. As to this enormous spatial and temporal temperature variability we question the use of mean temperature values as well as mean lapse rates in modelling ecological response to possible climate change (BARRY 1994; SÆTERSDAL a. BIRKS 1997; GOTTFRIED et al. 1999; GUISAN a. THEURILLANT 2000; DIRNBÖCK et al. 2003; FAGRE et al. 2003).

Despite different weather conditions we found that oceanic-continental differences were least significant within our multi-scale approach. This fact contradicts general assumptions of high mountain micro-climate determination by superior meteorological conditions in oceanic and continental regions (MOEN 1999), as stated in hypothesis c). Different macro-climatic sections along an oceanic-continental gradient are commonly used to distinguish between regional distribution patterns of vegetation types (FREMSTAD 1997), since it is assumed that the vegetation differs fundamentally across these regions (LAAKSONEN 1976; TUHKANEN 1986; MOE 1995; MOEN a. ODLAND 1993; MOEN 1999). Microclimatic determination is most decisive in explaining local vegetation patterns in high mountain landscapes (LÖFFLER 2003). Additionally, we showed that macro-scale climate conditions are significantly modified by micro-climatic phenomena. Thus, simple assumptions or approaches that are based on global circulation models to predict future macro-scale shifts of vegetation regions and biomes according to global warming (i.e. CRAMER 1997; WALKER et al. 2002; KLANDERUD a. BIRKS 2003; PAULI 2003a) have to be scrutinized according to our results.

Current scientific challenges accrue from the problem that modelling of climate change simulation and ecosystem response prognoses has led to the way of predicting changes to the exclusion of collecting the empirical data necessary to develop and validate robust models (ABER 1997; FAGRE et al. 2003). Moreover, nonlinearity of climate systems must be taken into consideration when assessing global climate change impacts on ecosystems (PETERSON 2000; RIAL et al. 2004). Initiatives like the multi-summit approach of GLORIA (GRABHERR et al. 1994; PAULI et al. 2003b) are based on standardised methodologies and allow a macro-scale comparison of mountain ecosystems. Since they focus on vegetation patterns and monitoring of changes, ecosystem complexity is poorly considered. Future research activities and tasks for the evaluation of climate variability in high mountains will have to be based on process studies along altitudinal gradients and associated catchments, monitoring studies to understand the nature of any changes (BECKER a. BUGMANN 2001; DIAZ et al. 2003), and integrated studies that distinguish ecosystem response to climate change vs. land use change (OLSSON et al. 2000; LÖFFLER et al. 2004). In conclusion, on the one hand, climate modelling in high mountains will have to include data from extensive investigations at different spatio-temporal scales (O'BRIEN et al. 2004). On the other, these models will have to be simple structured to allow parameterization of measured input data (BOULET et al. 2000; PAPE a. LÖFFLER 2004).

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