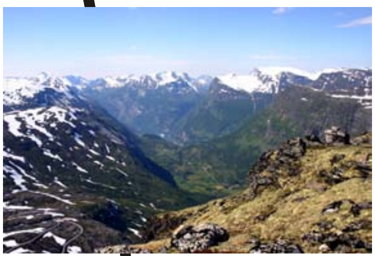
Near-Surface Temperature Conditions in High Mountain Environments - Analysis, Modeling Approaches and Ecological Relevance



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INHALT

ABBILDUNGSVERZEICHNIS

ABSTRACT

Framed by a long-term ecological research project in the central Norwegian Scandes, near-surface temperature conditions in a high mountain environment have been investigated. The study aimed at spatio-temporal analyses of ecological relevant temperatures along multiple gradients important for temperature conditions to characterize the micro-climatic differentiation of high mountains environments. Furthermore, approaches for modeling and regionalization of near-surface temperatures were to be developed, applicable for these environments. Moreover, the ecological relevance of temperature conditions was evaluated.

These aims arose from a combination of three aspects important for high mountain ecology: i) the proposed role of mountain environments as indicators for climatic change, ii) the general lack of knowledge about ecosystem functioning in the alpine environments of Norway on the contrary, and iii), the lack of ecologically relevant observational climatologic data for these environments, reinforced by the inappropriateness of common modeling or regionalization approaches.

The analysis of near-surface temperatures along governing gradients of relief, altitude, and continentality revealed the superior determination of temperature conditions by micro-scaled relief features. Thus, gradients at meso- and macro-scale were found to be overruled by micro-scale conditions. These results contradict the common research opinion stating that conditions at higher scale-levels first and foremost determine also local conditions. Moreover, approaches for implication of ecological models and regionalization of temperatures, commonly based on this assumption, need to be critically reflected. Standard meteorological observations at screen height, for instance, were found incapable of near-surface temperature conditions.

However, since temperature regionalization in mountain environments used to be based on the environmental lapse rate or geostatistical interpolation of air temperatures, a re-thinking is urgently requested. Neither the observational network, these approaches are based on, nor the recent numeric climatological models are suitable to capture the fine-scaled temperature variability important for ecological applications. Consequently, a new numeric physically-based modeling approach was developed and tested together with modified statistical approaches for its spatial applicability and validity to bridge the gap in micro- and meso-scale climatological modeling. The physically-based model performed best at nano-scale but clearly showed

limitations regarding its reasonable spatial applicability. Statistical models, however, performed consistent with intermediate accuracy throughout the spatial scales, indicating their potential for temperature modeling in high mountain environments where the auxiliary data needed for physically-based modeling are of limited availability. However, also the spatial performance of physically-based models could be improved significantly in future, if the necessary parameterizations are adapted to – or even better, developed for – high mountain environments.

The investigation of the ecological relevance of near-surface temperatures revealed a strong dependency between micro-climatic conditions and the biotic, enabling niche descriptions and climatic reconstructions. As such, the suitability of a habitat for an alpine grasshopper was related to temperature conditions that were also found to determine annual tree-ring width of a dwarf-shrub species. For the grasshopper, the micro-scale temperature variation turned out to be the most important environmental factor, whereas variations in annual growth of the dwarf-shrub species were first and foremost related to the regional climate signal that was linearly modified by the micro-scale conditions. However, regarding the spatial patterns of different vegetation types, again the micro-scale conditions proved to be most important.

Concluding, the findings of this study stress the importance of micro-scaled climatic differentiations in high mountain environments, to be captured by an appropriate observation network or adequate modeling approaches. Facing this background, common approaches of model implication and regionalization need to be critically reflected. New modeling approaches for near-surface temperatures are presented instead and evaluated, providing encouraging evidence that an appropriate spatial representation is possible with simple means. Moreover, the evaluation of the ecological relevance revealed besides the necessity to consider the interdependence of different spatial scales in an appropriate manner the ability to use mountain environments as indicator for climatic change.

ZUSAMMENFASSUNG

Vor dem Hintergrund eines langfristigen ökologischen Forschungsprojektes in den mittelnorwegischen Skanden wurden die oberflächennahen Temperaturverhältnisse im Hochgebirge untersucht. Ziel der Studie war die raum-zeitliche Analyse ökologisch relevanter Temperaturen entlang verschiedener, für die Temperaturverhältnisse wichtiger Gradienten um darüber eine Charakterisierung der mikroklimatischen Differenzierung von Hochgebirgslandschaften vorzunehmen. Weitergehend sollten Ansätze für die Modellierung und Regionalisierung der oberflächennahen Temperaturen entwickelt werden, die in alpinen Bereichen Anwendung finden können. Darüber hinaus wurde die ökologische Bedeutung der Temperaturverhältnisse analysiert.

Diese Ziele wurden aus der Kombination dreier wichtiger Aspekte in der Hochgebirgsökologie abgeleitet: a) der den Gebirgen zugeschriebenen Rolle des Indikators für den Klimawandel, b) dem gegenüber jedoch das generelle Wissensdefizit über die Funktionsweise alpiner Ökosysteme in Norwegen, und c) der Mangel an den für eine ökologische Betrachtung relevanten klimatischen Beobachtungsdaten für diese Gebiete, verstärkt durch unzureichende Ansätze der Modellierung und Regionalisierung.

Die Analyse der oberflächennahen Temperaturen entlang übergeordneter Relief-, Höhen- und Kontinentalitätsgradienten ergab eine übergeordnete Steuerung der Temperaturverhältnisse durch mikroskalige Reliefbedingungen, d. h. meso- und makroskalige Gradienten wurden durch mikroskalige Gradienten überprägt. Diese Ergebnisse widersprechen der gängigen Forschungsmeinung, dass die lokalen Verhältnisse überwiegend durch die Bedingungen auf höheren Skalenebenen bestimmt würden. Darüber hinaus müssen demnach Ansätze zur Implementierung ökologischer Modelle oder zur Regionalisierung von Temperaturen, die gewöhnlich auf dieser These aufbauen, kritisch hinterfragt werden. Es zeigte sich beispielsweise, dass oberflächennahe Temperaturbedingungen nicht durch meteorologische Standardbeobachtungen erfasst werden können.

Da jedoch die Regionalisierung der Temperaturen im Gebirge zumeist auf dem adiabatischen Temperaturgradienten oder einer geostatistischen Interpolation der Lufttemperaturen beruht, ist ein Umdenken dringend erforderlich. Weder das Beobachtungsnetzwerk, auf dem diese Ansätze basieren, noch die derzeitigen numerischen Klimamodelle sind in der Lage, diese für

ökologische Anwendungen wichtige kleinskalige Temperaturdifferenzierung wiederzugeben. Aus dieser Konsequenz heraus wurde ein neuer numerischer, physikalisch basierter Modellansatz entwickelt und zusammen mit modifizierten statistischen Ansätzen hinsichtlich der räumlichen Anwendbarkeit und Aussagekraft getestet, um die Lücke im Bereich der mikro- und mesoskaligen Klimamodellierung zu schließen. Das physikalisch basierte Modell lieferte standörtlich, also nanoskalig, die besten Ergebnisse, zeigte allerdings deutliche Limitierungen hinsichtlich seiner räumlichen Anwendbarkeit. Die statistischen Modelle dagegen ergaben Ergebnisse von mittlerer Genauigkeit konsistent für alle Skalen und zeigen damit ihr Potenzial für die Temperaturmodellierung im Hochgebirge, wo für die physikalisch basierte Modellierung erforderliche Eingangsdaten nur sehr beschränkt verfügbar sind. Allerdings könnte zukünftig auch die Leistungsfähigkeit der physikalisch basierten Modelle signifikant verbessert werden, wenn die notwendigen Parametrisierungen an Hochgebirgslandschaften angepasst, oder besser sogar, für sie entwickelt würden.

Die Untersuchung der ökologischen Bedeutung der oberflächennahen Temperaturen ergab eine starke Abhängigkeit zwischen mikroklimatischen Bedingungen und der Biotik, die grundsätzliche Nischenbeschreibungen und klimatische Rekonstruktionen zulässt. So konnte die Habitateignung für eine alpine Heuschreckenart durch Temperaturbedingungen ebenso beschrieben werden wie die jährlichen Jahrringbreiten einer Zwergstrauchart. Für die Heuschrecke stellten sich dabei die mikroskaligen Temperaturbedingungen als wichtigster Faktor heraus, bei der Zwergstrauchart dagegen das regionalklimatische Signal, das durch die mikroskaligen Bedingungen linear modifiziert wurde. Bei der Betrachtung der räumlichen Organisation der Vegetationstypen jedoch sind wiederum die mikroskaligen Bedingungen entscheidend.

Zusammenfassend wird die Bedeutung der mikroskaligen Temperaturdifferenzierung im Hochgebirge durch die Ergebnisse dieser Arbeit hervorgehoben. Diese Differenzierung muss durch geeignete Beobachtungsnetze oder adäquate Modellierungsansätze erfasst werden. Vor diesem Hintergrund sind die gängigen Ansätze der Modellierung und Regionalisierung kritisch zu hinterfragen. An ihrer Stelle werden neue Modellierungsansätze für oberflächennahe Temperaturen im Hochgebirge präsentiert und evaluiert, die den Beweis liefern, dass eine angemessene räumliche Repräsentierung der Temperaturen mit einfachen Mitteln möglich ist. Darüber hinaus lieferte die Untersuchung der ökologischen Bedeutung oberflächennaher Temperaturen neben dem Hinweis auf die Notwendigkeit, die Wechselwirkungen auf verschiedenen Skalen berücksichtigen zu müssen auch exemplarische Beweise für die Indikatorfunktion der Hochgebirge hinsichtlich des Klimawandels.

1 EINLEITUNG

1.1 Forschungskontext

Die vorliegende Arbeit ist in einen Forschungskontext eingebunden, der sich aus drei Hauptaspekten zusammensetzt. Der erste dieser Aspekte bildet gleichzeitig den übergeordneten Rahmen: Für die Hochgebirgsregionen der Erde wird ebenso wie für die arktischen Regionen aufgrund ihrer Sensibilität eine im Verhältnis zu anderen Ökosystemen schnelle und drastische Reaktion auf den Klimawandel erwartet (Beniston et al. 1997, Messerli & Ives 1997, Pauli et al. 2001, Theurillat & Guisan 2001, Dirnböck et al. 2003), so dass ihnen von Chapin III et al. (1992) oder Beniston & Innes (1998) eine Indikatorfunktion zugesprochen wird. Bereits kleine globale Veränderungen können sich massiv auf die komplexen, wechselwirkenden Muster und Prozesse – vom Wasserkreislauf über Flora und Fauna bis hin zum Menschen, der von diesen Ressourcen abhängig ist – auswirken (Thompson 2000, Beniston 2003). Nach Körner (2004) ist somit das menschliche Wohlergehen und insbesondere die Wasserversorgung direkt oder indirekt von der funktionellen Integrität der Hochgebirgsökosysteme, mit der Vegetation als Schlüsselkomponente, abhängig. Generell wird bis Ende des Jahrhunderts ein globaler Temperaturanstieg von 1,4 bis 4,0 K prognostiziert (Alley et al. 2007), jedoch mit großer regionaler Variabilität, der hinsichtlich ihrer ökosystemaren Auswirkungen eine wesentlich höhere Relevanz zugesprochen wird (Walther et al. 2002; Dullinger et al. 2004). Für Norwegen gelten Temperaturerhöhungen von je nach Region zwischen 1-2 K und Niederschlagserhöhungen von bis zu 23 % (jeweils bis 2050) als wahrscheinlich (Sygna & O´Brien 2001), für den kontinentalen Osten werden jedoch sommerliche Niederschlagsrückgänge um 5-10 % erwartet (Førland et al. 2000). Bedingt durch die klimatische Änderung prognostizieren verschiedene Autoren eine Modifikation der Artenzusammensetzung und Biodiversität (Callaghan et al. 1993; Chapin III et al. 2000) sowie eine Verschiebung der zonalen und hypsometrischen Ökosystemkonfigurationen (Molau & Larsson 2000, ACIA 2004) bis hin zu einer Verdrängung alpiner durch sub-alpine Ökosysteme (Aas & Faarlund 1995, Cramer 1997). Um Veränderungen abschätzen oder quantifizieren zu können, ist allerdings das Wissen über das rezente „Funktionieren“ dieser Ökosysteme unabdingbar (Reynolds et al. 1996, Dormann & Woodin 2002).

Die Hochgebirgsökologie wird durch ausgeprägte meteorologische und topographische Gradienten ebenso gesteuert wie durch die Höhenstufung oder komplexe Ausbildungen des Mikroreliefs (Billings 1973, Kudo et al. 1990, Jones et al. 2001, Körner 2003). Diese Parameter sind allerdings nicht zuletzt wegen ihrer Wechselwirkungen komplex und in ihren Auswirkungen auf die Ökosysteme noch nicht vollständig verstanden (Körner 2003). So ist trotz einiger früher (Fall-)Studien, die mit Schwerpunkt auf der Vegetation wichtige Ergebnisse geliefert haben (z. B. Fries 1917, Nordhagen 1936, Dahl 1956, Gjærevoll 1956) und Ergebnissen aus dem *International Biological Program* (z. B. Rosswall & Heal 1975, Wielgolaski 1975, Bliss et al. 1981) flächenhaft nur wenig über die Umweltbedingungen und resultierende Vegetationsmuster im norwegischen Hochgebirge bekannt (Fremstad 1997).

Zu diesem generellen ökosystemaren Forschungsdefizit als zweitem Kontextaspekt kommt die Hochgebirgsklimatologie als dritter, speziellerer Aspekt hinzu: Obwohl Hochgebirge ein wichtiges Element des Klimasystems sind und Effekte der großräumigen Orographie auf die atmosphärische Zirkulation und das Klima generell untersucht wurden und werden (z. B. Bolin 1950, Manabe & Terpstra 1974, Broccoli & Manabe 1992), stehen die klimatischen Charakteristika der Hochgebirge selbst, trotz ihrer Rückwirkung auf das Makroklima, weniger im Fokus (Beniston et al. 1997). So sind Hochgebirgsregionen zumeist durch einen Mangel an Messstationen gekennzeichnet, da sich diese auf die besiedelten Tallagen beschränken (Barry 1992, Price & Barry 1997). Entsprechend befinden sich beispielsweise in Mittelnorwegen entlang 62° N nur 10 von 107 amtlichen Messstationen oberhalb der alpinen Baumgrenze, obwohl die alpinen Bereiche dort rund 51 % der Landesfläche ausmachen (Pape 2006). Gleichzeitig sind allerdings klimatische Daten eine unabdingbare Voraussetzung zunächst für den Erkenntnisgewinn über das rezente Funktionieren der Ökosysteme und später für die Ökosystemmodellierung unter geänderten Rahmenbedingungen (Lookingbill & Urban 2003). Da diese Modellierung um ein realitätsnahes Abbild zu gewährleisten auf räumlich hochaufgelösten Skalenebenen erfolgen sollte, d.h. der Meso- oder Mikroskala, müssen demnach auch die Klimadaten in entsprechender Genauigkeit vorliegen (Lookingbill & Urban 2003). Aber gerade für diesen Auflösungsbereich ist sowohl das Observationsnetzwerk wie auch die Klimamodellierung unzureichend: Trotz intensiver Forschung seit mehreren Jahrzehnten (WMO 1972) und verschiedenster Ansätze (z. B. Joly et al. 2003, Chung & Yun 2004, Chung et al. 2006, Stahl et al. 2006, Joly & Brossard 2007) bleibt die Regionalisierung punktuell gewonnener klimatischer Daten insbesondere in Gebirgsbereichen mit komplexer Topographie problematisch. Ein weiteres grundlegendes Problem regionalisierender Ansätze ist auf die Tatsache zurückzuführen, dass die räumliche Variabilität meist keiner raum-zeitlichen Linearität unterliegt (Peterson 2000) und es an flächenhaft verfügbaren Datenebenen fehlt, auf deren Grundlage sich Variabilität und Gradienten bestimmen ließen. Auch die Klimamodellierung ist in diesem Skalenbereich schwach (Chen et al. 1999), da die räumliche Auflösung ihrer Rasterzellen noch um ein vielfaches unter der erforderlichen Auflösung liegt (vgl. z. B. Rivington et al. 2008). Vor diesem Hintergrund entwickelte physikalisch basierte „land surface schemes“ zur Modellierung oberflächennaher Austauschprozesse von Wärme, Feuchtigkeit und Impuls (z. B. Saunders et al. 1999a, 1999b) leiden jedoch unter ihrer eingeschränkten flächenhaften Anwendbarkeit, da sie zahlreiche Eingangsgrößen hinsichtlich Pflanzenphysiologie und Bodenphysik benötigen, die flächenhaft nicht zur Verfügung stehen (Boulet et al. 2000). Somit ist Fægri's mittlerweile drei Jahrzehnte alte Anmerkung, dass die wissenschaftliche Herausforderung in der Hochgebirgsforschung in Norwegen aus dem Erkenntnisgewinn über kleinskalige Temperatur- und

Schneedeckendifferenzierungen sowie übergeordnete Ozeanitäts-Kontinentalitätsgradienten bestünde (Fægri 1972: 68), zumindest hinsichtlich der Klimatologie nach wie vor aktuell: Klimatologische Daten in ausreichender raum-zeitlicher Auflösung für ökologische Folgeanwendungen stehen zumindest für das norwegische Hochgebirge nur sehr eingeschränkt zur Verfügung.

Vor dem Hintergrund dieser drei Aspekte, Klimawandel, ökologisches Forschungsdefizit und Klimadatenmangel im Hochgebirge, wurde bereits 1991 von der Arbeitsgruppe Geoökologie an der Universität Oldenburg unter Leitung von Prof. Dr. Jung ein langfristiges ökosystemares Forschungsprojekt in Mittelnorwegen etabliert. Im Rahmen dieses Projektes wird die Dynamik der raum-zeitlichen Gradienten von Schneebedeckung, Bodenfeuchte und Temperatur untersucht und ihre Korrelation zu Strukturgrößen wie Boden- und Vegetationstypen überprüft. Erste wichtige Ergebnisse sind beispielsweise durch Köhler et al. (1994), Löffler (1998, 2002a, 2003), Löffler & Wundram (2001, 2003) publiziert worden. Seit 2001 wurde das Projekt in Zusammenarbeit mit der Arbeitsgruppe Terrestrische Ökologie an der Universität Oldenburg um zoologische Aspekte erweitert (Löffler et al. 2001). Seitdem fokussiert es u. a. auf die flächenhafte Erfassung des kleinräumigen ökosystemaren Wirkungsgefüges innerhalb von Einzugsgebieten inklusive der Quantifizierung von Steuergrößen der abiotischen Prozesssysteme und Biozönosen sowie auf eine Nischenbeschreibung epigäisch lebender Arthropoden. Dabei wird dem Temperaturhaushalt eine übergeordnete Bedeutung beigemessen. Erste Ergebnisse sind durch Löffler & Finch (2005) publiziert. Dieses Forschungsprojekt, jetzt von der Arbeitsgruppe Klimatologie und Landschaftsökologie am Geographischen Institut der Universität Bonn weitergeführt und um weitere Teilaspekte, z. B. der Dendroökologie (Bär et al. 2006), erweitert, bildet den engeren Forschungskontext für die vorliegende Arbeit.

1.2 Zielsetzungen der Arbeit

Von dem skizzierten Forschungskontext und der daraus folgenden großen Bedeutung des Temperaturhaushalts für das ökosystemare Prozessgeschehen ausgehend, lassen sich die Zielsetzungen für die vorliegende Arbeit wie folgt umreißen:

- Raum-zeitliche Analyse der ökologisch relevanten oberflächennahen Temperaturenbedingungen entlang multiskaliger Gradienten im mittelnorwegischen Hochgebirge zur Charakterisierung der mikroklimatischen Differenzierung.
- Entwicklung von Ansätzen zur Modellierung und Regionalisierung ökologisch relevanter oberflächennaher Temperaturen im Hochgebirge zur Schließung der Lücke zwischen herkömmlichen standörtlichen und räumlichen numerischen Klimamodellen.

Beide Ziele wurden vor dem Hintergrund des rahmengebenden ökologischen Forschungsprojektes verfolgt, wodurch auch immer der Anwendungsorientierung, in diesem Fall also der Orientierung auf die ökologische Relevanz der Temperaturen, eine hohe Bedeutung beigemessen wurde. So erfolgte auch eine integrative Auswertung der Daten zusammen mit anderen Teilprojekten, um den steuernden Einfluss der thermischen Bedingungen auf die Verbreitung und Entwicklung von Tierarten bzw. auf das Jahrringwachstum von Zwergsträuchern zu quantifizieren.

1.3 Aufbau dieser Arbeit

Die Arbeit unterliegt entsprechend ihrer Zielsetzung einer Dreigliederung. Die Analyse der oberflächennahen Temperaturverhältnisse mündet in eine inhaltlich orientierte Charakterisierung, aus der methodische Konsequenzen in Form der Entwicklung von Modellierungsansätzen gezogen werden. Diesem Prozess nachgeschaltet ist wiederum die inhaltliche Auseinandersetzung mit den ökosystemaren Konsequenzen der Temperaturverhältnisse im Hochgebirge.

Die wesentlichen Ergebnisse der Arbeit liegen als Teilpublikationen vor, die an dieser Stelle kurz vorgestellt werden sollen, da auf sie im weiteren Verlauf Bezug genommen wird. Für eine detailliertere Betrachtung sei an dieser Stelle jedoch auf die Kapitel 3 Zusammenhang, 4 zentrale Aussagen und 5 Publikationen verwiesen.

Publikation I. *Löffler, J., Finch, O.-D., Naujok, J. & R. Pape (2001): Möglichkeiten der Integration zoologischer Aspekte in landschaftsökologische Untersuchungen von Hochgebirgen – Methodendiskussion am Beispiel ökologischer Prozesssysteme und Biozönosen. Naturschutz und Landschaftsplanung 33: 351-357.*

Publikation II. *Pape, R. & J. Löffler (2004): Modelling spatio-temporal near-surface temperature variation in high mountain landscapes. Ecological Modelling 178: 483-501.*

Publikation III. *Löffler, J. & R. Pape (2004): Across scale temperature modelling using a simple approach for the characterization of high mountain ecosystem complexity. Erdkunde 58: 331-341.*

Publikation IV. *Löffler, J., Pape, R. & D. Wundram (2006): The climatologic significance of topography, altitude and region in high mountains – a survey of oceanic-continental differentiations of the Scandes. Erdkunde 60: 15-24.*

Publikation V. *Pape, R. (2006): Klimadaten im Hochgebirge – Anspruch und Wirklichkeit. Norden 17: 45-50. Bremen.*

Publikation VI. *Pape, R. & J. Löffler (eingereicht): Modeling Near-Surface Temperature Conditions in High Mountain Environments – An Appraisal. Climate Research.*

Publikation VII. *Finch, O.-D., Löffler, J. & R. Pape (2008): Assessing the sensitivity of Melanoplus frigidus (Boheman, 1846) (Orthoptera: Acrididae) to different weather conditions: A modeling approach focussing on development times. Journal of Insect Science (angenommen).*

Publikation VIII. *Bär, A., Pape, R., Bräuning, A. & J. Löffler (2008): Growth-ring variations of dwarf shrubs reflect regional climate signals in alpine environments rather than topoclimatic differences. Journal of Biogeography 35: 625–636.*

Einen zusammenfassenden Überblick über die insgesamt verwendeten Materialien und Methoden gibt Kapitel 2, während Kapitel 6 und 7 die Arbeit mit einer kritischen Betrachtung bzw. einem Fazit zu Analyse, Modellierungsansätzen und ökologischer Bedeutung oberflächennaher Temperaturen im Hochgebirge abschließen.

2 MATERIAL UND METHODEN

2.1 Untersuchungsgebiet

Das Untersuchungsgebiet befindet sich in Mittelnorwegen und erstreckt sich entlang 62° nördlicher Breite von der Küste bis zur schwedischen Grenze, im folgenden als Makroskala bezeichnet (Abb. 1). Die Skanden erreichen in diesem Bereich ihre höchste Erhebung (Galdhøpiggen, 2469 m ü.d.M.). Ihre küstenparallele Erstreckung in Nord-Süd-Richtung führt zu einer deutlichen klimatischen Differenzierung zwischen der West- und Ostabdachung. Im Rahmen des langjährigen Forschungsprojektes sind in diesem Bereich zwei mesoskalige Untersuchungsgebiete ausgewählt worden, die diesen Ozeanitäts-Kontinentalitäts-Gegensatz repräsentieren. Das Untersuchungsgebiet Geiranger (62°03' N; 7°15' E) liegt in der inneren Fjordregion Westnorwegens und lässt sich nach Moen (1999) klimatisch als sub-ozeanisch mit mittleren jährlichen Niederschlagssummen von 1.500-2.000 mm charakterisieren. Das kontinentalste Gebiet Norwegens befinden sich nur rund 150 km östlich der Küste, wo das zweite Untersuchungsgebiet Vågå (61° 53´ N; 9° 15´ E) lokalisiert ist. Die mittleren Jahresniederschläge liegen hier bei nur rund 300-400 mm in den Tallagen (Moen 1999). Die alpine Stufe in beiden Gebieten erstreckt sich von der Baumgrenze bei etwa 840-880 m ü.d.M. in Geiranger bzw. 1.000-1.050 m ü.d.M. in Vågå bis zu den höchsten Erhebungen mit 1.775 bzw. 1618 m ü.d.M. und umfasst die untere und mittlere alpine Höhenstufe, sowie in Geiranger auch die obere alpine Stufe. Die untere alpine Stufe ist durch geschlossene Zwergstrauch- und Flechtenheiden geprägt, die mittlere alpine Stufe durch lückigere Vegetation dominiert von Grasartigen und Flechten (Dahl 1986). Darüber ist nur noch sehr spärliche bzw. keine Vegetation mehr zu finden. Bedingt durch die hohe Reliefenergie im westlichen Gebiet Geiranger werden größere Bereiche auch durch anstehendes Festgestein oder Blockfelder dominiert. In beiden Gebieten sind jeweils zwei repräsentative Kleinsteinzugsgebiete von unter vier Hektar Größe für die mikroskaligen Untersuchungen ausgewählt worden, sie befinden sich in der unteren und mittleren alpinen Höhenstufe (Abb. 1). Die Messungen selbst fanden standörtlich, d. h. nanoskalig statt.

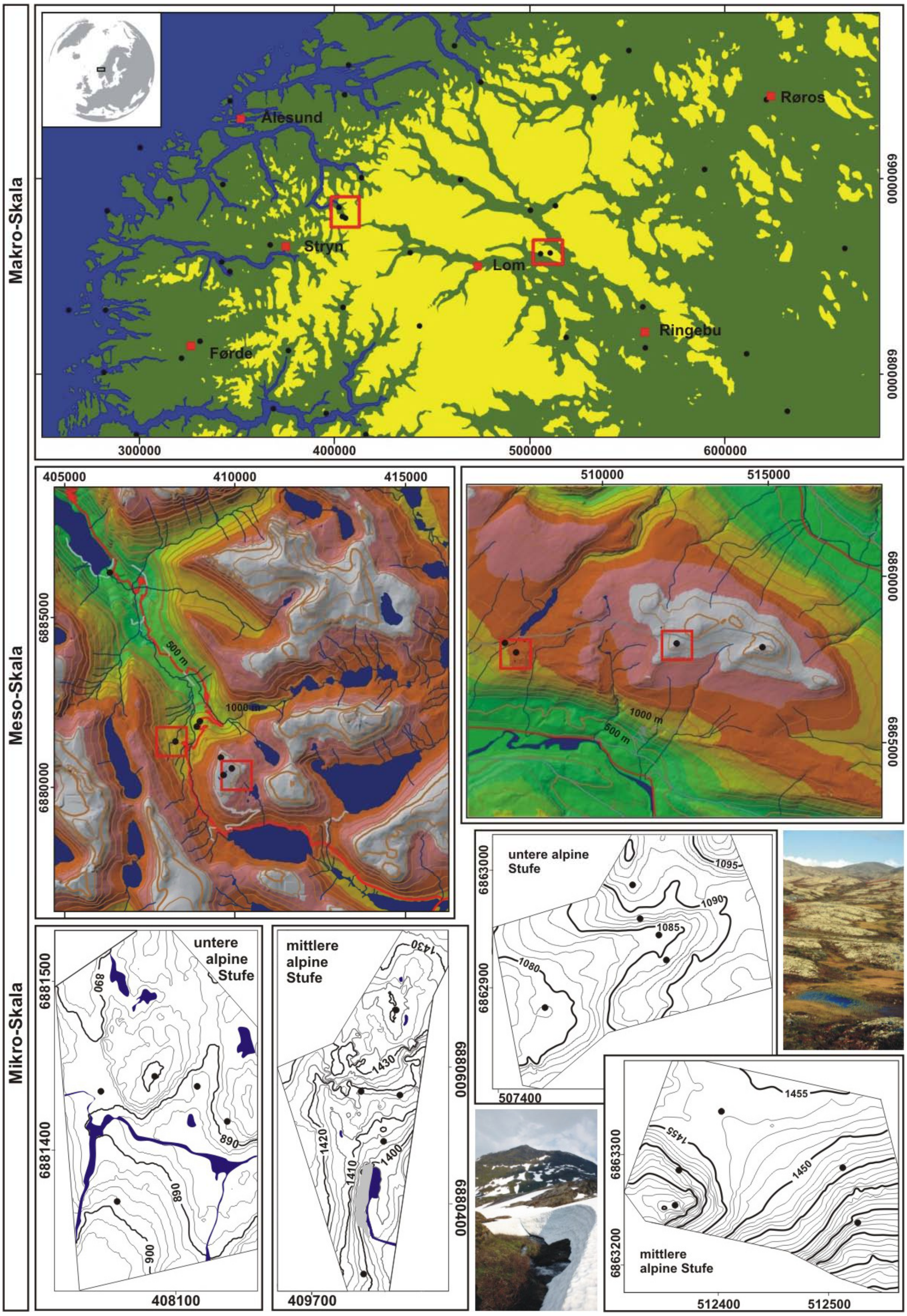

Abb. 1: Lage und Topographie der Untersuchungsgebiete in Mittelnorwegen. Die Gebiete oberhalb der Baumgrenze sind auf der Makroskala in gelb dargestellt; die roten Rechtecke zeigen die Lage der Untersuchungsgebiete der nächst feineren Skala an. Die Position von Messstationen und Dataloggern sind durch Punkte markiert. Die Fotos vermitteln einen Eindruck von der Landschaft in Ost- (oben) und Westnorwegen (unten).

2.2 Datengrundlage

Generell findet im Rahmen des Forschungsprojektes und dieser darin eingebetteten Arbeit ein für die Hochgebirgsökologie adaptiertes Skalenkonzept (Löffler 2002a), abgeleitet aus der Theorie der geographischen Dimensionen (Neef 1967, Leser 1997), Anwendung. Hierbei werden Landschaftskomplexe in hierarchischer Weise mit korrespondieren Skalenebenen (d.h. nano, mikro, meso, makro) verwendet, deren Übergang prinzipiell durch Emergenzsprünge charakterisiert ist (Löffler 2002b).

Im Rahmen der Arbeit wurde auf verschiedene Datengrundlagen zurückgegriffen, die an dieser Stelle vorzustellen sind. Der Schwerpunkt liegt auf den klimatischen Prozessdaten sowie auf Informationen zu klimatisch relevanten Strukturparametern wie z. B. Topographie und Vegetation. Zusätzlich wird ein kurzer Hinweis auf Daten gegeben, die im Rahmen des übergeordneten Forschungsprojektes von anderen Projektmitarbeitern erhoben und gemeinschaftlich hinsichtlich der ökologischen Bedeutung der bodennahen Temperaturen ausgewertet wurden.

Prozessdaten. Die Erfassung der Daten basiert auf der nanoskaligen, also punktuellen automatisierten Messung und Speicherung von Daten an meteorologischen Stationen sowie Dataloggern. Das Messdesign folgt dabei einem hierarchischen Aufbau. Auf der Nanoskala erfolgt die Erfassung von Boden-, Oberflächen- und Lufttemperaturen (-15, -1 und +15 cm Messhöhe) durch arbeitsgruppeneigene Datalogger mit pt100-Sensoren, oder durch meteorologische Stationen. Diese erfassen zusätzlich die Lufttemperatur in einem Meter Höhe über der Bodenoberfläche, die Globalstrahlung [Wm^{-2}], relative Luftfeuchtigkeit [%], Luftdruck [hPa], Flüssigniederschlag [mm], Windgeschwindigkeit [ms^{-1}] und Windrichtung [°], die Windparameter in zwei Metern über der Bodenoberfläche. Die Messung der Lufttemperatur erfolgt in allen Fällen strahlungsgeschützt und passiv ventiliert.

Ein mikroskaliges Untersuchungsgebiet wird durch fünf nanoskalige Messungen repräsentiert, die an den Hauptreliefstandorten (Kuppe, Südhang, Nordhang, Mulde, Sonderstandort wie Tiefenfläche oder Schneebett) lokalisiert sind und damit die größten zu erwartenden mikroklimatischen Unterschiede erfassen sollen. Ergänzt wird das Messnetz durch temporäre manuelle Messungen der Luft- und Bodentemperaturen an einer Vielzahl von nach Löffler (1998) repräsentativ ausgewählten Standorten bzw. entlang eines festgelegten Rasters zu Sonnenhöchststand, nach Sonnenuntergang und vor Sonnenaufgang zur Erfassung der räumlichen Variabilität.

Die mesoskaligen Untersuchungsgebiete werden durch zwei mikroskalige Gebiete entlang des Höhengradienten repräsentiert, erweitert durch eine nanoskalige Messung der Luft- und Bodentemperaturen im Bereich der Baumgrenze und der höchsten Erhebung. Für das Gebiet Geiranger stehen zusätzlich drei Messstationen des norwegischen geologischen Dienstes (NGU) entlang eines Höhengradienten (70, 700 und 1.460 m ü.d.M.) zur Verfügung, die zweistündliche Mittelwerte der Lufttemperatur in zwei Metern Höhe über der Bodenoberfläche liefern.

Das makroskalige Untersuchungsgebiet wird letztlich durch die beiden mesoskaligen Gebiete repräsentiert, deutlich erweitert durch 38 amtliche Stationen des norwegischen Wetterdienstes (DNMI) in flächenhafter Verteilung, die je nach Station Daten zu unterschiedlichen Prozessparametern und in unterschiedlicher zeitlicher Auflösung liefern (verfügbar unter http://www.eklima.no). Voraussetzung für ihre Berücksichtigung in dieser Arbeit war die Erfassung der Lufttemperatur, so gibt es eine deutlich höhere Anzahl an Messstationen, die allerdings nur Niederschlagsdaten bereitstellen.

Zusammenfassend standen Daten von insgesamt 45 meteorologischen Stationen und 20 Dataloggern für die weiteren Analysen im Rahmen dieser Arbeit zur Verfügung, ihre Position ist in Abb. 1 gezeigt.

Neben der standörtlichen Erfassung bieten Fernerkundungsdaten eine gute Möglichkeit, flächenhafte Daten bereitzustellen, wenn auch mit dem Problem behaftet, dass sie bei einer hohen räumlichen Auflösung i. d. R. eine geringe zeitliche Auflösung bzw. umgekehrt aufweisen. Im Rahmen der vorliegenden Arbeit wurden MODIS-Daten für die Abschätzung der Bewölkung genutzt (Produkt MOD06_L2, verfügbar über http://ladsweb.nascom.nasa.gov). Diese standen mindestens zweimal täglich, allerdings mit geringer räumlicher Auflösung von einem Kilometer, zur Verfügung. Für die flächenhafte Gewinnung von Oberflächentemperaturen konnten Landsat-ETM Daten in 60 m Auflösung vom 10.08.2004, 10:36 Uhr verwendet werden, indem die Informationen aus dem Band des thermischen Infrarots (TIR) in Temperaturen konvertiert wurden (vgl. z. B. Oppenheimer 1997). Für den 05.10.2007, 14:30 Uhr standen zusätzlich TIR-Daten von einer räumlich hochauflösenden Drachenbefliegung (vgl. Wundram & Löffler 2008) für das mikroskalige Gebiet in der unteren alpinen Höhenstufe Ostnorwegens zur Verfügung.

Zusätzlich wurde basierend auf digitalen Höhenmodellen (DHM, s. u.) die potentielle Globalstrahlung zum Zeitpunkt der TIR-Aufnahmen mit Hilfe der Software Solar Analyst (Fu & Rich 1999) berechnet.

Strukturparameter. Als klimatisch relevante Strukturparameter wurden insbesondere die Topographie und daraus abgeleitete Größen, die Vegetation sowie Substratverhältnisse betrachtet, da ihnen eine übergeordnete Bedeutung für den Energieumsatz und der daraus resultierenden Zustandsgröße Temperatur zukommt (z. B. Barry 1992, Oke 2001). Für die Untersuchungsgebiete standen DHM in unterschiedlicher räumlicher Auflösung zur Verfügung. Das makroskalige DHM basiert auf GTOPO30-Daten mit einer Auflösung von 30'', projiziert in UTM Zone 32 entspricht dies in Mittelnorwegen etwa einer Rastergröße von 500x500 m. Die mesoskaligen DHM wurden aus amtlichen topographischen Karten im Maßstab 1:50.000 mit einer räumlichen Auflösung von 30 bzw. 60 m generiert, entsprechend der Auflösung der Landsat-ETM Daten. Die submetrisch auflösenden mikroskaligen DHM basieren auf durchgeführten Oberflächennivellements bzw. sind im Fall des Gebietes in der unteren alpinen Stufe Ostnorwegens über photogrammetrische Verfahren aus hochaufgelösten Drachenluftbildern in Verbindung mit eingemessenen Referenzpunkten (vgl. Wundram & Löffler 2008) erzeugt worden.

Flächenhafte Daten über Vegetationstypen lagen im Rahmen des Forschungsprojektes für die mikroskaligen Gebiete basierend auf Kartierungen vor (für Ostnorwegen vgl. Löffler 1998) und wurden für die Mesoskala aus Fernerkundungsdaten durch unüberwachtes Clustering und anschließender wissensbasierter Nachklassifizierung abgeleitet (vgl. für die Methodik z. B. Johansen & Karlsen 2000, für Ostnorwegen Wundram 2003). Zusätzliche Aussagen über die Vegetation liefert der normalized difference vegetation index, kurz NDVI, abgeleitet aus Fernerkundungsdaten über das Verhältnis von Differenz zu Summe der Reflektion von nahem Infrarot und sichtbarem Rot.

Flächenhafte Informationen zu den Substratverhältnissen waren auf die beiden mikroskaligen Gebiete Ostnorwegens beschränkt (vgl. Löffler 1998, Löffler & Wundram 2003), Festgesteinsflächen und Blockfelder größerer Ausdehnung ließen sich jedoch mesoskalig aus Fernerkundungsdaten extrahieren.

Weitere Daten. Hinsichtlich der ökologischen Relevanz der oberflächennahen Temperaturen wurden im Forschungsprojekt überwiegend die mikroklimatischen Auswirkungen auf Vegetationsmuster untersucht (vgl. z. B. Löffler 2002a, 2003). Die Einbeziehung der Tierökologie seit 2001 und der Dendroökologie seit 2002 eröffnete neue Möglichkeiten einer integrativen ökosystemaren Auswertung der resultierenden Datensätze. So nimmt diese Arbeit Bezug auf die Auswertung von Fangdaten der Heuschreckenart *Melanoplus frigidus* und Jahrringbreitenzuwächsen der Zwergstrauchart *Empetrum hermaphroditum*.

2.3 Methodik

Nachfolgend werden die verwendeten Analyse-, Modellierungs- und Interpolationsmethoden in ihren Grundzügen vorgestellt, für eine detailliertere Darstellung wird an jeweiliger Stelle jedoch auf die Teilpublikationen verwiesen. Etwas breiteren Raum nimmt dagegen an dieser Stelle die Datenkontrolle und Datenbearbeitung ein, da sie die Voraussetzung für jede weitere Analyse der Daten bildet.

Datenkontrolle und Datenbearbeitung. Eine Voranalyse von Messdaten soll ihre Qualität und Aussagekraft für die nachfolgenden Analysen sicherstellen (Rapp & Schönwiese 1996). Technisch bedingte Messausfälle und –fehler können durch Stromausfälle bzw. geringe Stromspannung oder Überschreitung der Speicherkapazitäten entstehen. Ebenso können Messfehler durch direkte Sensorfehler, fehlerhafte Kalibrierung, fehlerhaftes Speichern auf dem Datalogger oder Fehler bei der Datenübertragung verursacht werden. Sensor- und witterungsbedingte Fehlmessungen können durch Einfrieren (Windsensor), Einschneien (Globalstrahlung) und starke Windböen (Niederschlag) hervorgerufen werden. Neben diesen eher technisch bedingten Ausnahmefehlern kommt es zu systematischen Fehlern, wie z. B. der Unterschätzung des Niederschlages durch Windeinfluss oder überschätzten Lufttemperaturen bei Strahlungswetterlagen aufgrund unzureichender Ventilation des Strahlungsschutzes. Diese Fehler galt es insbesondere für die Temperaturdaten zu identifizieren und soweit möglich durch eine Datenkorrektur zu beheben.

In Anlehnung an Rissanen et al. (2000) bestand die Datenkontrolle aus der manuellen Überprüfung a) des Wertebereichs, b) der zeitlichen Änderung der Werte und c) der zeitlichen Plausibilität für jede einzelne Datenreihe eines Standortes anhand ihrer graphischen Darstellung. Weiterhin erfolgte eine Überprüfung der horizontalen Plausibilität (Rissanen et al. 2000), d. h. ein Abgleich der einzelnen Standorte untereinander hinsichtlich Wertebereich und Synchronität.

Neben zahlreichen Fehlwerten durch unzureichende Batterieleistung, Wasserschäden bei Schneeschmelze, Sensordefekt durch Schneedruck oder Platinendefekt durch von Blitzschlag verursachte Überspannung konnten die folgenden Fehler im Datensatz identifiziert werden: 1) signifikante Abweichung der gemessenen Werte vom erwarteten Datenbereich durch Verlust der Kalibrierungsdaten des Temperaturdataloggers; 2) systematisch zu hohe oder niedrige Temperaturen bedingt durch ein Rücksetzen der spezifischen pt100-Widerstände in den Temperaturloggern aufgrund von Softwareinkompatibilität beim Auslesen der Daten; 3) „versteckte“ Datenausfälle bei fortlaufender Systemzeit, bedingt durch

Spannungsschwankungen; 4) in ihrer zeitlichen Abfolge duplizierte Datenreihen durch Speicherfehler, sowie 5) zeitliche Abweichungen durch falsche Systemzeiten.

Fehler nach 1) ließen sich nicht korrigieren, da sie zumeist auch mit zufälligen Schwankungen der Werte verbunden waren. Systematisch abweichende Datenreihen nach 2) konnten über einen Abgleich mit zeitgleichen Handmessungen grob korrigiert werden, die Feinkorrektur erfolgte über den Temperaturverlauf während der Schneeschmelze: Unter Schnee weisen die Temperaturkurven bedingt durch dessen Isolationsvermögen nur einen sehr abgeschwächten Tagesgang unterhalb 0°C auf, der nach Schneeschmelze entsprechend der atmosphärischen Situation wieder voll ausgeprägt ist. Während der Schneeschmelze liegt die Temperatur demnach kurzzeitig bei 0°C und kann somit für eine Korrektur der Datenreihe herangezogen werden. Die weiteren Fehler nach 3) bis 5) konnten durch standörtliche Vergleiche hinsichtlich der zeitlichen Synchronität der Temperaturschwankungen behoben werden.

Fehlende Daten der oberflächennahen Temperaturen wurden wiederum in Anlehnung an Rissanen et al. (2000) durch einen Modellierungsansatz (Publikation II) aufgefüllt, solange die Rahmenbedingungen für dessen Anwendung (schnee- und frostfreie Perioden, Messdaten der meteorologischen Station im Gebiet verfügbar) gegeben waren.

Analysemethoden. Für die Charakterisierung der mikroklimatischen Differenzierung von Hochgebirgslandschaften wurden Temperaturdaten entlang unterschiedlicher Gradienten hinsichtlich der sich ergebenden Unterschiede analysiert. Verglichen wurden a) nanoskalig die Temperaturen der unterschiedlichen Messhöhen, b) mikroskalig die Temperaturen einer Messhöhe an den verschiedenen Reliefpositionen, c) mesoskalig die Temperaturen der jeweiligen Messhöhen an gleichen Reliefpositionen entlang des Höhengradienten, sowie d) makroskalig die Temperaturen der jeweiligen Messhöhe an gleichen Reliefpositionen in der gleichen Höhenstufe entlang des Ozeanitäts-Kontinentalitätsgradienten. Der Vergleich erfolgte dabei auf Basis stündlicher Mittelwerte. Für Publikation III beschränkte sich der analysierte Zeitraum auf eine 14 tägige sommerliche Periode und umfasste die Vergleiche a) bis c), die Ergebnisse wurden als Korrelationsmatrizen unter Angabe der mittleren Abweichung als root-mean-squared-error (RMSE) dargestellt. Der Vergleichszeitraum wurde für Publikation IV auf ein komplettes Jahr und der Temperaturvergleich auf die Makroskala erweitert, nanoskalige Unterschiede wurden nicht analysiert. Die Darstellung der Temperaturunterschiede zwischen den Standorten erfolgte in Form von Isoplethendiagrammen zur Verdeutlichung der tages- und jahreszeitlichen Differenzierung, komplettiert durch zusammenfassende Histogramme.

Die Analysen hinsichtlich der ökologischen Relevanz der oberflächennahen Temperaturen folgten entsprechend der jeweiligen Fragestellung einem spezielleren Muster. Für die Habitatbeschreibung und Modellierung des Entwicklungszyklus von *M. frigidus* (Publikation VII) wurde über vier Jahre die Oberflächentemperatur am Südhang des unteralpinen mikroskaligen Gebietes in Ostnorwegen in Hinblick auf Wärmesummen analysiert und zu den Entwicklungsstadien der Heuschrecke in Beziehung gesetzt. Zur Abschätzung des Einflusses mikroklimatischer Bedingungen auf das Jahrringbreitenwachstum der Zwergstrauchart *E. hermaphroditum* wurden für einen Zeitraum von sechs Jahren Temperaturdaten von Kuppe, Nord- und Südhang des mittelalpinen mikroskaligen Gebietes in Ostnorwegen sowie der nächstliegenden DNMI-Station zu Mittelwerten unterschiedlicher Zeitperioden aggregiert sowie jährliche Aper- und Vegetationszeiten abgeleitet. Klima-Wachstumsbeziehungen wurden dann über Korrelationsanalysen und Regressionsbäume untersucht (Publikation VIII).

Modellierungsmethoden. Für Modellierungsansätze gibt es grundsätzlich zwei unterschiedliche Verfahren, die Verwendung finden können (vgl. z. B. Leser 1997): Die physikalisch basierte analytische Modellierung und die stochastische Modellierung. Im ersten Fall sind die Eingangsgrößen und Zustandsgleichungen über physikalische Zusammenhänge bekannt, es können also funktionsanalytische mathematische Methoden angewendet werden. Im zweiten Fall sind die Eingangsgrößen bekannt, die Funktionszusammenhänge werden aber nicht physikalisch basiert aufgelöst, sondern über statistische Zusammenhänge.

Im Rahmen der vorliegenden Arbeit wurden beide Verfahren angewendet und gegeneinander getestet (Publikation VI). Der physikalisch basierte Ansatz beruht dabei auf der Energiebilanz an der Erdoberfläche. Wird die Oberfläche im physikalischen Sinn als Grenzfläche verstanden, ohne Möglichkeit der Energiespeicherung (vgl. z. B. Oke 2001), wird die Energie aus der verfügbaren Nettostrahlung (Q^*) auf den Bodenwärmestrom (G_0) und den latenten (LE) sowie sensiblen (H) Wärmestrom aufgeteilt:

$$Q^* = G_0 + LE + H \text{ bzw.} \qquad (1)$$

$$Q^* - G_0 - LE - H = 0$$

Da diese Wärmeströme neben einer Vielzahl weiterer Faktoren (vgl. Oke 2001) direkt von der Oberflächentemperatur abhängig und über physikalische Beziehungen quantifizierbar sind, kann die Oberflächentemperatur bei ansonsten bekannten Randbedingungen zwar nicht analytisch, aber über iterative Verfahren bestimmt werden (Publikation II, VI).

Verglichen zu herkömmlichen „land surface schemes“ (z. B. Saunders et al. 1999a, 1999b, Cayrol et al. 2000) wurde bei der Umsetzung besonderes Gewicht auf einen stark vereinfachten Ansatz gelegt, der nur eine möglichst geringe Zahl an bekannten Randbedingungen benötigt („the simple, the best“ – Mostovoy et al. 2006), um eine flächenhafte Anwendung zu ermöglichen (Boulet et al. 2000). So wurde beispielsweise auf die Einbeziehung pflanzenphysiologischer Merkmale zur Abschätzung von Oberflächenwiderständen verzichtet, sowie Lufttemperaturen und Windgeschwindigkeiten mikroskalig als räumlich homogen betrachtet. Für die erfolgreiche Umsetzung des standörtlichen Modells aus Publikation II in eine mikro- und mesoskalige flächenhafte Anwendung (Publikation VI) waren jedoch noch weitergehende Parametrisierungen sowie die Einbeziehung eines räumlich differenzierten Windfeldes erforderlich, die dort näher beschrieben sind. Die Modellvalidierung erfolgte standörtlich gegen unabhängige Messdaten und flächenhaft für zwei Zeitpunkte gegen aus Fernerkundungsdaten abgeleiteten Oberflächentemperaturen.

Für die statistische Modellierung (Publikation VI) wurde ein Mittelweg zwischen reiner Statistik und physikalisch-basierter Modellierung gewählt (Jarvis & Stuart 2001): Potenzielle Eingangsparameter wurden hinsichtlich ihrer Relevanz für die oberflächennahen Temperaturen ausgewählt, wie z. B. die potentielle Globalstrahlung oder die Wolkenbedeckung. Als eigentliches statistisches Verfahren wurde die multiple Regression mit schrittweiser Variablenselektion gewählt, da diese sich in anderen Studien bereits als besonders geeignet erwiesen hat (Bolstad et al. 1998, Florio et al. 2004).

Interpolationsmethoden. Die geostatistische Interpolation von Klimaelementen ist ein Standard in der Klimatologie (vgl. z. B. Hijmans et al. 2005), wenngleich bei sehr geringer Stationsdichte nicht unstrittig (Barry 1992). Das Verfahren wurde in Form von Cokriging der Lufttemperaturen auf der Makroskala in Publikation VI angewendet, um flächenhafte Daten über die Lufttemperatur als Input für die Modellierungsansätze zu gewinnen. Temperaturrelevante Umweltvariablen wurden dazu zunächst statistisch basiert ausgewählt und flossen dann als Covariablen in die Interpolation ein (Publikation VI). Die Validierung erfolgte gegen unabhängige Messdaten. Eine Übertragung auf die Meso- und Mikroskala als Input für die o. g. Modellierung erfolgte dann über die dort höher aufgelöste Topographie in Verbindung mit aus den Messwerten abgeleiteten Höhengradienten der Temperatur.

3 FORSCHUNGSZUSAMMENHANG DER PUBLIKATIONEN

Im Folgenden soll der Zusammenhang der Teilpublikationen, die diese Arbeit ausmachen, verdeutlicht werden.

Der engere Rahmen für die vorliegende Arbeit wird in Publikation I aufgespannt, in der das übergeordnete ökologische Forschungsprojekt in Mittelnorwegen hinsichtlich der methodologischen und methodischen Herangehensweisen skizziert und Zielsetzungen vorgenommen werden. So wird hier u. a. eine Quantifizierung der Steuergrößen im ökologischen Prozess-Wirkungs-Gefüge ebenso angestrebt wie die Untersuchung von Abhängigkeiten zwischen Abiotik und Biotik, eine vergleichende Betrachtung der Ökosysteme und ihrer Kompartimente entlang übergeordneter Gradienten, sowie regionalisierende Aussagen über ökologische Prozesssysteme inklusive ihrer Modellierung.

Insbesondere der Modellierungsansatz wird am Beispiel der oberflächennahen Temperaturen – als Repräsentanten der ökosystemaren Steuergröße Energiehaushalt – methodisch in Publikation II aufgegriffen. Ein neu entwickeltes standörtliches, physikalisch basiertes Energiebilanzmodell wird in seiner Anwendung vorgestellt. Gleichzeitig wird inhaltlich auch eine vergleichende Betrachtung von Energie- und Wasserhaushaltskomponenten an vier Kuppenstationen entlang des Höhen- und Ozeanitäts-Kontinentalitätsgradienten vorgenommen.

Die vergleichende Betrachtung der Temperaturverhältnisse entlang verschiedener Gradienten zur Charakterisierung der mikroklimatischen Komplexität einerseits, sowie zur Überprüfung der Anwendbarkeit genereller Regionalisierungsmethoden der Klimatologie im Hochgebirge andererseits bildet auch den inhaltlichen Schwerpunkt der Publikationen III und IV.

Die in allen Publikationen mitschwingende Problematik der Verfügbarkeit von Klimadaten im Hochgebirge wird in Publikation V explizit in Form eines Literaturreviews thematisiert, das verschiedene methodische Lösungsansätze vorstellt und hinsichtlich ihrer Anwendbarkeit im Hochgebirge kritisch hinterfragt.

Dieser Gedanke wird in Publikation VI konsequent weitergeführt, indem die Leistungsfähigkeit von Modellierungs- und Interpolationsmethoden für flächenhafte Aussagen über oberflächennahe Temperaturen in für ökologische Anwendungen brauchbarer raum-zeitlicher

Auflösung evaluiert wird. Dafür wird der physikalisch basierte Modellansatz aus Publikation II wieder aufgegriffen und für eine räumliche Anwendbarkeit erweitert.

Die ökosystemare Bedeutung der komplexen Temperaturmuster, die sich aus den Publikationen III und IV ergeben, wird inhaltlich beispielhaft in den Publikationen VII und VIII evaluiert. Die Oberflächentemperaturen eines Standortes werden so in Publikation VII zur Habitatbeschreibung und Modellierung der Entwicklungsphasen der alpinen Heuschrecke *Melanoplus frigidus* herangezogen. Die Signifikanz oberflächennaher Temperaturen gegenüber dem regionalklimatischen Signal für Klima-Wachstumsbeziehungen bei der Zwergstrauchart *Empetrum hermaphroditum* wird dagegen in Publikation VIII thematisiert.

Zusammenfassend werden die inhaltlichen und methodischen Zielsetzungen aus Publikation I in den Folgepublikationen (II-VIII) konsequent aufgegriffen und umgesetzt. Dabei erfolgte eine Weiterentwicklung sowohl auf der inhaltlichen Ebene bis hin zu einer ganzjährigen Charakterisierung der oberflächennahen Temperaturverhältnisse entlang multiskaliger Gradienten in Publikation IV und der Evaluation ihrer ökosystemaren Bedeutung in den Publikationen VII und VIII, als auch auf methodischer Ebene. So wurden die sich aus den komplexen Temperaturverhältnissen ergebenden methodischen Konsequenzen hinsichtlich der Bereitstellung von geeigneten Daten in Publikation V erörtert. Das standörtliche Energiebilanzmodell aus Publikation II wurde für eine räumliche Anwendung erheblich modifiziert und zusammen mit weiteren methodischen Ansätzen in Bezug auf die Leistungsfähigkeit für die flächenhafte Bereitstellung von Temperaturdaten in Publikation VI evaluiert. Eine explizite Verknüpfung methodische – inhaltliche Ebene liefert Publikation VIII, da hier das standörtliche Modell für das Ersetzen von Fehlwerten in den Datenreihen eingesetzt wurde.

4 ZENTRALE AUSSAGEN DER PUBLIKATIONEN I - VIII

Die zentralen Aussagen der Publikationen werden getrennt nach den drei Aspekten Analyse, Modellierungsansätze und ökologische Bedeutung von oberflächennahen Temperaturen im Hochgebirge im Folgenden zusammengefasst.

Analyse. Die oberflächennahen Temperaturverhältnisse im mittelnorwegischen Hochgebirge wurden entlang übergeordneter Gradienten auf unterschiedlichen räumlichen Skalen analysiert (Publikationen II-IV).

Die gefundenen Ergebnisse widersprechen weit verbreiteten Arbeitshypothesen in der Hochgebirgsklimatologie und –ökologie, die besagen, dass übergeordnete klimatologische Phänomene, wie der Ozeanitäts-Kontinentalitätsgradient, die mikroklimatischen Verhältnisse maßgeblich steuern (z. B. Jäger 1968, Wallén 1970, Moen 1999). Auf dieser Annahme fußen beispielsweise generelle Ansätze zur Datenextrapolation und Modellierung (Beniston 2003, Dirnböck et al. 2003). Ebenso wird für diese Zwecke häufig auch von einer regionalen und zeitlichen Homogenität des höhenwärtigen Temperaturgradienten ausgegangen (Dirnböck et al. 2003). Die Ergebnisse belegen jedoch die übergeordnete Bedeutung der mikroskaligen Temperaturdifferenzierung, durch die übergeordnete klimatologische Gesetzmäßigkeiten in ihrer Ausprägung relativiert oder sogar egalisiert werden. Es konnte ebenfalls gezeigt werden, dass der höhenwärtige Temperaturgradient extremen zeitlichen und regionalen Schwankungen unterliegt (Publikationen III und IV). Darüber hinaus führten die Ergebnisse zu der generellen Feststellung, dass meteorologische Standardmessungen in einer Höhe von zwei Metern über der Bodenoberfläche ungeeignet sind, die mikroklimatische Differenzierung der oberflächennahen Bereiche im Hochgebirge zu erfassen (Publikation III).

Vor dem Hintergrund dieser aus einem umfangreichen Messprogramm resultierenden neuen Erkenntnisse werden die bisherigen Ansätze der Datenextrapolation und die darauf basierende Modellierung von ökosystemaren Auswirkungen des Klimawandels im Hochgebirge (vgl. z. B. Barry 1994; Sætersdal & Birks 1997; Gottfried et al. 1999; Guisan & Theurillant 2000; Dirnböck et al. 2003; Fagre et al. 2003) kritisch hinterfragt. Als Konsequenz wird die Notwendigkeit einer räumlich und zeitlich hochauflösenden Betrachtung von ökosystemaren Prozessen im Hochgebirge postuliert (Publikationen III und IV).

Modellierungsansätze. Basierend auf den Erkenntnissen aus der Analyse der oberflächennahen Temperaturen wird in Publikation IV geschlussfolgert, dass eine Modellierung der Temperaturverhältnisse auf Daten aus unterschiedlichen raum-zeitlichen Skalen basieren muss, aber gleichzeitig für eine räumliche Anwendung auch einfach genug gehalten sein muss und dabei auf Publikation II verwiesen. Das Thema Klimadaten und Klimamodellierung im Hochgebirge wird in den Publikation II, V und VI thematisiert. So wird in Publikation V die Lücke zwischen Anspruch und Wirklichkeit von Klimadaten für Bereiche oberhalb der alpinen Baumgrenze durch ein Review der Literatur verdeutlicht. Für die Charakterisierung der Ökosysteme und die Modellierung ökosystemarer Auswirkungen des Klimawandels werden Temperaturdaten in adäquater raum-zeitlicher Auflösung benötigt. Aufgrund der geringen Stationsdichte liegen diese als reale Messwerte allerdings kaum vor, und wenn, nur als wenig aussagekräftige (vgl. Publikation III) Lufttemperaturen in zwei Metern Höhe über der Bodenoberfläche. Herkömmliche Interpolationsverfahren in der Klimatologie (z. B. Hutchinson 1995, Martinez-Cob 1996) ermöglichen ein Abbild der klimatischen kleinräumigen Bedingungen nur bei einer sehr hohen Stationsdichte. Die Einbeziehung weiterer erklärender Parameter (z. B. Höhe, Topographie) in die Interpolation ermöglicht jedoch eine signifikante Verbesserung der Ergebnisse (z. B. Thomas & Herzfeld 2004), so dass Lufttemperaturfelder zumindest basierend auf Mittelwerten generiert werden können. Herkömmliche Modellierungsansätze sind ebenfalls nicht in der Lage, die kleinräumige Variabilität wiederzugeben, da sie entweder über eine zu geringe räumliche Auflösung verfügen (Beniston et al. 1997, Rivington et al. 2008), oder bei primär standörtlicher Anwendbarkeit ein zu großes Maß an Eingangsdaten erfordern (Boulet et al. 2000).

Ein neuer physikalisch basierter Modellansatz wird dementsprechend in Publikation II vorgestellt, der basierend auf Lufttemperaturen, Luftfeuchtigkeit und Windverhältnissen in zwei Metern über der Bodenoberfläche in Verbindung mit Angaben über die Strukturgrößen Relief, Boden und Vegetation die standörtliche Modellierung der oberflächennahen Temperaturen in -15, -1 und +15 cm Abstand zur Bodenoberfläche mit großer Genauigkeit ($r \geq 0.9$, mittlerer Fehler ≤ 1 K) ermöglicht. Hervorzuheben ist dabei die geringe Erfordernis umfangreicher und schwierig zu erhebender Eingangsparameter, die diesen Ansatz von bisherigen Modellen unterscheidet und erst eine erfolgreiche Anwendung in Hochgebirgsräumen ermöglicht.

Eine flächenhafte Anwendung und Evaluation von geostatistischen Interpolationsmethoden sowie physikalisch und statistisch basierter Modellansätze auf der Mikro-, Meso- und Makroskala liefert Publikation VI. Es konnte gezeigt werden, dass Interpolationsmethoden unter Einbeziehung geeigneter topographischer und atmosphärischer Covariablen auf der Makroskala auch bei höherer zeitlicher Auflösung (Tagesmaxima und –minima) gute Ergebnisse liefern ($r \geq 0.875$). Dabei zeigte sich insbesondere das Potenzial von Fernerkundungsdaten (hier: MODIS) bei der Ableitung der atmosphärischen Randbedingungen als Covariablen bei der Interpolation, während bislang die aus Fernerkundungsdaten abgeleiteten Oberflächentemperaturen direkt genutzt wurden (Mostovoy et al. 2006), was die Anwendung allerdings auf wolkenfreie Bedingungen beschränkt hat.

Im direkten Modellvergleich zwischen physikalisch und statistisch basierter Modellierung (Publikation VI) zeigt sich die standörtliche Stärke des physikalischen Ansatzes ($r = 0.94$), der auf Publikation II basiert, aber für die räumliche Anwendung stark modifiziert wurde. Dessen Genauigkeit lässt allerdings bereits bei mikroskaliger Anwendung stark nach ($r = 0.74$; Mesoskala $r = 0.55$) und zeigt dadurch die Limitierungen dieses Ansatzes. Diese Einschränkungen der Vorhersagegenauigkeit konnten auf die für eine räumliche Anwendung erforderliche Parametrisierung der für den Energieumsatz an der Erdoberfläche wichtigen Prozesse zurückgeführt werden. Hochgebirgsspezifische Ansätze für die Parametrisierung liegen allerdings bislang nicht vor, die Übertragbarkeit herkömmlicher Ansätze wird durch dieses Ergebnis jedoch stark in Frage gestellt. Der statistische Ansatz, basierend auf multipler linearer Regression, zeigt im Vergleich zur physikalisch basierten Modellierung eine mittlere Güte der prognostizierten Werte auf der betrachteten Mikro- und Mesoskala ($r = 0.71$ bzw. $r = 0.83$). Trotz der gezeigten deutlichen Schwächen bei der räumlichen Übertragbarkeit stellt die statistische Modellierung demnach ein probates Mittel für die flächenhafte Abschätzung von Oberflächentemperaturen dar (Publikation VI).

Darüber hinaus zeigt sich die Notwendigkeit einer angemessenen Berücksichtigung der unterschiedlichen räumlichen Skalen bei Interpolations- oder Modellierungsansätzen, so dass die Entwicklung sog. skalenfreier Klimadaten, die durch die bloße Erhöhung der topographischen Auflösung erzielt wird (vgl. z. B. Wang et al. 2006) als kritisch zu beurteilen ist. Da es allerdings zumeist an Temperatur- und Klimadaten von den für ökosystemare Modellierungen wichtigen Skalenebenen mangelt, bleibt die Temperaturmodellierung im Hochgebirge schwierig (Publikation VI).

Ökologische Bedeutung. Die oberflächennahen Temperaturen wurden hinsichtlich ihrer ökologischen Bedeutung in zwei Fallbeispielen untersucht.

Die polyphage Heuschrecke *M. frigidus* tritt oberhalb der alpinen Baumgrenze ausschließlich isoliert an thermisch begünstigten unteralpinen Südhanglagen auf (Publikation VII). Gegen eine Futterpräferenz für bestimmte dort vorkommende Pflanzenarten spricht, dass diese eine räumlich weitere Verbreitung aufweisen, so dass neben der Bodenfeuchte vor allem das mikroskalige Temperaturmuster als wichtigste Umweltvariable für die Bestimmung der Habitateignung anzusehen ist. Über die kontinuierliche Messung der Oberflächentemperatur, die an einem Standort im Habitat der Heuschrecke über vier Jahre erfolgte, konnten die effektiven thermischen Bedingungen des alpinen Habitats erstmals charakterisiert werden. Weiterhin erfolgte basierend auf den Temperaturdaten eine Modellierung der Entwicklungszeit vom Ei bis zum adulten Tier. Entsprechend des Witterungsverlaufs nach der Schneeschmelze konnte eine große interannuelle Variabilität der Entwicklungszeit von bis zu drei Wochen nachgewiesen werden. Bedingt durch die thermische Sensitivität wird das Potential von *M. frigidus* als Indikatorart im Rahmen des Klimawandels hervorgehoben, die schnellere Reaktionen auf Änderungen erwarten lässt als die Vegetation (Publikation VII).

Der mikroklimatische Einfluss auf das Jahrringbreitenwachstum der Zwergstrauchart *E. hermaphroditum* wird in Publikation VIII evaluiert. Dabei konnte generell die Temperatur als limitierender Faktor für das Wachstum herausgestellt werden – die mittleren Sommertemperaturen bestimmen die Breite der Jahrringe, die Zeit der Schneeschmelze bzw. die Länge der Vegetationsperiode dagegen ist unbedeutend. Für die Gefäßbildung ist das Wasserdargebot insbesondere in der späteren Wachstumsperiode von Bedeutung. Verglichen mit dem regionalklimatischen Signal ist der Einfluss der mikroklimatischen Differenzierung allerdings gering. So konnte an den unterschiedlichen Standorten eine Differenzierung der mittleren Wachstumsraten nachgewiesen werden, die auf die größere Häufigkeit wärmerer Temperaturen am südexponierten Hang zurückzuführen ist. Somit ändern die mikroklimatischen Verhältnisse zwar die absoluten Zuwachsraten, das übergeordnete regionalklimatische Signal wird dabei aber nicht modifiziert. Dies steht in scheinbarem Widerspruch insbesondere zu den Publikationen III und IV, ist aber auf zwei Umstände zurückzuführen: Die Länge der Aperzeit und damit auch der Vegetationsperiode als ein wichtiges Merkmal der mikroklimatischen Differenzierung spielt, wie gezeigt werden konnte, für das Jahrringbreitenwachstum keine Rolle. Die starke Korrelation des Zuwachses mit der mittleren Sommertemperatur belegt, dass die Jahrringbreite eher als Integral der sommerlichen Bedingungen anzusehen ist. – Über längere Zeitintervalle integriert tritt allerdings auch die mikroklimatische Differenzierung zurück, so dass über die Vegetationsperiode gemittelt die mikroklimatischen Unterschiede in der Größenordnung von 0.5 K liegen.

Mit diesen Analysen konnte das Potenzial von *E. hermaphroditum* für Klimarekonstruktionen basierend auf dendroökologischen Untersuchungen in Bereichen oberhalb der alpinen Baumgrenze belegt werden.

5 PUBLIKATIONEN I - VIII

5.1 Publikation I

Löffler, J., Finch, O.-D., Naujok, J. & R. Pape (2001)

Möglichkeiten der Integration zoologischer Aspekte in landschaftsökologische Untersuchungen von Hochgebirgen – Methodendiskussion am Beispiel ökologischer Prozesssysteme und Biozönosen.

Erschienen in:

Naturschutz und Landschaftsplanung 33: 351-357.

Möglichkeiten der Integration zoologischer Aspekte in landschaftsökologische Untersuchungen von Hochgebirgen

Methodendiskussion am Beispiel ökologischer Prozesssysteme und Biozönosen

Von Jörg Löffler, Oliver-D. Finch, Jürgen Naujok und Roland Pape

Zusammenfassung

Die zeitliche Dynamik des klimatisch gesteuerten Temperaturhaushalts von Hochgebirgslandschaften wird mit Hilfe eines umfangreichen Messprogramms in exemplarischen Einzugsgebieten untersucht und räumlich abgebildet. Eine damit verbundene ganzjährige Erfassung ökologisch relevanter Prozesse wie Schneeverteilung, Schneeschmelze, Frostwechsel, Bodenerwärmung, Bodenfeuchteänderung etc. soll zur Kenntnis übergeordneter Funktionen in den untersuchten Ökosystemen beitragen. Die Organisation und Mobilität von Tierlebensgemeinschaften in diesen Räumen wird am Beispiel epigäisch lebender Arthropoden (Spinnen, Lauf- und Kurzflügelkäfer) auf ihre komplexen dynamischen und flächenhaften Zusammenhänge analysiert. Die so punktuell modellierbaren ökosystemaren Wirkungsgefüge werden in ihrer räumlichen Vernetzung untereinander in einem GIS aggregiert. Die Koppelung von zeitdynamisch-funktionalen Datensätzen mit raumstrukturellen Informationen ermöglicht eine Darstellung der komplexen landschaftsökologischen Verhältnisse und eine Prognose der Entwicklung von Lebensgemeinschaften unter veränderten Umweltbedingungen. Das Projekt zielt auf eine vergleichende Betrachtung von Ökosystemen der alpinen Höhenstufen des ozeanisch sowie kontinental geprägten Hochgebirges Mittelnorwegens ab und strebt regionalisierende Aussagen über ökologische Prozesssysteme und Lebensgemeinschaften an. Hiermit soll ein Beitrag zur Integration zoologischer Aspekte in die Landschaftsökologie geleistet werden.

Summary

Ecological Process Systems and Biocoenoses in the Norwegian High Mountains - A Contribution to the Integration of Zoological Aspects into Landscape Ecology

The temporal dynamics of the energy balance within high mountain landscapes are investigated by means of complex measurements and transmitted to small catchment areas for spatial analysis. Throughout the year ecological processes like the distribution of snow during winter, snow melting, freeze-thaw-action, soil temperature dynamics, changes in soil moisture etc. are analysed as to the ecosystem functioning. The organisation and mobility of zoo-coenoses in these areas is investigated with regard to the spatial and dynamical correlations as an example of epigeic arthropods (Araneae, Carabidae, and Staphylinidae). In this way, modelling of ecosystem interactions at the spot is possible and quantified local results are entered into a GIS for spatial analysis. The combination of temporal data about ecosystem functioning and spatial information about ecosystem structures leads to a comprehensive landscape-ecological characterisation and prognosis of the development of biocoenoses under environmental changes. The project aims at evaluating the differences among ecosystems along the oceanic-continental gradient from Western to Eastern Norway. It also seeks to regionalise the results on ecological process systems and biocoenoses so that they can be transferred to a larger area of the Central Norwegian mountains. Thus the methodological approach addresses the integration of zoological aspects into landscape ecology.

1 Einleitung

Die oberhalb der Baumgrenze gelegenen skandinavischen Gebirgslandschaften (Fjells) weisen im Vergleich zu den meisten Lebensräumen in der mitteleuropäischen Kulturlandschaft einen relativ naturnahen Zustand auf. Bei ökosystemarer Betrachtungsweise fällt besonders ihre Differenziertheit sowie kleinräumige Komplexität auf (vgl. z.B. MOEN 1999). Sie unterliegen im Wesentlichen nur einer extensiven Beweidungsnutzung. Bei genauerer Betrachtung zeigen sich selbstverständlich auch in diesen Fjellgebieten Auswirkungen anthropogener Einflüsse, die zumindest in Teilen Nord-Norwegens bereits eine durch Nutzungsintensivierung (Überweidung mit Rentieren) ausgelöste Landschaftsdegradation erkennen lassen (LÖFFLER 2000). Gerade aufgrund ihrer extremen Labilität gegenüber jeglichen Umweltveränderungen (z.B. wachsendem Nutzungsdruck) sind Hochgebirgslandschaften auch weltweit zunehmend Gegenstand der aktuellen Diskussion um eine nachhaltige Entwicklung (vgl. BERNES 1993, KALTENBORN 1999, MESSERLI & IVES 1997). Traditionell konzentrieren sich die Forschungen in Mitteleuropa allerdings auf die Alpen, so dass in den skandinavischen Hochgebirgen aufgrund weniger und zumeist regional eng begrenzter Untersuchungen ein Forschungsdefizit vorliegt.

Die wenigen, zum Teil sehr detaillierten Untersuchungen dieser Hochgebirgsökosysteme zeigen eine starke Schwerpunktbildung im biotischen (z.B. BAADSVIK 1974, DAHL 1956 und 1998, FREMSTAD 1997, OTTESEN 1996) oder im bodenkundlich-analytischen Bereich (z. B. ELLIS 1979, 1983, 1985), wobei jeweils integrative Ansätze mehr oder weniger stark vernachlässigt werden. Untersuchungen von Teilen des multifaktoriellen Wirkungsgefüges der Standortfaktoren sind bisher nur vereinzelt z.B. im Rahmen des International Biological Programs (IBP) erfolgt (vgl. BLISS et al. 1981, WIELGOLASKY 1975). Methodisch wie auch methodologisch wegweisend ist aus geoökologischer Sicht die Arbeit MOSIMANNS (1985) zur Funktion subarktischer und alpiner Geoökosysteme in der Finnmark (Norwegen) und in den Schweizer Alpen, mit der die Möglichkeiten topologischer Untersuchungen von Ökosystemen an quantifizierbaren Teilsystemen aufgezeigt und problematisiert werden. Seit 1985 haben sich die technischen Möglichkeiten wesentlich verbessert, so dass Probleme der Umsetzung der Konzeption heute weniger ins Gewicht fallen. Für die topologische Dimension (Mikroskala) liegen mit dieser Konzeption der „landschaftsökologischen Komplexanalyse“ umfangreiche Erfahrungen vor, die die Möglichkeiten einer hoch integrativen Ökosystemforschung mit flächenhafter Aussage und zeitdynamischer Betrachtung belegen (vgl. u.a. LESER et al. 1990, POTSCHIN 1998).

Landschaftsökologische Untersuchungen, welche die Komplexanalyse nach MOSIMANN (1985) zur Grundlage haben, werden von Mitgliedern der Arbeitsgruppe Geoökologie an der Universität Oldenburg in einem langfristig angelegtem Forschungsvorhaben seit 1991 im mittelnorwegischen Hochgebirge durchgeführt. Im Mittelpunkt stehen Untersuchungen zur Landschaftsstruktur und zu Ökosystemfunktionen. Es wurde eine kleinräumige Geoökovarianz festgestellt, die es unmöglich macht, aus Mitteleuropa bekannte Gesetzmäßigkeiten zur Korrelation von Parametern wie Vegetation, Humus, Säuregrad und Boden auf diese Gebiete zu übertragen. Beschrieben werden konnten bisher

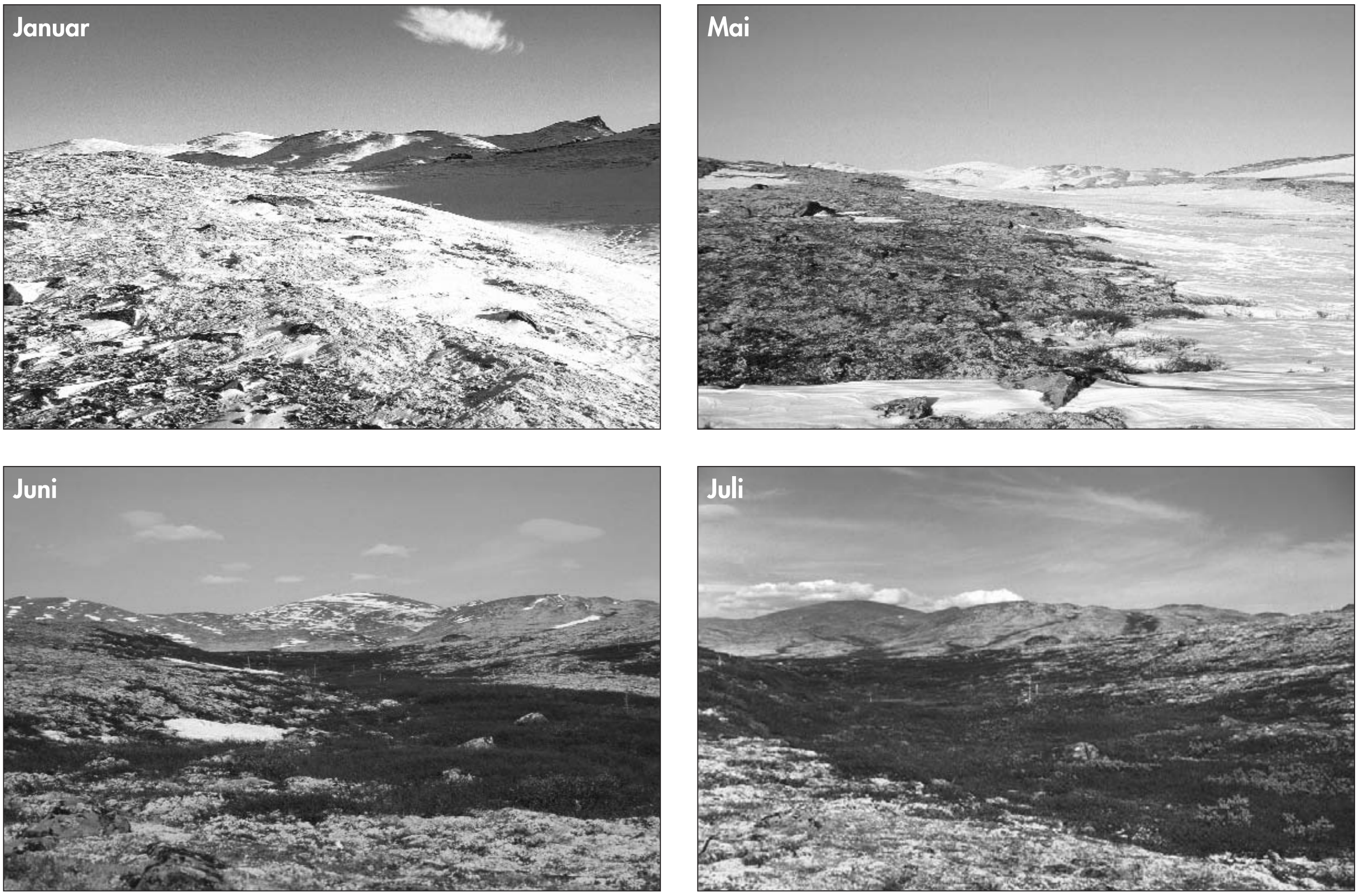

Abb. 1 a-d: Zeitliche Sequenz verschiedener Prozesszustände im Jahresgang einer Hochgebirgslandschaft am Beispiel des Untersuchungsgebiets in der unteren alpinen Höhenstufe des kontinentalen Untersuchungsraums. Die kleinräumigen Reliefverhältnisse bedingen eine sehr markante Schneeverteilung. In den norwegischen Fjellgebieten werden vielfach Nord-Süd-Expositionsgegensätze angetroffen, die sich aus der großräumigen glazialen Struktur des Reliefs erklären. Südexponierte Hanglagen erhalten aufgrund ihrer Leelage zur winterlich vorherrschenden Windrichtung eine relativ mächtige und frühzeitige Schneebedeckung, während nordexponierte Luvlagen und Tiefenlagen eine spätere Schneebedeckung erfahren. In niederschlagsreichen Wintern kommt es zur völligen Auffüllung der Mulden mit Schnee, der eine bis Mitte Mai anhaltende Isolation zur Folge hat. Zudem kommt es trotz Südexposition in den am mächtigsten mit Schnee bedeckten Hangfußlagen zur späten Ausaperung.

Korrelationen zwischen Vegetationsdecke und Bodentypenverteilung, Humusformen, Relief und Wasserhaushalt. Die Auswirkungen von Schneebedeckung, Luft-, Oberflächen- und Bodentemperatur wurden ebenfalls analysiert. Insgesamt ergibt sich in den exemplarisch untersuchten Kleinsteinzugsgebieten eine komplexe, kleinräumig differenzierte Organisation dieser Ökosysteme, die zudem durch eine markante zeitliche Dynamik der Schneedeckenverteilung zum Ausdruck kommt (Abb. 1; KÖHLER et al. 1994, LÖFFLER 1997, 1998).

Während vergleichsweise umfangreiche vegetationskundliche Untersuchungen vorliegen (s.o.), existieren nur wenige, umfassende Untersuchungen zu den in norwegischen Fjellgebieten auftretenden wirbellosen Tierarten. Unter den Gesichtspunkten der Biodiversität und der Erkundung der Lebensstrategien sind Kenntnisse über die Auswirkungen der dort herrschenden Faktoren auf die Fauna von besonderem Interesse (vgl. z.B. OTTESEN 1996). Ein zentrales Ziel des hier vorgestellten Projekts ist, in die landschaftsökologischen Prozesssystemanalysen Untersuchungen der terrestrischen Biozönosen der Fauna zu integrieren. Damit soll ein weiterer Schritt in Richtung einer umfassenden Charakterisierung der Strukturen, Funktionen und Dynamik der Hochgebirgsökosysteme gegangen werden.

2 Untersuchungsräume und Untersuchungsgebiete

In Mittelnorwegen ergibt sich von der Küste ins Landesinnere – also von Westen nach Osten – ein großräumiger Ozeanitäts-Kontinentalitäts-Gradient, der Einfluss auf die Hochgebirgsökosysteme nimmt: Die Küstengebirge weisen ein deutlich ozeanisches Klima auf, während nur 100 km weiter östlich subkontinentale Verhältnisse vorherrschen. Die alpine Höhenstufung der jeweiligen Gebirgszüge lässt sich gliedern in die (1) untere alpine Stufe, welche durch niedrige Gebüsch- und Heidevegetation gekennzeichnet ist, die (2) mittlere alpine Stufe mit dominierender grasartiger Vegetation und die (3) obere alpine Stufe mit nur noch stark lückiger Vegetation. Die letztgenannte Stufe fehlt allerdings in vielen Gebirgszügen aufgrund zu geringer absoluter Höhe.

Auf der Grundlage großräumiger Übersichtskartierungen (vgl. LÖFFLER 1998) wurden im Rahmen des Forschungsvorhabens zwei Gebirgsmassive als repräsentative Untersuchungsräume des ozeanischen und subkontinentalen mittelnorwegischen Hochgebirges ausgewählt. In diesen Untersuchungsräumen erfolgten Abgrenzungen je eines Untersuchungsgebietes in der unteren und mittleren alpinen Stufe, die als exemplarische Teileinzugsgebiete hinsichtlich ihrer kleinräumig flächenhaften Differenzierung untersucht werden.

Der subkontinental geprägte Untersuchungsraum ist bei 61°53'N und 9°15'E im Raum Vågå/Oppland gelegen (vgl. Abb. 2, zur näheren Beschreibung des Raumes s.a. KÖHLER et al. 1994, LÖFFLER 1998). Hierbei handelt es sich um die Region höchster Aridität in ganz Norwegen mit Niederschlagssummen von etwa 300 mm pro Jahr.

Das ozeanisch geprägte Untersuchungsgebiet liegt mit 62°03'N und 7°15'E in der inneren Fjordregion West-Norwegens im Raum Stranda/Møre og Romsdal und ist mit jährlichen Niederschlagssummen von 1500 bis 2000 mm als humid anzusehen.

3 Methodologie und Methodik

3.1 Generelles Vorgehen

Der theoretische und methodologische Rahmen ist aus der landschaftsökologischen

Komplexanalyse nach MOSIMANN (1984, 1985) abgeleitet. Die Vorgehensweise wird entsprechend technischer und prinzipieller methodischer Anforderungen in den Hochgebirgslandschaften adaptiert und forschungspraktisch erweitert (KÖHLER et al. 1994, LÖFFLER 1998, LÖFFLER & WUNDRAM i.Dr.). Basierend auf diesem auf ökosystemare Haushaltsuntersuchungen ausgerichteten Forschungsansatz erfolgen exemplarische Untersuchungen biotischer und abiotischer Elemente in vier Einzugsgebieten zweier Höhenstufen des mittelnorwegischen Hochgebirgsraums. Von diesen vier Gebieten werden die zwei im subkontinentalen Raum gelegenen Einzugsgebiete bereits seit einigen Jahren untersucht. Hier wurden seit Juni 1994 (in mehreren Teilschritten) ganzjährig schreibende Klimastationen zur Erfassung der lokalen Windverhältnisse, Globalstrahlung, Luft- und Bodentemperaturen, Luftfeuchte sowie des Niederschlags aufgestellt. Zudem wurden weitere Datalogger zur langfristigen Speicherung lokaler Boden- und Lufttemperaturen installiert. Eine Darstellung sämtlicher bereits angefallener Daten und deren Auswertung vor allem aus ökosystemarer Sicht erfolgte inzwischen (LÖFFLER & WUNDRAM 1999, i.Dr.). Ansätze zur energetisch gesteuerten Pedogenese im Hochgebirge wurden ebenfalls publiziert (LÖFFLER 1998, 1999).

Die beiden westlichen Gebiete wurden im Sommer 2000 ergänzenden Übersichtskartierungen der Strukturparameter unterzogen. Die Übersichtskartierungen führten zu digitalen Geländemodellen mit submetrischer Genauigkeit für alle vier Untersuchungsgebiete. Auf diesem Maßstab erfolgten anschließend Detailkartierungen der strukturellen Parameter ohne Berücksichtigung zeitlich-dynamischer Phänomene. In den dabei angewandten standardisierten Verfahren hat das Prinzip der Elementarflächen eine besondere Bedeutung. Alle visuell linienscharf erfassbaren Parameter führen zur Festlegung von kleinsten Aufnahmeflächen. U.a. erfolgten Reliefuntersuchungen und pflanzensoziologische Aufnahmen in Anlehnung an BRAUN-BLANQUET. Die Durchwurzelungsintensität, die Substrat- und Bodentypen sowie die Humusformen inkl. morphodynamischer Profildifferenzierungen bzw. Mehrschichtigkeiten wurden bestimmt. Weiterhin wurden Skelettgehalte und das Porenvolumen erhoben. Jeder Standort wurde hinsichtlich seiner bodenphysikalischen und -chemischen Eigenschaften charakterisiert. Die Verfahren richteten sich nach AG BODEN (1994), HARTGE & HORN (1989), MOSIMANN (1985) und SCHLICHTING et al. (1995).

Die entsprechenden Ergebnisse wurden in einem Geographischen Informationssystem (GIS) abgelegt, und es erfolgte eine rechnergestützte Verschneidung der Datenebenen zur strukturellen Ökotopkennzeichnung in den vier Untersuchungsgebieten. Von zoologischer Seite wurde im Sommer 2000 ein Probedurchlauf zur Erfassung der in verschiedenen Ökotopen auftretenden Wirbellosen-Arten durchgeführt. Dabei wurde ausschließlich auf Bodenfallenfänge zurückgegriffen, da mit dieser effektiven und relativ einfachen Methode erfahrungsgemäß ein Großteil der als Zeigerorganismen besonders geeigneten, epigäisch aktiven Arthropoden erfasst wird (vgl. z.B. FINCH 2001). Das so erhaltene Tiermaterial wurde zunächst auf grober taxonomischer Ebene bearbeitet (Abb. 3), um erste Ergebnisse hinsichtlich der Stetigkeit und der Dichte der in den alpinen Lebensräumen auftretenden Wirbellosen zu erhalten. Diese Ergebnisse werden im nachfolgend beschriebenen Untersuchungsprogramm z.B. bei der Auswahl der Zeigertiergruppen berücksichtigt.

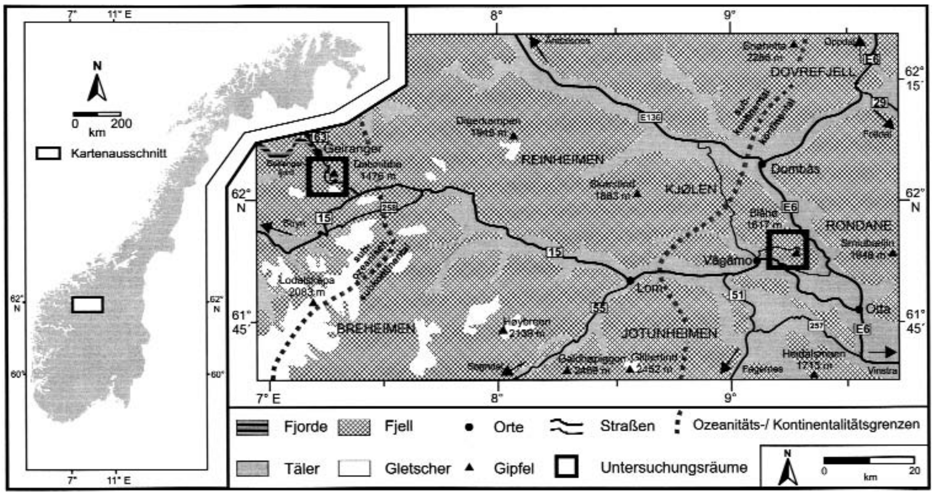

Abb. 2: Lage der Untersuchungsräume in Mittelnorwegen.

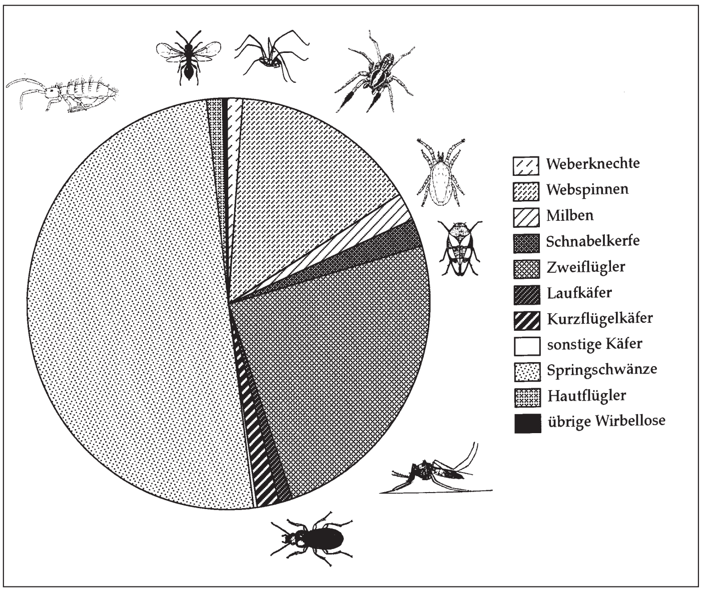

Abb. 3: Individuen-Anteile einzelner Taxa in den Bodenfallenfängen aus allen repräsentativen Standorten im östlichen Untersuchungsraum (97 Fallen, im Mittel 7 Tage exponiert [20.06. bis 29.06.2000]; n = 2034 Ind.).

3.2 Konzept

Das lokale Klima wird als wichtiger Faktor mit starken Auswirkungen auf die physikalischen, chemischen und biotischen Prozesse angesehen. Daher liegt den Untersuchungen ein umfangreiches Messprogramm der abiotischen Faktoren zugrunde. Darauf aufbauend werden die Lebensgemeinschaften von Flora und Fauna analysiert. Die Auswahl der Probeflächen für die faunistischen Erfassungen orientiert sich dabei eng an dem räumlichen Wirkungsgefüge, wie es in Form der Ökotope zum Ausdruck kommt.

3.3 Einzelmethodiken und Techniken

In jedem Untersuchungsgebiet sind eine Klimastation und mehrere Datalogger in repräsentativ nach LÖFFLER (1998) ausgewählten Teilflächen installiert. Sie liefern ganzjährig stündliche Mittelwerte zu verschiedenen klimatischen Messparametern und gestatten Rückschlüsse auf deren saisonale Dynamik. Hinweise auf kleinräumige Unterschiede einzelner Parameter werden mit Handmessungen in verschiedenen Teilflächen bei charakteristischen Witterungsverhältnissen der verschiedenen Jahreszeiten abgesichert (s.u.).

Für die zoologischen Untersuchungen ergibt sich unter Beachtung der Untersuchungsziele, dass als Zeigertiergruppen ausschließlich Arthropoden in Betracht kommen. Durch ihre geringen Raumansprüche sind sie zur Untersuchung der kleinräumigen Heterogenität innerhalb der Fjellgebiete besonders geeignet. Im Gegensatz zu verschiedenen phytophagen Arthropoden (Zikaden, Blattkäfer u.a.), deren Vorkommen häufig an

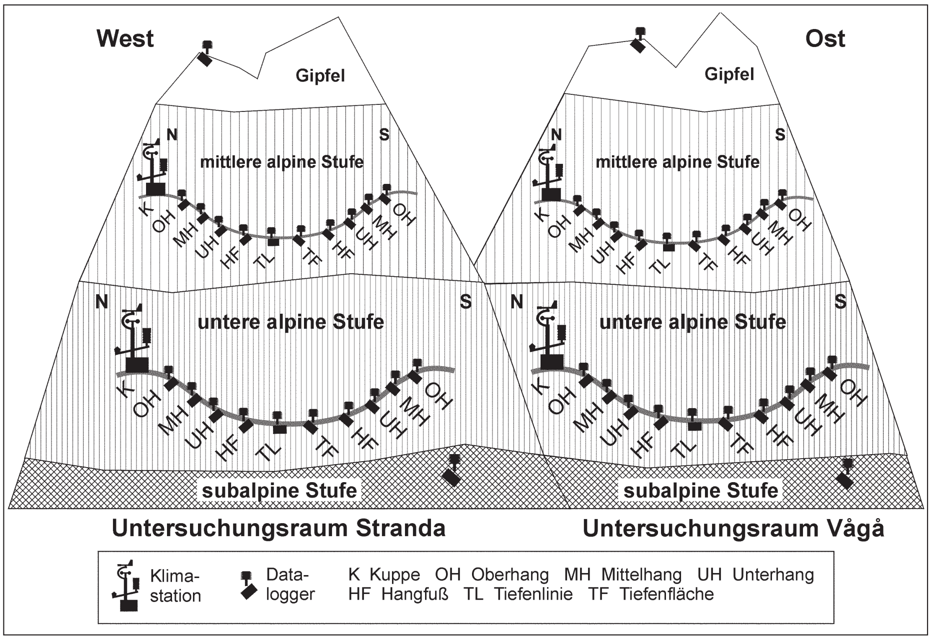

Abb. 4: Schema des Aufbaus der Messeinheiten in den jeweiligen Einzugsgebieten der verschiedenen Höhenstufen in den west- und ostnorwegischen Untersuchungsräumen.
Stationäre Temperaturmessungen dienen der ganzjährigen Registrierung, diskontinuierliche Messungen bieten die Möglichkeit einer flächenhaften Erfassung. Ganzjährig stündliche Mitteltemperaturen werden an einem Standort je Untersuchungsgebiet (Kuppenlage) in den Messhöhen – 30, – 15, – 1, + 15, + 100 cm gemessen. An zehn weiteren Standorten pro Untersuchungsgebiet (Ober- Mittel-, Unterhang und Hangfuß in Nord- und Südexposition sowie Tiefenlinie und Tiefenfläche) werden ganzjährig in – 15, – 1 und + 15 cm Boden- bzw. Luft-Temperaturen im 10-minütigen Intervall aufgezeichnet. Zudem erfolgt zur Ermittlung des hypsographischen Gradienten die Messung der Boden- bzw. Luft-Temperaturen in – 15, – 1 bzw. + 15 cm an je einem Kuppenstandort in der subalpinen Stufe (Birkenwald) und in der oberen alpinen Stufe (im Bereich der höchsten Gipfel des jeweiligen Untersuchungsraums).

spezifische Pflanzenarten gebunden ist, lassen vor allem die epigäischen zoophagen Arthropoden (Laufkäfer, Spinnen u.a.) Verteilungen in Abhängigkeit vom saisonal differenzierten Faktorenkomplex erwarten. In den geplanten Untersuchungen sollen die Laufkäfer (Carabidae), Kurzflügelkäfer (Staphylinidae) und Webspinnen (Araneae) sowie die Heuschrecken (Caelifera, Ensifera) bearbeitet werden. Diese vier Gruppen stellen neben einzelnen weiteren, aus Zeitgründen nicht zu bearbeitenden Tiergruppen die auf der Bodenoberfläche zu verschiedenen jahreszeitlichen Perioden adäquat erfassbaren bzw. hoch aktiven Arten dar (z.B. HÅGVAR et al. 1978). Für sie sind die taxonomischen und ökologischen Kenntnisse deutlich besser als z.B. für die Milben und Collembolen, die ebenfalls hohe Aktivitätswerte auf der Bodenoberfläche zeigen (Abb. 3). Außerdem lassen sie sich gut mittels Bodenfallen erfassen (Käfer, Spinnen) bzw. in den vorhandenen Ökotopen ohne größere Probleme bei Geländebegehungen erheben (Heuschrecken-Erfassung durch Linientransekt-Begehungen mit Zählungen der angetroffenen Individuen). Abgesehen von verschiedenen Nachteilen (s.u.) ist die Bodenfallen-Methode auch bei der Untersuchung von Hochgebirgslebensräumen gut einsetzbar, da die Fallen sehr effektiv Tiere erfassen, einfach im Gelände zu handhaben sind und die Fänge während der gesamten schneefreien Saison durchgeführt werden können (vgl. auch OTTESEN 1996). Auswertungen können u.a. hinsichtlich der Artenzusammensetzung und saisonaler Änderungen der Aktivität in Abhängigkeit vom Kleinstlebensraum für die epigäisch lebenden Wirbellosen erfolgen, wodurch sich Rückschlüsse auf standörtliche Unterschiede und auf die Dynamik der Populationen in den Flächen ziehen lassen (s.u.). Einen weiteren Vorteil des Bodenfalleneinsatzes stellt die relative Witterungsunabhängigkeit dar. Durch die ständig im Gebiet exponierten Fallen werden auch während kurzzeitiger „Schönwetterperioden" Tiere gefangen.

3.4 Arbeitsprogramm

An je einem Standort (in Kuppenlage) pro Arbeitsgebiet werden mittels der jeweiligen Klimastation Globalstrahlung, Luftdruck, Windrichtung und -geschwindigkeit, Luftfeuchte sowie Regen-Niederschlag als stündlicher Mittelwert ganzjährig registriert. Stündliche Temperaturmessungen zur Ermittlung des energetischen Prozessgeschehens werden mit Hilfe von Klimastationen und zusätzlichen Dataloggern durchgeführt (vgl. Abb. 4).

Weiterhin erfolgt in den vier Arbeitsgebieten in jeweils parallel erfassten verschiedenen Reliefpositionen eine Messung des Niederschlags mit Totalisatoren. An allen repräsentativen Teilstandorten wird während der sommerlichen Messperiode die Evaporation mit Hilfe von Piché-Evaporimetern und Tankverdunstungsmessern (nach MOSIMANN 1983) in der Messhöhe + 30 cm parallel ermittelt. Mit Ausnahme der ständig vernässten Standorte wird in 5 cm Messtiefe pro Teilfläche das Sickerwasser mit Hilfe von selbst entwickelten Kleinlysimeter-Totalisatoren (nach MOSIMANN 1985; verändert) aufgefangen, mengenmäßig bestimmt und für Stoffhaushaltsuntersuchungen bereitgestellt. Die biotische Aktivität stellt als erfassbarer Parameter im ökosystemaren Geschehen eine quantifizierbare Größe dar. Sie wird als Zelluloseabbaurate an allen Standorten als mittlerer Tagesabbau [mg] und monatliche Abbaurate [%] im humosen Oberboden (5 cm Tiefe) und im minerogenen Unterboden (15 cm Tiefe) bestimmt. Mit diesem Verfahren kann die biotische Aktivität als messbare Korrelationsvariable in Abhängigkeit von der jeweiligen standörtlichen Situation erfasst werden (vgl. z.B. MOSIMANN 1985).

In allen weiteren Ökotopen finden in den Messhöhen – 15, – 5, – 1, + 15, + 30 und + 100 cm diskontinuierlich manuelle Temperaturmessungen statt. Parallel zu diesen Temperaturmessgängen werden standörtliche Daten der relativen Luftfeuchtigkeit in jeweils + 15 cm Messhöhe erhoben sowie Windmessungen und Wasserstandsmessungen (einfache Feldbrunnen) durchgeführt. Diese Erhebungen dienen der Erfassung der räumlichen Variabilität bei unterschiedlichen Witterungsverhältnissen und haben eine Bedeutung für die Einstufung der Standortansprüche der Wirbellosen. Zur Zeit der mächtigsten Schneedecke wird in allen Arbeitsgebieten mit Hilfe eines Schneeoberflächennivellements die Schneedeckenmächtigkeit bestimmt. Zudem wird mit einer Schneesonde (vgl. WOHLRAB et al. 1992) die Dichte der Schneedecke ermittelt, um das Wasseräquivalent der jeweiligen standörtlichen Schneedecke zu berechnen. An allen Standorten werden unter Einsatz von TDR-Feldmessgeräten in 15 und 5 cm Bodentiefe diskontinuierliche Bodenfeuchtemessungen durchgeführt. Über die Berechnung der entsprechenden Werte für alle übrigen Punkte im Untersuchungsraum entsteht mit Hilfe eines Geographischen Informationssystems eine Informationsschicht über die jeweiligen Faktorenverhältnisse (vgl. als Beispiel für den Strahlungshaushalt STUMBÖCK 1995).

Zoologische Erhebungen sollen in insgesamt 100 der strukturell in einem GIS gekennzeichneten und klassifizierten Ökotopen der vier Untersuchungsgebiete erfolgen. Um repräsentative und für eine kleinräumige Differenzierung des Standortmosaiks adäquate Fangergebnisse zu erhalten, werden in jedem jeweils mehrere Quadratmeter einnehmenden Ökotop fünf Bodenfallen aufgestellt (Σ = 500 Fallen). Als Fangzeiten sind zunächst die schneefreien Phasen der Jahre 2001 und 2002 geplant (Anfang/Mitte Juni bis Anfang September; Leerungsrhythmus 14-täglich; Fangflüssigkeit: 3 % Formalin und Entspannungsmittel). Aufgrund der spezifischen Klima- und Bodenverhältnisse sind die Fallen mit Plexiglasdächern zu versehen und in dauerhaft im Boden eingebrachten Rohren einzusetzen. In Anlehnung an die im Sollingprojekt (ELLENBERG et al. 1986) verwendeten Fallen wird das Dach mit einem PE-Ring verschraubt, der gleichzeitig das Glas in dem im Boden eingebrachten Rohr hält. Als ergänzende zoologische Methoden sind Handaufsammlungen für bestimmte Kleinstlebensräume sowie für die Kartierung der Heuschreckenvorkommen Transektbegehungen vorgesehen.

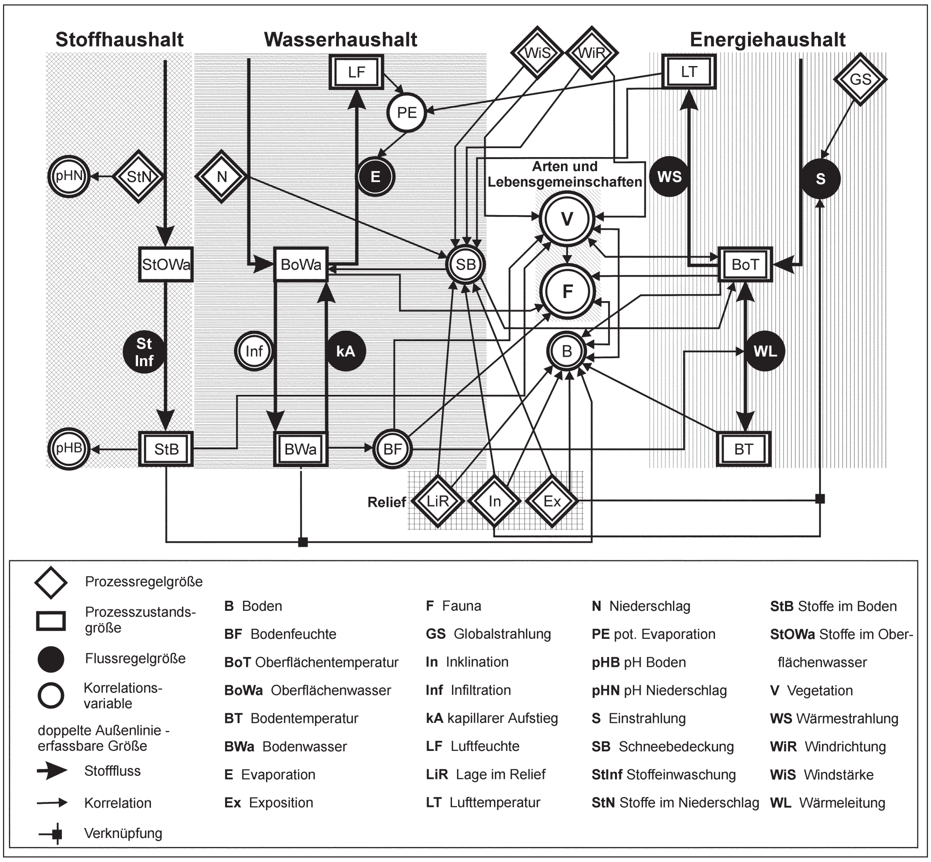

Abb. 5: Standörtliches Konzept- und Simulationsmodell als Prozess-Korrelations-System.

Die wichtigsten dynamischen Eingangsgrößen der betrachteten Hochgebirgsökosysteme sind Globalstrahlung (GS) und Niederschlag (N). Das Relief steuert dabei primär über die Einstrahlung den Energiehaushalt, während es in Verbindung mit Windrichtung (WiR) und Windstärke (WiS) direkt die Schneebedeckung (SB) und darüber bei Schneeschmelze das Wasserangebot an der Oberfläche (BoWa) bedingt. Der Stoffhaushalt ist eng an den Wasserhaushalt gekoppelt und wird durch die messbare Eingangsgröße der mit dem Niederschlags- und Schmelzwasser verlagerten Stoffe (StN) gesteuert. Diese drei übergeordneten abiotischen Teilsysteme stehen in Wechselwirkung zueinander und bedingen in ihrer Gesamtheit die floristischen und zoologischen Strukturmerkmale des biotischen Teilsystems, das vorrangig hinsichtlich der Arten und Lebensgemeinschaften untersucht wird. Die aus diesem Grund im Systemmodell jeweils als Korrelationsvariablen dargestellten Fauna- und Vegetationskomplexe stellen für sich genommen Teilmodelle dar, die gegenwärtig als „blackbox" formuliert sind. Bezogen auf einzelne Vegetationsgesellschaften oder einzelne Tierarten lässt sich hier in Abhängigkeit von den abiotischen Faktoren die Präsenz oder Absenz am Standort oder – auf einzelne Tierarten bezogen – auch die Aktivitätsdichte prognostizieren.

3.5 Methodenkritik

Ausgehend von der Tatsache, dass landschaftliche Strukturen aufgrund der real existierenden, nahezu unendlichen Differenziertheit bei zunehmender Vergrößerung des Betrachtungsmaßstabs nur unter Berücksichtigung geographischer Betrachtungsdimensionen analysierbar sind, wird nach Löffler (1998) ein Konzept zur dimensionsgebundenen Untersuchung der Strukturen von Hochgebirgsökosystemen angewandt und am Beispiel der chorologischen, topologischen und punktuell-standörtlichen Betrachtung mit entsprechenden Genauigkeitsansprüchen adaptiert. Die punktuell-vertikale Detailliertheit der Untersuchung muss dabei zwangsläufig mit zunehmender Größe und Flächenhaftigkeit der Untersuchungsobjekte zugunsten einer räumlichen Aussage verloren gehen (Hersperger 1995). Wichtig ist, dass bei großräumigen Betrachtungen eine Kennzeichnung der Zusammenhänge mehr auf allgemeinen Gesetzmäßigkeiten beruht als auf Detailzusammenhängen; diese müssen in großmaßstäbigen Untersuchungen präzisiert und auf Richtigkeit bzw. Unschärfe der Gesetzmäßigkeiten geprüft werden. Die formulierten Ansprüche an eine in verschiedenen Dimensionen geographischer Betrachtungen (Neef 1963, 1967) ausgerichtete Untersuchung setzen vor dem Hintergrund der in der Literatur geläufigen landschaftsökologischen Ansätze einige methodische Prämissen und Abstraktionen voraus (Leser 1997).

Die chorologische Untersuchung z.B. im Sinne von Haase (1991) sieht zwar konzeptionell eine Herleitung chorologischer Gefüge der Landschaft auf der Grundlage topologischer Kenntnisse vor, kann jedoch im konkreten Fall (und dieses bedingt natürlich zum Teil der großräumige Ansatz) diesem Anspruch im Detail nicht immer gerecht werden. Demnach wird trotz postuliertem induktiven Vorgehens auf deduktive Verfahren zurückgegriffen. Das bedeutet, dass eine Übertragung derartiger Verfahren auf nur teilweise oder gänzlich unerforschte Regionen, in denen die Gesetzmäßigkeiten im Zusammenwirken verschiedener Faktoren noch nicht bekannt sind, nur schwer umzusetzen ist. Die vorliegende Arbeit versucht deshalb, eine strengere Herleitung der inhaltlichen Gesetzmäßigkeiten der Heterogenität von Ökochoren auf der Grundlage einer konsequent induktiven Aggregation topologischer Inhalte vorzunehmen. Dieses gelingt zwar hinsichtlich einer allgemeinen verbalen Charakterisierung und exemplarischen Kennzeichnung, nicht jedoch unmittelbar hinsichtlich einer Kartierung und Abgrenzung realer Raumeinheiten heterogener Mosaike (Löffler 1998). Hierfür sind die visuell wahrnehmbaren Kriterien unzureichend, und eine Kartierung der notwendigen weiteren Parameter ist vom Arbeitsumfang her nicht für einen entsprechend großen Raum leistbar. Eine konkrete Grenzziehung in Form einer kartographischen Darstellung kann letztlich nur über eine zusätzlich deduktive Charakterisierung der größeren Raumeinheiten z.B. in zunehmend stärkerem Maße durch Fernerkundung erfolgen (Leser 1997).

Besonders wichtig ist, dass sich die Ergebnisse großräumiger Untersuchungen im Detail auch mit kleinräumig-flächenhaften bzw. punktuellen Aufnahmen decken. Je nach Untersuchungsansatz sind Ziel der Aussagen und Wahl der Methoden gegeneinander abzuwägen. Zudem muss beachtet werden, dass die Arbeit im Hochgebirge eine relativ intensive Einarbeitung in die verschiedenen Merkmalskombinationen erfordert. Diese ist natürlich bei kleinräumigen Untersuchungen mit einer hohen Zahl von Erhebungen wesentlich leichter als bei großräumigerer Vorgehensweise mit schwierigem direkten Vergleich. Bezüglich der Datengenauigkeit ist das hier gewählte Raster der Erhebungen den realen Verhältnissen angepasst, und es liegt eine hinreichende Genauigkeit z.B. im topologischen Bereich der Linienführung der abgegrenzten Flächen vor. Dabei erweist sich vor allem das Vorgehen der Erfassung der so genannten Elementarflächen als sinnvoll und methodisch abgesichert, da einerseits Subjektivität bei der Flächenfindung vermieden wird und andererseits die analytische Weiterverarbeitung der flächenhaften Datenebenen ohne Inflation der Flächenzahlen möglich wird (Löffler 1998).

Hinsichtlich der inhaltlichen Gewichtung und Zielsetzung landschaftsökologischer Untersuchungen stellt die punktuelle Erfassung und Messung aufgrund ihrer individuellen Betrachtung ohne direkten räumlichen Bezug zunächst eine Methodik von untergeordneter Bedeutung dar. In der Kombination mit räumlichen Erhebungen im Sinne von Kartierungen kommt ihr jedoch eine übergeordnete funktionale Wertigkeit zu, da hierdurch eine prozessorientierte Präzisierung flächenhafter Datensätze ermöglicht wird und rückwirkend Detailsachverhalte mittels extrapolierter Prozesskorrelationen in die Fläche übertragbar sind (Löffler & Wundram im Dr.).

Die Arbeit mit „repräsentativen Standorten", an denen einzelne Landschaftselemente in ihrer vertikalen Verknüpfung analysiert werden, wird legitimiert durch die Definition von Repräsentativitätskriterien, die, auf die Fläche angewandt, zu räumlichen Bezugseinheiten punktueller Mess- und Fangdaten führen (Mosimann 1985). Akzeptiert man ein derartiges synthetisches Verfahren, wird eine Extrapolation von Punktdaten der Prozesshaushaltsmessungen und zoozönotischen Felderfassungen auf räumliche Einheiten gleicher bzw. ähnlicher struktureller Ausstattung möglich. Je nach Betrachtungsdimension greifen dabei unterschiedlich detaillierte Definitionskriterien, so dass die in der Realität ohnehin stets als Kontinuum anzutreffenden Landschaftsausschnitte synthetisch zu Ökotopen, Ökochoren etc. reduziert werden, um die räumliche Betrachtung bewältigen zu können. Aufgrund der theoretisch letztlich völlig willkürlichen Begründung von Repräsentativitätskriterien für die Abgrenzung von landschaftsökologischen Einheiten ergeben sich sehr unterschiedliche flächenhafte Größenordnungen der jeweiligen Bezugsräume.

Eine detaillierte Kritik der Mess- und Erfassungsmethoden muss für die in den zoologischen Untersuchungen eingesetzten Bodenfallen erfolgen. Mit ihnen werden nicht Populationsdichten (Individuen/Fläche), sondern Fangzahlen der Tiere in einem bestimmten Zeitabschnitt (Individuen/Bodenfalle x Standzeit) ermittelt (vgl. u.a. Heydemann 1956, Kuschka 1998). Es geraten ausschließlich am Boden laufende Arthropoden in die Fallen, so dass die Intensität der Bewegungen der Individuen einer Art („Aktivitätsdichte“) einen entscheidenden Einfluss auf das Fangergebnis hat. Beeinflusst wird die Aktivität u.a. durch das Nahrungs- und Strukturangebot, die Bodenfeuchte und -temperatur sowie den Raumwiderstand (im Sinne von Heydemann 1956 als Maß für die Menge der Hindernisse der lokomotorischen Aktivität). Hinzu kommen weitere dichteunabhängige, aber auch dichteabhängige (z.B. Populationsgröße) und individuenspezifische (z.B. Körpergröße, Gesundheitszustand) Faktoren (Kuschka 1998).

Über die Bodenfallenmethode sind bereits sehr viele methodenanalytische Untersuchungen durchgeführt worden. Das gilt sowohl in qualitativer Hinsicht ([nicht] erfasste Arten) als auch in quantitativer Hinsicht (u.a. Adis 1979, Kuschka 1998). Es wird bei weitem nicht jedes Individuum gefangen, welches an den Rand der Bodenfalle kommt. Manche Baldachinspinnen werden unter bestimmten Bedingungen im Mittel erst nach 57-maliger Begegnung mit dem Fallenrand tatsächlich erfasst (Topping 1993). Bei Untersuchungen der Zusammenhänge zwischen Laufaktivität, Abundanz und entsprechenden dynamischen Veränderungen zeigte sich, dass eindeutige Beziehungen sehr schwer konstruierbar sind und von zahlreichen Faktoren abhängen (z.B. Curtis 1980, Kuschka 1998, Topping & Sunderland 1992). Ein entscheidender Vorteil der Bodenfallenmethode ist aber in der Möglichkeit einer weitgehend standardisierten Erfassung großer Individuen- und Artenzahlen zu sehen, wenn – wie in der vorliegenden Untersuchung – eine ausreichende Anzahl typengleicher Fallen eingesetzt wird. Bei regelmäßiger Kontrolle und sorgfältiger Wartung können die bodenlebenden Arten kontinuierlich für die Fangintervalle ermittelt werden, und eine qualitative und/oder eine halbquantitativ-vergleichende Auswertung ist durchaus zulässig (Topping & Sunderland 1992). In großräumigen oder intensiven Untersuchungsprogrammen ist ein weiterer Vorteil z.B. die verhältnismäßig geringe Geländearbeit bei hoher Erfassungseffektivität (s.o.). Hierfür gibt es bisher trotz aller Kritik keine geeigneten Alternativen zum Einsatz von Bodenfallen, so dass durch ihre Verwendung in der vorliegenden Untersuchung bei Abwägung aller Vor- und Nachteile die zurzeit mit Abstand geeignetste Methode gewählt wurde.

4 Angestrebte Ergebnisse

Neben den strukturellen und prozesshaushaltlichen Untersuchungen sind die faunistischen Analysen eine Voraussetzung zur Klärung biotischer Teilaspekte. Gerade unter dem Gesichtspunkt der Standortdifferenzierung und -dynamik sind Untersuchungen der mobilen Tiere aufschlussreich. Die Untersuchungen zielen entsprechend der Auswahl der Untersuchungsgebiete entlang von klimatischen Gradienten auf verschiedene Maßstabsebenen ab:

kleinmaßstäbige Untersuchungsziele:
► flächenhafte Erfassung des kleinräumigen Wirkungsgefüges innerhalb von Einzugsgebieten in der unteren und mittleren alpinen Höhenstufe;
► Charakterisierung der Zoozönosen von Hochgebirgs-Ökosystemen in Hinblick auf verschiedene Aspekte der Biodiversität, wie z.B. Artenzusammensetzung und -reichtum, ökologische Gilden und Interaktionen zwischen Artengruppen (vgl. z.B. Kratochwil 1999, Schaefer 1996);
► biozönotischer Vergleich der Tierartengemeinschaften von unterer und mittlerer alpiner Stufe sowie entlang des übergeordneten Ozeanitäts-Kontinentalitäts-Gradienten von West- nach Ost-Norwegen;
► Ableitung von Abhängigkeiten zwischen den abiotisch gesteuerten Prozesssystemen und der zeitlich-räumlichen Dynamik der Populationen ausgewählter Tiergruppen;
► Quantifizierung von Steuergrößen der abiotischen Prozesssysteme und Biozönosen.

Ziele der großmaßstäbigen Untersuchungen:
► Ermittlung von Korrelationen zwischen der räumlichen Verteilung von Tierarten und der Anordnung der Ökotope; diese ausgewiesenen Raumeinheiten integrieren verschiedene ökologische Parameter (Reliefunterschiede, Bodenfeuchte, Bodenerwärmung etc.), deren Wirkung mittels geeigneter statistischer Methoden (multivariate Analysen) auf die Fauna zu prüfen ist (Jongman et al. 1995);
► Ableitung von typischen Tierartengemeinschaften der Ökotope sowie Benennung von Differenzialarten und Charakterarten für die einzelnen Lebensraumtypen (z.B. Refseth 1980, Schultz & Finch 1997);
► Prüfung der Nachvollziehbarkeit der klassifizierten Ökotope auf deren verschiedenen hierarchischen Ebenen für die Fauna; auch die anhand der einzelnen Kriterien ermittelten Lebensraumeinteilungen lassen sich entsprechend jeweils getrennt voneinander aus faunistischer Sicht bearbeiten – dieses führt möglicherweise zu einer verbesserten Klassifizierung der Ökotope in den Hochgebirgsökosystemen anhand stenotoper Arten.

weitere Aspekte:
Am Beispiel der Einzugsgebiete der jeweiligen Höhenstufe soll zunächst die vertikale standörtliche Situation der elementaren Ökosysteme erfasst werden. Dieses führt zur kleinräumigen Übertragung von Prozessgrößen in die Fläche. Aus diesen Daten sollen dann durch flächenhaft vergleichende Betrachtungen laterale Prozessverknüpfungen rekonstruiert und somit Nachbarschaftsbeziehungen und Wechselwirkungen abgeleitet werden. Aus den Messdaten gefolgerte klimatische Regelmäßigkeiten können in Hinblick auf ihre Bedeutung für die Ökosystemprozesse in den jeweiligen Einzugsgebieten quantifiziert werden. So wird letztendlich auch eine qualitative und quantitative Modellierung der Beziehungen zwischen Ökosystemkompartimenten möglich.

Die Ergebnisse der zoologischen Untersuchungen werden in ein GIS zur räumlichen Analyse eingegeben. Für jede der vorgefundenen Arten ist somit für die eingemessenen Parameter eine relativ exakte Nischenbeschreibung möglich (vgl. Ottesen 1996). Die Standortansprüche der Arten können durch die parallel ermittelten biotischen und abiotischen Faktoren nachvollziehbar dargestellt werden. Mittelfristig kann das zu einer genauen Einstufung der Anspruchsprofile der auftretenden Tierarten führen.

Mit Hilfe rechnergestützter Verfahren wird eine qualitative und quantitative Analyse standörtlich gemessener abiotischer Prozessgrößen (vgl. z.B. Hinzman et al. 1996, Reynolds et al. 1996) und eine Kopplung mit den flächenhaft erhobenen Strukturparametern Exposition, Inklination, Reliefform, Lage im Relief, Substrat, Geomorphodynamik, Boden, Vegetation und Fauna durchgeführt (vgl. z.B. Judas et al. 1998). Weiterhin können die zoologischen Daten für einzelne Arten zur Erstellung von Habitatmodellen genutzt werden (Kleyer et al. 2000). Die Übertragbarkeit sowohl der anhand der Originaldaten ermittelten Artengemeinschaften und Zeigerarten als auch die der Habitatmodelle ist in späteren Arbeitsschritten in Raum und Zeit zu validieren.

Das theoretische Grundgerüst für die Untersuchungen wird über ein Systemmodell dargestellt (vgl. Abb. 5). Dieses zeigt zunächst statisch und qualitativ die Wechselwirkungen zwischen den einzelnen abiotischen und biotischen Strukturkompartimenten auf. Die jahreszeitlich-zyklische Dynamik der Ökosysteme wird dann daraus rechnergestützt auf Grundlage der quantitativen Untersuchungen modelliert. Aus der an den Tagesgang des Energiehaushalts angepassten Betrachtung der Systemdynamik mit Hilfe von Stundenmitteln der Messwerte wird über die ganzjährige Untersuchung eine saisonale Charakterisierung der Ökosysteme erreicht.

Zusammenfassend führt also die Verschneidung von flächenhaften biotischen und abiotischen Strukturdaten mit standörtlichen Prozessdaten zu einer räumlichen Zuordnung der Prozessgrößen auf strukturell begründete Flächenareale. Die streng induktive Kopplung von zeitlich-dynamischen Prozesskennwerten mit räumlichen Strukturparametern mündet in einer ökologischen Karte, in der Ökotope als elementare Bausteine der Landschaft mit einheitlicher abiotischer Struktur, gleichen Lebensgemeinschaften sowie ähnlichen energetischen, wasser- und stoffhaushaltlichen Prozesssystemen abgebildet werden. Sind zeitlich-dynamische Prozesskennwerte räumlich in einer Datenebene verfügbar, müssen sich auch Nachbarschaftsbeziehungen und Wechselwirkungen der Ökotope ableiten lassen. Dieser Schritt geht als rekonstruktives Verfahren über die landschaftsökologische Synthese (vgl. LESER 1997) hinaus und kann besonders wegen der Verfügbarkeit faunistischer Daten weiter reichende Ergebnisse liefern. Eine Übertragbarkeit des Ansatzes auf andere Untersuchungsräume ist gegeben.

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5.2 Publikation II

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Modelling spatio-temporal near-surface temperature variation in high mountain landscapes

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Abstract

A surface energy balance model (SEB), describing the fluxes of latent and sensible heat as well as the ground heat flux at different surfaces, was developed to simulate substrate, surface and air temperature variations in high mountain landscapes at a high temporal resolution of one hour. Classical atmospheric forcing was imposed at a reference level. The SEB model was calibrated and tested using micro-meteorological measurements collected at different sites within four catchments of the low and middle alpine belt of western and eastern central Norway. These sites represent the most common alpine vegetation types. Agreement between the model predictions and measurements was good: in all cases at least 80% of the variance in the measurements was explained by the model. In the present stage, the model contains limitations concerning the effects of a snow pack and should be applied to the snow-free season, only. Nevertheless, comparably simple SEB models, like this one, can be employed to intensify knowledge about detailed-scaled micro-spatial temperature differentiation and its effects on high mountain ecosystem functioning. Due to its simplicity it is suitable for remote sensing utilization enabling the application along broad-scale altitudinal and oceanic-continental gradients.

Keywords: Energy balance model; Temperature variation; High mountain ecosystems; Norway

1. Introduction

This study is framed by a long-term research project on high mountain ecology established in 1991 in central Norway (Köhler et al., 1994; Löffler, 1998; Löffler et al., 2001; Löffler and Wundram, 2003). It analyses dynamics of snow, soil moisture and temperature gradients correlated with landscape structures. Interrelations between vegetation cover, spatio-temporal distribution patterns of epigeic arthropods, periglacial patterns, soil types, humus, snow cover thickness, snow melting and water balance features as well as air, surface and soil temperature regimes are analysed and mapped in detailed-scaled micro-spatial resolution. The background of this project is best described by the following statements: the Norwegian fells as high mountain landscapes above timberline are characterised by their differentiation of ecosystems and fine-scaled complexity (Körner, 1995, pp. 56–57, Moen, 1999, pp. 115–121). Steep meteorological and topographical gradients as well as altitudinal zonation and complex relief micro-features most decisively affect the alpine ecology (Billings, 1973; Molenaar, 1987; Barry, 1992; Fremstad, 1997; Walker et al., 2001). Those gradients are complex and their impact on the environment is not yet fully understood (Körner, 1999). With focus on Fennoscandian alpine vegetation

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many case studies have been conducted; recent supplements of literature are given by Gjærevoll (1990), Dahl (1998), Wielgolaski (1998) and Moen (1999). But since environmental conditions and vegetation patterns in the higher elevations are not well known in Norway (Fremstad, 1997), scientific challenges in the mountain geography of northern Europe are still to intensify research on fine-scale temperature and snow-cover determinants, and superior broad-scale oceanic-continental gradients (Fægri, 1972, p. 98).

Major results of the project indicate the energy balance and resulting near-surface temperatures, i.e. temperatures below the standard meteorological screen height of 2 m, to be controlling factors within ecosystem functioning (Köhler et al., 1994; Löffler, 2002, 2003). For instance, temperature dynamics of near-surface substrate and air layers should particularly be supposed to influence the activity and distribution of epigeic arthropods during the vegetation period (Ottesen, 1996). Specific gradients of the temperature dynamics between the ecosystems as to spatial changes in topography and altitude had to be expected in concordance with Isard and Belding (1989) and Dahl (1998). Fig. 1 shows a process-correlation model illustrating the frame of this paper: Energy fluxes and related temperatures are controlling factors with regard to ecosystem functioning. Moreover, they are a result of the trans-functional interactions between the different partial complexes of the ecosystem. These outcomes were accomplished within a dense net of measurements at meteorological stations, temperature data loggers, and hand-held equipment established within four catchments (each smaller than 5 ha) representing the low and middle alpine belt of western and eastern central Norway. Such an approach based on extensive measurements can hardly be transferred to larger spatial dimensions at the meso- or macro-scale to investigate governing gradients. Thus, utilisation of modelling approaches is to be preferred instead.

Numerical modelling for operational weather prediction covers a wide range of scales, down to a resolution of about 10 km, accomplished by general

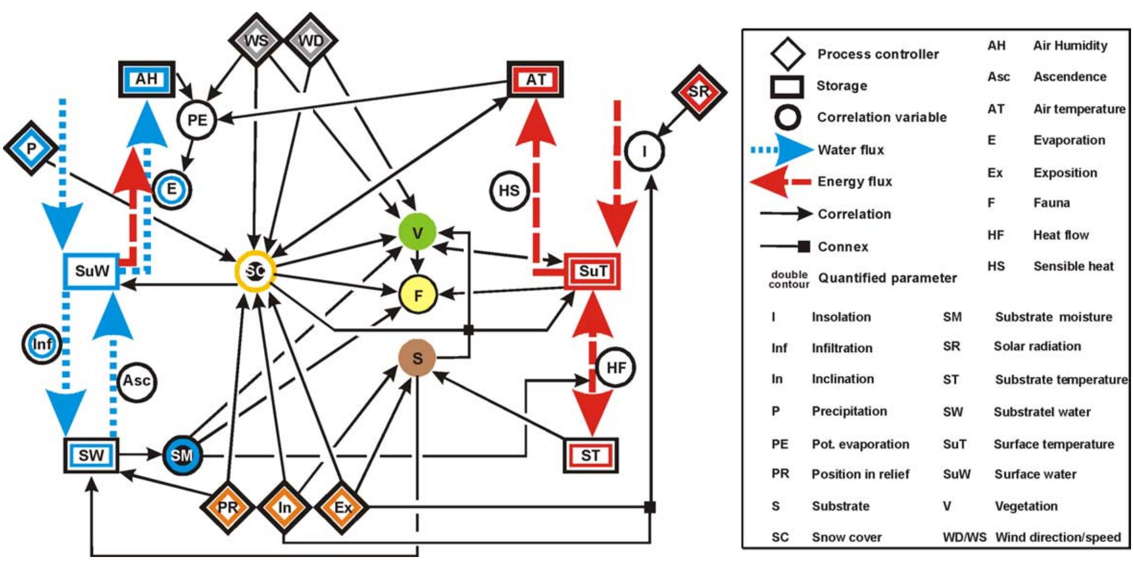

Fig. 1. Ecosystem approach as simplified process correlation model with major water and energy balance compartments (Löffler et al., 2001). Most important process determining input fluxes are solar radiation (SR) and precipitation (P). Relief, with exposition (Ex) and inclination (In), controls insolation (I), and results—by sensible heat flux (HS)—in air temperature and—by heat flow (HF)—in surface and substrate temperatures, respectively. In combination with air temperature, precipitation, wind speed (WS), and wind direction (WD) relief is responsible for snow cover formation (SC). During snow melt the water equivalent of the snow pack produces a certain amount of surface water (SuW) which, in combination with the infiltration capacity (Inf), affects the substrate water system (SW). Characteristic temperature profiles (SuT/ST) result from relief induced verified radiation inputs, vegetation (V), and substrate moisture conditions. Energy balance in turn is correlated with vegetation, fauna (F) and substrate (S) compartments. For simplification not all correlations are shown, lateral processes are neglected.

circulation models (GCM) and their downscaling (e.g. Land et al., 1999; Rummukainen et al., 2001; Denby et al., 2002). Models appropriate for these scales cannot resolve fine-scale differentiations conditioned by the complex topography of high mountain landscapes, as for example the influence of different insolation patterns or slope winds (Noppel and Fiedler, 2002). The results are important deficiencies in prediction, for boreal and tundra landscapes generally reinforced by “at best incomplete and at worst incorrect” representation of the land surface (Harding et al., 2001, p. 15). Identifying the interface between land surface and atmosphere as key area in reducing uncertainties in prediction has led to the development of one-dimensional soil-atmosphere-vegetation-transfer (SVAT) models for the micro-scale (e.g. Jansson and Karlberg, 2001; Cayrol et al., 2000), combining schemes from different disciplines (meteorology, plant physiology, etc.). This combination enables pretty exact simulations of energy fluxes and temperatures, but underlies the general problem of its applicability as stated by Boulet et al. (2000, p. 117): “Detailed soil–vegetation–atmosphere transfer (SVAT) models, especially when they exhibit small time and space steps, are difficult to use for the investigation of the spatial and temporal variability of land surface fluxes. The large number of parameters they involve (physical or geometrical parameters as well as parameters appearing in the empirical relationships) requires detailed field studies and experimentation to derive parameter estimates. Moreover, classical experimental set-ups give local values, whereas larger-scale (i.e. grid) values would be required. On the other hand, running these models for each point location is intractable“. Furthermore, this jump in scale, i.e. from the macro- to the micro-scale, exhibits a gap between micro-scale 1D models neglecting lateral processes and macro-scale 3D GCMs or their downscaling. This gap is only basically bridged by spatial meso-scale models for the climate of urban environments (e.g. Bruse, 1999), but restricted to the environment they were made for. As opposed to this, water balance models cover a wide range of scales (e.g. Bronstert and Plate, 1997; Arnold et al., 1998). As indicated, neither a suitable 1D model, nor a spatially fine-scaled numerical model for the energy balance of high mountain ecosystems is available.

Consequently, the aims of this paper are:

(a) Introducing of a comparably simple one-dimensional surface energy balance model. The purpose of the model is to simulate ecologically relevant near-surface temperatures at user-defined heights (default $+15$, -1, and -15 cm) at a time step of one hour providing an adequate resolution of the driving variables. For applications in remote and poorly investigated landscapes as the regarded high mountain areas as well as a robust mathematical implementation, the number of required parameters needs to be restricted (Franks et al., 1997; Gupta et al., 1998). This is even more important when considering large scales where parameters need to be achieved by remote sensing.
(b) Illustrating temperature dynamics along complex gradients at different scales.

2. Materials and methods

2.1. General methodological concept, measurements and spatial approach

The entire approach of the project is based on an extensive programme of structure analyses and mappings as well as process measurements of different environmental parameters as state-of-the-art within the frame of the *landscape ecological complex analysis* (Mosimann, 1984, 1985; Steinhardt, 2002). From the theoretical ecosystem model landscape structures are derived to determine landscape processes that were investigated following a structurally defined concept model. Furthermore, process measurements enabled quantified modelling of the different ecosystem compartments (e.g. energy balance, water balance, development of habitat models). Finally, coupling these sectoral models enabled the prediction of future developments (e.g. Gilmanov, 1993; Duttmann, 1999; Wenkel, 1999) to be used for scenarios and recommendations according to land management, as already used for non-alpine landscapes (Dierssen and Windhorst, 2000).

The investigations were carried out in central Norway. A broad-scale transect was used along the climatic gradient from coast to inland across the Scandes, resulting in latitudinal and altitudinal observations.

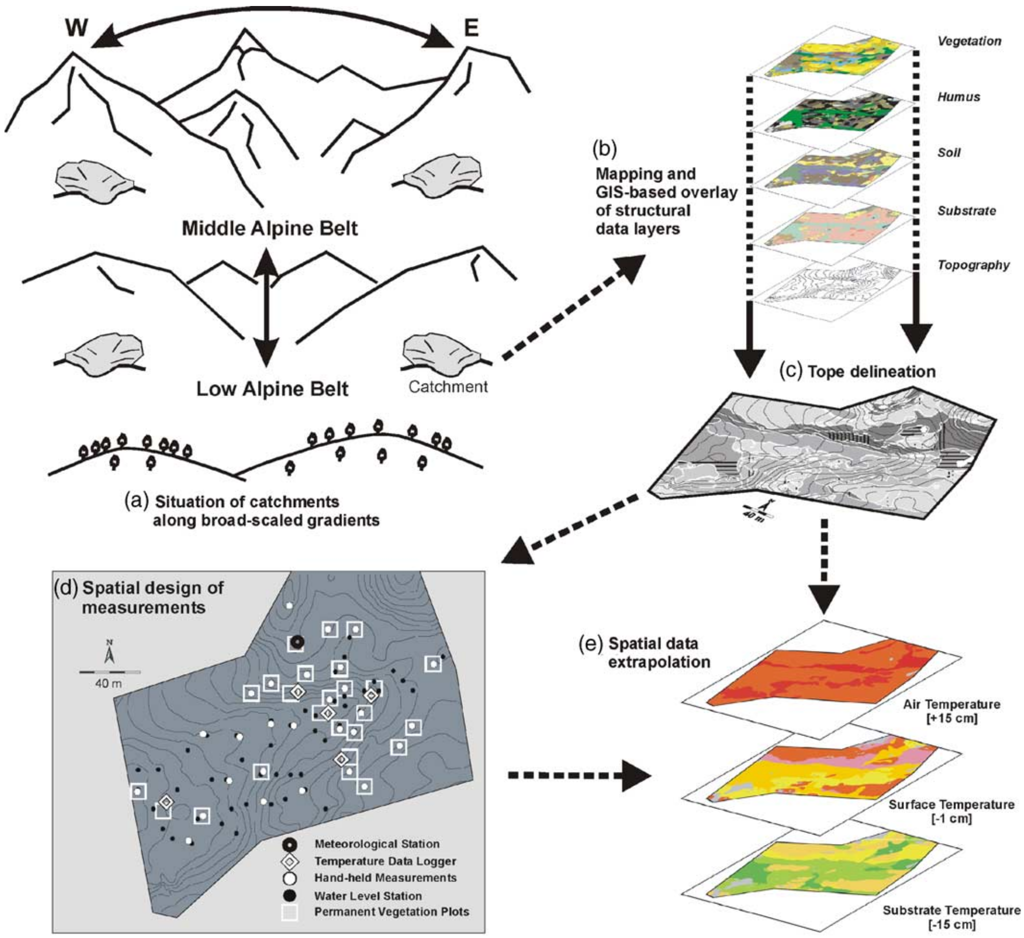

Fig. 2. Spatial organisation of measurements, use of equipment at different types of stations, and sensor positions. Within each of the four catchments situated along broad-scaled latitudinal and altitudinal gradients (a) fine-scaled structural mappings and their GIS-based overlay (b) were used to delineate tope geometries (c). They determine the spatial design of measurements (d) based upon four hierarchical levels of stations: A meteorological station installed in each catchment was used to measure the long-term dynamics as an example of superior climate elements. Measurements of long-term dynamics were completed by temperature data logger installed at mean relief positions (southern and northern exposure as well as depressions). To dense the spatial resolution of the measurements hand-held equipment was used during characteristic weather situations and seasons. Furthermore, a spatial net of water level stations provided spatio-temporal data of the water balance. The measured values were spatially extrapolated based on the tope geometries (e), differentiated for the different layers.

Four investigation areas were chosen as representative catchments and delimited in the low and middle alpine belts. Fig. 2 illustrates the spatial organisation of measurements, the use of equipment at different types of stations, and sensor positions. Within each catchment along broad-scaled latitudinal and altitudinal gradients (a), fine-scaled structural mappings and GIS-based overlay routines (b), were used to delineate tope geometries (c).Topes are defined as areas to be characterised by quasi-homogeneous contents and functions with regard to ecological factors (Leser, 1997, pp. 147–148), being analogous to the hydrological response units used in hydrology (Flügel, 1996). These highly integrating tope type geometries determined the position of measurements (d) based on four hierarchical levels of stations. The arrangement followed premises on weighing the highest spatial resolution possible, the most quantitative results measurable by the lowest priced instruments available. Seasonal dynamics were assessed by means of con-

Table 1
Organisation of measurements within each catchment

Parameter	Meteorological station (1)[a]		Data logger (4)[a]		Hand-held (40–50)[a]	
	Measured	Height (cm)	Measured	Height (cm)	Measured	Height (cm)
Global radiation	×	100	–	–	–	–
Air temperature	×	15, 200	x	15	×	15, 100, 200
Substrate temperature	×	−1, −15, −30	x	−1, −15	×	−1, −5, −15
Wind direction/wind force	×	200	–	–	×	15, 100, 200
Air humidity	×	200	–	–	×	15, 100, 200
Substrate moisture	×	−15, −30	–	–	×	−1, −5, −10, −15
Precipitation	×	100	–	–	× (totaliser)	30
Air pressure	×	–	–	–	–	–

[a] Number of sites.

tinuous measurements within topes representing the main relief positions, taken throughout the year in hourly intervals by meteorological stations (ridge) and temperature data loggers (south- and north-facing mid slopes, depressions). Additionally, spatial differentiations were investigated using hand-held measurements within those tope types not covered by automatic equipment during several characteristic climatic situations and seasons. Furthermore, a spatial net of water level stations provided spatio-temporal data of the water balance. The measured values were spatially extrapolated based on the tope geometries (e), differentiated for the different layers. The organisation of total measurements is described in Table 1. Based on provided pt100 temperature sensors, surface temperature measurements were critical as to unshadowed sensor material reflection, absorption-induced heating surplus, and real surface conditions being not represented using shadowed measurements. Thus, measurements of substrate temperatures closest to the surface were established at −1 cm depth.

Within the spatial approach, the delineated tope geometries additionally functioned as a basis for data extrapolation. After their validation by measurements, data achieved by one measurement or by a simulation run were defined valid for the tope as a whole. Based on this agreement, analyses of similarities with regard to temperature dynamics on a broader spatial level, such as the entire catchment in this case, allowed larger units to emerge. The approach enabled spatial statements about temperatures based on just a few measurements for the sake of local accuracy. Thus, the spatial statements given in this paper were concerned with temperature ranges in steps of 2 K.

2.2. Model description

For the evaluation of near-surface temperature variations at a site a common approach was used balancing the energy fluxes at the surface based on well-known physical equations (see later). The resulting one-dimensional, i.e. vertical, model represents temperature variations within an air layer of 1 m height above a layered soil profile covered with vegetation. Meteorological standard data were used as driving forces in the model and were given as measured values.

2.2.1. In- and output of the model and its technical implementation

As discussed above, common SVAT models use a high amount of input data for the most accurate estimation of surface fluxes possible. To avoid time-consuming and labour-intensive determinations of empirical variables input data easy to deduce were used within this model, only. Consequently, simulation of near-surface temperature dynamics was based on:

- mappings of site depending structures as relief (controlling height above sea level, aspect, inclination), substrate (mineral, organic), and vegetation type (determining stand height, leaf area index, albedo), respectively their derivation from remote sensing,
- measurements of time depending variables (driving forces) as global radiation, air temperature and wind speed at 2 m, relative humidity, precipitation, barometric pressure, and

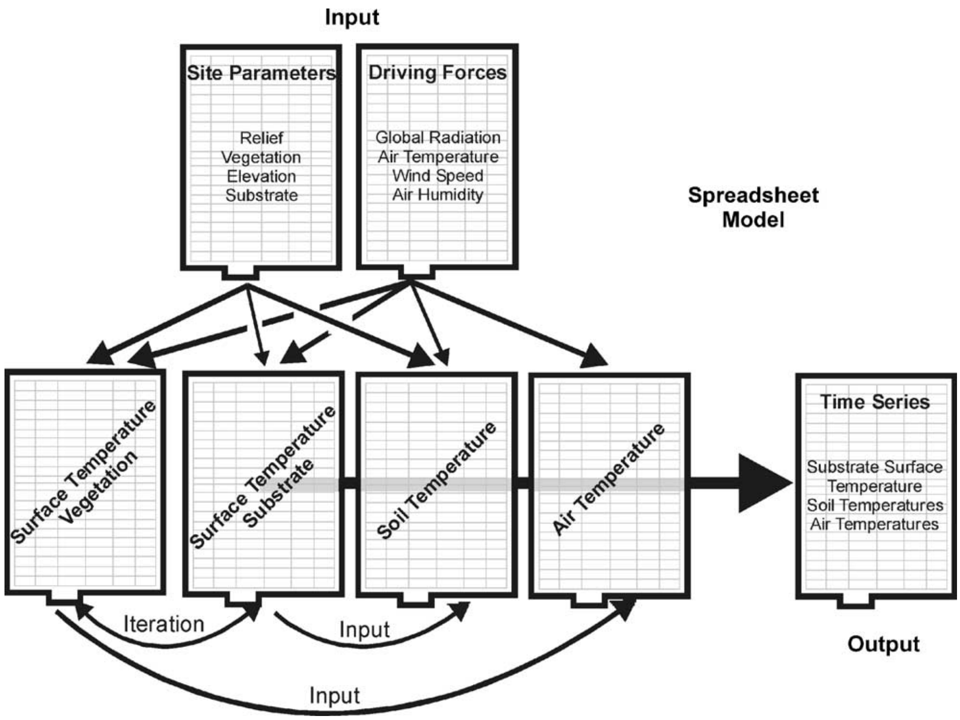

Fig. 3. Internal structure of the spreadsheet model. Site parameters served as input based on the tope concept, driving forces were meteorological data from a nearby station. Surface temperature of vegetation and substrate were calculated by solving its energy balance within iteration approaches. Afterwards they were used to calculate air and substrate temperatures. Time series of substrate surface, air and substrate temperatures were the model output.

- calculations of the spatial distribution of the actual and maximum possible radiation depending on the relief (Fu and Rich, 1999).

Besides the output of air temperature at +15 cm (hereafter referred to as $T + 15$), surface temperature (hereafter referred to as $T - 1$) and substrate temperature at a depth of −15 cm (hereafter referred to as $T - 15$), the governing sensible, latent, and ground heat fluxes also served as an output. Additionally, the water equivalent of the latent heat flux was used for the estimation of potential evaporation.

The model calculations were implemented using simple spreadsheets. The internal model structure consisted of seven compartments (Fig. 3, for mathematical details see below): (1) database of site depending environmental factors, (2) time series of variable input factors, (3) calculation routines of vegetation surface temperature, i.e. solving its energy balance by iteration, (4) calculation routines of ground surface temperature, again by solving its energy balance by iteration (5) calculation of substrate temperature, (6) air temperature, and finally (7) resulting time series of calculated values. The results were easily to visualized by spreadsheet routines and imported into a GIS for spatial analysis and extrapolation.

2.2.2. Basic assumptions

The surface temperature as driving force for heat fluxes, both in the air and the substrate, needed to be estimated first as the basis for further calculations. It was deduced from the balance between the energy fluxes at the surface, as expressed by Eq. (1). In this approach, the surface was seen physically as being the interface between substrate and air, without any vertical extension. Thus, energy could not be stored at the surface—the energy input needed to be equal to the energy output; the sum of energy fluxes was zero:

$$R_n + H_L + H_S + H_G = 0 \tag{1}$$

Each term in Eq. (1) was broken down into constituent parts and form a complete equation set consisting of net-radiation (R_n), evaporative flux (H_L), sensible heat flux (H_S), and ground heat flux (H_G), which was resolved to obtain the surface temperature.

The model represented temperatures of both bare and vegetation-covered substrates. In the latter case, the approach was expanded to include two surfaces: one of the substrate and one of the vegetation canopy. Generally, the description of energy fluxes given in the following sections was valid for both surfaces. Necessary modifications for the canopy surface were also given.

Starting with the discussion of Eq. (1), the net available radiant energy (R_n) was found to consist of two components (Eq. (2.1)): The absorbed solar flux at the surface (R_s) depending on global radiation R_{glo}, and the albedo of the surface (A, given as fraction) supposed to be independent of sun angle. The second component was the net long-wave flux (L_n) based on the temperature difference between the surface and the overlying medium according to the Stefan–Boltzmann–Law with σ being a constant of $5.67 \times 10^{-8}\,\mathrm{Wm^{-2}\,K^4}$. The equation for the net radiation of the substrate surface was given by

$$R_n = R_s + L_n = R_{glo}(1 - A_{sfc})(1 - A_c) \times \exp(-C\,\mathrm{LAI}) + \sigma(T_c - T_{sfc})^4 \quad (2.1)$$

The amount of solar radiation absorbed at the substrate surface (subscript sfc) not only depends on the albedo but also on the properties of the covering vegetation canopy (subscript c) expressed according to Schelde (1996, p. 8) by an empirical constant ($C = 0.5$) and the leaf area index LAI supposed to be 0–2.5 according to Bliss et al. (1981).

Regarding the canopy surface, the net long wave flux was more complex because of interactions with the atmosphere. Thus, Eq. (2.1) was changed to Eq. (2.2) according to Kondratyev (1969) to include a correction term for the actual vapour pressure of the air (e_a, Eq. (2.1.1), Mitchell et al., 1997: Eq. 52, 53), and an approximation of cloud cover (Mitchell et al., 1997: Eq. 58) by the ratio between actual global radiation R_{glo} and calculated maximum possible global radiation R_{glomax} (Fu and Rich, 1999). During night times when no global radiation was measured, cloud cover until midnight was roughly estimated from the mean ratio R_{glo}/R_{glomax} during the last 3 h before sunset and afterwards from the mean ratio during 3 h after sunrise.

$$R_n = R_s + L_n = R_{glo}(1 - A_c)(1 - \exp(-C\,\mathrm{LAI})) + \left(\frac{0.9 R_{glo}}{R_{glomax} + 0.1}\right)(0.34 - 0.14(e_a)^{1/2})\sigma T_a^4 + \sigma(T_a - T_c)^4 \quad (2.2)$$

$$e_a = e_s\,\mathrm{rH} \quad (2.2.1)$$

In Eq. (2.2.1), rH was the relative humidity as fraction, and e_s, the saturation vapour pressure (hPa) at actual air temperature in 2 m (T_a) calculated according to Mitchell et al. (1997: Eq. 52) by

$$e_s = \exp\left(\frac{54.88 - 5.03\ln(T_a) - 6791}{T_a}\right) \quad (2.2.1.1)$$

The net radiation itself was balanced by the upward flux of sensible heat (H_S, Eq. 3) into the atmosphere, the heat flux into the ground (H_G, Eq. (4)) and the latent heat flux (H_L, Eq. (5)) into the atmosphere.

2.2.3. Calculation of sensible heat flux

The flux of sensible heat was calculated using an aerodynamic approach mentioned by Fleagle and Businger (1963, p. 195):

$$H_s = \frac{c_a \rho_a k^2 (v_2 - v_1)(T_2 - T_1 + \Gamma(z_2 - z_1))}{(\ln(z_2/z_1))^2 \Phi_H} \quad (3)$$

In Eq. (3), c_a was the specific heat of air (1009 J $\mathrm{kg^{-1}\,K^{-1}}$, Oke, 2001, p. 44), ρ_a was the density of air ($\mathrm{kg\,m^{-3}}$) calculated by Eq. (3.1), k, the Karman constant (0.41), v, wind velocity ($\mathrm{ms^{-1}}$), T, temperature, Γ, the adiabatic lapse rate of temperature ($9.72 \times 10^{-3}\,\mathrm{K\,m^{-1}}$) and z, the height of measurement. To consider the stability of the atmosphere, a stability function for heat (Φ_H, Eq. (3.2)) according to Bruse (1997, p. 14) was included depending on the Richardson number Ri calculated by Eq. (3.2.1) (Oke, 2001, p. 380).

$$\rho_a = \frac{0.01276(\mathrm{PB_{sl}} - 0.0115E + 5.44\,10 - 7E^2)}{1 + 0.0367(T_a - 273.15)} \quad (3.1)$$

$\mathrm{PB_{sl}}$ in Eq. (3.1) represented the barometric pressure at sea level (hPa), and E, the elevation of the site (m).

$$\Phi_{\mathrm{H}} = \left(\frac{1-6\,Ri}{1-4\,Ri}\right)^{1/2} \quad \text{if } Ri < 0$$
$$\Phi_{\mathrm{H}} = \frac{1}{(1+2\,Ri)^{1/2}} \quad \text{if } Ri = 0 \tag{3.2}$$

$$Ri = \frac{g}{T}\frac{(T_2-T_1)/(z_2-z_1)}{((v_2-v_1)/(z_2-z_1))^2} \tag{3.2.1}$$

In Eq. (3.2.1), g was the acceleration due to gravity ($\mathrm{m\,s^{-2}}$), T with subscript, the temperature at the measurement heights z_1 and z_2, T without subscript, the mean of these two values and v, wind velocity at the two heights z_1 and z_2. In the above-mentioned equations the subscripts 1 and 2 referred to the surface itself and the vegetation canopy in case of the substrate surface to be regarded, otherwise they referred to the canopy surface and the air at 2 m.

This aerodynamic approach required measurements of both vertical temperature and wind velocity gradients. As the wind velocity was measured continuously at a height of 2 m only, its vertical profile had to be estimated. According to Oke (2001, p. 381) the wind velocity gradient between 2 m and the canopy surface as well as between both surfaces was estimated with the equation

$$\frac{v_2-v_1}{z_2-z_1} = \frac{v^*\ln(z_2/z_1)}{k\,(z_2-z_1)} \tag{3.3}$$

provided the friction velocity (v^*) given by Eq. (3.3.1) with h being the height of the vegetation canopy:

$$v^* = \frac{kv_{2\mathrm{m}}}{\ln(2/0.131h^{0.997})} \tag{3.3.1}$$

2.2.4. *Calculation of ground heat flux*

The ground heat flux H_{G} ($\mathrm{Wm^{-2}}$) was expressed by

$$H_{\mathrm{G}} = \frac{\lambda\,\Delta T}{\Delta z} \tag{4}$$

where λ was the thermal conductivity of substrate ($\mathrm{Wm^{-1}\,K^{-1}}$), ΔT, the temperature difference between surface and first measurement point within substrate and Δz, the depth of the first measurement point within substrate. Thermal conductivity is a complex function of soil solids and soil moisture. For unfrozen mineral substrate an empirical conductivity function was adapted from Kersten (1949)

$$\lambda = 0.1442\,(c_1\log\theta_{\mathrm{w}} + c_2)10^{(c_3\rho_{\mathrm{s}})} \tag{4.1}$$

where c_1, c_2, c_3 were constants depending on whether the substrate was dominated by clay, silt or sand, θ_{w} described the volumetric water content (%), and ρ_{s} is the dry bulk density of the substrate ($\mathrm{g\,cm^{-3}}$). For the predominating silty sand the following parameterisation was used: $c_1 = 1.24$, $c_2 = -0.11$, $c_3 = 0.62$, $\rho_{\mathrm{s}} = 1.6$.

Thermal conductivity of organic matter was estimated by a function adapted from a figure in De Vries (1975):

$$\lambda = 0.06 + 0.005\,\theta_{\mathrm{w}} \tag{4.2}$$

2.2.5. *Calculation of latent heat flux*

The latent heat flux H_{L} ($\mathrm{Wm^{-2}}$) was calculated using the combination method suggested by Penman and reported in Mitchell et al. (1997) for the case of a saturated surface

$$H_{\mathrm{L}} = \frac{s(R_{\mathrm{n}}-H_{\mathrm{G}}) + c_{\mathrm{a}}\rho_{\mathrm{a}}(e_{\mathrm{s}}-e_{\mathrm{a}})/r}{s+\gamma} \tag{5}$$

where s was the slope of the saturation vapour pressure curve (10^3 $\mathrm{Pa\,K^{-1}}$) (Eq. (5.1)), γ, the psychrometer constant (10^3 $\mathrm{Pa\,K^{-1}}$) (Eq. (5.2)), and r the aerodynamic resistance ($\mathrm{sm^{-1}}$) (Eq. (5.3)).

$$s = \frac{e_{\mathrm{s}}}{T_{\mathrm{a}}(6791/T_{\mathrm{a}} - 5.03)} \tag{5.1}$$

$$\gamma = 6.610^{-4}(\mathrm{PB_{sl}} - 0.0115\,E + 5.4410^{-7}E^2) \tag{5.2}$$

$$r = \frac{6.25(\ln(10-d)/z_0)^2}{v_{2\mathrm{m}}} \quad \text{if site is covered by vegetation,}$$
$$r = \frac{350}{v_{2\mathrm{m}}} \quad \text{for bare ground} \tag{5.3}$$

In Eq. (5.3) the displacement height d (m) (Eq. (5.3.1)) and the surface roughness length z_0 (m) (Eq. (5.3.2)) were calculated depending on the vegetation height h (m).

$$d = 0.702\,h^{0.979} \tag{5.3.1}$$

$$z_0 = 0.131\,h^{0.997} \tag{5.3.2}$$

Eq. (5) describes non-water-limited conditions. Considering that water to become limiting and actual evaporation to be less than potential, a simple approach proposed by Tanner (1967) was used assuming water to be equally available throughout the entire soil water range but not accessible at the permanent wilting point. As continuous measurements of soil moisture at the driest sites within the investigation areas indicated, water contents were constantly higher than at the permanent wilting point (Löffler, 2002). For simplification the actual latent heat flux was assumed to be equal to the potential heat flux described by Eq. (5).

2.2.6. Iteration approach to obtain the surface temperature

The unknown quantity within the energy flux equations was the surface temperature enabling the equation system of Fig. 4 to be solved according to temperature of both the substrate surface and the canopy surface.

A numerical solution was prevented, because many parameters in these equations were indirectly or directly related to the surface temperature itself. The solution was found by iterations as to *regula falsi* (Bruse, 1997, p. 25). This approach consisted of the following steps:

(a) Two initial surface temperature values (T^0 and T^1) were chosen. For T^0 the temperature of the former time step was used; T^1 is set to be $T^0 + 0.2$.
(b) These two temperatures were used to calculate the energy balance according to Eq. (6.1) resulting in two balance values F^0 and F^1:

$$F^{\mathrm{X}} = R_{\mathrm{n}} + H_{\mathrm{G}}(T^{\mathrm{X}}) + H_{\mathrm{L}}(T^{\mathrm{X}}) + H_{\mathrm{S}}(T^{\mathrm{X}}) \quad (6.1)$$

(c) Inserting these two values into Eq. (6.2) yields a new value T^2 for the surface temperature:

$$T^2 = \frac{T^1 - F^1(T^1 - T^0)}{F^1 - F^0} \quad (6.2)$$

(d) It was set $T^0 = T^1$ and $T^1 = T^2$; steps (b) and (c) were repeated until the convergence criterion $|T^1 - T^0| = 0.001\,\mathrm{K}$ was reached.

The canopy surface temperature was calculated first, using the substrate surface temperature of the former time step. Then the result was used to calculate a new substrate surface temperature and vice versa. In this way, the definite temperatures were found by iteration.

2.2.7. Estimation of substrate temperature variations

The substrate layer was assumed to have homogenous thermal properties. Using a backward difference scheme provided by Hanks and Ashcroft (1980, p. 136) it was possible to approximate the non-steady state heat flux equation numerically by Eq. (7).

$$\frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{D_{\mathrm{h}}(T_{i-1}^j - 2T_i^j + T_{i+1}^j)}{\Delta z^2} \quad (7)$$

where the i subscripts referred to depth increments, Δz distance apart and the j superscripts referred to the time increments, Δt time apart, and D_{h} being the thermal diffusivity ($10^{-6}\,\mathrm{m^2\,s^{-1}}$) of the substrate given for silty sand by Eq. (7.1) and for organic matter by Eq. (7.2).

$$D_{\mathrm{h}} = \frac{1.7554 \log \theta_{\mathrm{w}} - 0.1557}{1.115 + 0.042\theta_{\mathrm{w}}} \quad (7.1)$$

$$D_{\mathrm{h}} = \frac{0.06 + 0.005\,\theta_{\mathrm{w}}}{0.5 + 0.042\theta_{\mathrm{w}}} \quad (7.2)$$

Eq. (7) provides a computational scheme to estimate substrate temperatures as a function of time and depth. However, the solution required knowledge of the vertical temperature gradient at the beginning of the calculation (known initial conditions) and substrate surface temperature as a function of time (known upper boundary conditions) as well as information about the temperature at a certain depth as a function of time (known lower boundary conditions). For simplification the lower boundary condition was assumed to be constant over time. This assumption was valid at depths of 0.2 and 0.5 m (diurnally) or 3 and 8 m (annually) (Peixoto and Oort, 1992, p. 221) and depended on the value of D_{h}.

2.2.8. Estimation of air temperature variations

Different from the approaches directly linked to the energy balance used for calculation of the surface temperature and soil temperatures, air temperatures were estimated more simple. The air temperature was assumed to decrease (at night) or increase (at daytime) logarithmically with height according to Eq. (8) (Geiger, 1961, pp. 82–84),

$$T_1 - T_2 = c \ln \frac{z_1}{z_2} \quad (8)$$

where c was an empirical constant. It was estimated by resolving Eq. (8) for c and using the modelled temperature of the vegetation surface and the measured air temperature at a height of 2 m. Thus, the air temperature at every height was calculated using Eq. (8.1),

$$T^{z} = T^{1} + c \ln \frac{z}{2} \tag{8.1}$$

where the z superscript referred to the unknown air temperature at the height z and the 1 superscript referred to the air temperature at the height of 2 m.

2.3. Model evaluation

The model was calibrated for different sites, including lichen heath covered ridge positions, mid slopes covered by dwarf shrub heath and depressions with mire vegetation using measured temperatures. The site depending parameters albedo, LAI and soil water content were then adjusted by minimising the difference between observed and calculated surface temperature for 168 data points.

The goodness of temperature representation after minimising was tested against independent hourly temperature measurements (a) throughout 14 days for the ridge positions and (b) one exemplary day for slopes and depressions. It was presented using mean bias of calculated versus observed values and its standard deviation as well as r^2-values of a linear regression.

3. Results

3.1. Local sites along broad-scale gradients

The transition from oceanic to continental conditions in central Norway marks the governing macro-scale latitudinal gradient to be regarded (Aune, 1993). At meso-scale, the altitudinal gradient is characterised by increasing precipitation and decreasing temperatures (Barry, 1992). Four ridge positions chosen as representative examples for the low and middle alpine altitudinal belt in the western and eastern Norwegian high mountain region illustrate vertical near-surface temperature dynamics and water fluxes. Results of the simple approach to apply the adiabatic lapse rate of 0.6 K per 100 m to calculate middle alpine air temperature (2 m) from observed air temperatures in the low alpine belt are summarised in Table 2. Air temperatures at a height of 2 m above the surface do not represent temperatures in all near-surface strata properly, as shown in Table 3. More detailed investigation were necessary. The chosen time interval from 1st to 14th July 2001 (Fig. 4a and b) represented different weather conditions typical of summer months among oceanic and continental conditions. Furthermore, observed temperatures and precipitation agreed well with the long-term means of the official stations No. 16740 (1976) (Lesja, Oppland) at 626 m in the eastern investigation area, and No. 60500 (1930) (Tafjord, Møre og Romsdal) in the western investigation area at 15 m given by DNMI (2003).

Table 2
Accuracy of estimated air temperatures at 2 m for the middle alpine ridge positions, using measured low alpine temperatures and the adiabatic lapse rate of 0.6 K per 100 m in comparison with observed values

$T+200$ calculated/$T+200$ observed	West	East
mb	0.132	−0.635
std	1.233	1.178
r^2	0.884	0.938

Accuracy is expressed as mean bias (mb), its standard deviation (std) and r^2-values (linear regression).

During the summer months, the oceanic western Norwegian mountains (Fig. 4a) were characterised by preominantly cloudy conditions due to their position on the western side of the Scandes currently affected by cyclones. Consequently, the input of solar radiation was low, only about 45% of its maximum possible extent, and the precipitation sum exceeded 78 mm (middle alpine: 100 mm) within the considered period.

Fig. 4. (a) Vertical water and temperature fluxes in ridge positions of the low and middle alpine altitudinal belts in western Norway (raw data from hourly intervals, evaporation line from daily intervals with interpolated curvature); oceanic low alpine ridge position at 900 m above sea level with *Rhacomitrium laguminosum* lichen heath; oceanic middle alpine ridge position at 1400 m above sea level with *Carex bigelowii* lichen heath. (b) Vertical water and temperature fluxes in ridge positions of the low and middle alpine altitudinal belts in eastern Norway (raw data from hourly intervals, evaporation line from daily intervals with interpolated curvature); continental low alpine ridge position at 1,100 m above sea level with *Arctostaphylos uva-ursi* lichen heath; continental middle alpine ridge position at 1450 m above sea level with *Luzula confusa* lichen heath.

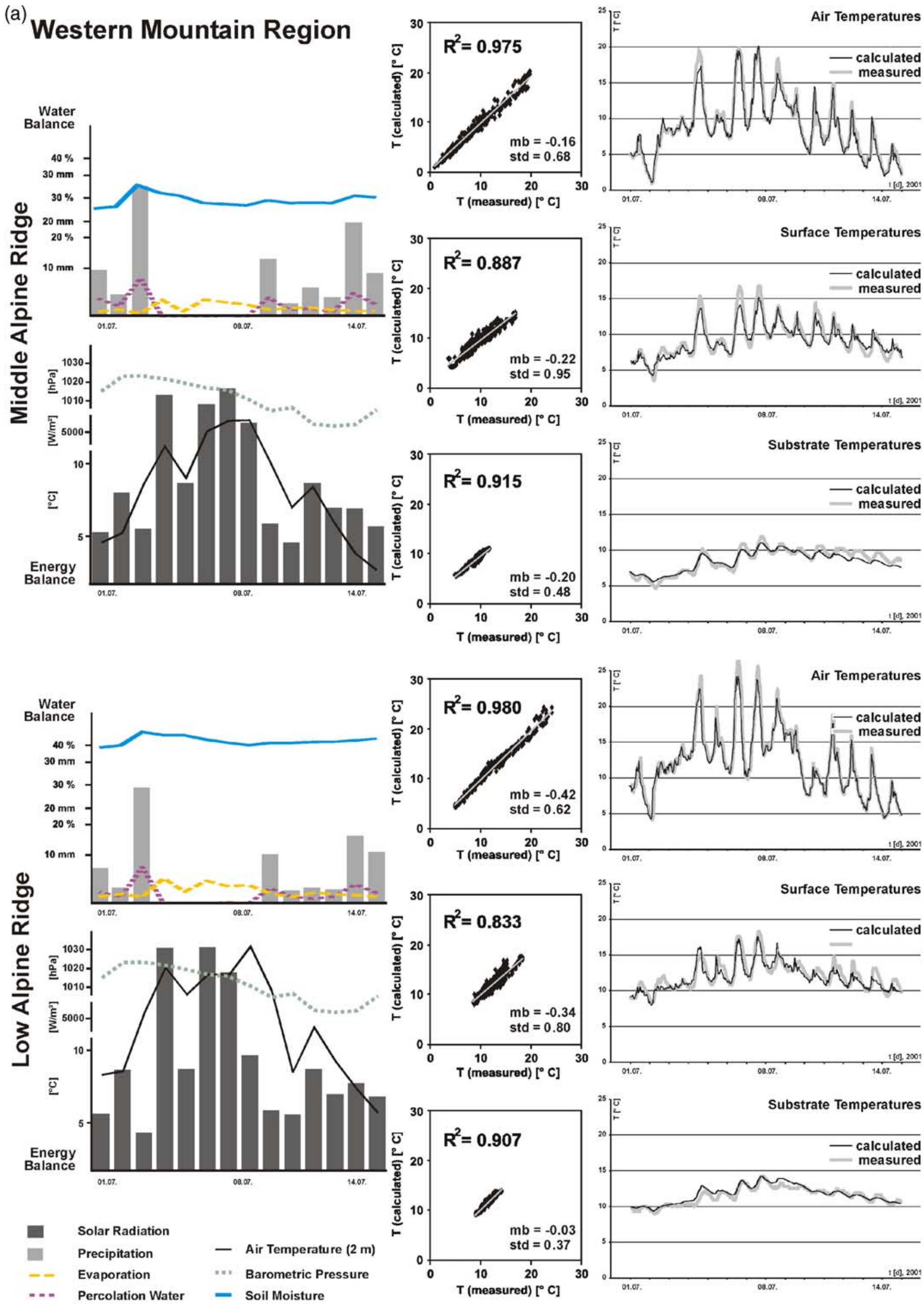
(a)
Western Mountain Region
Middle Alpine Ridge
Low Alpine Ridge
Water Balance
Energy Balance
R² = 0.975
mb = -0.16
std = 0.68
R² = 0.887
mb = -0.22
std = 0.95
R² = 0.915
mb = -0.20
std = 0.48
R² = 0.980
mb = -0.42
std = 0.62
R² = 0.833
mb = -0.34
std = 0.80
R² = 0.907
mb = -0.03
std = 0.37
T (calculated) [° C]
T (measured) [° C]
Air Temperatures
Surface Temperatures
Substrate Temperatures
calculated
measured
Solar Radiation
Precipitation
Evaporation
Percolation Water
Air Temperature (2 m)
Barometric Pressure
Soil Moisture

Fig. 4.

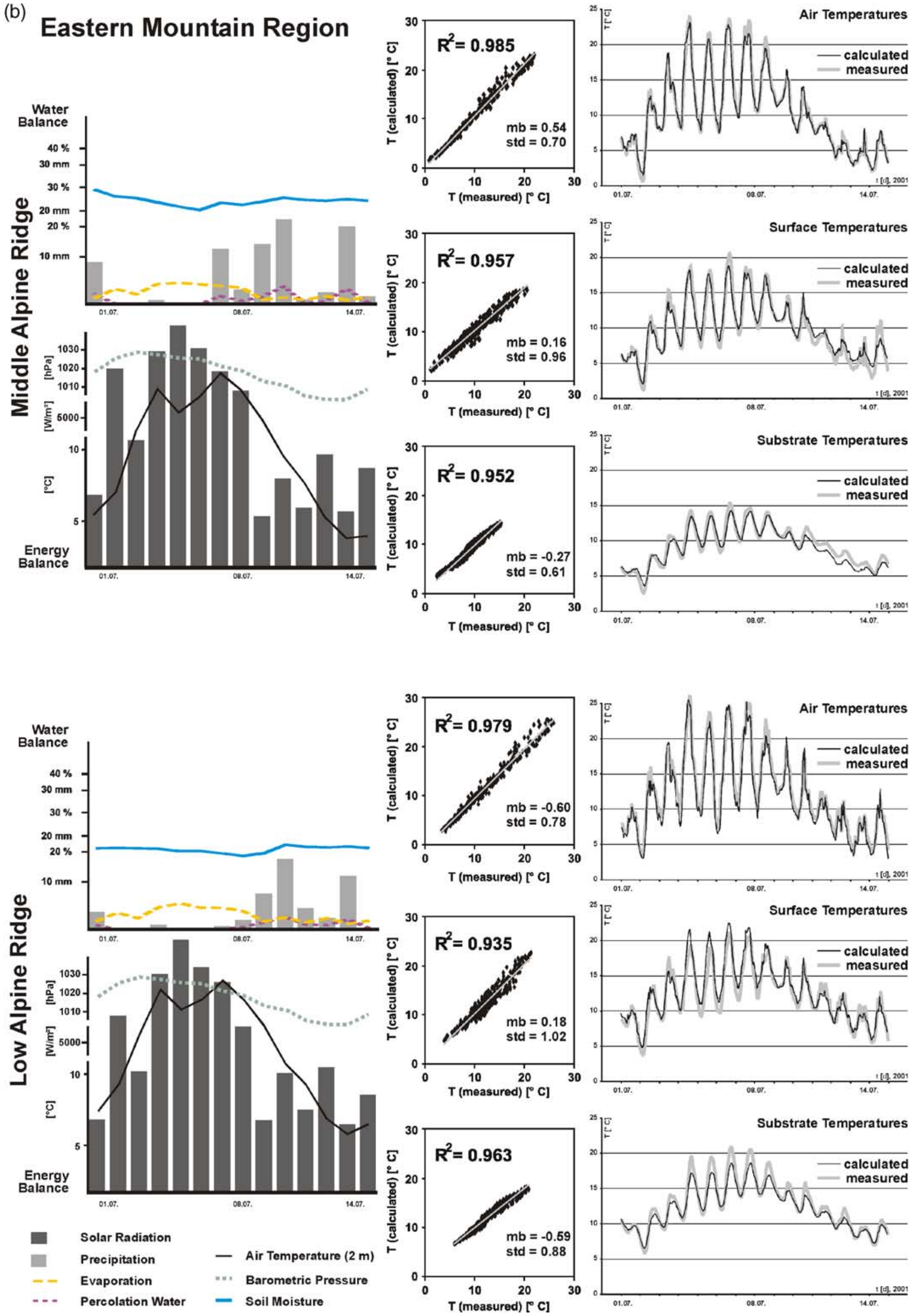

Fig. 4. (*Continued*).

Table 3
Correlation between air temperature at 2 m ($T + 200$), air temperature at 15 cm ($T + 15$), surface temperature ($T - 1$), and substrate temperature ($T - 15$), expressed as mean bias (mb), its standard deviation (std) and r^2-value (linear regression)

	West			East		
mb[a]	0.348	1.100	0.657	−0.459	0.085	0.121
std[a]	3.450	2.348	1.150	2.826	1.624	1.030
r^2[a]	0.161	0.619	0.933	0.681	0.879	0.962
	$T - 15/T + 200$	$T - 1/T + 200$	$T + 15/T + 200$	$T - 15/T + 200$	$T - 1/T + 200$	$T + 15/T + 200$
mb[b]	−0.187	0.604	0.760	1.211	1.179	0.752
std[b]	3.600	2.924	1.333	2.485	1.383	0.956
r^2[b]	0.222	0.523	0.912	0.735	0.927	0.977

Values are given for four ridge positions each two in the low and middle alpine belt of western and eastern Norway.
[a] Middle alpine belt ($T + 200$).
[b] Low alpine belt.

Temperature dynamics at 2 m, on the one hand, corresponded with input of solar radiation and, on the other hand, were superimposed by the influence of prevailing weather situations indicated by barometric pressure. Despite high rates of potential evaporation (38 and 30 mm), the substrate remained saturated as an effect of frequent rainfalls and percolation processes, also inhibiting strong surface temperature dynamics due to the resulting high heat capacity. As substrate moisture also affects the thermal diffusivity, substrate temperature dynamics were very low. Due to the technique of measurement, highest temperature dynamics were not found at the surface, as they referred to a depth of −1 cm reinforced by the isolation of a dense vegetation cover, but in the air ($T + 15$). Representation of near-surface temperature dynamics using the modelling approach was very good for both sites, reaching r^2-values >0.8 combined with low biases.

Although substrate, vegetation and summer air temperatures (2 m) were similar to those of the western region, near-surface temperature dynamics was much more pronounced under continental climatic conditions in the eastern mountains (Fig. 4b): lower degrees of cloudiness were common, irradiance was about 60% of its possible extent, and precipitation was commonly reduced to short convective showers resulting in 46 (75) mm. Additionally, high potential evaporation rates of about 54 (35) mm were present in a relatively dry atmospheric layer with 62 (90)% relative humidity compared to 78 (85)% in the western mountain region. This dry situation especially in the low alpine belt affected substrate moisture to a less extent. Obviously, the volumetric moisture content was low compared to the western mountain region but remained constant above permanent wilting point. In combination, great diurnal irradiance and nocturnal cooling due to less cloud cover, as well as moisture induced low heat capacity and great thermal diffusivity of the substrate resulted in strong near-surface temperature dynamics. Variations were very well represented ($r^2 > 0.9$) using this modelling approach.

3.2. Fine-scale spatial temperature dynamics

The investigation of fine-scale near-surface temperature differentiation within the catchments was enabled by measurements or, more feasible, simulation of temperatures for every single location. To verify the spatial applicability of the model, it was applied to the main topographic positions in the low alpine belt of eastern Norway among a high pressure situation on 5 July 2001 (Fig. 5).

Due to their high sensitivities, substrate type, substrate moisture, and vegetation cover were adjusted for an application of the model to these sites, whereas wind speed and air temperature (2 m) throughout the small catchment were assumed to be equal to measured values at ridge position. Irradiance was calculated depending on topography. For the calculation of surface temperatures of organic substrate, i.e. *Sphagnum* moss, no differentiation was made between canopy surface and substrate surface.

Data achieved by simulation were found in reasonable agreement with measured values (i.e. r^2-values

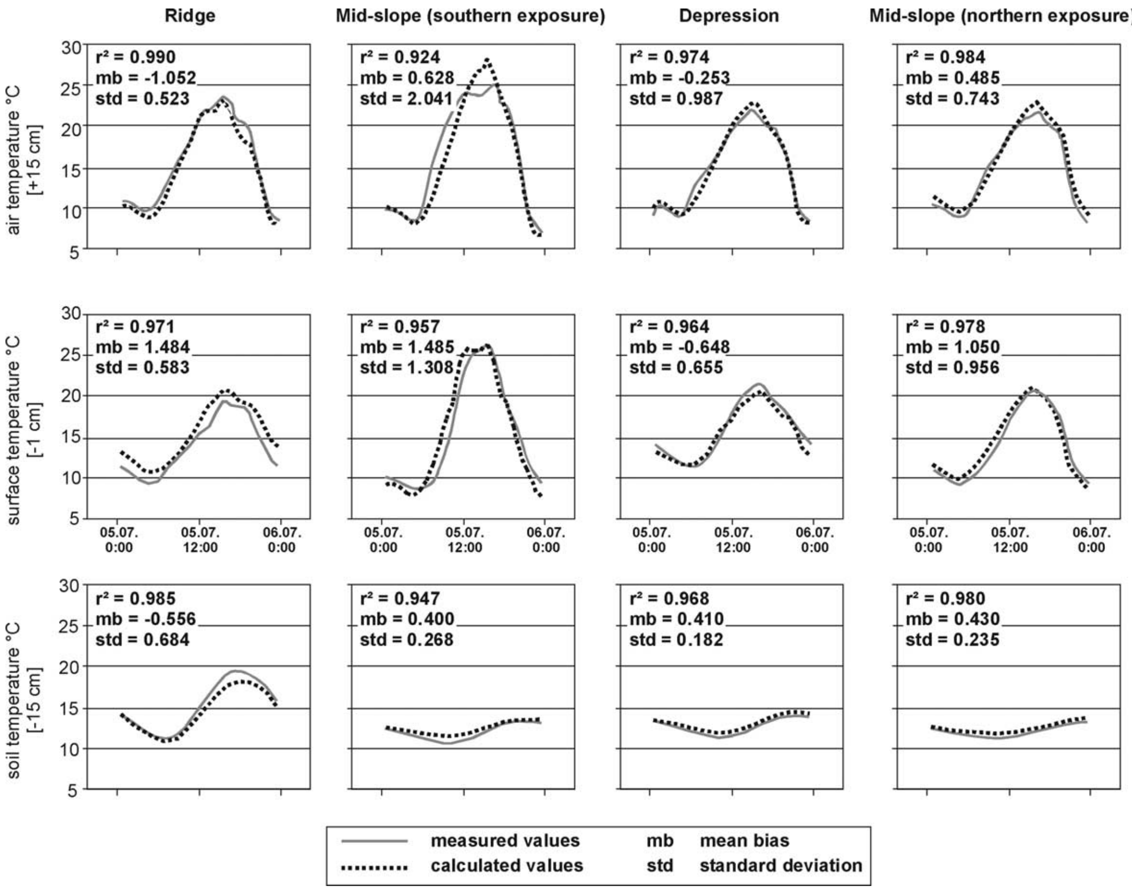

Fig. 5. Diurnally measured and calculated temperatures for characteristic topographical positions in the low alpine belt of continental eastern Norway.

> 0.9, Fig. 5) and were used for spatial extrapolation within the catchment. One example of this extrapolation based on the tope concept is shown in Fig. 6. The three surface, air, and substrate layers were differentiated for characteristic diurnal situations: before sunrise (3:00 h MET), high noon (13:00 h), and after sun set (21:00 h). The simulated spatial temperature patterns were validated using hand-held measurements within a micro-spatial net of 48 locations and found in reasonable agreement of ±1 K. Thus, although heterogeneous micro-topography and vegetation structures were most obvious within the delineated topes the model utilization based on the tope concept proved to be sufficient according to its spatial and temporal resolution.

4. Discussion

Regional and local climate besides other parameters are controlling factors with regard to ecosystem functioning (Fremstad, 1997), but the assessment of meteorological data is a general problem in high mountain research. As generally stated by Price and Barry (1997), most official meteorological stations are to be found in the valleys. At 62° North in central Norway only 6 of 107 stations are situated above alpine timberline. Consequently, common approaches of spatial data interpolation based on statistics (e.g. Fleming et al., 2000; Hutchinson, 1995) are critical due to the general lack of data from higher elevations. A simple, but common approach to assess altitudinal gra-

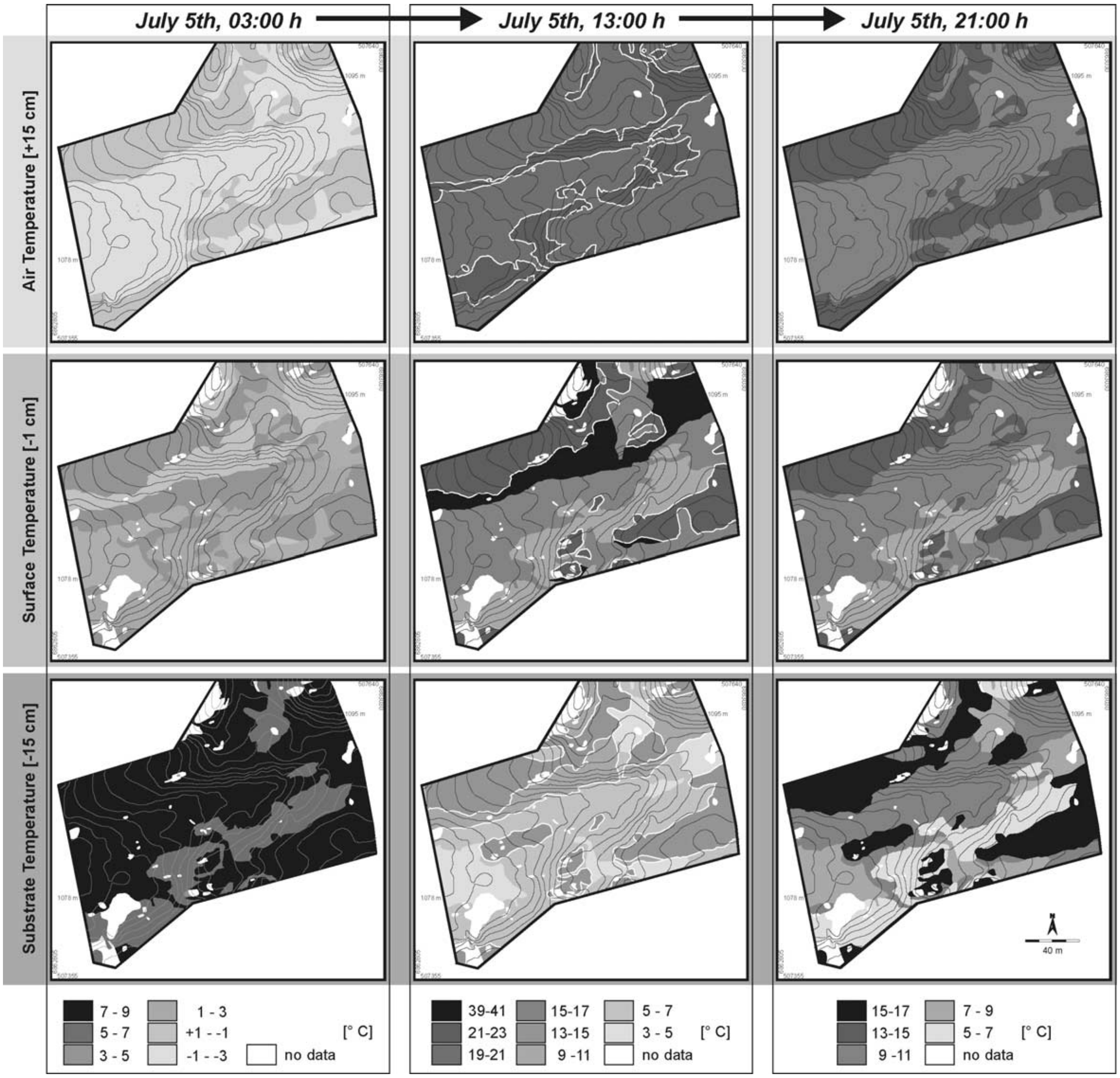

Fig. 6. Simulated spatio-temporal variation of substrate (−15 cm), surface (−1 cm), and air (+15 cm) temperatures. The figure illustrates micro-spatial gradients of temperatures within a small east–west-oriented catchment with pronounced northern and southern exposure of slopes, wind exposed ridges, and linear and plain depressions. Vertical temperature profiles were simulated for three diurnal stages during a high pressure weather situation. Maps were based on tope type polygons—thus, sharp and abrupt spatial changes in temperature conditions are artefacts. The simulation runs were validated by 48 field measurements justifying modelled results within an accuracy of ±1 K.

dients is based on the adiabatic lapse rate of temperature (Whiteway et al., 1995), despite increasing biases when regarding higher temporal resolution instead of long-term means (Table 2). However, the ecological relevance of the (mean) air temperature at a height of 2 m above ground commonly used for these approaches seems to be questionable (Leser, 1997, p. 194), especially in high mountain landscapes where vegetation cover seldom extends beyond heights of 1 m. Additionally, temperature regimes at this height cannot be transferred to the surface or substrate layers (Table 3).

On the other hand, common model applications designed for an accurate representation of near-surface conditions (SVAT models) are not applicable in poorly investigated areas or at large scales due to their data requirement (Boulet et al., 2000). Despite its simplicity compared to these models, the energy balance model presented in this paper enabled pretty exact representation of near surface temperature dynamics: At least 80% of the variance of observed temperatures among different governing atmospheric conditions was explained (Fig. 4a and b). Furthermore, it was shown that the general trend of low temperature dynamics in oceanic region compared with pronounced dynamics in the continental region manifested in general precipitation and air temperature regimes (Aune, 1993).

Furthermore, spatial statements about temperature dynamics were enabled using the approach of tope delineation as climatologic response units combined with a vertically structured one-dimensional model (Fig. 6). Simulation runs for five sites were used to represent temperature dynamics within the entire catchment within an accuracy of ±1 K despite neglecting lateral processes.

In general, the goodness of the model was tested for different sites among different summer conditions so far (Fig. 4a and b, Fig. 5). But despite its accuracy it contained the following limitations:

- The link between water and energy balance (Fig. 1) was not sufficiently integrated in the model as substrate moisture was roughly estimated depending on precipitation events.
- Effects of a snow pack were not represented.
- The model needs to be evaluated for larger areas, using remote sensing data as site depending input and derived meteorological input data as driving force.

5. Conclusions

It is shown that it was possible to get useful results with this simple spreadsheet modelling approach. Though, dealing with a spatial approach in high mountain landscapes the model calculating temperature variations had to be simple, since detailed parameterisation of a complex model would not have been feasible. The numerous parameters not being available within the frame of the landscape ecological project prevents available SVAT models from being applied. As a result, these models could not be compared with the presented model that was based on simple parameterisation being verified by a large amount of field data instead. It was shown that extensive parameterisation of complex models was avoided by extensive field measurements for the validation of a simple model. To sum up, the modelling approach served as a sufficient tool to simulate large map scale micro-spatial temperature variations to be used for the explanation of ecosystem functioning in high mountain catchments. Combining investigations in different catchments along altitudinal and oceanic-continental gradients, for instance, will result in a process-oriented geographical comparison of alpine landscapes. Spatial extrapolation into broader scales combined with regionalisation approaches could also be supported with a simple model that simulates spatial temperature variations on the basis of field measurements in a wider net. Applying this model to smaller map scales facilitates the approach of regionalisation resulting in generalised spatial data for the sake of precise local accuracy. Such geographically based procedures enable spatio-temporal modelling of ecosystem functioning for different scales (Wendland and Kunkel, 1998; Krysanova et al., 1999; Bronstert et al., 2001; Diekkrüger et al., 2001; Fohrer et al., 2001; Steinhardt and Volk, 2002). In general, quantification of biogeochemical cycles and energy fluxes in catchments and regionalisation of results into larger areas can be considered as perspectives in ecosystem analysis (Withers and Meentemeyer, 1999). Additionally, Gottfried et al. (1999) refer to functional data for high mountains being necessary to understand and to explain current systems in order to draw scenarios of future changes in alpine environments.

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5.3 Publikation III

Löffler, J. & R. Pape (2004)

Across scale temperature modelling using a simple approach for the characterization of high mountain ecosystem complexity.

Erschienen in:

Erdkunde 58: 331-341.

Dazu: Beilage I

ACROSS-SCALE TEMPERATURE MODELLING USING A SIMPLE APPROACH FOR THE CHARACTERIZATION OF HIGH MOUNTAIN ECOSYSTEM COMPLEXITY

With 6 figures and 1 supplement (III)

JÖRG LÖFFLER and ROLAND PAPE

Zusammenfassung: Skalenübergreifende Temperaturmodellierung unter Verwendung eines einfachen Ansatzes zur Charakterisierung der Ökosystemkomplexität im Hochgebirge

Ein einfacher Modellierungsansatz wurde zur Charakterisierung der Komplexität von Hochgebirgsökosystem verwendet, um die Dynamik der oberflächennahen Temperaturen zu simulieren. Die Heterogenität der untersuchten Landschaft führte zu einem skalenübergreifenden Vorgehen, das die vertikalen Interaktionen am Standort (Nano-Skala), die kleinräumige Differenzierung innerhalb von Einzugsgebieten (Mikro-Skala) und den Höhenstufenwandel eines gesamten Gebirgsmassivs (Meso-Skala) verknüpfte. Das Modell wurde anhand detaillierter Messungen an verschiedenen Standorten kalibriert. Nach einer Modellvalidierung mit Daten sehr hoher zeitlicher Auflösung waren die Simulationsläufe zufrieden stellend. In allen Fällen konnte das Modell die Varianz der gemessenen Temperaturen mit einer Genauigkeit von über 80% erklären. Nachfolgend wurden Korrelationen zwischen generellen meteorologischen Trends und der mikroklimatischen Differenzierung untersucht. Die Hypothese war, dass übergeordnete Witterungsverläufe als meteorologische Phänomene ihre Entsprechung in der mikroklimatischen Situation (v.a. in der Dynamik der oberflächennahen Temperaturen) finden und somit für die Steuerung der ökosystemaren Funktionsweise verantwortlich gemacht werden können. Die Ergebnisse zeigten jedoch, dass die kleinräumigen Verhältnisse ihren Ausdruck in komplexen Grundzügen des Temperaturwandels entlang großräumiger Höhengradienten finden. Der generell zur Beschreibung der Höhenwandels herangezogene adiabatische Koeffizient konnte deshalb nicht zur Interpretation des vorgefundenen ökosystemaren Wirkungsgefüges verwendet werden. Die Abweichungen zwischen den Messwerten und den allgemeinen Annahmen wurden in Korrelationsmatrizen aufgezeigt. Schließlich konnte die Komplexität der ökosystemaren Steuerung durch den Energiehaushalt mit Hilfe von Temperaturgradienten erklärt werden, die durch eine skalenübergreifende Multiregressionsanalyse ermittelt wurden. Es wurde somit gezeigt, unter welchen raum-zeitlichen Rahmenbedingungen und mit welchen Abweichungen die standörtlichen Verhältnisse den generellen meteorologischen Annahmen entsprechen.

Summary: A modelling approach was practised to characterize the complexity of high mountain ecosystems using a new simple model to simulate near-surface temperature variations. The heterogeneity of the investigated landscape led to an across-scale procedure that combined vertical interactions at single locations (nano-scale), micro-spatial differentiations within small catchments (micro-scale), and altitudinal changes of an entire mountain system (meso-scale). The model was calibrated on detailed measurements for different sites. Simulation runs were satisfactory according to model validation based on data with high temporal resolution. In all cases, more than 80% of the variance of observed temperatures was explained by the model. We analysed correlations between general meteorological trends and local climatic differentiations. The hypothesis was that different overlying meteorological phenomena (i.e. different weather situations) would find their expression in micro-climatic conditions (especially in the variation of near-surface temperatures) superiorly determining ecosystem functioning. It turned out that the micro-spatial conditions resulted in complex principles of thermal changes along altitudinal broad-scale gradients. So, the adiabatic lapse rate, commonly used to describe the altitudinal zonation, did not explain the different mosaics of ecosystems. We illustrated the biases between measurements and common assumptions by means of correlation matrices. To conclude, the complexity of the ecosystem determining energy balance was described by complex differences of temperature gradients that were achieved from across scale multi-regression analysis. It was shown to which degree local site conditions corresponded with meteorological assumptions under different spatio-temporal conditions.

1 *Introduction*

1.1 Complexity in northern high mountains

Northern high mountain landscapes above the timberline show diverse micro-spatial patterns of ecosystems that function most heterogeneously according to interaction and combination of different environmental parameters (KÖRNER 1995; MOSIMANN 1985; SHAVER a. JONASSON 1999). Steep meteorological and topographical gradients, as well as altitudinal zonation and complex relief micro-features, most decisively affect the alpine ecology (BILLINGS 1973; KUDO et al. 1999; JONES et al. 2001). Those gradients are complex and their impact on the environment is not yet fully understood (KÖRNER 1999). With their focus on Fennoscandian alpine vegetation many case studies have been conducted very early (e.g. documented by PÅHLSSON

1994). Since little is known about environmental conditions and vegetation patterns at higher elevations (FREMSTAD 1997), however, the scientific challenge in mountain geography of northern Europe is still to intensify research on fine-scale temperature and snow cover determinants, and superior broad-scale oceanic-continental gradients (FÆGRI 1972). Consequently, convictions on the environmental determination of the northern high mountain vegetation could be scrutinized as to new results of a long-term landscape ecological project (KÖHLER et al. 1994).

1.2 Across-scale concept

The concept of multiple scales was adopted to 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).

Some explanations of the determination of high mountain ecosystems that dominate literature were found insufficient regarding different spatial scales (LÖFFLER 2003). The fine-scale topography was supposed to impact upon the vegetation within two major causal chains (DAHL 1956; BILLINGS 1973; MAY 1976; MOLENAAR 1987; ISARD a. BELDING 1989; WALKER et al. 2001). Simplified, these chains are: a) exposed site – thin snow cover – strong prevailing winds – enforced evapotranspiration – lack of soil moisture – drought stress – cold winters but long vegetation period, and b) lee slope – thick snow cover – shelter against winds and low temperatures – sufficient supply of water but short vegetation period. By quantifying soil moisture and micro-climate variability we showed that a lack in water availability was not found at any time. Instead, complex spatio-temporal temperature gradients affected the vegetation superiorly (LÖFFLER 2004).

Moreover, the altitudinal gradient across the alpine belts had been explained by temperature and precipitation means corresponding with specific changes in the vegetation (FÆGRI 1972; MYKLESTAD 1993; HUGGETT 1995; VIRTANEN et al. 1999). So, higher elevations had principally been understood as being under harder environmental conditions (GJÆREVOLL 1990; FREMSTAD 1997). Our results on micro-climatic determination of the vegetation gave evidence that higher precipitation resulted in earlier and thicker sheltering snow cover at higher elevations. Hence, the lowest temperatures were found at lower altitudes as to inversions, where snow cover was thinnest and frost damage was most affecting (LÖFFLER 2003). All in all, the results showed that vegetation was above all determined by prevailing near-surface temperature variations resulting from complex factor constellations at different sites (LÖFFLER 2002a).

As shown in figure 1, thermoisopleth diagrams were used to illustrate the complex daily and annual variations of near-surface temperatures. Three layers were analysed, air temperature at 15 cm height above ground (referred to as T+15 hereafter), sub-surface temperature measured at 1 cm depth below ground (referred to as T–1 hereafter), and substrate temperature at 15 cm depth below ground (referred to as T–15 hereafter). These were chosen for site comparison along topographical gradients, micro-spatial ecotope type characterization, and broad-scale analysis of altitudinal changes. The three near-surface temperature layers were analysed as to their synchronicity (by means of r^2, defined as the variance of one curve explained by another) and their deviation (by means of RMSE, defined as a measure of deviation) against the standard meteorological air temperatures at 2 m height (referred to as T+200 hereafter). Figure 1 schematically explains 13 different ecological processes combined with dominant temperature conditions near ground over time (LÖFFLER a. WUNDRAM 2001). With this diagram we explained both vertical temperature profiles and spatial temperature differentiations: these differed extraordinarily within a fine-scale focus and statistically corresponded significantly with the distribution of plant species and vegetation types (LÖFFLER 2003). In addition, spatial near-surface temperature differentiations were particularly supposed to determine abundances of epigeic arthropods (OTTESEN 1996).

Combining investigations in different catchments along altitudinal gradients resulted in a process-oriented geographical comparison of alpine landscapes (LÖFFLER a. WUNDRAM 2003). Spatial extrapolation into broader scales combined with regionalization approaches were supported with a simple model that simulated spatial temperature variations on the basis of field measurements in a wider net (PAPE a. LÖFFLER 2004). Within the ecosystem approach of this long-term project, across-scale concepts were needed to quantify biogeochemical cycles and energy fluxes in catchments and to regionalize the results into larger areas as also expressed by WITHERS and MEENTEMEYER (1999).

1.3 Modelling approach

Regional and local climate are controlling factors with regard to ecosystem functioning (FREMSTAD 1997), but the assessment of meteorological data is a general problem in high mountain research, since most official meteorological stations are located in the valleys (Price a. Barry 1997). Consequently, common approaches of spatial data interpolation (Hutchinson 1995; Fleming et al. 2000) are critical due to the general lack of data from higher elevations. Furthermore, a simple but common approach to assess altitudinal gradients is based on the adiabatic lapse rate of temperature (Whiteway et al. 1995). In such approaches the (mean) air temperature at two metres height above ground is used. But, its ecological relevance seemed to be ques-

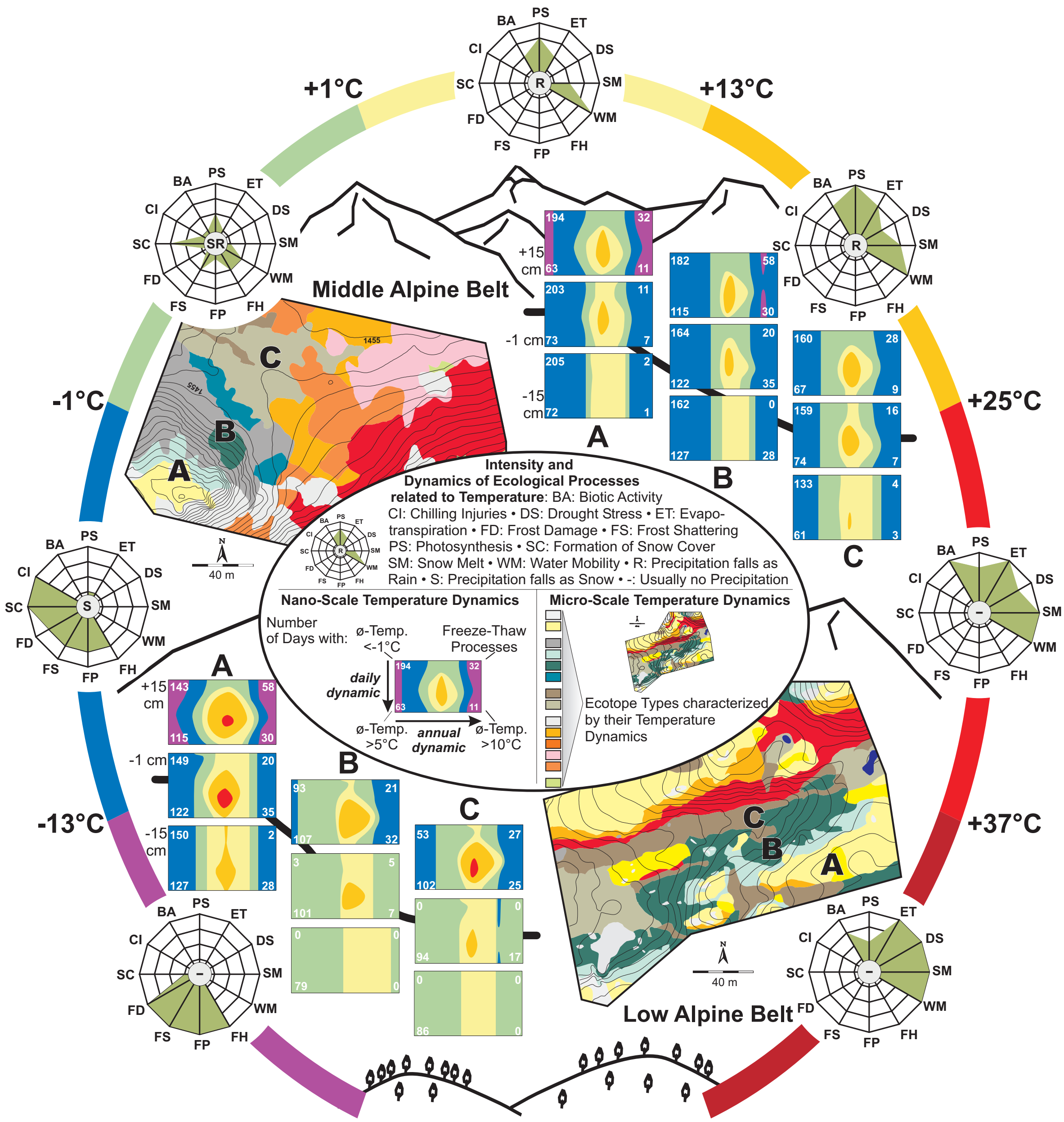

Fig. 1: Across-scale concept for the characterization of high mountain ecosystems along vertical site specific, topographical, and altitudinal gradients (Orig.)

Skalenübergreifendes Konzept zur Charakterisierung von Hochgebirgsökosystemen entlang vertikaler standortspezifischer, topographischer und höhenwärtiger Gradienten tionable, especially in high mountain landscapes where vegetation cover seldom extends beyond heights of one metre (LESER 1997).

Numerical models for operational weather prediction cover a wide range of scales accomplished by general circulation models (GCM) and their down-scaling (RUMMUKAINEN et al. 2001; DENBY et al. 2002). Models appropriate for these scales cannot resolve fine-scale differentiations conditioned by the complex high mountain topography (NOPPEL a. FIEDLER 2002). The results are important deficiencies in prediction, for boreal and tundra landscapes generally reinforced by "at best incomplete and at worst incorrect" representation of the land surface (HARDING et al. 2001, 15).

Identifying the interface between land surface and atmosphere as the key area in reducing uncertainties in prediction has led to the development of one-dimensional soil-vegetation-atmosphere-transfer (SVAT) models (JANSSON a. KARLBERG 2001; CAYROL et al. 2000). These enable pretty exact simulations of energy fluxes and temperatures, but are subject to the general problem of their applicability (BOULET et al. 2000): Especially when they exhibit small time and space steps, they are difficult to use for the investigation of the spatial and temporal variability of land surface fluxes. The large number of parameters they involve requires detailed field studies and experimentation to derive parameter estimates. Thus, running such models on each point location is intractable.

In addition, the transition of scales exhibits a gap between micro-scale 1D models neglecting lateral processes and macro-scale 3D GCMs. This gap is only basically bridged by spatial meso-scale models for specific landscapes (e.g. BRUSE 1999). As opposed to this, water balance models cover a wide range of scales (BRONSTERT a. PLATE 1997; ARNOLD et al. 1998).

Consequently, we developed a suitable 1D, spatially fine-scaled numerical model for the energy balance of high mountain ecosystems that was used as a basis for across scale modelling from catchment to altitudinal zonation (PAPE a. LÖFFLER 2004).

Applying models to smaller map scales facilitates the approach of regionalization resulting in generalized spatial data for the sake of high local accuracy. Such geographically based procedures enable spatio-temporal modelling of ecosystem functioning for different scales (KRYSANOVA et al. 1999; BRONSTERT et al. 2001).

1.4 Aims and objectives

This paper deals with high mountain landscapes of Norway, methods to analyse spatial patterns and dynamics of alpine ecosystems, and a modelling approach to simulate superior processes that determine their functioning principles. The primary aim of this study was to assess the significance of simple standard methods dealing with temperature interpolation along topographical and altitudinal gradients (e.g. the adiabatic lapse rate). We supposed meteorological phenomena such as specific events during different weather situations to find their expression in micro-spatial climatic conditions such as local near-surface temperature profiles. Thus, the secondary aim was to quantify these superior determinants of high mountain ecosystem complexity. Eventually, the tertiary aim of this project was to model high resolution spatio-temporal patterns of high mountain landscapes and to predict their determining dynamics.

2 Area descriptions, methods, techniques

2.1 Area description

As a consequence of the north-southward stretch of the Scandes, central Norway shows a clearly defined oceanic-continental gradient between western and eastern slopes of the mountain chain. 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. The alpine altitudinal zonation is differentiated into a low-alpine belt, dominated by shrub and heather communities, and a middle-alpine belt, dominated by grassy vegetation (DAHL 1986). It reaches from the tree-line at about 1,000–1,050 m a.s.l. to the highest peak, the Blåhø, with 1,618 m a.s.l. The entire mountain massif above the tree-line comprises an area of roughly 50 km^2. The transition zone between low- and middle-alpine belts is found at around 1,350 m a.s.l. (Fig. 2).

2.2 Methods and techniques of field investigation and data analysis

Small characteristic catchments were delimited in each altitudinal belt. The two catchments were mapped and measurements were transposed from representative sites into space. Figure 3 illustrates the topographical structure of the study sites, the spatial organization of measurements, parameters measured as well as the use of technical equipment at the different types of stations. The arrangement followed premises on weighing the highest spatial resolution possible, the most quantitative results measurable, by the lowest priced instruments available. In each catchment one ecological base station, several major and minor ecological stations as well as numerous water level stations were installed. Seasonal ecosystem dynamics was assessed by means of measurements taken throughout the year at hourly intervals by data loggers, registering air and soil temperature, precipitation, solar radiation, air humidity, soil moisture, wind direction, and wind speed. Spatial differentiations of temperature, soil moisture, and wind speed were investigated using hand-held measurements at various locations during several characteristic climatic situations and seasons. Additional data were received from the NORWEGIAN METEOROLOGICAL INSTITUTE (1991–2002) comprising of long-term measurements at the official station Kjøremsgrende Nr. 16740 (1976) (Lesja, Oppland) at 626 m a.s.l.

Resulting data were organized digitally in a data base, combined and structured into a GIS for spatial analysis. Mapped spatial data layers, such as vegetation types, relief features, snow cover conditions etc., were used to define structural ecotope types by overlay rou-

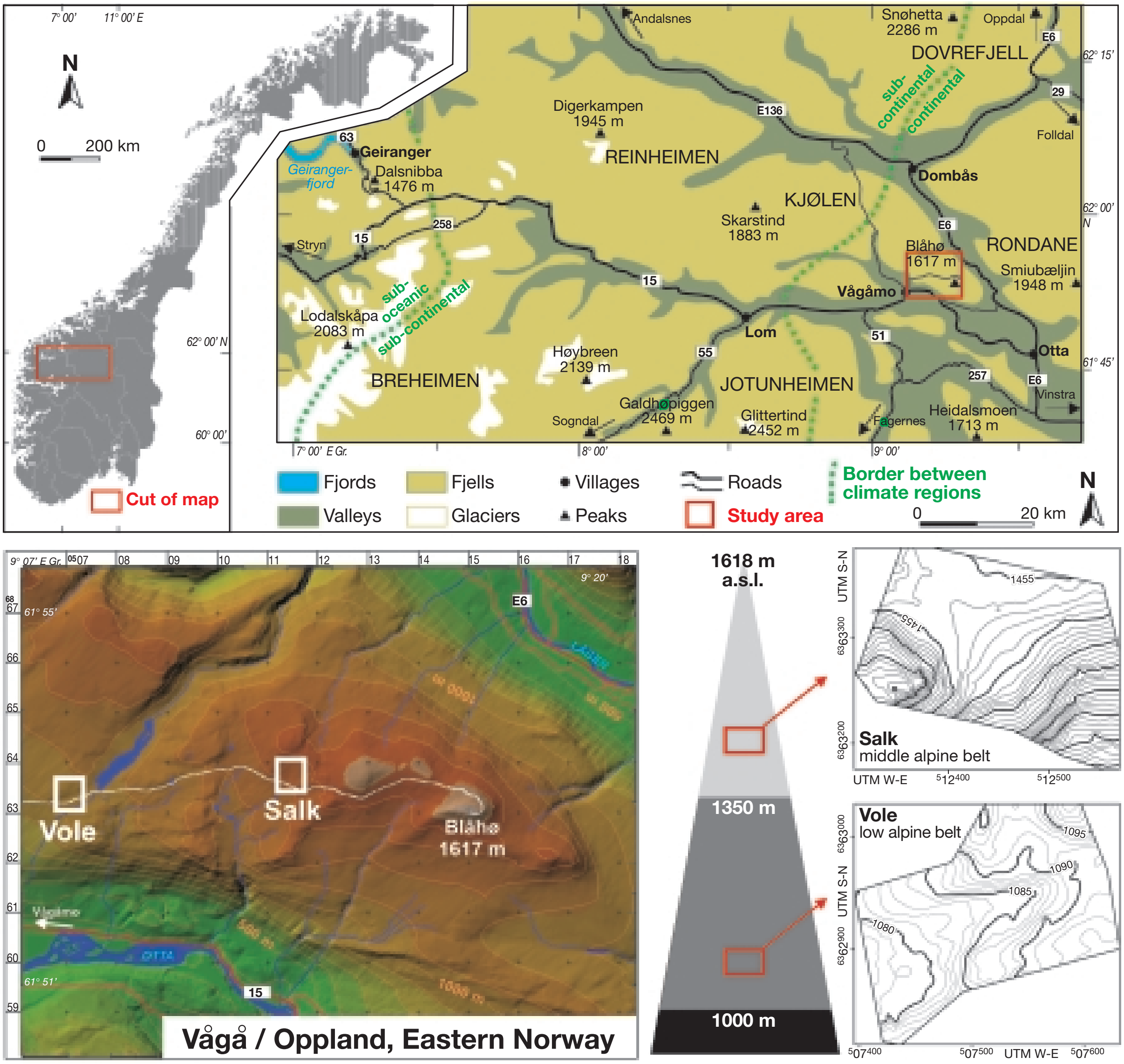

Fig. 2: Location and topography of the study area in central Norway (Orig.)

Lage und Topographie des Untersuchungsraums in Mittelnorwegen tines. Ecotopes were defined as quasi-homogeneous areas that function with regard to different ecological factors (LESER 1997), being analogous to the hydrological response units used in hydrology (FLÜGEL 1996).

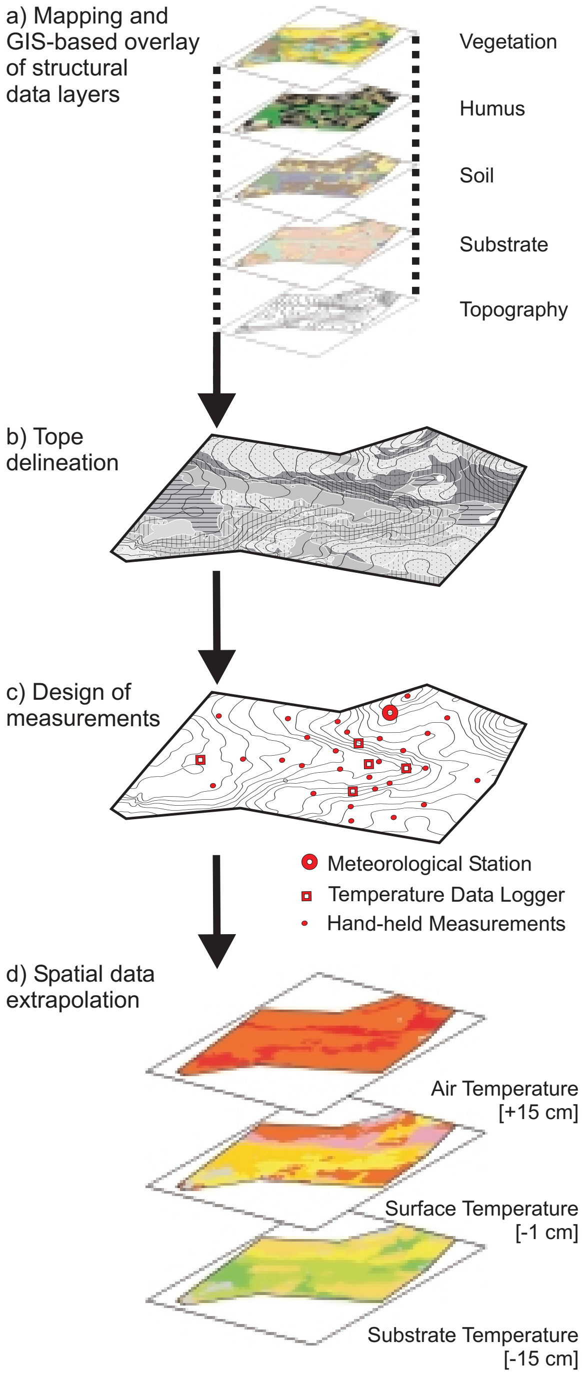

Fig. 3: Spatial organisation of investigations (Orig.)
Räumliche Organisation der Untersuchungen

These highly integrating tope-type geometries determined the position of measurements based on four hierarchical levels of stations and functioned as spatial basis for data extrapolation. Ecological regularities statistically deduced from all functional data were quantified and generalized for each catchment.

2.3 Modelling approach and model implementation

Near-surface temperature variations at a site were calculated according to the modelling approach of PAPE and LÖFFLER (2004). Balancing the energy fluxes at the surface led to a high temporal resolution of temperatures based on a set of physical equations (Fig. 4). The resulting one-dimensional, vertically structured energy balance model represents temperature variations within an air layer of two metres height above a layered soil profile covered with vegetation. Meteorological standard data were used as driving forces in the model and were given as measured values.

As discussed above, common SVAT models use a high amount of input data for accurate estimations of surface fluxes. To avoid time-consuming and labour-intensive determinations of empirical variables, only input data easy to deduce were used within this model. Consequently, simulation of near-surface temperature dynamics was based on:

– mappings of site-dependent structures as relief (controlling height above sea level, aspect, inclination), substrate (mineral, organic) and vegetation type (determining stand height, leaf area index, albedo), and their derivation from remote sensing, respectively,

– measurements of time-dependent variables ("driving forces") as global radiation, air temperature, and wind speed at 2 m height, relative humidity, precipitation, barometric pressure, and

– calculations of the spatial distribution of actual and maximum possible radiation depending on the relief (FU a. RICH 1999).

Besides the output of air temperature, sub-surface temperature, and substrate temperature, the governing sensible, latent, and ground heat fluxes also served as output data. Moreover, the water equivalent of the latent heat flux was used to estimate potential evaporation.

Model calculations were implemented using spreadsheets. The internal model structure consisted of seven compartments: 1) database of site-dependent environmental factors, 2) time series of dynamic input factors, 3) calculation routines of vegetation surface temperature, i.e. solving its energy balance by iteration, 4) calculation routines of ground surface temperature, again by solving its energy balance by iteration, 5) calculation of substrate temperature, 6) air temperature, and finally 7) resulting time series of calculated values. The results were visualized by spreadsheet routines and imported into a GIS for spatial analysis and extrapolation.

The surface temperature as the driving force for heat fluxes, within both the air and the substrate, needed to be estimated first as the basis for further calculations. It was deduced from the balance between the energy fluxes at the surface. Each flux was broken down into constituent parts and formed a complete equation set consisting of net-radiation (R_n), evaporative flux (H_L), sensible heat flux (H_S), and ground heat flux (H_G), which was resolved to obtain the surface temperature.

The net available radiant energy (R_n) was found to consist of two components: the absorbed solar flux at the surface (R_s) depending on global radiation R_{glo}, the relief, and the albedo of the surface (A, given as fraction) supposed to be independent of sun angle. The second component was the net long-wave flux (L_n) based on the temperature difference between the surface and the overlying medium according to the Stefan-Boltzmann-Law. The amount of solar radiation absorbed at the substrate surface (subscript sfc) not only depends on albedo but also on properties of the covering vegetation canopy (subscript c) expressed according to SCHELDE (1996, 8) by an empirical constant (C = 0.5) and the leaf

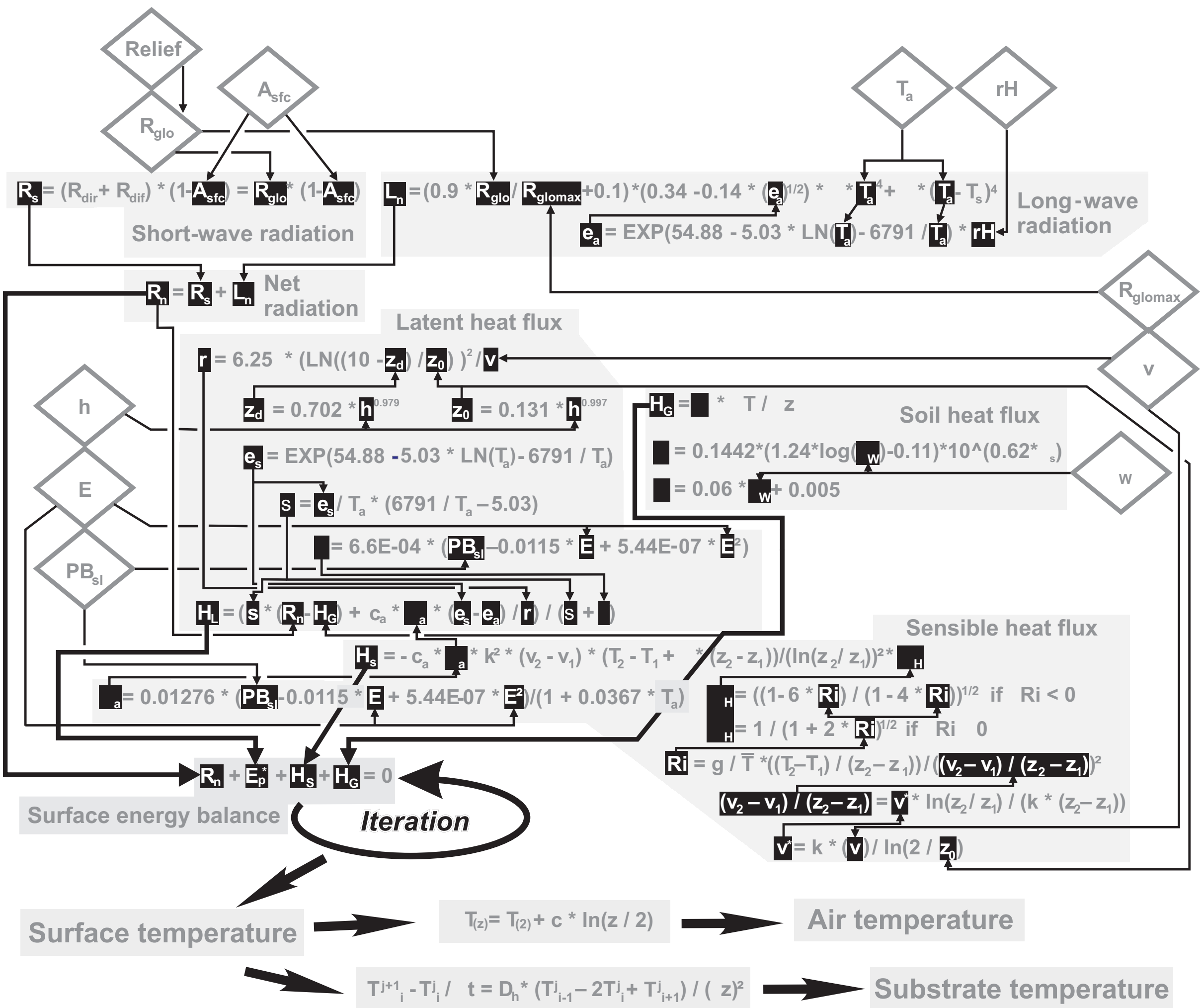

Fig. 4: Architecture of the superior 1D energy balance model, explanations are given within the text (after: LÖFFLER a. PAPE 2003)

Architektur des übergeordneten 1D-Energiehaushaltsmodells; nähere Erläuterungen im Text area index LAI supposed to be 0–2.5 according to BLISS et al. (1981).

Regarding the canopy surface, the net long wave flux was more complex because of interactions with the atmosphere. According to KONDRATYEV (1969) a correction term for the actual vapour pressure of the air was included (e_a, MITCHELL et al. 1997: Eq. 52, 53), and an approximation of cloud cover (MITCHELL et al. 1997: Eq. 58) was used by the ratio between actual global radiation R_{glo} and calculated maximum possible global radiation R_{glomax} (FU a. RICH 1999). During night times when no global radiation was measured, cloud cover until midnight was roughly estimated from the mean ratio R_{glo}/R_{glomax} during the last three hours before sunset and afterwards from the mean ratio during three hours after sunrise. Due to the small spatial extent of the investigated catchments (each less than 5 hectares), spatial variability of cloudiness was neglected.

Relative humidity (rH) was used as fraction, and e_s as the saturation vapour pressure [hPa] at actual air temperature in 2 m (T_a) calculated according to MITCHELL et al. (1997: Eq. 52). The net radiation itself was balanced by the upward flux of sensible heat (H_S) into the atmosphere, the heat flux into the ground (H_G) and the latent heat flux (H_L) into the atmosphere.

The flux of sensible heat was calculated using an aerodynamic approach mentioned by FLEAGLE and BUSINGER (1963, 195), where c_a was the specific heat of air (1,009 $Jkg^{-1}K^{-1}$, OKE, 2001, 44), ρ_a the density of air [kgm^{-3}], k the Karman constant (0.41), v wind velocity [ms^{-1}], T temperature, Γ the adiabatic lapse rate of temperature (9.72 10^{-3} km^{-1}) and z the height of measurement. To consider the stability of the atmosphere and to account for a wider applicability of the profile method, generally being restricted to neutral stability of the atmosphere, a stability function for heat (Φ_H) according to BRUSE and FLEER (1998) was included, depending on the Richardson number Ri (OKE 2001, 380). PB_{sl} represented the barometric pressure at sea level [hPa], and E, the elevation of the site [m]. g was the acceleration due to gravity (ms^{-2}), T with subscript, the temperature at the measurement heights z_1 and z_2, T without subscript, the mean of these two values and v, wind velocity at the two heights z_1 and z_2. In the above-mentioned equations the subscripts 1 and 2 referred to the surface itself and the vegetation canopy in case of the substrate surface to be regarded, otherwise they referred to the canopy surface and the air at 2 m.

This aerodynamic approach required measurements of both vertical temperature and wind velocity gradients. As wind velocity was measured continuously at a height of two metres only, its vertical profile had to be estimated. According to OKE (2001, 381) the wind velocity gradient between 2 m and the canopy surface as well as between both surfaces was estimated using the friction velocity (v^*) with h being the height of the vegetation canopy.

Ground heat flux H_G [Wm^{-2}] was expressed by H_G, with λ as the thermal conductivity of substrate [$Wm^{-1}K^{-1}$], ΔT, the temperature difference between surface and first measurement point within substrate and Δz, the depth of the first measurement point within substrate. For unfrozen mineral substrates an empirical conductivity function was adapted from KERSTEN (1949) where c_1, c_2, c_3 were constants depending on whether the substrate was dominated by clay, silt or sand, θ_w described the volumetric water content [%], and ρ_s was the dry bulk density of the substrate [gcm^{-3}]. For the predominating silty sand the following parameterization was used: $c_1 = 1.24$, $c_2 = -0.11$, $c_3 = 0.62$, $\rho_s = 1.6$. Thermal conductivity of organic matter was estimated by a function adapted from DE VRIES (1975).

Latent heat flux H_L [Wm^{-2}] was calculated according to Penman as reported in MITCHELL et al. (1997) for a saturated surface, where s was the slope of the saturation vapour pressure curve [10^3 PaK^{-1}], γ the psychrometer constant [10^3 PaK^{-1}], and r the aerodynamic resistance [sm^{-1}]. Considering water to become limiting and actual evaporation to become less than potential, a simple approach was used assuming water being equally available throughout the entire soil water range, but not accessible at the permanent wilting point TANNER (1967). As continuous measurements of soil moisture at the driest sites within the study areas indicated, the water content was constantly higher than at the permanent wilting point (LÖFFLER 2002a). For simplification the actual latent heat flux was assumed to be equal to the potential heat flux.

The only remaining unknown quantity within the energy flux equations was the surface temperature enabling the equation system to be solved according to the temperature of both substrate surface and canopy surface. A numerical solution was prevented, because many parameters were indirectly or directly related to the surface temperature itself. The solution was found by iterations as to *regula falsi* (BRUSE a. FLEER 1997):

a) Two initial surface temperature values (T^0 and T^1) were chosen. For T^0 the temperature of the former time step was used; T^1 set to be $T^0 + 0.2$.

b) These two temperatures were used to calculate the energy balance resulting in two balance values F^0 and F^1.

c) Inserting these two values yielded a new value T^2 for the surface temperature.

d) It was set $T^0 = T^1$ and $T^1 = T^2$; steps b) and c) were repeated until the convergence criterion $|T^1 - T^0| \leq 0.001$ K was reached.

The canopy surface temperature was calculated first, using the substrate surface temperature of the former time step. Then the result was used to calculate a new substrate surface temperature and vice versa. As such, the definite temperature was found by iteration.

The substrate layer was assumed to have homogenous thermal properties. Using a backward difference scheme provided by HANKS and ASHCROFT (1980), it was possible to approximate the non-steady state heat flux equation numerically, where the subscripts i referred to depth increments, Δz distance apart, and the superscripts j referred to the time increments, Δt time apart, and D_h being the thermal diffusivity (in 10^{-6} m^2s^{-1}) of the substrate given for silty sand and for organic matter separately.

The air temperature was assumed to decrease (at night) or increase (at daytime) logarithmically with height (GEIGER 1961, 82-84), where c was an empirical constant. It was estimated for c and using the modelled temperature of the vegetation surface and measured T+200. Thus, the air temperature at every height was calculated, where the superscript z referred to the unknown air temperature at the height z and the superscript 1 referred to T+200.

2.4 Model Calibration and Validation

The model was calibrated for different sites, including lichen heath-covered ridge positions, mid slopes covered by dwarf shrub heath, and depressions with mire vegetation using measured temperatures. The site-dependent parameters albedo and LAI were then adjusted by minimizing the difference between observed and calculated surface temperature for 168 data points. This approach was used because the initial settings were not measured but taken from literature. Nevertheless, adjustments were made within a realistic range given in literature.

The goodness of temperature representation after minimizing was tested against independent hourly temperature measurements throughout fourteen days. It was presented using root mean square errors (hereafter referred to as RMSE) as well as r^2-values of a linear regression:

– r^2, as $\left(\dfrac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n\sum X^2 - (\sum X)^2]\,[n\sum Y^2 - (\sum Y)^2]}}\right)^2$

– RMSE, as $\sqrt{\dfrac{\sum (X-Y)^2}{n}}$

3 Results

The results were based on a fourteen-day summer period of representative measurements and model calculations illustrated by means of temperature curves derived from hourly means (Suppl. III). After that, a comparison of four different layers of temperatures was practiced on the nano-scale: I, air temperature T+200, II, air temperature T+15, III, sub-surface temperature T–1, and IV, substrate temperature T–15. Furthermore, three different sites along micro-spatial topographical gradients were compared on the micro-scale: A, ridge position, B, mid-slope position (north-facing), and C, depression. Finally, comparing the low- and middle-alpine belts, general altitudinal trends were assessed on the meso-scale. These comparisons were all based on measured temperatures.

The different steps of across-scale modelling and comparison were presented in 14 diagrams showing temperature curves to assess the model quality and to demonstrate the detailed variation of temperatures, as well as the following three types of correlation matrices:

– nano-scale: I, II, III, and IV
– micro-scale: A, B, and C
– meso-scale: low-alpine, and middle-alpine

As such, Supplement I illustrates the local temperature variation near ground, the relief-determined differentiation of energetic site conditions, and the adiabatic lapse rate of temperatures with altitude. Figure 5 is used to sum up the general results of the adiabatic temperature biases during different weather situations.

3.1 Model accuracy

The model explained more than 80% ($r^2 \geq 0.805$) of the variance of observed temperatures combined with low biases (RMSE ≤ 1.448) for all regarded sites and layers within the low and middle alpine belts. So, no further setbacks were necessary to fit the model. Best accuracy was found regarding soil temperatures ($r^2 \geq 0.91$, RMSE ≤ 0.59), except the low alpine depression with higher biases. Worst biases ($r^2 \leq 0.89$, RMSE ≥ 0.87) were observed for the sub-surface temperature, except the low alpine ridge with better accuracy. The air temperature was intermediate. We used the measured values for the following comparisons.

3.2 Nano-scale results

Vertical temperature dynamics at each site, within both the low- and middle-alpine belts, were characterized by similar rules within different quantities: most pronounced at the sub-surface (T–1), slightly decreasing towards the air, and nearly extinct within the substrate layer due to its conservative thermal regime. Consequently, best correlations were found between T+200 ↔ T+15 (mean r^2 of 0.86), and T+15 ↔ T–1 (mean r^2 of 0.82), respectively. On the contrary, absolute temperatures were badly represented, as indicated by RMSE greater than 1.2. Furthermore, T+200 could not be used to represent T–1 or T–15 (mean r^2 of

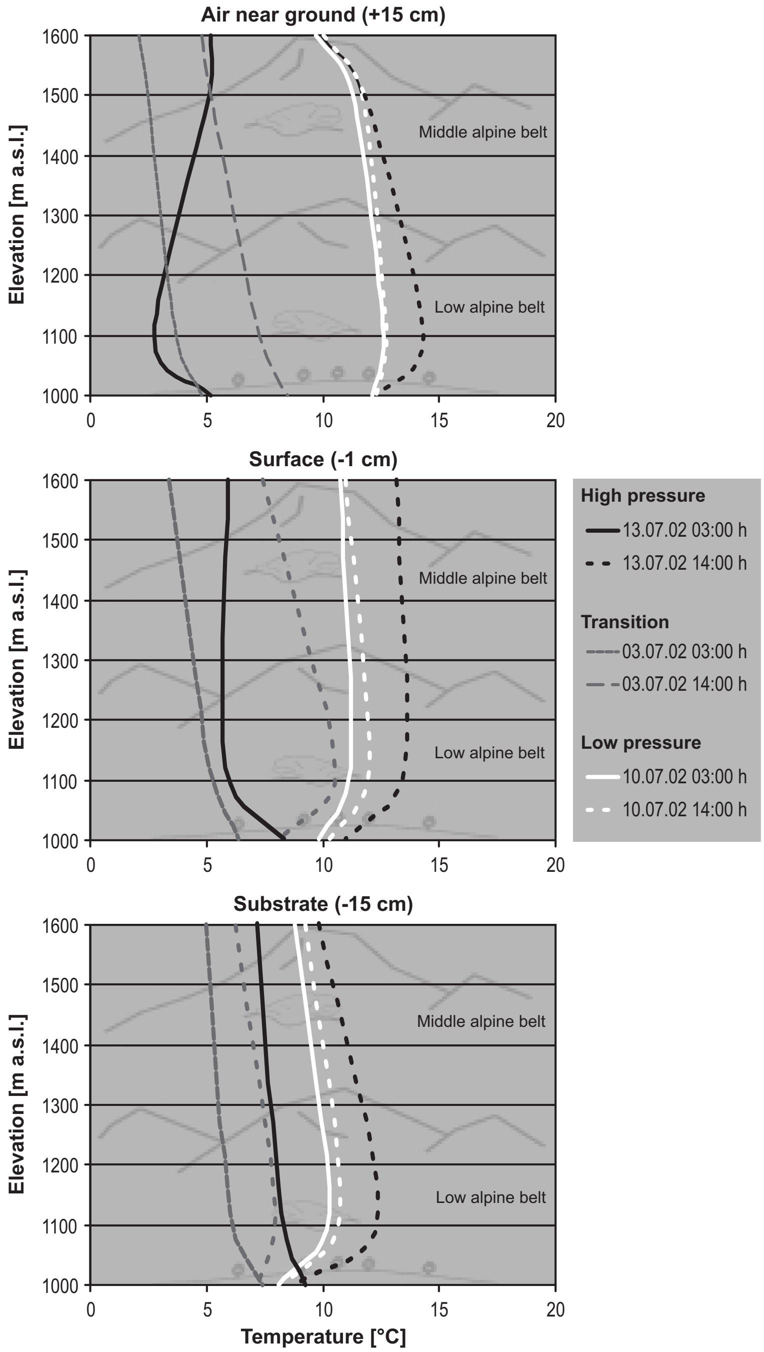

Fig. 5: General results of adiabatic temperature lapse rates during different summer weather situations for near-surface temperatures (Orig.)

Generalisierte Ergebnisse zum adiabatischen Temperaturgradient während verschiedener sommerlicher Wetterlagen für oberflächennahe Temperaturen

0.67 and 0.44 with RMSE ≥ 1.9 and 2.1). In fact, the temperature regime of the substrate was not at all represented by the other layers due to its smooth curvature induced by retarded heating and cooling. Worst representation was found within the low-alpine depressions as a result of water-saturated organic substrates.

Micro-scale results

3.3.1 Middle-alpine temperatures at different sites

The air temperature T+15 at all sites within the middle-alpine belt was highly correlated, indicated by r^2 greater than 0.96 and low RMSE of ≤ 1.0. This result accorded with generally high wind speeds at all sites even during cloudless high pressure weather situations. T+15 during the summer did not distinguish the differences of site conditions.

Using T–1 and T–15, respectively, we found higher biases in the correlation between the ridge sites on the one hand and slopes and depressions on the other. High soil moisture in the depressions and negative influence of shadowed conditions in northern exposures caused higher biases, as found while comparing slopes and depressions. Both sub-surface and substrate reacted with an r^2 of 0.83–0.86 and an RMSE of 1.28–1.87. On the contrary, the correlation of T–1 and T–15 between slopes and depressions was found to be very high: r^2 ≥ 0.96; and RMSE of 1.13 for sub-surface, 0.44 for substrate conditions, respectively. In general, middle-alpine ridges showed warmer sub-surface and substrate conditions due to a lower substrate moisture than slopes and depressions. The difference in temperature dynamics of T–1 and T–15 between all sites was most decisive.

3.3.2 Low-alpine temperatures at different sites

Similar to the middle-alpine belt, T+15 at all sites showed high correlations, indicated by r^2 greater than 0.96 and low RMSE of ≤ 1.6. This result pointed to effective mixing processes despite lower wind speeds in the low-alpine belt. Also here, T+15 during the summer did not distinguish the differences of site conditions.

Again, we found higher biases in the correlation between the ridge sites on the one hand and slopes and depressions on the other. High soil moisture combined with organic substrates in the depressions and negative influence of shadowed conditions in northern exposures caused higher biases, as found while comparing slopes and depressions. The sub-surface reacted with an r^2 of 0.85–0.89 and an RMSE of 1.07–1.38. Regarding the substrate layer, differences were even more pronounced with r^2 of 0.47 and RMSE of 2.14 (A–B), and r^2 of 0.58 and RMSE of 1.87 (A–C), respectively. The correlation of T–1 and T–15 between slopes and depressions was found to be slightly higher: r^2 ≥ 0.71; and RMSE of 1.54 for sub-surface, 0.44 for substrate conditions. Again, the ridges showed generally warmer sub-surface and substrate conditions with pronounced dynamics due to a lower substrate moisture than slopes and depressions. These behaved quite similarly, but were differentiated according to their substrate conditions (mineral – organic). The difference in temperature dynamics of T–1 and T–15 between all sites was most decisive.

3.4 Meso-scale results – altitudinal gradients

The correlation of T+15 curvature at the sites A–B–C between the low- and middle-alpine belts was found with an accuracy of > 84%; but high RMSE of 1.96–3.00 pointed to an insufficient representation of absolute temperatures. The high correlation indicated that overlying weather conditions, like passing frontier systems that control cloudiness, radiation etc., influenced the reaction of micro-climate with similar intensity without pronounced modification according to site properties. The high biases with altitude could be explained by the adiabatic lapse rate. But its deviation of ± 0.9 K from the general adiabatic lapse rate of –0,6 $K/100m^{-1}$ pointed to a complex daily variation of micro-climatic conditions with altitude induced by the overlying weather situation (nocturnal development of inversions etc.).

The synchronicity of curvature between T–1 was found with a r^2-value of 0.76 at the ridges; 0.62 in the depressions; and 0.48 on the slopes. Consequently, overlying weather conditions did not influence the reaction of micro-climate with similar intensity at different altitudes, i.e., the reaction was modified according to site differentiations. This fact had to be expected from micro-spatial results (lower correlation of T–1 between different sites). Thus, the response of the sub-surface to weather conditions was complex. The varying lapse rate of up to ± 1.3 K from the mean value –0.4 $K/100m^{-1}$ could not be explained by the weather situation only, but by micro-climatic variability along site differentiations. North-exposed slopes of different altitudes for instance differed according to percentage of vegetation cover that was found to be > 90% in low-alpine belt and < 30% in the middle-alpine belt, respectively.

Like the sub-surface, the substrate layer of different sites was not influenced with similar intensity by the overlying weather situation. The synchronicity of curvature between T–15 was found with a r^2-value of 0.93 at the ridges; 0.80 in the depressions; and 0.54 on the slopes, all controlled by site-dependent differentiations. Thus, best correlation with lowest RMSE was found between the similar ridges, whereas worst correlation was found between depressions according to the different conditions regarding hydrology and substrate. The lapse rate was found to be in good concordance with the general adiabatic lapse rate of –0.6 $K/100m^{-1}$, with variations of ± 0.5 K, only.

Figure 5 exemplifies the lapse rates of temperature along the altitudinal gradient for different overlying weather situations. During low pressure weather situations, all near-surface layers at the ridges showed no differences in temperature between night and day. The low-alpine belt tended to be warmest compared with higher altitudes and the birch forest below, due to global radiation not hindered by fog or dense canopy of trees. Thus, temperatures in all layers increased from the sub-alpine to the low-alpine belt and slightly decreased towards higher elevations (air layer: –0.3 $K/100m^{-1}$ due to effective turbulent mixing during windy periods). During transitional weather situations, the lapse rate was found to be in best concordance to the general adiabatic lapse rate of –0.6 $K/100m^{-1}$, during both nights and days. Extreme conditions were found during high pressure weather situations expressed by T+15 in the low-alpine belt. Highest daily and lowest nocturnal values were measured with an amplitude of 12 K. Compared with the ridges of the middle-alpine and sub-alpine belts daily values were at least 2 K higher at noon and 2 K colder before sunrise. We interpreted this phenomenon with differentiated spatial inversion patterns, sheltering barriers of the densely structured forest-line against cold air streams, and shading effects of the tree canopy layer. We also measured highest daily T–1 and T–15 values during high pressure weather situations, whereas sub-surface temperatures were identical in the low- and middle-alpine belt during days and nights. Obviously, altitude affected neither intense radiative heating nor inversion cooling at the ridges. Substrates reacted differently showing cooler conditions with altitude, but no daily amplitude in the forests. The difference between similar sub-surface but reduced substrate heating in the middle-alpine belt compared with the low-alpine phenomena was explained by higher substrate moisture in higher elevations, affecting thermal properties of substrate. Substrate temperatures in the forests did not show any daily amplitude during all different weather situations. All in all, summer temperature conditions could not be differentiated in total values along altitudinal gradients. We found similar minima in the low- and middle alpine belts, but during different weather situations. Highest summer temperatures were found in the low-alpine belt, but middle-alpine conditions were often much warmer than those of the forests.

4 Discussion

4.1 Across scale: vertical profiles – site differentiations – altitudinal gradients

In comparison with modelled vertical temperatures profiles, the extraordinary biases from meteorological standard data showed that environmental conditions near-ground differ from overlying climatic circulation patterns described by Wallén (1975). Quantifying the differences between general assumptions and meteorological predictions of T+200, and the eco-climatic conditions of T+15, T–1, and T–15, we showed that subsurface and substrate conditions could not be predicted sufficiently, or even transferred from standard meteorological data. Near-surface temperatures at all different sites showed extremely high biases from the T+200. T+15 was poorly represented by T+200 (high RMSE), but had acceptable synchronicity. Over and above that, regarding higher temporal resolutions instead of long-term means, we found increasing deviation of temperatures from the adiabatic lapse rate. All in all, the extraordinary differences at all scales led us to conclude that the ecosystem determination is in situ enforced by micro-climatic conditions apart from meteorological trends. The complexity of the vertical energetic profile of near-surface conditions was now taken as to represent the superior determinant for ecosystem functioning. This was plausible according to the previous assumptions, since we could correlate vegetation patterns with micro-climate (Löffler 2003). The results could help to densify the net of available vertical temperature profiles that are rare for northern high mountain landscape (Wielgolaski 1975; Bliss et al. 1981).

The above-stated problem of representing vertical temperature differentiation by means of meteorological standard data was reinforced regarding the spatial micro-scale. It was shown that near-surface air layers could not be used to explain differences in sub-surface and substrate temperatures among different sites during the observed representative summer period. The air temperature behaved similarly ($r^2 \geq 0.96$, RMSE $\leq$ 1.0), whereas sub-surface and substrate temperatures differed extraordinarily as a result of site-dependent thermal properties (Löffler 2002a).

Approaches based on adiabatic lapse rate calculations (Whiteway et al. 1995) were found to be limited, at least according to a high temporal resolution of daily temperature variations, but in most cases also according to differentiation of various weather situations. The approach to assess altitudinal gradients based on the adiabatic lapse rate of temperature could be used to generalize mean summer conditions over weeks. As such, our results do not touch general climatologic features of high mountains (BARRY 1992). We showed that micro-climatic phenomena were not expressed by the general mean conditions. The altitudinal gradient differed over diurnal and nocturnal time spans and resulted in complex temperature constellations. These had been found decisively to affect the environmental conditions of alpine plant life (CHAPIN a. SHAVER 1985). Furthermore, a group of higher alpine species were proved to be negatively correlated with high summer temperatures (DAHL 1998; GOTTFRIED et al. 1999). Temperature limit curves for species based on average temperatures of warmest and coldest months (HINTIKKA 1963; MOEN 1999) were used for geographical generalization, but proved to be unacceptable for ecological explanations. Thus, average values should not be used to characterize site conditions, but allow the potential of broad-scale distribution patterns to be calculated and interpreted.

SHAVER et al. (1986) had demonstrated that average growth on the long term was correlated with long-term average temperature, whereas inter-annual variations in temperature and growth were not at all correlated. KÖRNER et al. (1986) proved that the root-zone substrate temperature along a forest – grassland altitudinal transect was consistently higher under a low structured vegetation than under forest. HAVRANEK (1972) had pointed out that the substrate temperature might affect tree growth along the tree-line, which was the basic assumption for the hypothesis on tree-line determination by KÖRNER (1999). These assumptions were supported by our measurements. Moreover, similar results of substrate temperatures – plant life correlations, contributed earlier, stressed the importance of extreme environmental conditions (LÜDI 1938; BLISS 1956; MOSER et al. 1977).

4.2 Ecosystem complexity

There is no doubt about alpine ecosystems being complex in structure and micro-spatial diversity patterns (CHAPIN a. KÖRNER 1995; MOLAU 2003). The general assumptions to interpret these mosaics were causal descriptions (BILLINGS 1973; MOLENAAR 1987; ISARD a. BELDING 1989; STANTON et al. 1994). Moreover, substrate temperature variations had been found to be responsible for diurnal changes in CO_2 efflux. Over the course of the day sub-surface temperatures, measured as T–1, had been found to be best correlated with respiration activity (NADELHOFFER et al. 1991; OBERBAUER et al. 1992). We used those suggestions in a long-term project and analysed differences between low- and middle-alpine vegetation throughout different catchments. We discussed the correlations between the data sets of plant species composition with our micro-climatic results. The analysis showed that none of the different factors completely determined the vegetation along altitudinal gradients. Soil moisture was found with high significance, but did not explain species diversity patterns of the well-drained sites. Different clusters of plant species compositions were found along several vectors. The strongest correlation between vegetation and micro-climate was ruled by the number of days with sub-surface freeze-thaw processes, expressed by daily T–1 variations between –1 and +1° C. These conditions were found more frequently with increasing altitude. By way of contrast, maximum sub-surface temperatures correlated with specific groups of plant species most frequently found in early low-alpine snow beds. The two combined vectors indicated that the altitudinal change of vegetation was closely correlated with local sub-surface temperature attributes. These results proved that the high mountain ecology of plant species was most decisively determined by specific site conditions (LÖFFLER 2003). Since our simple model enabled the calculation of near-surface energetic constellations with high temporal resolution, we could easily predict near-surface temperature variations in small catchments (LÖFFLER a. WUNDRAM 2001; LÖFFLER a. PAPE 2003).

5 Conclusions

We conclude that high mountain ecosystems are determined by complex near-surface temperature gradients. These are not feasible with standard approaches like interpolation of meteorological standard data based on the adiabatic lapse rate, or statistics. Instead, intensive measurements or simple modelling approaches are needed for sufficient representation of micro-climatic conditions. We were able to calculate temperature variations with high spatial and temporal resolution using a very simple approach compared with common SVAT applications. The measurements used to describe the local energy balance were helpful to understand ecosystem functioning. They were necessary to calibrate the model for different site conditions. Biases between our data and general adiabatic models were clearly expressed by different purposes they

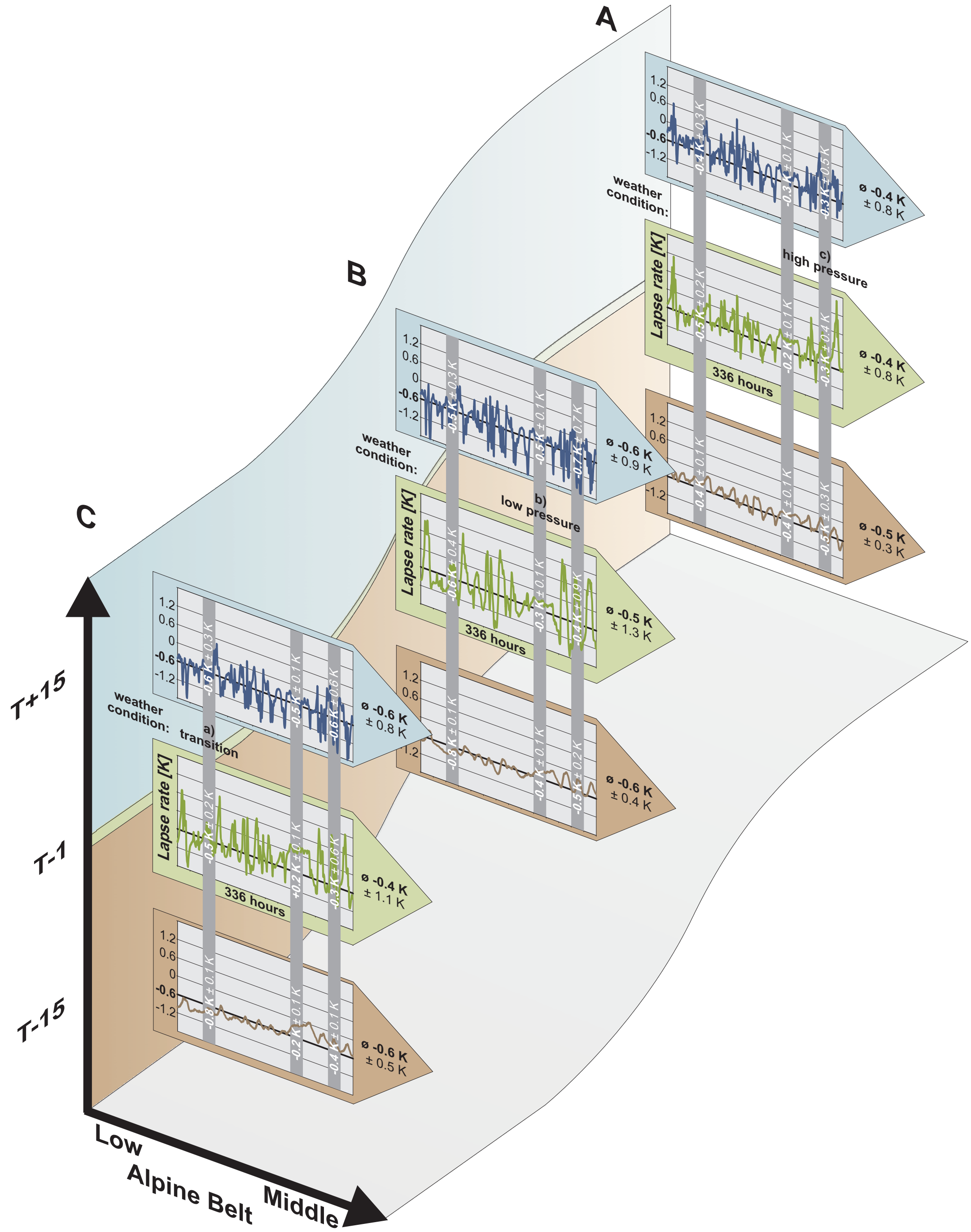

Fig. 6: Scheme of across spatio-temporal scale temperature gradients in alpine landscapes. The variation of near-surface temperatures (T+15, T–1, T–15) at different sites was expressed by the deviation of the adiabatic lapse rate against meteorological standards (T+200) over a characteristic summer period of 336 hours. Representative transitional (a), low pressure (b) and high pressure (c) weather situations were regarded separately. Finally, mean and standard deviation with altitude were summed up along the gradient of the alpine belts (Orig.)

Schema skalenübergreifender raum-zeitlicher Temperaturgradienten in alpinen Landschaften. Die Variation der oberflächennahen Temperaturen an verschiedenen Standorten ist mit Hilfe ihrer Abweichungen vom adiabatischen Gradienten gegen meteorologische Standards über eine 336-stündige Sommerperiode ausgedrückt. Repräsentative Übergangs-, Tiefdruck- und Hochdruckwetterlagen werden separat betrachtet should by applied to. The adiabatic lapse rate (e.g., WHITEWAY et al. 1995) was found to agree with average calculations, but proved to be useless for predicting high resolution micro-climatic phenomena. Complex site conditions were expressed and summarized by complex thermal properties (Fig. 6). The altitudinal gradient [K/100 m] of T+15, T–1 and T–15 at ridges (A), northern exposure (B) and depression (C) showed pronounced amplitudes around the adiabatic lapse rate of –0.6 K/100 m, which was best represented by the substrate layer. Short term, the diurnal and nocturnal deviations showed characteristic curvatures for representative weather situations which best fit to the adiabatic lapse rate among transitional weather situations. Long term, the mean altitudinal lapse rate of temperature for each individual layer was well represented by the adiabatic lapse rate, but its standard deviation quantified deviations from this general assumptions.

We bridged the gap between intensive measurements for parameterization of SVAT models (i.e., CAYROL et al. 2000) and general models with our new simple energy balance model that was based on few input variables only. Since the model was run with high accuracy, we succeeded in proving its applicability for further ecosystem research.

Within the discussion of climate change (i.e., HOUGHTON et al. 1990) 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) and finally lead to a replacement of alpine by sub-alpine ecosystems (CRAMER 1997), respectively. Thus, based on our results we are concerned that the prediction of high resolution temperature conditions for specific sites is necessary to understand the complex local interactions of plant species and environment.

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5.4 Publikation IV

Löffler, J., Pape, R. & D. Wundram (2006)

The climatologic significance of topography, altitude and region in high mountains – a survey of oceanic-continental differentiations of the Scandes.

Erschienen in:

Erdkunde 60: 15-24.

Dazu: Beilage II

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)

JÖRG LÖFFLER, ROLAND PAPE and DIRK WUNDRAM

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

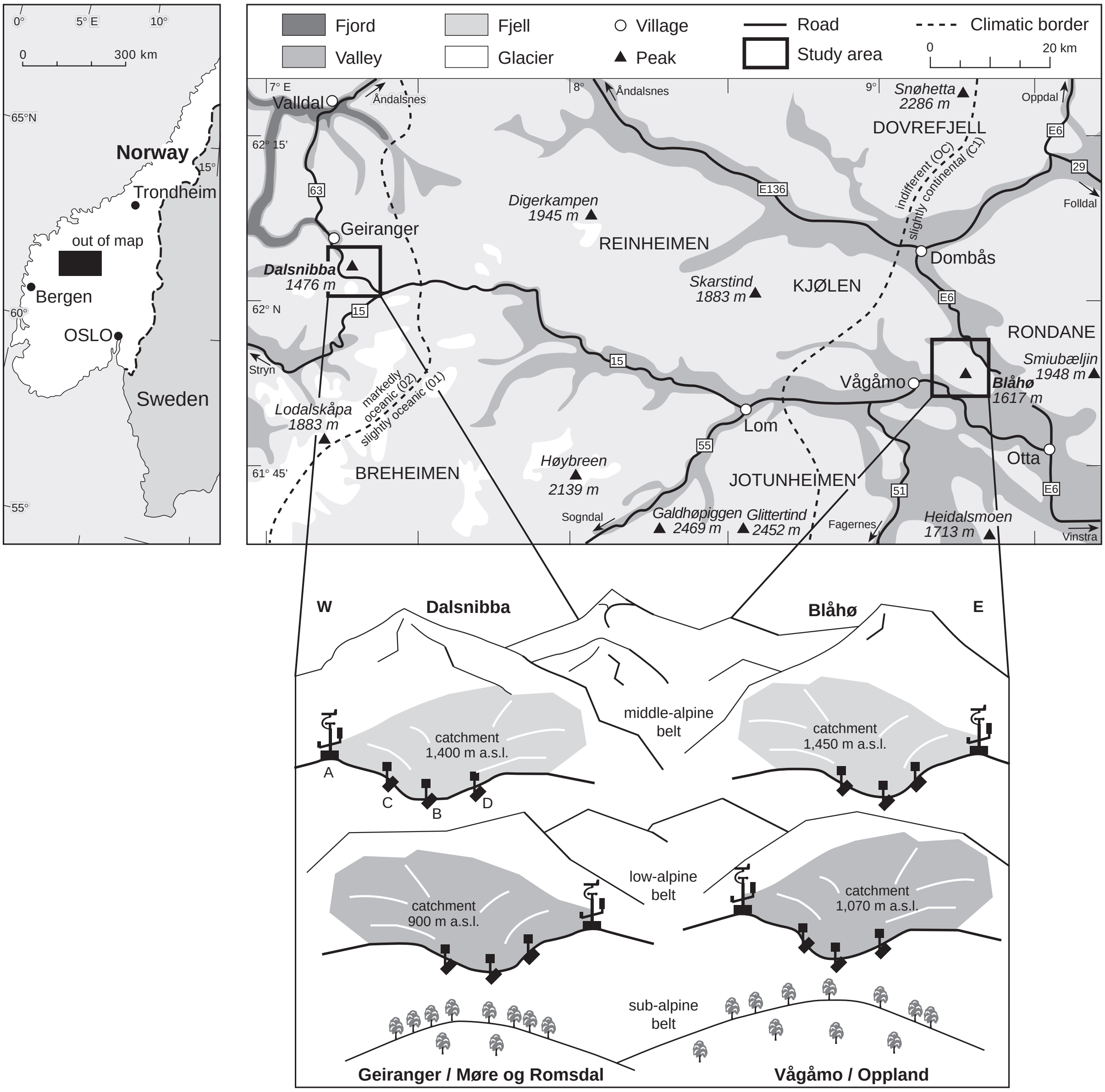

Fig. 1: Location of study areas in Central Norway and scheme of investigated catchments. Investigations were conducted along the transect ridge (A, with meteorological station), south-exposed mid-slope (C), north-exposed mid-slope (D) and depression (B, as C and D with temperature loggers).

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

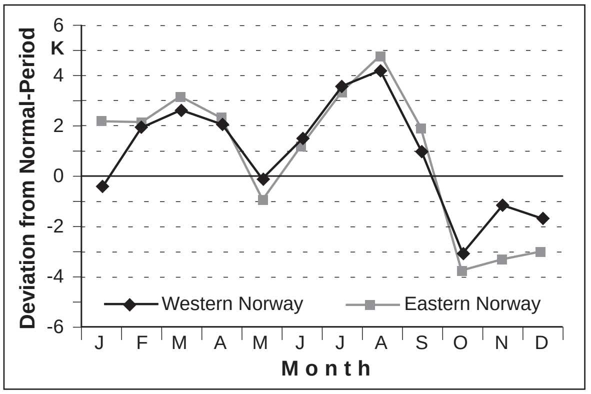

Fig. 2: Deviation of monthly mean temperatures during the investigation period from the normal-period.

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.

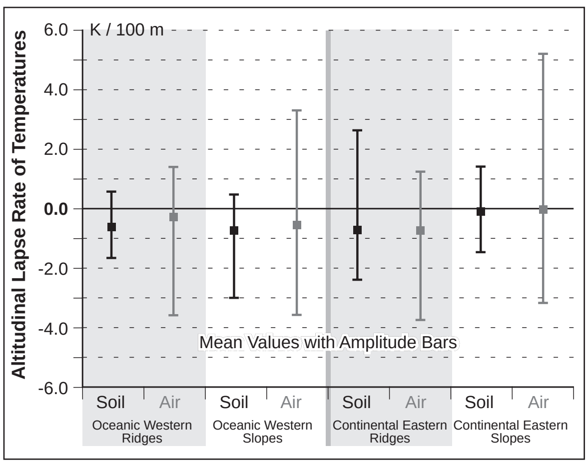

Fig. 3: Altitudinal lapse rate of temperature in the western and eastern investigation areas at ridge positions and south-facing slopes, given separately for soil and air temperatures. Annual means and their range of minimum and maximum values are shown.

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). Micro-climatic 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, non-linearity 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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5.5 Publikation V

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Klimadaten im Hochgebirge – Anspruch und Wirklichkeit.

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Klimadaten im Hochgebirge: Anspruch und Wirklichkeit

von

Roland Pape*

Zusammenfassung

Ein Review der relevanten Literatur zu klimatischen Betrachtungen in Hochgebirgsräumen offenbart eine Diskrepanz zwischen Anspruch und Wirklichkeit in Bezug auf flächenhafte Klimadaten. Für die Abschätzung der Folgen des Klimawandels sind detaillierte Informationen zur Funktionsweise der Ökosysteme erforderlich. Einerseits liegen diese als kleinräumig-detaillierte Erkenntnisse zu klimatischen Bedingungen und ihren ökosystemaren Auswirkungen vor, andererseits stellt ihre Regionalisierung jedoch eine der großen wissenschaftlichen Herausforderungen dar: Gebräuchliche Ansätze werden kurz vorgestellt und hinsichtlich ihrer Limitierungen diskutiert. Bisherige Szenarien zum Klimawandel beruhen somit mangels detaillierter Daten häufig auf der deduktiven Übertragung kleinmaßstäblich gewonnener Erkenntnisse auf größere Maßstabsebenen – ein Verfahren, das vor dem Hintergrund der kleinräumigen Differenziertheit der Hochgebirge fragwürdig erscheint.

Abstract

A review of relevant literature about climatic aspects in high mountain areas reveals a discrepancy between requirements and reality when regarding spatial climatic data. The estimation of consequences of climatic change requires detailed information about ecosystem functioning. On the one hand detailed information about climatic conditions and their ecological effects is available at large map-scales but, on the other hand, their regionalization represents one of the large scientific challenges. Common approaches are briefly introduced and discussed with regard to their limitations. Thus, present scenarios of climatic change are based on the deductive transmission of data acquired on smaller map scales to larger map scales due to the lack of detailed data. - A procedure that appears doubtful when regarding the small-scaled differentiation of high mountain areas.

1 Einleitung

Aufgrund ihrer extremen Labilität gegenüber jeglichen Umweltveränderungen werden arktisch-alpine Landschaften als besonders sensibel gegenüber Klimaveränderungen angesehen (BENISTON et al. 1997, PAULI et al. 2001, THEURILLAT & GUISAN 2001, DIRNBÖCK et al. 2003). In der Diskussion über den Klimawandel (HOUGHTON et al. 1990; WALTHER et al. 2002) wird für sie eine im Verhältnis zu anderen Bereichen schnelle und drastische ökosystemare Änderung erwartet, so dass Ihnen eine Indikatorfunktion zukommt (CHAPIN III et al. 1992, BENISTON & INNES 1998). Allgemein wird zwar von einer Erwärmung des Klimas um 1,9 bis 5,2 K bis Ende des Jahrhunderts mit besonders großen Änderungen in der Arktis und in den Hochgebirgen bei gleichzeitiger Erhöhung der Niederschläge ausgegangen (IPCC 1998), allerdings ist die Genauigkeit der Vorhersagen bisher mit großen Unsicherheiten behaftet. Neben der regionalen Varianz bereiten v. a. Interaktionen zwischen Einstrahlung, Temperatur und Bewölkung, Erwärmung, Puffer durch Ozeane etc. Probleme (SHACKLEY et al. 1998). Für Norwegen gelten Temperaturerhöhungen von je nach Region zwischen 1-2 K und Niederschlagserhöhungen von bis zu 23 % (jeweils bis 2050) als wahrscheinlich (SYGNA & O´BRIEN 2001), für den kontinentalen Osten werden jedoch sommerliche Niederschlagsrückgänge um 5-10 % erwartet (FØRLAND et al. 2000). Bedingt durch die klimatische Änderung prognostizieren verschiedene Autoren eine Änderung der Artenzusammensetzung und Biodiversität (CALLAGHAN et al. 1993; CHAPIN III et al. 2000) sowie eine Verschiebung der zonalen und hypsometrischen Ökosystemkonfigurationen (MOLAU & LARSSON 2000, ACIA 2004) bis hin zu einer Verdrängung alpiner durch sub-alpine Ökosysteme (AAS & FAARLUND 1995, CRAMER 1997). Um Änderungen abschätzen oder quantifizieren zu können, ist allerdings das Wissen über das rezente „Funktionieren“ dieser Ökosysteme unabdingbar (REYNOLDS et al. 1996, DORMANN & WOODIN 2002), ebenso muss das Klimasystem auf verschiedenen Skalenebenen untersucht werden (ACIA 2004).

Hochgebirge sind ein wichtiges Element des Klimasystems, Effekte der großräumigen Orographie auf die atmosphärische Zirkulation und das Klima generell waren und sind Gegenstand zahlreicher Untersuchungen (BOLIN 1950, MANABE & TERPSTRA 1974, BROCCOLI & MANABE 1992). Die klimatischen Charakteristika der Hochgebirge selbst standen weniger im Fokus, obwohl ihre mikro- und mesoklimatischen Prozesse auf das Makroklima zurückwirken (BENISTON et al. 1997). Die Hochgebirgsökologie wird insbesondere durch ausgeprägte meteorologische und topo-

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graphische Gradienten ebenso wie die Höhenstufung oder das Mikrorelief bestimmt (BILLINGS 1973). Das Zusammenspiel dieser Faktoren ist komplex und wie ihr ökosystemarer Einfluss bislang nicht vollständig erforscht (KÖRNER 1999). Obwohl die Vertiefung von Kenntnissen zur kleinräumigen Differenzierung der Temperaturen und Schneedeckendauer sowie übergeordneter Ozeanitäts-Kontinentalitätsgradienten im Hochgebirge Skandinaviens schon früh postuliert wurde (FÆGRI 1972), ist über die Umweltbedingungen immer noch wenig bekannt (FREMSTAD 1997). Aktuelle Untersuchungen in Norwegen (LÖFFLER et al. 2005) belegen z. B. im mikro-, meso- und makroskaligen Vergleich der Temperaturgradienten, dass der mikroskalige reliefbedingte Temperaturgradient am stärksten ausgeprägt ist. Dies widerspricht der Annahme, dass regionale Klimaunterschiede (in Norwegen insbesondere der Ozeanitäts-Kontinentalitäts-gradient) am stärksten entwickelt sind und die lokalen Bedingungen steuern (MOEN 1999). Hierauf baut aber u. a. die Abgrenzung verschiedener Vegetationstypen auf (FREMSTAD 1997), da starke Unterschiede in der Vegetation entlang des Gradienten erwartet werden (MOEN 1999). Dieser Ansatz kann somit ebenso wie die auf makro-skaligen Modellierungen zum Klimawandel basierenden Aussagen zu Änderungen der Vegetationszonen und Biome (AAS & FAARLUND 1995, CRAMER 1997) kritisch hinterfragt werden. Gerade auch für den letzten Punkt sind demnach klimatologische Informationen auf Skalenebenen erforderlich, die um ein Vielfaches kleiner sind als die typischen Rastergrößen selbst hochauflösender numerischer Klimamodelle (BENISTON et al. 1997).

Dieser kurze Überblick zeigt ein offensichtliches Dilemma auf: Einerseits wird eine durch den Klimawandel induzierte Veränderung der Ökosysteme gerade in alpinen Bereichen erwartet, andererseits offenbaren widersprüchliche Aussagen einen geringen Kenntnisstand über ihre rezenten klimatischen Bedingungen und deren ökosystemarer Steuerungsfunktion. Die Ursachen und mögliche Lösungsansätze sollen in dem folgenden methodischen Überblick beleuchtet werden.

2 Messtechnische Erfassung und räumliche Extrapolation von Klimadaten

Die messtechnische Erfassung von Klimadaten stellt prinzipiell die einfachste Methode dar, um zu punktuell gültigen Erkenntnissen zu gelangen. Der räumliche Schwerpunkt der Klimaerfassung liegt zumeist jedoch nur auf dem durch den Menschen intensiv genutzten Teil einer Landschaft. Auf Hochgebirge übertragen bedeutet dies also v. a. Messungen in den Tallagen. Dies resultiert in einem generellen Mangel an Messdaten aus dem Hochgebirge (PRICE & BARRY 1997), der am Beispiel Mittelnorwegens verdeutlicht wird: Entlang 62 ° N liegen nur 10 von 107 amtlichen Wetterstationen oberhalb der alpinen Baumgrenze, die alpinen Bereiche nehmen hier aber 25.100 km² bzw. 51 % der Fläche ein (vgl. Abb. 1). Zu dieser inadäquaten Datenlage kommt die von LESER (1997) gestellte Frage der Repräsentanz der standardisiert in 2 m Höhe erfassten Daten für einen Bereich mit niedrigwüchsiger Vegetation unter einem Meter. Detaillierte Untersuchungen in einem räumlichen Netz unterschiedlicher Standorte im ostnorwegischen Hochgebirgsraum belegen dann auch die geringe ökologische Aussagekraft der so ermittelten Werte (LÖFFLER & PAPE 2004).

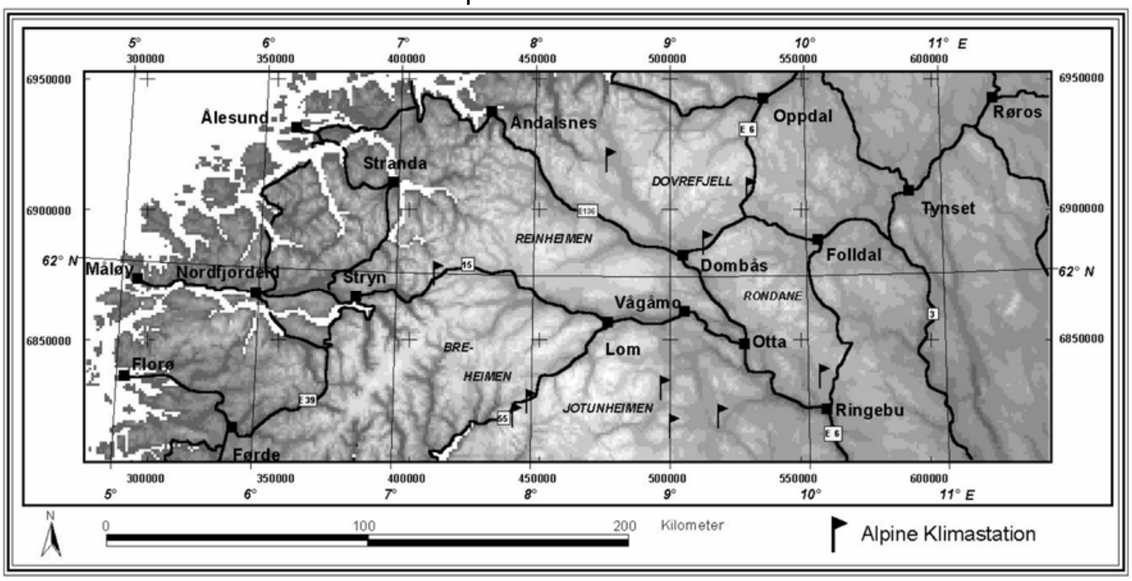

Abb. 1: Amtliche Klimastationen oberhalb der alpinen Baumgrenze in Mittelnorwegen

Punktuell erhobene Daten gelten zunächst nur für den jeweiligen Standort, angestrebt wird aber eine flächenhafte Aussage. Trotz intensiver Forschung seit mehreren Jahrzehnten (WMO 1972) bleibt die Regionalisierung klimatischer Daten insbesondere in Gebirgsbereichen mit komplexer Topographie, die die klimatische Variabilität entscheidend bestimmt (BARRY 1992, BECKER & BUGMANN 1997), problematisch. Ein weiteres grundlegendes Problem regionalisierender Ansätze ist auf die Tatsache zurückzuführen, dass die räumliche Variabilität meist keiner raum-zeitlichen Linearität unterliegt (PETERSON 2000) und es an flächenhaft verfügbaren Datenebenen fehlt, auf deren Grundlage sich Variabilität und Gradienten bestimmen ließen.

Eine lokale Erfassung der kleinräumigen klimatischen Variabilität ist, wenn auch mit hohem Messaufwand, noch möglich (LÖFFLER & WUNDRAM 1997). Dieses Verfahren lässt sich allerdings nicht mehr ohne weiteres auf Hochgebirgsräume von wenigen Quadratkilometern Größe ausdehnen. Gefordert ist auf dieser Maßstabsebene ein Ansatz, der weitgehend ohne Messungen auskommt. Denkbar ist prinzipiell die Extrapolation der im großmaßstäbig orientierten Verfahren gewonnenen Daten und daraus abgeleiteter Erkenntnisse in größere Landschaftsausschnitte über strukturell begründete Raumeinheiten, die aus Fernerkundungsdaten abgeleitet werden. Dieses von LÖFFLER & WUNDRAM (2001) erfolgreich im ostnorwegischen Hochgebirgsraum angewandte Verfahren basiert auf der Theorie der geographischen Dimensionen (zusammengefasst in LESER 1997). Die punktuell-vertikale Detailliertheit der Untersuchung muss dabei zwangsläufig mit zunehmender Größe und Flächenhaftigkeit der Untersuchungsobjekte zugunsten einer räumlichen Aussage verloren gehen (HERSPERGER 1995).

Die Tatsache, dass zahlreiche arktisch-alpine Pflanzen in ihrer Verbreitung von den standörtlichen Temperaturverhältnissen abhängig sind (DAHL 1998), nutzen BROSSARD et al. (2002) und KARLSEN & ELVEBAKK (2003): Über die auf umfangreichen Analysen basierende Bestimmung artspezifischer Thermophilie-Indices in Verbindung mit Fernerkundungsdaten werden großräumige bioklimatische Kartierungen ermöglicht.

Ein einfacher Ansatz zur höhenwärtigen Extrapolation von Temperaturen beruht auf dem adiabatischen Temperaturgradienten von 0,6 K / 100 m (RUNNING et al. 1987). Seine Anwendung erscheint allerdings aufgrund seiner zeitlich sehr stark ausgeprägten Variabilität (z. B. durch winterliche Inversionen) zweifelhaft (LÖFFLER et al. 2005).

Multivariate oder geostatistische Verfahren (z. B. HUTCHINSON 1995a, MARTINEZ-COB 1996), „state of the art“ in der Klimatologie, ermöglichen ein Abbild der klimatischen kleinräumigen Variabilität nur mit einer unrealistisch hohen Stationsdichte, die gerade im Hochgebirge nicht gegeben ist (s. o.). Die Einbeziehung von Höheninformationen aus digitalen Geländemodellen in den Prozess der Regionalisierung (z. B. HUTCHINSON 1995b FLEMING et al. 2000, GOOVAERTS 2000) führt nur dann zu detaillierteren Ergebnissen, wenn die Höhe auch tatsächlich die klimatische Variabilität erklärt. Vielfach sind es jedoch eher komplexere topographische Parameter wie relative Höhenunterschiede, Exposition etc. die einen höheren Erklärungsanteil besitzen (THOMAS & HERZFELD 2004). Nichtsdestotrotz ermöglicht dieses Verfahren v. a. eine großräumige Charakterisierung der Temperatur- und Niederschlagsverhältnisse auf der Basis von Mittelwerten; für Gesamtnorwegen vgl. MOEN (1999). Ein kombinierter Ansatz zur Analyse des Topographie-Einflusses auf klimatische Faktoren mittels Principal Component Analysis (PCA), multipler Regression und Residuen-Kriging (BENICHOU & LEBRETON 1987) führt in modifizierter Form zu einer signifikanten Verbesserung klimatischer Karten von China (THOMAS & HERZFELD 2004) und wurde in ähnlicher Form auch im skandinavischen Raum angewandt (TVEITO et al. 2000).

3 Modellierung von Klimadaten

Die numerische Modellierung im Bereich der Wettervorhersage bzw. Klimaforschung umfasst einen weiten Skalenbereich, ausgehend von den globalen Zirkulationsmodellen (GCM, z. B. LAND et al. 1999). Diese stimmen in Bezug auf die globale Mitteltemperatur zumeist überein, zeigen untereinander aber starke Abweichungen bei regionaler Betrachtung (RÄISÄNEN 2001). Dementsprechend bieten diese Modelle kein vernünftiges Abbild der regionalen und lokalen rezenten klimatischen Verhältnisse (GROTCH & MACCRACKEN 1991). Es liegen stattdessen verschiedene Ansätze vor, Ergebnisse der GCM im Zuge eines analytischen oder empirisch-statistischen Downscaling auf eine regionale Skalenebene zu übertragen: vgl. z. B. RUMMUKAINEN et al. 2001 und DENBY et al. 2002 (analytisch), sowie BENESTAD 2003 (statistisch). Entsprechende Modellansätze lassen sich aber ohne eine angemessene Berücksichtigung der topographischen Differenziertheit von Hochgebirgen (vgl. Abb. 2) nur eingeschränkt auf regionale bzw. lokale Verhältnisse in Hochgebirgsbereichen übertragen (BENISTON 2003). Das Resultat bei der Anwendung großräumiger Modelle sind signifikante Defizite in der Vorhersagegenauigkeit, die für das Boreal und die Hochgebirgsbereiche generell durch eine „bestenfalls unvollständige, schlimmstenfalls falsche“ Parametrisierung der Landoberfläche verstärkt wird (HARDING et al. 2001).

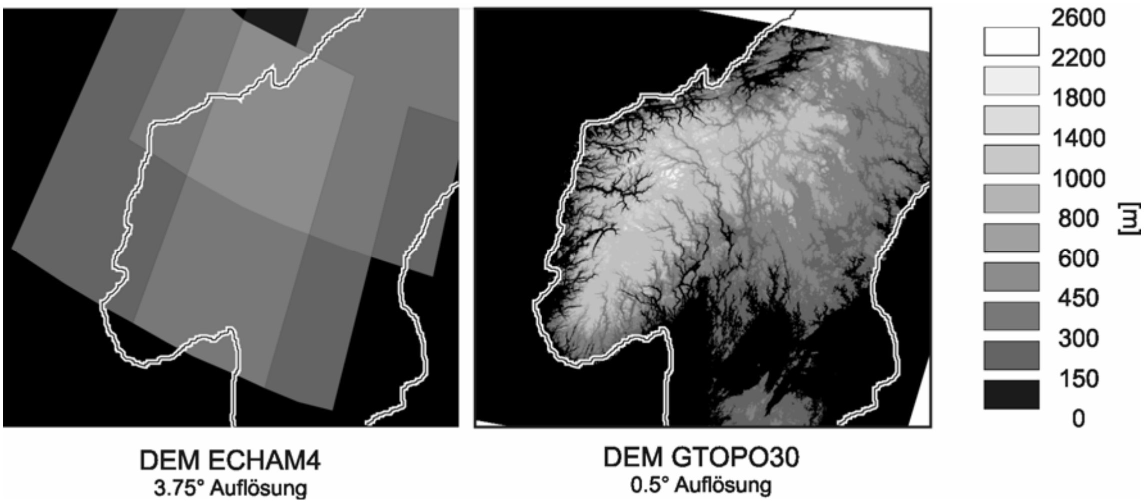

Abb. 2: Räumliche Auflösung des dem ECHAM4-GCM zugrunde liegenden Höhenmodells (links, nach RUMMUKAINEN et al. 2001) verglichen mit der ± realen Topographie nach GTOPO30. Die höchste Erhebung der Skanden nach ECHAM4 liegt demnach bei 450-600 m gegenüber realen 2400 m!

Die Identifikation der Schnittstelle Erdoberfläche-Atmosphäre als Schlüssel zur Reduktion von Ungenauigkeiten hat zu einer verstärkten Entwicklung mikroskaliger Modelle für diesen Bereich geführt: Eindimensionale „soil-vegetation-atmosphere-transfer” (SVAT) Modelle (z. B. JANSSON & KARLBERG 2001) kombinieren verschiedene Disziplinen von der Meteorologie über die Bodenphysik bis zur Pflanzenphysiologie. Sie ermöglichen zwar eine exakte Simulation, erfordern aber ein großes Maß an spezifischen Input-Daten, die z. T. über Laboruntersuchungen gewonnen werden müssen und somit eine großräumige Anwendung verhindern (BOULET et al. 2000). Ein zur Verfügung stehendes einfaches Modell zur Berechnung der oberflächennahen Temperaturdynamik (Pape & Löffler 2004) hängt in seiner flächenhaften Aussagequalität stark von der Qualität der Inputparameter „klimatische Rahmenbedingungen“ und „Vegetation“ ab, die wiederum aus großräumigeren Modellen bzw. Fernerkundungsdaten mit ihren vorgenannten Limitierungen abgeleitet werden müssen.

4 Fazit

Der vorangegangene methodische Überblick zur Gewinnung von Klimadaten im Hochgebirge offenbart ein Problem der räumlichen Auflösung, das durch die komplexe Topographie und damit verbundene klimatische Variabilität (BARRY 1992, BECKER & BUGMANN 1997) hervorgerufen wird.

Die vorgestellten Ansätze von LÖFFLER & WUNDRAM 2001, BROSSARD et al. 2002 bzw. KARLSEN & ELVEBAKK 2003 extrapolieren über umfangreiche mikroskalige Untersuchungen gewonnene Erkenntnisse auf strukturell begründete Raumeinheiten, die aus Fernerkundungsdaten v. a. über die Vegetation als hochintegrativer Indikator raumzeitlicher Temperaturvariabilität in Verbindung mit dem Relief abgeleitet wurden. Der limitierende Faktor dieser Ansätze ist die Verfügbarkeit von räumlich hochauflösenden Fernerkundungsdaten, die über die Qualität der Aussagen entscheidet: Diese stehen seit dem Einsatz neuer Systeme (IKONOS und Quickbird) zwar theoretisch zur Verfügung, die erheblichen Kosten und die fehlende individuelle Kontrolle über Aufnahmezeitpunkt, Wolkenbedeckung etc. schränken den Nutzen aber stark ein. Verbesserungen sind nur durch den Einsatz kostengünstigerer Verfahren, z. B. der Luftbildfotographie mit Drohnen oder Fesseldrachen (ABER et al. 1999), zu erwarten. Verfahren der räumlichen Interpolation von Messdaten über Höhengradienten oder statistische Ansätze führen zwar von vornherein zu einer großräumigen Charakterisierung der klimatischen Verhältnisse (TVEITO et al. 2000), lassen aber nur bei einer unrealistisch hohen räumlichen Stationsdichte aussagekräftige regionale bzw. lokale Ergebnisse erwarten (Thomas & Herzfeld 2004). Auch die Auflösung gebräuchlicher räumlicher Klimamodelle reicht nicht aus, regionale oder sogar lokale Verhältnisse abzubilden (GROTCH & MACCRACKEN 1991, BENISTON et al. 1997, BENISTON 2003). Ansätze zur Verbesserung der regionalen und lokalen Aussageschärfe über empirisch-statistisches Downscaling (BENESTAD 2003) sind viel versprechend, unterliegen aber durch die geringe Stationsdichte der gleichen Limitierung wie der statistische Interpolationsansatz. Eindimensionale Modelle bilden dagegen die lokalen, d.h. standörtlichen, Bedingungen sehr gut ab (PAPE & LÖFFLER 2004). Das Problem ihrer flächenhaften Anwendung liegt in der Generierung der erforderlichen Eingangsparameter aus Fernerkundungsdaten für die Vegetation und über statistische Extrapolation oder Modellierung für die klimatischen Rahmenbedingungen, jeweils mit den oben genannten Limitierungen.

Mit flächenhaften Klimadaten im Hochgebirge ist eine Diskrepanz zwischen Anspruch und Wirklichkeit verbunden: Für die Abschätzung der Folgen des Klimawandels sind detaillierte Informationen zur Funktionsweise der Ökosysteme erforderlich (REYNOLDS et al. 1996, DORMANN & WOODIN 2002). Einerseits liegen diese als kleinräumig-detaillierte Erkenntnisse zu klimatischen Bedingungen und ihren ökosystemaren Auswirkungen vor (z. B. LÖFFLER & WUNDRAM 2003, andererseits stellt ihre Regionalisierung jedoch eine der großen wissenschaftlichen Herausforderungen dar (JENSEN & BOURGERON 2001, STEINHARDT & VOLK 2003). Bisherige Szenarien zum Klimawandel beruhen somit mangels detaillierter Daten häufig auf der deduktiven Übertragung kleinmaßstäblich gewonnener Erkenntnisse auf größere Maßstäbe (z. B. GUISAN & THEURILLANT 2000; DIRNBÖCK et al. 2003) – ein Verfahren, das zumindest fragwürdig erscheint (ACIA 2004, LÖFFLER et al. 2005).

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5.6 Publikation VI

Pape, R., Wundram, D. & J. Löffler

Modeling Near-Surface Temperature Conditions in High Mountain Environments – An Appraisal.

Eingereicht bei:

Climate Research

Modeling Near-Surface Temperature Conditions in High Mountain Environments – An Appraisal

by Roland Pape, Dirk Wundram and Jörg Löffler

ABSTRACT: Facing the need of temperature data for high mountain environments at spatial and temporal resolutions reasonable for ecological modeling, the present paper addresses the evaluation of both, physically and statistically based modeling or interpolation of near-surface temperatures in a high mountain environment at sub-daily time scales and differing spatial scales. Emphasis is laid on the selection of guiding environmental variables for temperature interpolation at macro-scale, a comparison of physically and statistically based modeling at meso- and micro-scale, and scaling issues are discussed. Geostatistical interpolation was found to perform very well at macro-scale if additional topographic and atmospheric covariables, the latter provided by remote sensing, are considered. Physically-based modeling performed best at site-level, revealing spatial limits of reasonable applicability due to limited input data. Statistical modeling based on multiple linear regression, however, showed results of intermediate accuracy throughout the spatial scales, providing encouraging evidence that we can find a simple approach to estimate near-surface temperature fields in high mountain environments. Moreover, the study revealed the necessity of an appropriate handling of scaling issues in temperature modeling to achieve satisfactory results, albeit this seems to be hampered by the starting point of the whole discussion – the lack of observational data at finer spatial scales.

KEY WORDS: Surface energy balance model · Spatial interpolation · Ecologically relevant temperatures · Scaling · Scandes

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1. INTRODUCTION

Mountain environments are due to their fragility among the most sensitive to climatic change (Beniston et al. 1997, Pauli et al. 2001, Theurillat & Guisan 2001, Dirnböck et al. 2003). The distribution of plants, for instance, is to a major extent determined by the spatial differentiation in temperature, soil moisture conditions, and snow cover (Gjærevoll 1990, Dahl 1998, Wielgolaski 1998, Moen 1999), three environmental factors directly affected by climatic change. Studies on vegetation patterns, however, often rely on a single proxy variable as a convenient way of representing these environmental factors – elevation (Whittaker 1978, Grytnes 2003). Obviously, regimes of both, temperature and moisture are related to elevation due to the environmental lapse rate and the increase in precipitation with altitude, but these vary substantially in space and time (Rolland 2003). Facing such variations, the common practice of adjusting mean station temperatures to a reference altitude using solely lapse rates is likely to produce non-comparable and therefore misleading results (Barry 1992). Moreover, large-scale patterns related to altitude or climatic regime (i.e. degree of continentality) are strongly modified or even superimposed by effects of local topography (e.g. Löffler & Pape 2004, Löffler et al. 2006). Consequently, Lookingbill & Urban (2003) stressed the necessity to develop more descriptive models of key ecological constraints directly affected by climatic change, i.e. temperature rather than elevation, in order to model future ecological processes.

To be accurate enough, such models of ecosystem response need to be hosted at the meso- or micro-scale, where detailed environmental patterns which tend to level off at regional to global scales cannot be ignored. Since the overall and differential spatial performance of these models is essentially dependent on the accuracy of input data, also the required climatic data have to be provided at this spatial scale. However, attaining these data with sufficient accuracy is hampered by two logistical issues. First, since routine meteorological observations are available at discrete points in space, typically separated by a distance of 30–50 km or more, a spatial interpolation is necessary to produce data with a sufficient resolution. However, weather stations are especially sparse in mountain regions as they are mostly located at lower elevations where the watersheds are populated (Barry 1992) – a fact that is likely to limit interpolation accuracy over mountainous regions. Second, it is at the micro-scale that the current climate models are still particularly insufficient (Chen et al. 1999) since the required resolution is far below the typical grid-size even of the highest resolution numerical models (e.g. Rivington et al. 2008). Since numerous climatological details of mountain environments are simply overlooked by common climate models it has consequently been recognised that comprehensive physically-based land-surface schemes are needed in atmospheric models to adequately simulate near-surface exchanges of heat, moisture and momentum (e.g. Saunders et al. 1999a, b). However, the required input data for these schemes, especially vegetation physiological parameters and soil characteristics, are commonly unavailable for larger spatial extents in remote mountainous regions. Facing this dilemma, an increasing number of (geo-)statistical approaches for the interpolation of climatic parameters at high spatio-temporal resolution has recently been published (e.g. Lookingbill & Urban 2003, Joly et al. 2003, Chung & Yun 2004, Chung et al. 2006, Stahl et al. 2006, Joly & Brossard 2007) that also account for environmental effects or use remote sensing data.

Facing this background, the present paper addresses the evaluation of both, physically and statistically based modeling and interpolation of near-surface temperatures in a high mountain environment at sub-daily time scales and differing spatial scales with the following specific objectives:

1. To derive environmental guiding variables for the interpolation of temperatures at different scales.
2. To compare the performance of physically-based modeling and statistically-based interpolation.
3. To address scaling issues or the question if there exist scale-limits until an approach might be applied reasonably.

2. MATERIALS AND METHODS

2.1 Materials

Study areas. The study was conducted in central Norway along 62° N, representing the macro-scale (Fig. 1). The mountain chain of the Scandes reaches with 2,469 m a.s.l. its highest elevation in this region, resulting in a clearly defined oceanic-continental gradient between the western and eastern slopes of the mountain chain. Within the frame of a long-term ecological project (Löffler 2002, 2003, Löffler & Finch 2005) two meso-scaled areas were chosen as to represent the climatic differences (Fig. 1): The study area Geiranger (62°03’ N; 7°15’ E) within the inner fjords region of western Norway is climatically characterized 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 study area Vågå (61° 53´ N; 9° 15´ E), showing according to Moen (1999) the highest aridity found in Norway with precipitation sums of about 300–400 mm per year in the valleys. The alpine belt expands from 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 at 1,775 m a.s.l. in Geiranger and 1,618 m a.s.l. in Vågå. It comprises the low-alpine belt characterized by dwarf-shrub and lichen heaths, the middle-alpine belt dominated by chionophobous lichens and graminoid species and in Geiranger also the high-alpine belt with glaciated areas. Regarding Fig. 1, the steep topography of the Geiranger area is apparent when compared to the mostly gentle sloping Vågå area. In both areas, two micro-scaled catchments have been chosen as to represent the low- and middle-alpine belt, from which the one in the low-alpine belt of the Vågå area (Fig. 1) will be considered in this study.

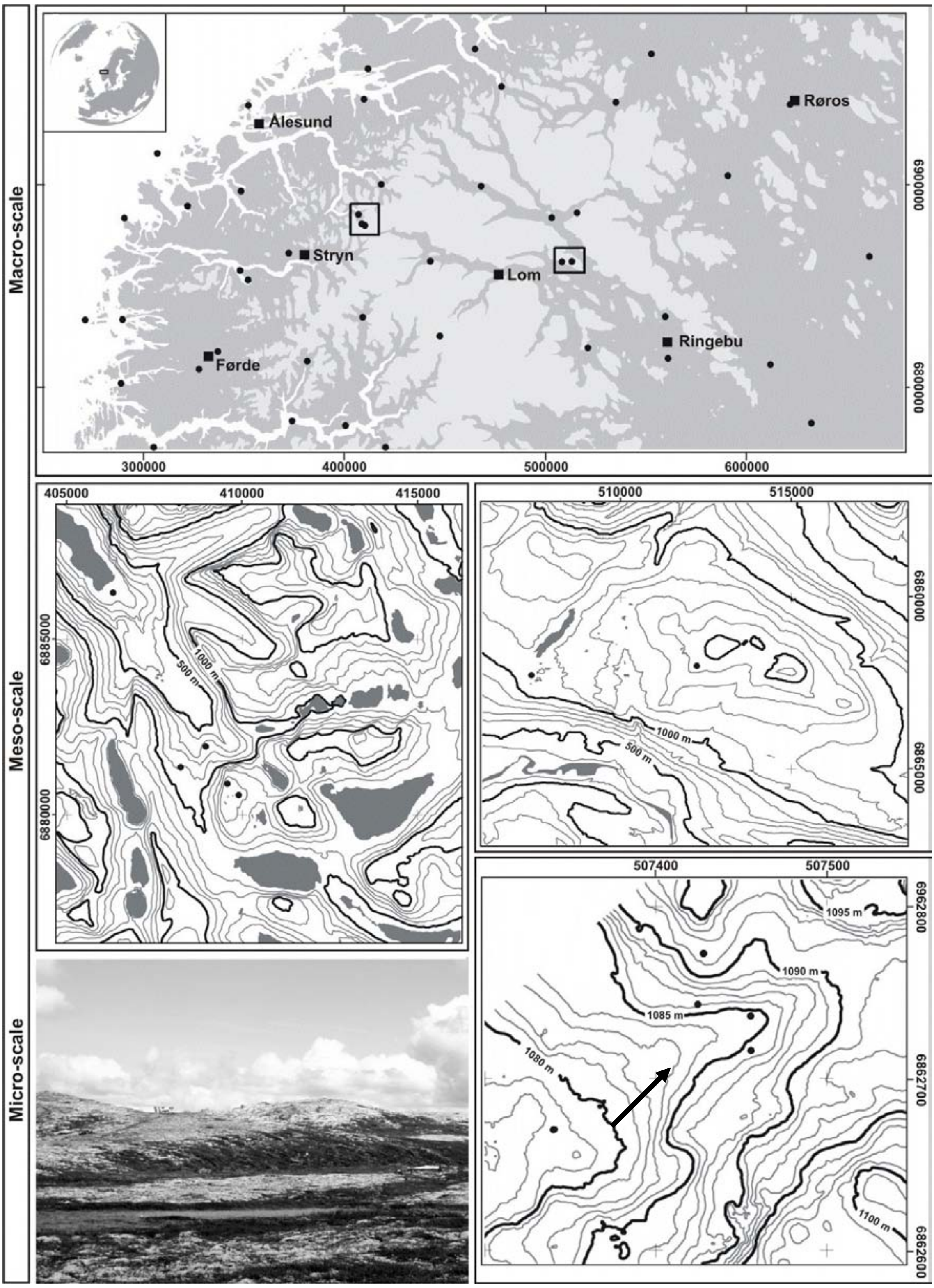

Fig. 1: Study areas at macro-, meso-, and micro-scale in central Norway. At macro-scale, areas above alpine tree-line are shown in light grey; dark grey at meso-scale indicates water surfaces. Rectangles represent the position of the study areas at next finer scale, whereas the location of 45 weather stations providing the data for the analyses in this study is marked by dots. At the micro-scale, dots also represent the position of near-surface temperature data loggers. The photograph gives an impression of the fine-scaled variability of this high-mountain landscape, the arrow in the map indicates the direction of view.

Climatological data. The climatological data used for this study were obtained from 45 weather stations at locations shown in Fig. 1. The stations are operated by the Norwegian Meteorological Service (38, DNMI, data available at http://www.eklima.no), the Norwegian Geological Service in the Geiranger area (3, NGU) and our own in the Geiranger and Vågå area (4, GIUB). In addition to one weather station, four data loggers are located in the micro-scaled catchment representing main topographic positions. The data comprised of air temperatures at two metres height (T_A) for the year 2004 as daily maxima (T_{AMX}) and minima (T_{AMN}) for the DNMI stations, two-hourly means (NGU) and hourly means (GIUB). The data loggers record temperatures as hourly means at -15, -1 and +15 cm distance to the soil surface, hereafter referred to as T_S, T_{SFC}, and T_{A15}. These temperatures are also recorded at the GIUB stations, with global short-wave radiation (K↓), precipitation, relative humidity, wind speed at two metres above ground (u) and wind direction in addition. All measurement-sites are referred to as nano-scale.

Remote sensing data. Complementary to the above mentioned ground-based observations at discrete points in space, spatial data on land surface temperature (LST) with a resolution of 1 km were obtained for each day/night in 2004 from TIR MODIS data. Additional data on LST at 60 m resolution were available for the day of year (hereafter: doy) 223 originating from an overpass of Landsat 7 ETM at 10:36 am. Ancillary data on daily (for some MODIS products: 8 day-period) cloud cover, snow cover, surface albedo, and NDVI were also derived from the MODIS and Landsat ETM data. For the micro-scaled catchment high-resolution (0.1 m) RGB and TIR aerial photos based on kite aerial photography (Wundram & Löffler 2008) were available for doy 278 at 14:30. Spatial patterns of vegetation at meso- and micro-scale were derived by maximum likelihood classification based on ground truthing plots.

Topographic data. For the macro-scale, a DEM was derived from GTOPO30 data, projected to WGS84 UTM zone 32 resulting in a spatial resolution of 500 m. At meso-scale, a DEM with a resolution of 30 m (to match the Landsat ETM scene) is based on topographic maps of the Norwegian Mapping Authority at scale 1:50,000. For the micro-scale, a DEM at 0.1 m resolution was derived by photogrammetry from kite aerial photos in conjunction with the nivellement of ground control points (Wundram & Löffler 2008).

2.2 Methods

Geostatistical interpolation of T_{AMX} and T_{AMN}. Over extensive areas like our macro-scaled region, deriving spatially distributed data using process-based approaches might be impractical for reasons of computational and theoretical complexity or the unavailability of data. Interpolation will be used instead, adopting a ''middle ground'' between data-based geostatistical interpolation and process-based meteorological modeling (Jarvis & Stuart 2001). This approach is achieved by choosing to guide the process of interpolation using indices developed from atmospheric, topographic and land cover data that are hypothesized to influence the climatic conditions.

A set of 16 potential guiding variables (Table 1) was derived, especially accounting for topographic effects like potential solar radiation, height above local minimum or flow accumulation that might affect temperature patterns. For each single variable its power of explanation was tested separately for T_{AMX} and T_{AMN} using stepwise linear regression for 52 independent days in 2004. The five variables that were most included in the regressions and had the highest partial correlations (Jarvis & Stuart 2001) were then chosen as environmental guiding variables for a cokriging procedure of temperatures. Cokriging was chosen as it has been proven to be the most usable interpolator for temperature fields besides regional regression (Bolstad et al. 1998, Florio et al. 2004, Halit et al. 2004). The accuracy of the resulting temperature maps was tested against observations of two independent weather stations withheld from the cokriging procedure.

Table 1: Potential guiding variables for temperature interpolation

northing	*distance to coast*
easting	*height above local minimum (3x3, 5x5, 7x7 window)*
altitude	*height below local maximum (3x3, 5x5, 7x7 window)*
potential solar radiation	*terrain ruggedness (as standard deviation of elevation within 3x3, 5x5, 7x7 window)*
cloud cover (from MODIS data)	*flow accumulation*

Physically-based LST modeling. Due to the limited amount of input data available compared to the input data needed for land surface schemes, we chose a rather simple energy balance approach developed for such data-limited applications (Pape & Löffler 2004). The model estimates surface temperatures by iterative solution of the energy balance constituted by net radiation (Q*) on the one hand and sensible, latent and ground heat fluxes (H, LE and G_0) on the other. Originally developed for point applications, it has been implemented in a GIS for micro- and meso-scale applications here, albeit it does not account for lateral effects. The lack of spatial information on soil characteristics and plant physiological parameters forced further simplifications compared to the original settings of the model to enable its spatial applicability. Instead of an analytical solution, the soil heat flux was parameterized as a ratio of net radiation (e.g. de Bruin & Holtslag 1982, Kustas & Daughtry 1990) leading to G = *a*Q*, with *a* chosen as (i) constant value of 0.15, and (ii) -0.27 NDVI + 0.39, to account for its dependence on vegetation cover (Jacobsen & Hansen 1999). The factor *a* is different for daytime and night-time, because during daytime the energy provided by Q* is shared between G_0 and the turbulent heat fluxes, while these are nearly negligible during night-time and G_0 makes up the largest part of Q*. Thus, the modeling approach was restricted to daytime.

Evapotranspiration was estimated by the modified Priestley-Taylor concept (Priestley & Taylor 1972, van Ulden & Holtslag 1985, de Rooy & Holtslag 1998) instead of the original Penman-Monteith approach (Monteith 1981) in order to avoid the estimation of aerodynamic and surface resistances.

The resulting set of equations is as follows, where the energy balance is given by

$$Q^* = H + LE + G_0 \tag{1}$$

with net radiation according to de Bruin & Holtslag (1982) estimated by

$$Q^* = K{\downarrow} - K{\uparrow} + L{\downarrow} - L{\uparrow} = (1 - A)K{\downarrow} + 5.31*10^{-13}T_A^6 - 0.95\sigma T_0^4 \tag{2}$$

where A denotes the albedo, σ, the Stefan-Boltzmann constant [$Wm^{-2}K^{-1}$] and T_0, the temperature at the effective surface taken as LST. Both temperatures are given as absolute temperatures [K]. In our case, K↓ was based on reference observations spatially corrected for topography (Oke 2001), A was estimated from remote sensing data, and T_A was taken from the above mentioned interpolation approach but corrected for the higher resolution-topography at micro- and meso-scales using actual temperature lapse rates derived from measurements.

The sensible heat flux is estimated using an aerodynamic approach (Oke 2001):

$$H = -C_a k^2(u(T_A - T_0)/[\ln(z_A/z_0)]^2)(\Phi_M\Phi_H)^{-1} \tag{3}$$

where C_a is the heat capacity of air [$Jm^{-3}K^{-1}$], k, the von Karman's constant (0.41 m), z_A, the height of air temperature measurement (2 m), z_0, the surface roughness length [m], and finally $(\Phi_M\Phi_H)^{-1}$, a stability correction dependent on the Richardson number Ri during stable cases (Ri > 0) by

$$(\Phi_M \Phi_H)^{-1} = (1 - 5Ri)^2 \quad (4a)$$

and during unstable cases (Ri <0) by

$$(\Phi_M \Phi_H)^{-1} = (1 - 16Ri)^{3/4} \quad (4b)$$

The Richardson number itself is estimated by

$$Ri = g / T\,((T_A - T_0)(z_A - z_0)) / u^2 \quad (5)$$

where g is the acceleration due to gravity [ms^{-2}] and T without subscript, the mean of T_A and T_0.

Since this approach requires a spatial wind field, the distribution of wind speed within the area was approximated using a simple approach proposed by Böhner (2004): The relative increase or decrease in wind speed reflects specific distance-related effects of orography due to luv and lee exposure. For eight discrete sectors of wind direction (N, NE, E, ...) a coefficient of wind speed reduction is derived that enables a spatial quantification of variations in wind speed determined by orography, if observations at one reference station are provided. The coefficient constitutes of slope angle functions upwind (subscript u) and downwind (subscript d), given by

$$W_u = \sum_{i=1}^{n} 1/d_{uhi} \tan^{-1}(d_{uzi} / d_{uhi}^{0.5}) / \sum_{i=1}^{n} 1/d_{uhi} + \sum_{i=1}^{n} 1/d_{dhi} \tan^{-1}(d_{dzi} / d_{dhi}^{0.5}) / \sum_{i=1}^{n} 1/d_{dhi} \quad (6a)$$

$$W_d = \sum_{i=1}^{n} 1/\ln(d_{dhi}) \tan^{-1}(d_{dzi} / d_{dhi}^{0.5}) / \sum_{i=1}^{n} 1/\ln(d_{dhi}) \quad (6b)$$

where d_{hi} is the distance to raster cell i, and d_{zi}, the difference in height to raster cell i. The corresponding parameter functions are given by

$$luv = 1 + \ln(1 + W_u) \qquad \text{if } W_u > 0 \quad (7a)$$

$$luv = (1 + \ln(1 - W_u))^{-1} \qquad \text{if } W_u < 0$$

$$lee = (1 + \ln(1 + W_d))^{0.5} \qquad \text{if } W_d > 0 \quad (7b)$$

$$lee = (1 + \ln(1 - W_d))^{-0.5} \qquad \text{if } W_d < 0$$

Finally, the wind speed u is calculated using the reference observation u_r by

$$u = u_r\,(luv * lee)^{0.25} \quad (8)$$

The latent heat flux is calculated according to the modified Priestley-Taylor concept by

$$LE = \alpha s(Q^* - G_0)/(s + \gamma) + \beta \quad (9)$$

where α is an empiral constant ranging from 0 for very dry conditions when no evaporation occurs to 1.26 for saturated conditions, s, the slope of saturation vapour versus temperature curve [PaK^{-1}], γ, the psychrometric constant [PaK^{-1}], and β, an empirical constant of 20 Wm^{-2}. The value of α was chosen depending on the vegetation type according to literature: Results from studies in the Arctic indicate that the value for α in dry regions characterized by sedge tussocks, mosses, lichens, and shrubs is at or near 1.00 (Rouse & Stewart 1972, Stewart & Rouse 1976, Rouse et al. 1977). In wet areas characterized by wet sedge tundra and small ponds, a number of studies have indicated that appropriate α values should be at or above 1.26 (Stewart & Rouse 1976, Roulet & Woo 1986, Bello & Smith 1990, Rovanesk et al. 1996).

As already mentioned, ground heat flux is parameterized in two forms as

$$G_0 = 0.15Q^* \quad (10a)$$

and

$$G_0 = (-0.27\ NDVI + 0.39)Q^* \tag{10b}$$

where NDVI is derived from the Landsat ETM scene.

This set of equations is then solved for LST using an iterative approach. In this study, the performance of the model was tested at nano-, micro-, and meso-scale against measurements of LST.

Statistically-based LST modeling. Similar to the interpolation of air temperatures, we sought to adopt a physical basis for this modeling approach. Independent environmental variables were chosen with respect to their relevance for surface temperatures and comprised (i) $K\downarrow$ based on reference observations but spatially corrected for topography (Oke 2001), (ii) albedo, (iii) NDVI, and (iv) the G_0/Q^* ratio as derived from remote sensing data. Furthermore, (v) the Priestley-Taylor coefficient α based on vegetation types, and (vi) the topographic wetness index (TWI) were treated as surrogates for soil moisture conditions. Finally, (vii) the spatial wind field as described above, and (viii) the interpolated air temperatures, corrected for the actual height above sea-level, were considered.

A multiple linear regression model using stepwise selection routines was established at micro- and meso-scale, treating LST derived from remote sensing data for doy 223 and 278 as the dependent variable. The dataset was split randomly to use one third for model building and two thirds for model validation. Moreover, the spatial transferability of these empirical models was tested by applying the model of the Geiranger area in Vågå and vice versa.

3. RESULTS

Geostatistical Interpolation of T_{AMX} and T_{AMN}. Regarding the selection of the best guiding variables for interpolation of daily air temperatures, we detected a differentiation between maximum and minimum temperatures. Maximum temperatures were best described using elevation (-), cloud cover (-) and terrain ruggedness in a 5x5 window (+) besides northing and easting. Minimum temperatures also showed a dependence on elevation (-), cloud cover (+), northing, and easting, but furthermore on distance to coast (-) and height above local minimum at a 3x3 window (+). Corresponding signs of correlation are given in brackets. These variables were chosen as guiding variables for the further interpolation process based on cokriging. Exemplary results of temperature maps are shown for two high pressure situations to the left in Fig. 2, with a typical winterly temperature inversion at doy 17 and a clear sky summer condition at doy 213. The oceanic-continental differentiation is obvious. The overall performance of the interpolation approach has been tested against observations of two independent weather stations, indicating a good agreement of interpolated and measured temperatures (Fig. 2).

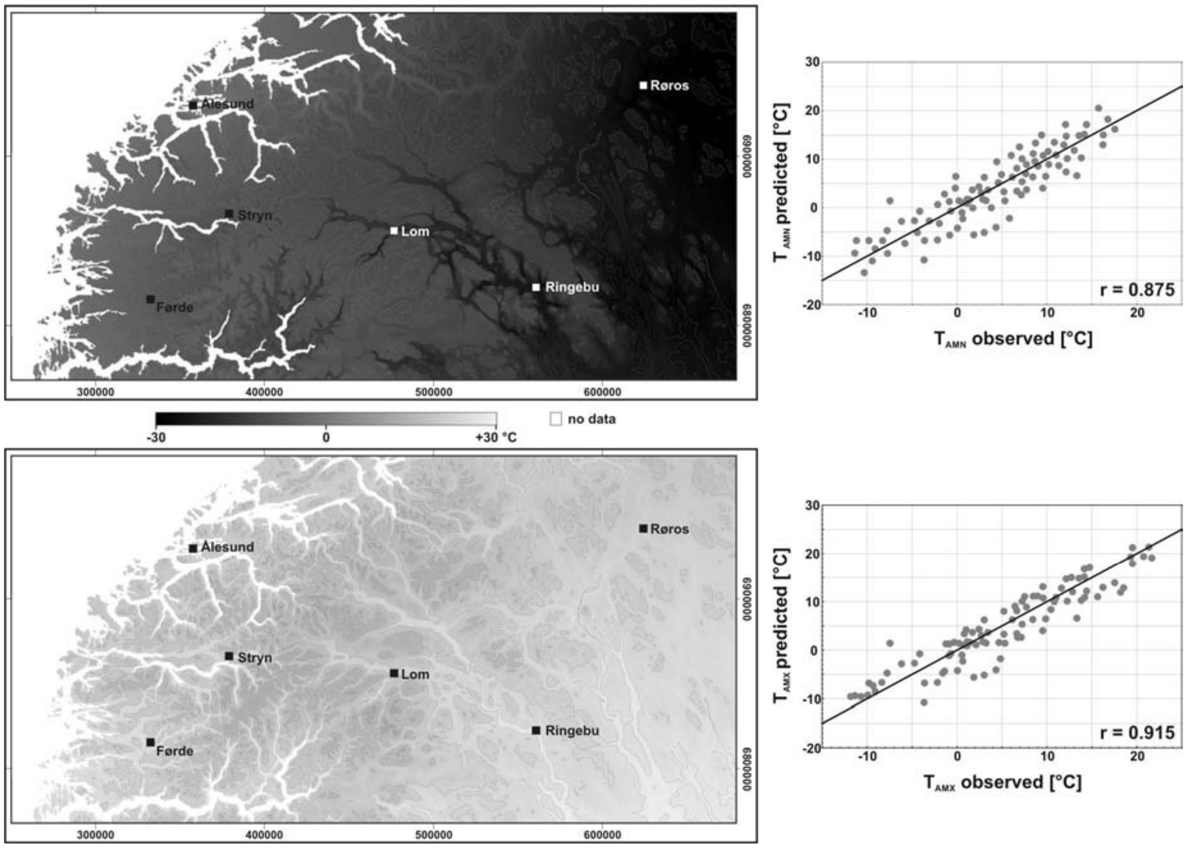

Fig. 2: Results of temperature interpolation based om cokriging, exemplary shown for T_{AMN} at doy 17 (upper left) and T_{AMX} at doy 213 (lower left). Correlation biplots to the right show the overall performance based on data of two independent weather stations for T_{AMN} (top) and T_{AMX} (bottom), respectively. The line represents the y = x function.

Physically-based LST modeling. The physically based modelling approach of surface temperatures has been applied from site-level to meso-scale. The results have been validated against independent measurements, i.e. time series of LST measured by data loggers at site-level, and spatial information about LST by TIR aerial photographs at micro-scale as well as by TIR Landsat ETM data at meso-scale. A strong decline in accuracy and ability to predict LST while increasing the spatial extent is obvious from the correlation biplots given in Fig. 3. The model performs very well at nano-scale (r = 0.943), but tends to overestimate low temperatures and to underestimate high temperatures at micro-scale, resulting in a lower r of 0.742. At meso-scale, the model mostly overestimates temperatures accompanied with a large scatter, resulting in poor r-value of 0.551.

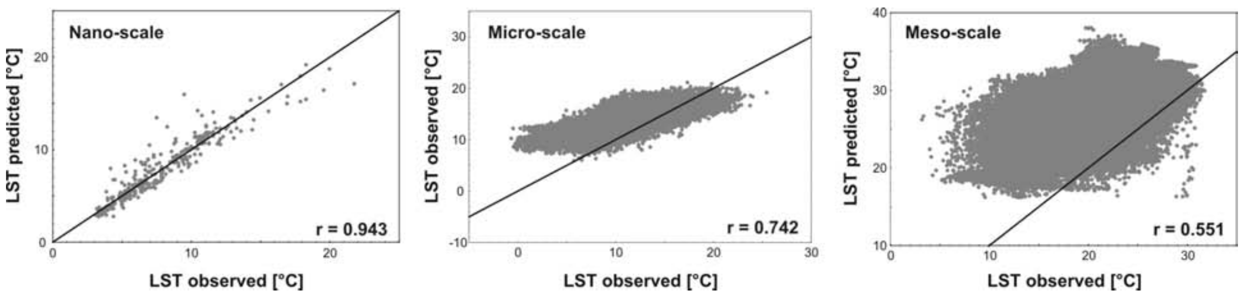

Fig. 3: Correlation biplots of observed vs. predicted LST at different spatial scales estimated by the physically-based modeling approach. The y = x function is given as line.

Statistically-based LST modeling. Statistically-based modeling has been applied from micro-scale to meso-scale. The independent variables chosen by the automatic stepwise selection routine are consistent throughout the different scales and comprise K↓, the G_0/Q^*-ratio, and TWI, with K↓ showing the highest partial correlation coefficients ranging from 0.670 to 0.752. Consequently, the full models are able to explain between 51 % and 68 % of the spatial temperature variance with a standard error of estimate ranging from 1.8 to 2.6 K. The performance of the model at micro- and meso-scale is shown as correlation biplot in Fig. 4. However, the accuracy of the models diminished when transferred to another area as shown by the biplot to the right in Fig. 4, indicating their limited validity.

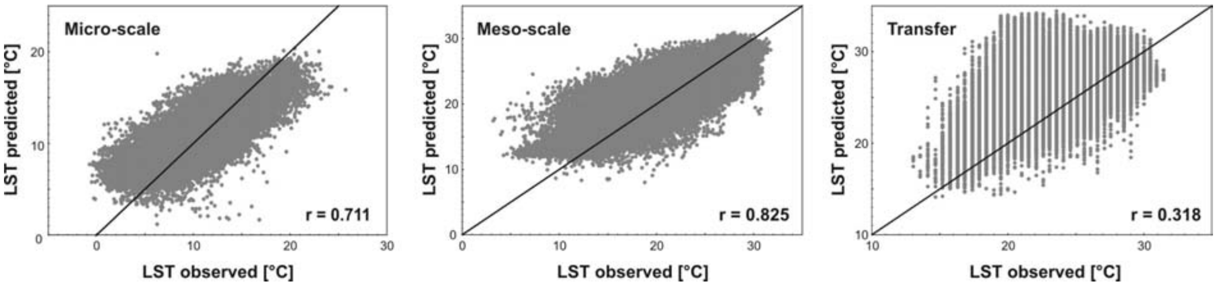

Fig. 4: Correlation biplots of observed vs. statistically predicted LST at micro- and meso-scale. The biplot to the right shows the limited performance of a meso-scale model transferred to another area. The line represents the y = x function.

4. DISCUSSION

The proper choice of environmental guiding variables for temperature interpolation is an important step assuring the quality of produced temperature fields that is needed for further reasonable climatological or ecological modelling (e.g. Jarvis & Stuart 2001, Monestiez et al. 2001, Lookingbill & Urban 2003). This is even more important when regarding interpolation of daily maxima and minima temperatures instead of e.g. monthly means, since data at higher temporal resolution are expected to reflect more complex relationships that level off at larger time scales (Lookingbill & Urban 2003, Chung & Yun 2004). However, it is very important to consider these extremes as recently done in an increasing number of studies (e.g. Chung et al. 2006, Mostovoy et al. 2006) since they are important measures in ecology (e.g. Körner 2003). Coming back to the guiding variables, we found a differentiation between variables important for maxima and minima temperatures in agreement with previous results (e.g. Jarvis & Stuart 2001). Topography proved not to be as important for T_{AMX} as for T_{AMN}, reflecting the effect of cold air drainage on minimum temperatures. Distance to coastline was found as another important variable determining T_{AMN} as it mirrors the gradient in continentality not represented by the easting-variable due to the fjord-shaped coastline. For both T_{AMX} and T_{AMN}, cloud cover as derived from remote sensing data (MODIS) proved to be important as it determines the radiation balance. This circumstance reveals the interesting opportunity to aid temperature interpolation by atmospheric data provided by remote sensing. Mostovoy et al. (2006) already used MODIS-derived LST to aid interpolation of air temperatures. However, their approach is restricted to clear-sky conditions and hence of limited applicability in mountain regions characterized by a high degree of cloudiness. Using the derived guiding variables in a cokriging approach for the interpolation of T_{AMX} and T_{AMN} we achieved a good agreement ($r \geq 0.875$) between interpolated and observed temperatures at two independent weather stations, verifying the approach as suitable also for mountainous regions.

It has been shown by Löffler & Pape (2004) that surface temperatures in high mountain environments tend to be decoupled from air temperatures at common screen-level, i.e. variations in LST are not reflected by air temperature patterns. Thus, the representativeness of screen-level measurements for ecological applications in high mountain environments needs to be critically questioned as already done by Leser (1997). As a consequence, the interpolated air temperatures served in a further step as input for a physically-based modeling of surface temperatures.

The model was applied throughout different spatial scales, from nano-scale to meso-scale and validated against measured or remote sensing-derived LST. Despite several simplifications of the model necessary for spatial application in regions with limited data availability, the performance at nano-scale was very good ($r = 0.943$). However, already at micro-scale and further on at meso-scale the performance declined drastically until r equals 0.551, probably resolving limitations of the parameterizations used. For example, the wind-field is parameterized rather simple, albeit Böhner (2004) found reasonable results. The Priestley-Taylor concept utilized for estimating latent heat flux has been shown to provide acceptable accuracy for predicting daily evaporation in Arctic ecosystems if the value of the α coefficient is known (Rouse et al., 1977). However, α values have been shown to vary over time and space related to changes in vegetation type and state, soil moisture, and meteorological conditions (Rovanesk et al. 1996, Mendez et al. 1998, Engstrom et al. 2002). Hence, our approach of assuming constant values for α taken from literature and depending solely on vegetation type might have caused erroneous results. Further inaccuracy might arise from parameterization of the ground heat flux G_0. Liebethal & Foken (2007) found in their evaluation of six parameterizations that all of them had the potential to produce results matching measured ones very well, but only if all conditions and restrictions of the respective approaches were taken into account. For the linear approach used in this study, they found a pronounced variability of the factor a in space and time related to soil moisture and vegetation height. Also we yielded a better performance of the model when a was expressed as function of NDVI rather than treated as a constant (data not shown). However, the function of NDVI used here to express a was found by Jacobsen & Hansen (1999) for comparable vegetation types, but might due to its empirical character not easily be transferred to other regions. Moreover, the NDVI might not reflect differences in vegetation height and soil moisture conditions adequately, although a high correlation between NDVI and moisture status was found by Ostendorf & Reynolds (1993). These drawbacks probably explain the decline in model performance when applied at larger spatial extents, indicating a spatial limit for reasonable applicability. Consequently, our findings stress the importance of appropriate parameterizations that need to be developed for high mountain regions, since they could not easily be transferred from the environments they have originally been developed for.

Due to the complexity of physically-based modeling approaches, we tested also the performance of a simpler approach based on statistics, following a recent trend in research (e.g. Chung et al. 2006, Stahl et al. 2006, Joly & Brossard 2007). As a result, up to 68 % of the spatial variance in surface temperature could be related to irradiance, G_0/Q^*-ratio as a function of NDVI, and TWI. Even better results might have been achieved if another measure of soil moisture conditions than the TWI, which has been proven to reflect soil moisture better for wet than for dry or intermediate conditions (Sulebak et al. 2000), had been used. However, the approach performed similar throughout the different spatial scales, supporting statistical approaches to be an adequate means of modelling temperature fields in high mountain environments, albeit flawed with a limited transferability to other regions.

Moreover, the statistical approach revealed other important facts: Neither the Priestley-Taylor coefficient α, the wind-field, nor the interpolated air temperature at a height of two metres above ground contributed statistically significant to the variability of surface temperature. The first two facts might be attributed to a wrong parameterization, also responsible for the limited performance of the physically-based modeling approach. More interesting is the apparent insignificance of air temperature: It might be related to the already mentioned decoupling of air- and surface temperatures, but it is even more likely that it reveals scaling issues with the question to what extent modeling or interpolation approaches can be applied reasonably to other spatial scales. Especially when regarding a meso-scale area of steep topography accompanied by a complex differentiation in irradiance and wind field, it is questionable if air temperatures interpolated at macro-scale can be downscaled using solely elevation as corrector as done by Wang et al. (2006) and also in this study. It is rather obvious that other or additional parameters gain importance that probably levelled off at larger spatial extents as found by Xu et al. (2004). For instance, we conducted a series of hand-held measurements on air temperatures at an equally-spaced raster of 20 m at micro-scale (data not shown), that revealed a differentiation of temperatures dependent on wind exposure. As such, it might be wrong to use the macro-scale temperature-field at finer scales as it renders erroneous results. Thus, an appropriate handling of scaling issues is inevitable for temperature modeling as already proposed by Rosenzweig (1995) and Chave & Levin (2003) for ecological issues. However, this appropriate handling is hampered by the lack of observations at finer spatial scales, a fact that leads us back to the starting point of the whole discussion about temperature interpolation and modeling. Without climatological reference data from the spatial scales important for ecological applications, i.e. the meso- and micro-scale, an appropriate estimation of temperature patterns remains difficult.

5. CONCLUSIONS

Facing the need of temperature data for high mountain environments at spatial and temporal resolutions reasonable for ecological modeling, we evaluated interpolation and modeling approaches of daily maximum and minimum air temperatures as well as surface temperatures at different spatial scales that should compensate the lack of observational data. Geostatistical interpolation was found to perform very well at macro-scale if reasonable environmental guiding variables were chosen. Physically-based modeling performed best at nano-scale, whereas statistical modeling showed results of intermediate accuracy throughout the spatial scales. In spite of the limitations of the latter approach, the results provide encouraging evidence that we can find a simple approach based on statistics to estimate near-surface temperatures in high mountain environments spatially. The limited spatial applicability of physically-based models, however, revealed further research towards an appropriate parameterization of near-surface processes in high mountain regions to be necessary. Moreover, the study revealed the necessity of an appropriate handling of scaling issues in temperature modeling to achieve satisfactory results, albeit this seems to be hampered by the starting point of the whole discussion – the lack of observational data at finer spatial scales.

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5.7 Publikation VII

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Assessing the sensitivity of Melanoplus frigidus (Boheman, 1846) (Orthoptera: Acrididae) to different weather conditions: A modeling approach focussing on development times

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Assessing the sensitivity of *Melanoplus frigidus* (Boheman, 1846) (Orthoptera: Acrididae) to different weather conditions: a modeling approach focussing on development times

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Introduction

The large majority of species in the Acrididae (grasshoppers) taxon are xero-thermophilic. They are species-rich in warmer biomes and an increase in latitude leads to a decrease in species richness (Beier, 1972) − just as for many other animal groups (Kouki, 1999). Furthermore, only comparatively few species have managed to colonize alpine environments successfully (e.g., Harz, 1975, Ingrisch, 1995, Mikhailov & Olschwang, 2003). Thus, mountains are poor in grasshopper species (Beier, 1972). In Europe, when compared to mountain chains of the mainland (e.g. the Alps), the Scandes are especially poor in species, possibly due to incomplete colonization of the Scandinavian peninsula since the last deglaciation (Solbreck, 1993, Brandmayr *et al*., 2003). However, from a global perspective the number of cold-adapted Orthoptera is not as low as one might expect. For instance, Mani (1968) listed more than 30 genera occurring in high mountain areas of the world.

Melanoplus frigidus [syn. *Podisma frigida* Boh.; *Bohemanella frigida* (Boh.); see Litzenberger and Chapco (2001) for additional notes on nomenclature] is an element of the Palaearctic fauna that shows a disjunct distribution throughout Europe. This distribution is typical of boreo-alpine species; it occurs only in Fennoscandia and in the Alps (Mani, 1968, Harz, 1975). Outside Europe it can also be found in northern Russia, Siberia, the Altai Mountains, northern Mongolia, Manchuria, Kamchatka as well as in

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Alaska and northern Canada (Mani, 1968). *M. frigidus* is the only species of the Catantopinae tribe occurring both in North America and in Eurasia (Sergeev, 1999). In Fennoscandia, its Norwegian distribution reaches from the southern tip of the country to the northern Finnmark, the Swedish population from Härjedalen and Jämtland to Lapland. It is also distributed in Finnish Lapland and Karelia, in the corresponding Russian region and in the northerly provinces of the Kola Peninsula (Harz, 1975; Holst, 1986; Hansen, 2002). *M. frigidus* is widespread in the mountains, being the only grasshopper species colonizing mountainous habitats as high as the low alpine belt (Holst, 1986). There it prefers warm, south-exposed slopes. It also occurs in sunny clearings of birch forests (Harz, 1975; Hansen, 2002; Finch, pers. obs. 2003). *M. frigidus* (Fig. 1) is a relatively ungainly, normally brachypterous Caelifera species that is neither able to fly nor to stridulate. Macropterous individuals seldom occur. Body size ranges from 17 to 20 mm in males and from 24 to 26 mm in females (Holst, 1986).

Generally, ecotherms are adapted to relatively high temperature optima within the temperature range they experience, with higher body temperatures leading to faster development (Willmer *et al.*, 2000). Seasonal heat availability (degree days) was suggested to limit distribution of several insects by determining where and when a species can successfully complete its life cycle (Hodkinson & Bird, 1998). In particular, cool years should be a severe selection factor at the species' upper range margin.

Due to the importance of temperature we present continuously recorded data regarding the natural temperature regimens of four successive years (2001−2004) in the low alpine habitat of *M. frigidus*. Using these data our study aimed at modeling the effects of temperature on the duration of the postembryonic development for *M. frigidus* after it has finished overwintering in the egg stage (diapause). The modeling for climatically rather different seasons is of particular importance since field observations of early instars of this species are difficult. The reasons for this are that the populations are mostly small, with low densities, which results in observational problems, for example, juveniles of the first stages in early spring. Additionally, we present data on vegetation and soil moisture as further factors structuring the habitat of *M. frigidus*. A description of these dimensions of the ecological niche of *M. frigidus* is important when considering the use of this grasshopper as an indicator organism of climate change effects on alpine zoo-coenoses (Sømme, 1993; Solbreck, 1993; Ingrisch, 1995; Hodkinson & Bird, 1998; Hofgaard *et al.*, 1999).

Fig. 1. *Melanoplus frigidus* (Boheman, 1846), male (Photo: O.-D. Finch).

Materials and methods

Investigation area

A comprehensive long-term landscape ecological research project established in the Central Norwegian Scandes in 1991 (e.g. Köhler *et al.*, 1994; Löffler, 2002, 2003; Löffler & Wundram, 2003) was extended from 2001 to emphasize zoological components (Löffler *et al.*, 2001; Naujok & Finch, 2004; Finch & van der Kooij, 2005; Löffler & Finch, 2005).

One of our research regions is located near Vågåmo (Oppland). It is situated around 61°53′ N and 9°15′ E in the most continental region of Norway. The annual precipitation is low (300−600 mm), the amount depending on the altitudinal level (Löffler, 2003). The timberline reaches 900−1 050 m ASL. The low alpine belt has its upper limit at a maximum of 1 350 m, followed by the middle alpine belt which reaches to the highest peaks of the mountains (Mt. Blåhϕ, 1 617 m ASL).

We established a number of study sites along the alpine altitudinal gradient. Two catchment areas (= watersheds) were chosen for detailed study: one in the low alpine belt, situated between 1 080 and 1 100 m ASL with an area of approximately 3.1 ha ("Vole"), and another one in the middle alpine belt, located between 1 420 and 1 470 m ASL (3.8 ha; "Salk"). Additionally, in order to validate faunistic results from these two main investigation areas, six further study sites were established between the tree line and the highest peak, but no climate data were recorded for these sites.

Recording and modeling

M.elanoplus frigidus was frequently hand-searched at south-exposed slopes across the low and middle alpine belt throughout the field season. Plant species composition and abundance were mapped using a transect through the catchment area that included the habitat of the grasshopper. Temperature was measured at the four main topographical positions (ridge, depression and mid-slope in both southern and northern exposure) as these sites were believed to denote the largest micro-climatic differences within the catchment areas. At ridge position one meteorological station recorded (apart from other elements of the general climate, such as wind speed) the dynamics of air (+100/+15 cm) and soil surface (−1/−15/−30 cm) temperature throughout the year at hourly intervals. Temperature data of the other positions were obtained by means of data loggers at +15, −1 and −15 cm, providing the same temporal resolution. Temperature measurements were taken using pt100 sensors with an accuracy of ± 0.1°K. Soil moisture at each site was obtained using hand-held Time Domain Reflectometry (TDR)-measurements.

Alpine acridids like *M. frigidus* deposit their egg clutches within the top 1−2 cm of the soil (Ingrisch, 1995), thus soil temperature measurements at 1 cm below the surface provide the most valuable data to estimate the seasonal heat availability needed to model larval development. Besides moisture (see below), temperature is one of the most important factors for a successful and quick embryonic and larval development of grasshoppers (Detzel, 1998). In spring, several temperature values are expected to be crucial for acridids. As for *M. frigidus* the main parameters in our model are difficult to estimate exactly, we therefore decided to use two alternative approaches. The first one uses the accurate values that exist for *Chortippus parallelus*. The threshold of this species seems to be useful for our study, as it is not a strictly alpine species like *M. frigidus* but a species occurring in warm as well as in cold and moist places (van Wingerden *et al.*, 1991). Thus, its threshold may reflect the ecological behavior of a more euryoecios species not well adapted to alpine conditions. Post-diapause development of this species is inhibited below 8.8°C (Ingrisch & Köhler, 1998). For *M. frigidus* itself, after overwintering in diapause, a developmental threshold temperature of approximately 8°C also seems likely. Laboratory experiments by Ingrisch (1996) suggested that the threshold has to be somewhere above 5°C.

At a constant temperature of 25°C, post-diapause development of *M. frigidus* takes 5 days before hatching from the eggs (Ingrisch, 1996). Thus, a heat sum of 1 944 $K \cdot h^{-1}$ above 8.8°C is accumulated, assuming the same lower developmental threshold temperature as for *Ch. parallelus*. According to Ingrisch (1996), when a threshold of 5.0°C is used, the heat sum during post-diapause development amounts to 2 400 $K \cdot h^{-1}$.

Postembryonic development should be finished during summer (late June and early July), whenever the insects have experienced sufficient heat sums to complete development. Although larval development can be expected to be also related to a given range of temperatures, we decided not to model temperature-dependent postembryonic development times and instead used a fixed postembryonic time span from the literature. Having observed *M. frigidus* basking, it seemed to be very difficult to assess the actual heat sum accumulated by an individual insect in a specific area. For our modeling approach we assumed that under alpine conditions *M. frigidus* undergoes five larval stages, each with a duration of approximately 10 days (Carron, 1996). These values enable us to model development times for the four successive years of measurements, which include climatically quite different seasons. We modeled (a) post-diapause development time spans for egg emergence using developmental degree-hours by adding the average number of degrees per hour above 8.8°C till 1 944 K · h^{-1}, and above 5.0 °C till 2 400 K · h^{-1} were reached, respectively. Furthermore, (b) dates of adult molt were calculated by the model by adding 50 days to the modeled time span of (a).

Since we have no further observations on the very discrete microhabitat (upper, middle or lower southern exposed slopes), for these calculations, temperature data from a logger installed at the southern exposed mid-slope in the low-alpine investigation area "Vole" were used (at a soil depth of -1 cm, in the following referred to as "surface temperature"). Apart from heat sums, moisture is also important for egg and embryonic development as well as for early instar survival of grasshoppers (Ingrisch & Köhler, 1998). For example, eggs may absorb contact water which might influence the development. Thus, for the 4 years we also supply data on discontinuously measured soil moisture of the upper 15 cm.

Finally, in order to determine the maximum lifespan, 13 mature specimens caught during late September 2004 were transferred to the laboratory. They were kept in cages under laboratory conditions, with additional food and moisture supply until they died through senescence.

Results

Type of habitat

M elanoplus frigidus was the only grasshopper species that was observed above the tree line in the low alpine belt. No other species of Caelifera and no Ensifera were present. Populations of *M. frigidus* were also observed below the tree line in openings of grazed birch wood. However, above the tree line it was not found in all the habitat types. Small populations existed only at southern exposed slopes of the low alpine belt up to an altitude of 1 200 m ASL.

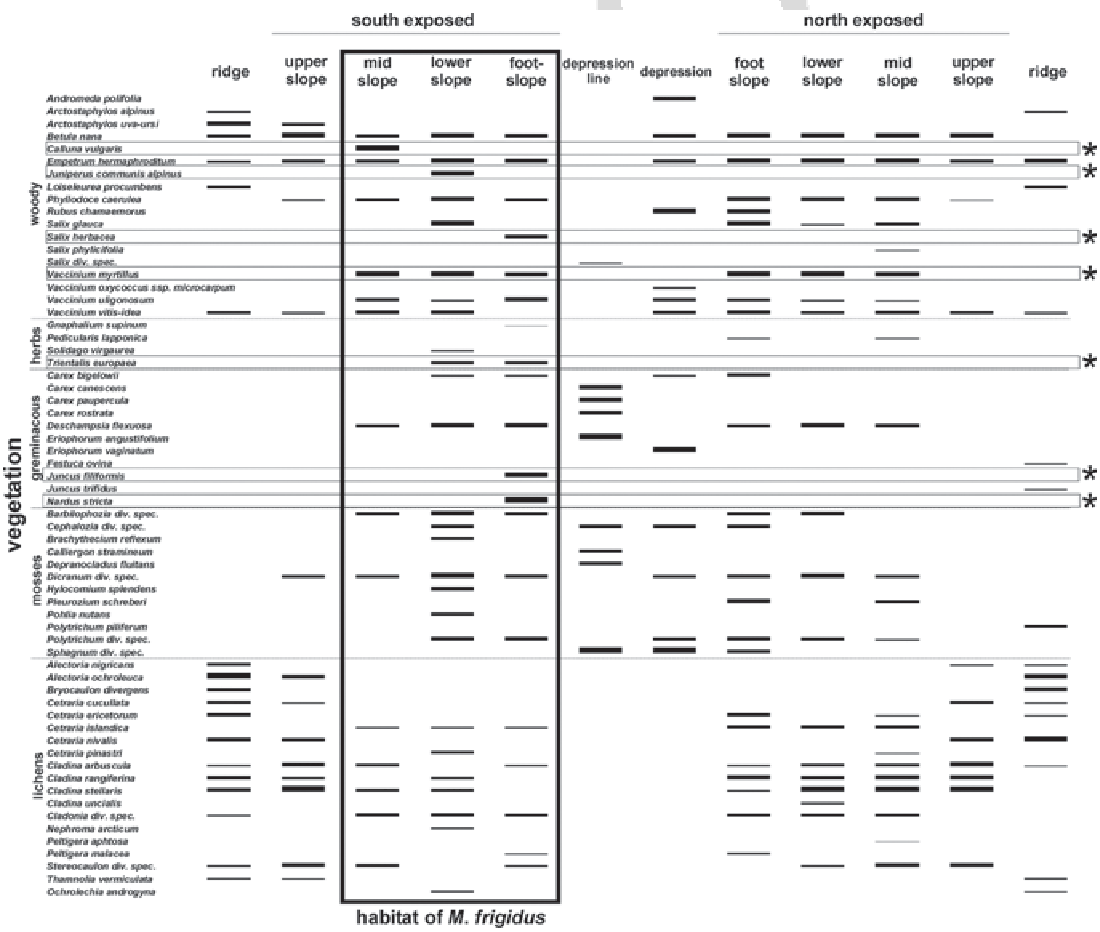

Fig. 2. Plant species composition and abundance (10-scaled beams in height according to the Braun-Blanquet method) along a transect through the investigated catchment area that included the habitat of *Melanoplus frigidus* (approx. 1090 m ASL). Characteristic vascular plant species are marked with an asterisk.

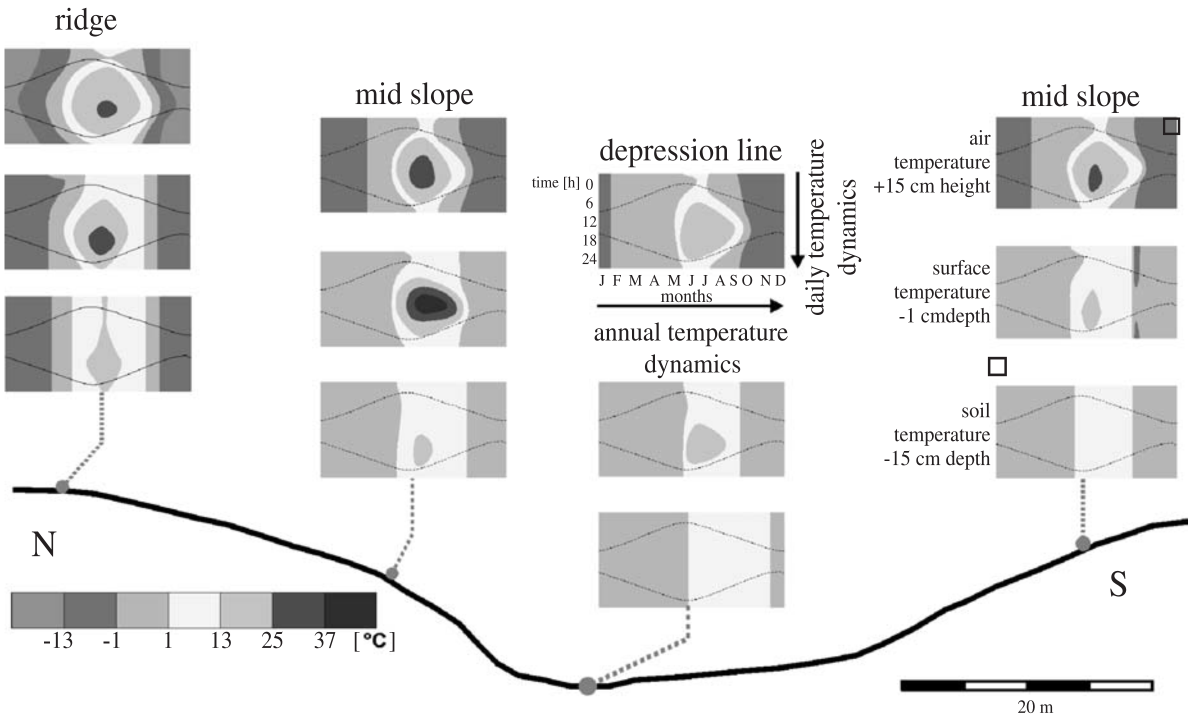

Fig. 3. Spatio-temporal variability of the near-surface temperatures along a transect through a small catchment area colonized by Melanoplus frigidus. Thermo-isoplete diagrams combine daily (*y*-axis) temperature dynamics of a whole year (*x*-axis) and are given for three different heights (+15 cm, −1 cm, and −15 cm from soil surface) at the four main positions: ridge, depression line and northern/southern exposed slope, respectively.

These slopes are characterized by a specific composition of plants (Fig. 2). In the habitat of *M. frigidus*, vegetation consists of shrub-rich heath, dominated by *Vaccinium myrtillus*, and at lower altitudes also dominated by *Calluna vulgaris*. *M. frigidus* was also observed at southern exposed foot slopes dominated by mats of the grass *Nardus stricta*. In contrast, the grasshopper was missing in the wet, boggy depressions, throughout the northern exposed slopes, and in the lichen heath habitats at ridge positions, respectively. These were also the positions that were exposed to extremely cold temperatures during winter (ridge) or that showed moderate temperatures throughout the year (depression, northern mid-slope) (Fig. 3). Thus, within the investigated small catchment area, *M. frigidus* colonizes only the warmest microhabitats. There, highest temperatures during the summer months were reached at soil surface. Maximum surface temperatures (hourly means) in the habitat of the grasshopper amounted to 29.4°C in 2001, and 31.2°C in 2004 (Table 1).

That the species is not found in the middle alpine belt implies that even in the low alpine belt the colonized habitats only just fulfilled the species requirements. Population size was clearly below 100 individuals (imagines) at all studied sites. A rough estimate for September 2003 using color marks on all available individuals showed that the population size in the low alpine catchment area "Vole" was below 50 individuals. In this area a population of *M. frigidus* was observed during all of the four successive years.

Table 1. Characteristics of the soil temperature (T: 1 cm below surface) from the years 2001 − 2004 for the snow-free season. Corresponding values for the whole years are given in brackets. Calculations for 2004 are based on data up to 27 September.

	2001	2002	2003	2004
Length of season [d]	137	137	140	>135
T_{max} [°C]	29.4	29.5	30.7	31.2
T_{mean} [°C]	8.2 (3.2)	10.0 (4.0)	9.0 (3.6)	8.8 (4.5)
T_{min} [°C]	−1.6 (−1.6)	0.5 (−3.7)	0.7 (−1.8)	0.3 (−0.1)
Heat-sum >5°C [K]	12 183	16 266	14 670	13 312
Heat-sum >8.8°C [K]	5 422	6 723	5 539	4 800

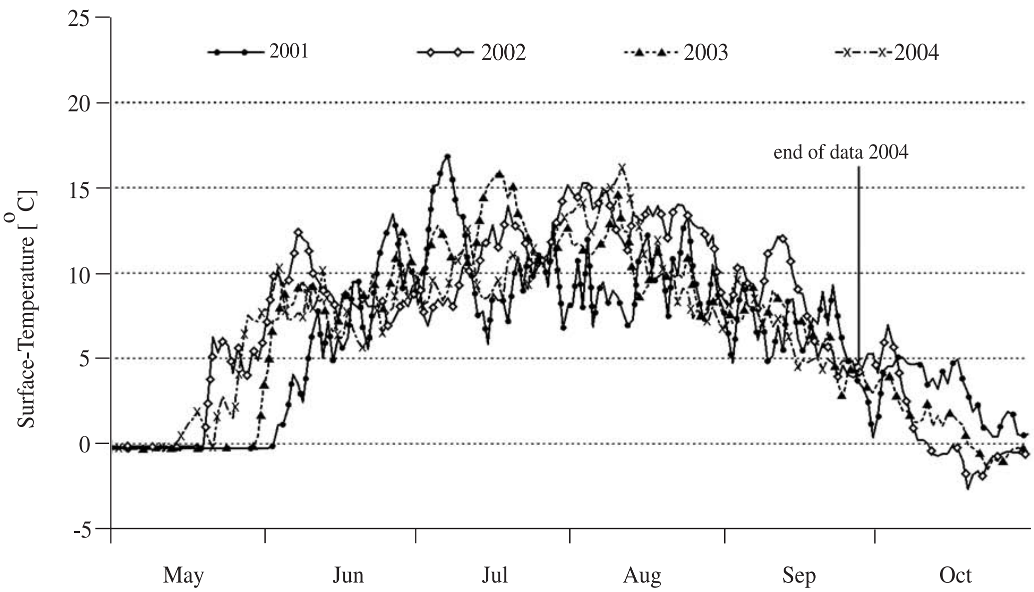

Fig. 4. Soil temperatures (daily means at 1 cm below surface) in the habitat of *Melanoplus frigidus* (south-exposed slope) during the years 2001–2004.

Development time

We made the following observations regarding the life history of *M. frigidus*: Under laboratory conditions all mature specimens died before October 26. During spring, only immature specimens were observed in the field. In 2001, during the first half of July (around July 9), they reached half the size of adults and thus seemed to be in the middle of their larval development (3rd instar). The same year, adults were observed from the middle of August (August 18) onwards.

Between May and October –which is usually the snow-free season– of 2001 to 2004, strong differences in surface temperatures in the low alpine investigation area "Vole" were recorded at the southern exposed habitat of *M. frigidus* (Fig. 4). During 2001 (coldest season) heat sums calculated from hourly mean temperatures above 5.0°C between May and October were 3 925 K · h^{-1} less than those calculated for 2002 (warmest season; with a heat sum of 16 266 K · h^{-1}; Fig. 5). The reason for this was that in 2001 the snow-free season started late.

Due to varying surface temperatures at the beginning of the snow-free period of each of the four quite different

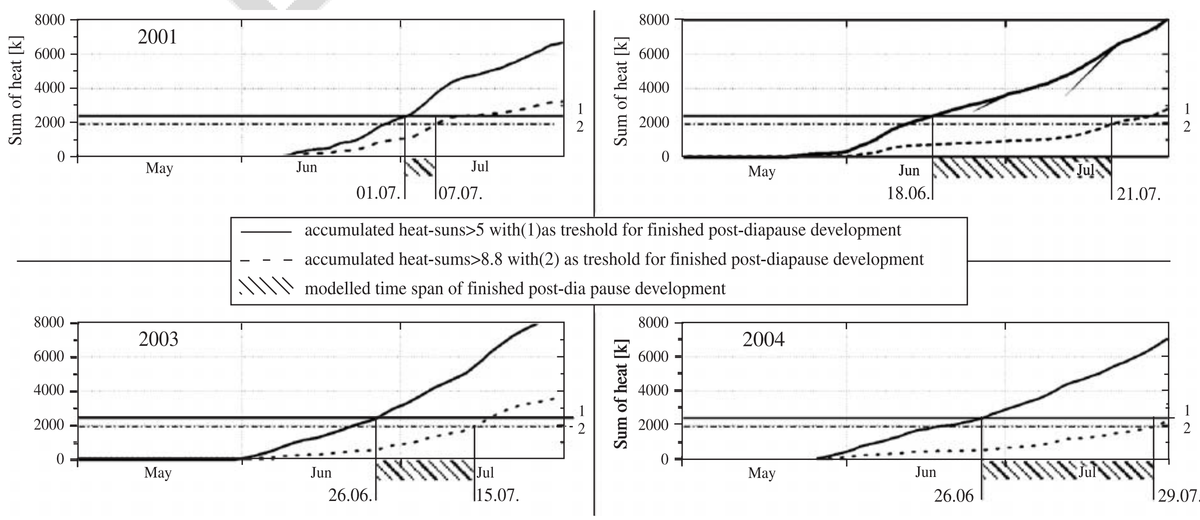

Fig. 5. Estimated spring postdiapause development times until hatching from eggs for Melanoplus frigidus for the years 2001 – 2004.

showed strong variation (Fig. 5). Greatest differences were calculated between the 2 years 2001 and 2004 when the 8.8 ºC threshold is used. A heat sum of 1 944 K·h-1 above 8.8ºC (and therefore supposed hatching from eggs) was reached on July 7,2001, whereas in 2004 it was not reached until July 29. This implies an overall great plasticity of larval development. Furthermore, due to the assumed time span of 50 days for postembryonic larval development, these variations continued in our calculations until adult molt (Fig. 6). A marked delay of 3 weeks was modeled for the coldest spring (2004), in contrast to the warmest spring (2001). According to the model, during the 2001 season *M. frigidus* was possibly already reproducing while during 2004 they just reached the 2nd larval stage.

During the 4 years of recording, soil moisture in the upper soil layer amounted up to 35% in the spring and to 20% − 30% in the autumn and was overall very similar within and between the vegetation periods (Fig.7).

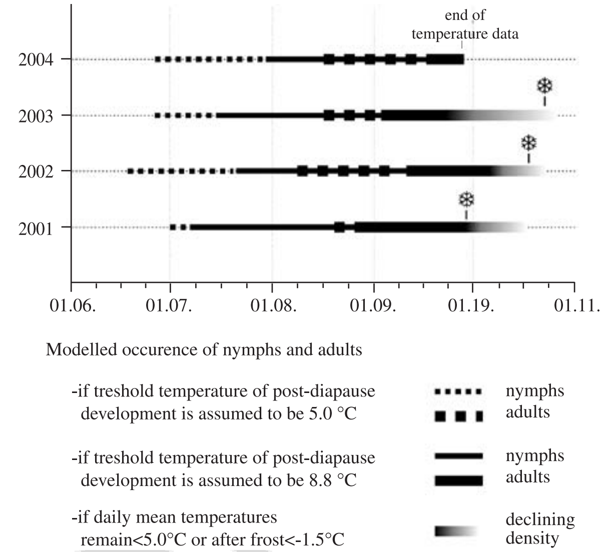

Fig. 6. Estimated postembryonic development of larvae of *Melanoplus frigidus* (estimated end of postdiapause development, see Fig. 5); time of maturation ecdysis was modelled by adding 50 days for five larval instars according to Carron (1996); first frosts (−1.5ºC) in autumn are indicated by snowflakes.

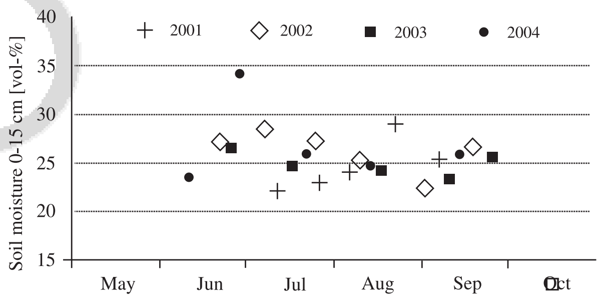

Fig. 7. Hand held measured soil moisture values in the upper soil layer of the habitat of Melanoplus frigidus (southern-exposed slope) during the years 2001−2004.

Discussion

Development time

Soil surface temperature and soil moisture conditions are crucial for the colonization of cold areas by grasshoppers. As observed also for high latitude arthropods (Hodkinson, 2003), thermophilic alpine species like *M. frigidus* usually colonize only the most favorable microhabitats. Therefore, requirements of the species concerning soil moisture, soil temperature and sunlight in the extreme environment are all satisfied (Detzel, 1998).

Since data about the alpine environment of *M. frigidus* are scarce, we present maximum surface temperatures and first estimates of thermally effective season lengths. Furthermore, our modeling delivers first estimates of phenologies in climatically quite different years. With the measurements of soil surface temperature and soil moisture carried out in the field, important conditions needed to describe the appropriate effective thermal environment of the animal were given (Hodkinson, 2003). Unfortunately, urgently needed field observations to validate the fitting success of our model are still lacking. Recording of egg hatching and maturation dates were not gathered in the field so far, for instance, due to general difficulties in alpine research (e.g. accessibility of study areas in spring).

Overall, our modeling of post-diapause development is only a rough estimate, as calculations were done using heat sums above the lower developmental threshold temperature of 8.8ºC of *Ch. parallelus* (Ingrisch & Köhler, 1998). We also modeled using heat sums above 5.0ºC (Ingrisch, 1996). Other acridid species show higher threshold temperatures [e.g., *Ch. biguttulus*: 11ºC; *Ch. mollis*: 17ºC (van Wingerden *et al*., 1991)], and calculations based upon these values would have added up to longer time spans needed till the young grasshoppers would emerge from the eggs. Further variation in the modeled development times resulted from different weather conditions during spring, for example in the year 2001 temperature raised fast and also was quickly above 8.8ºC, whereas in 2004 (and 2002) degrees above 8.8ºC were achieved only later in the season.

However, the completion of the life cycle of univoltine alpine species like *M. frigidus* is limited by season length. It must thus, during the brief season, develop relatively faster than their conspecifics from low altitudes (Samietz *et al*., 2005). Generally, under field conditions a polymorphism in development strongly alters emergence (Ingrisch

& Köhler, 1998). The overwintering stage strongly determines time to adulthood (Dingle *et al.*, 1990, Dingle & Mousseau, 1994, Berner *et al.*, 2004). Here, detailed further studies of the overwintering stage of *M. frigidus* at different altitudes are required.

Overwintering of *M. frigidus* normally takes place in the egg stage in the ground, usually during winter and early spring months, under the snow cover of the south-facing slopes. Thus, the harsh environmental conditions during winter are bridged with a phase of reduced metabolism and suppressed development (Leather *et al.*, 1996). In the Alps, clutch size of *M. frigidus* varies between 2 and 17 eggs per clutch, with an average of 8.8 eggs. Overall, on average each female only produced 18.2 eggs in a total of 2−4 clutches (Ingrisch, 1996). Oviposition in our study area is expected to take place throughout late August, September and early October, until temperature prevents reproduction, or until adults die either of old age, as observed in the laboratory, or because of strong frosts.

Ingrisch (1996) mentioned environmental conditions that can modify the usually univoltine life cycle of *M. frigidus*. He suggested that under certain circumstances (deposition of clutches in the very late vegetation period; early frosts and thus insufficient heat at the end of the season) embryonic development of *M. frigidus* may take all of the first summer after the eggs were laid (= superpause). Then, they overwinter twice before juveniles hatch at the beginning of the second summer. However, in our case, the soil may have been sufficiently warmed for juveniles to hatch during all of the four springs for which we were able to model postembryonic development time spans.

Based on constant heat sums, which are expected to be essential during spring, we estimated that cooler seasons substantially delay larval hatch and reaching of adulthood. In this context a significant loss of fitness can be assumed (Berner *et al.*, 2004).

Population size

Reproduction rates of *M. frigidus* are low (see above), thus the small populations in the alpine habitats are in accordance with expectations. Generally, populations of stenotopic Acrididae inhabiting small areas can be as small as the populations of *M. frigidus* and survive for at least several years. Detzel (1998) mentioned a population of *Oedipoda caerulescens* (L., 1758) that had been observed during four successive years with population sizes between 22 and 88 individuals in an area of 0.1 ha (0.022−0.088 individuals/m^2).

Within the low alpine belt investigated during this study, different small populations of *M. frigidus* seemed to form a structured, possibly continuous metapopulation. As the species is expected to be relatively sedentary, most populations appeared to be separated by ridges with large lichen heath habitats. Higher densities of *M. frigidus* than observed by us were recorded: for example, Ingrisch (1995) observed densities of 0.4−1.7 individuals per m^2 (only imagos) and 0.8−28.5 individuals per m^2 (including larvae) in the Engadin (Alps) at 2 500 m ASL, and also at Finse (Hardangervidda) higher densities occur (Sϕmme, pers. comm.2 003).

Moisture

Detzel (1998) mentioned that above all at least lowland acridids may be predominant indicators of moisture, because laboratory studies showed that their temperature preferences are very similar. In contrast, especially during the egg stage, the potential to maintain constant moisture values is adapted according to their xero- and hygrophily, respectively. Eggs of some acridids have been shown to develop appropriately at 30%−50% air moisture after water absorption during winter, while other species needed values of up to 100% (Ingrisch & Köhler, 1998). Having measured relatively low moisture values ranging from 20%−40 % in the upper soil layer (0−15 cm) of the southern exposed slope during both spring and autumn, it is not clear if eggs of *M. frigidus* can sufficiently absorb contact water during these seasons. Furthermore, so far we were not able to identify the exact microhabitat of egg deposition. As *M. frigidus* occurs at south-facing slopes and thus is confronted with a steep moisture gradient from the wet depression to the relatively dry ridge, egg deposition at foot slopes, near the depression line, would guarantee more constant high moisture conditions than at microhabitats located above, at the steeper slope.

Cold adaptation

Several of the various adaptations of insects to the alpine environment (Sϕmme, 1997) appear in *M. frigidus*. One main behavioral adaptation consists in individuals of *M. frigidus* warming themselves when the sun is shining and air temperature is low (e.g., in the morning as well as in spring and autumn) in order to reach their optimum activity temperature. They climb up on the low vegetation and expose themselves to direct sunlight until they are sufficiently warmed up (L. Sϕmme, pers. comm. 2003, and Finch, pers. obs. 2003). Similar behavior ("basking") was observed for several other species of grasshoppers and locusts in alpine and other habitats (Mani, 1968; Uvarov, 1977; Begon, 1983; Chappell, 1983). Recently, for North American congeners of *M. frigidus* in the *M. sanguinipes* / *M. devastator* species complex a variation in this thermoregulatory behavior has been shown to exist between populations from an altitudinal gradient. There, individuals from high altitude up-regulate body temperature to higher levels than individuals from lower altitudes (Samietz *et al.*, 2005). Thus, thermoregulatory behavior is an important contributor to life history adaptations that adjust grasshopper phenologies to variation in season length.

Furthermore, it is unknown for *M. frigidus*, if the different color morphs of the females also play a role in the specific increase of body temperature while basking, as it was documented for species of the genus *Tetrix* (Forsman, 1997, 1999; Forsman *et al.*, 2002).

In some polar and alpine environments, organisms may potentially face problems of respiratory water loss (Sϕmme, 1989; Hodkinson, 2003). This may also be the case in our relatively dry, continental study area (Moen, 1999). Thus, the hard sclerotized integument of *M. frigidus* can be understood as a morphological adaptation to avoid desiccation during warm days of the dry summer months. Furthermore, it may improve cold tolerance. The wing atrophy of *M. frigidus* (Fig. 1) was described as an adaptation to high wind speeds and regular occurrence of storms in alpine environments. Individuals capable of flying will more often leave the populations by being blown away to unsuitable surroundings (Uvarov, 1977; Sϕmme, 1989; 1997).

In conclusion, *M. frigidus* seems to be able to rapidly exploit rising temperatures by basking and actively selecting warm microhabitats within the alpine environment, thus it is fitted with the important adaptations of arthropods living in cold environments (Hodkinson, 2003).

Habitat

In our study, alpine populations of *M. frigidus* were restricted to south-facing slopes, where we measured the most favorable temperature conditions and an intermediate soil moisture condition. As snow cover is one of the main factors determining specific vegetation patterns (Löffler, 2003), it is sure that strong correlations between vegetation and the occurrence of the grasshopper existed. Thus, the vegetation can be used as a reliable predictor variable for the occurrence of the grashopper. However, the question whether the distribution of the phytophagous *M. frigidus* is determined mainly by vegetation patterns rather than by microclimatic conditions (especially temperature and moisture) cannot be satisfactorily answered yet, since field and laboratory experiments are missing. But a food preference for plant species typical of the southern exposed slopes (*V. myrtillus*, *N. stricta* and others) seems unlikely. Most plant species appear at various sites and are not restricted to southern exposed slopes. Thus, if the distribution pattern is determined by food plants, *M. frigidus* should have a much wider distribution. Furthermore, grasshoppers generally do not specialize on specific host plants, in contrast to, for example, butterflies (Wettstein & Schmid, 1999). Therefore, we believe that within alpine areas temperature (in combination with secondary correlated factors like soil moisture and vegetation) is the most important environmental factor for *M. frigidus*.

In Norway, *M. frigidus* is widely distributed in mountainous regions (see Introduction). In our study area it was not recorded above the low alpine belt (up to 1 200 m ASL). However, in the Finse area the species reaches altitudes of up to 1 300−1 400 m ASL (Sϕmme, pers. comm. 2003). Also, in the Unterengadin (Alps) *M. frigidus* occurs at elevations of 2 200 m and above. There its upper distribution limit is around 2 800 m ASL, and an upper distribution limit for Arcridids is expected to lie at around 3 000 m ASL −a value that is lower in the northern Alps (Nadig, 1 986; Ingrisch & Köhler, 1998). Such local variations in the altitudinal distribution of the species is likely to be caused by differences in the regional climate. In this context, the `mass elevation effect? which becomes obvious when comparing altitudinal belts, latitude and degree of continentality has to be considered (Sϕmme, 1989, Moen, 1999). Before using *M. frigidus* as a climate indicator, regional variations in altitudinal distribution patterns should be taken into account. Due to cool climate, *M. frigidus* seems to be well at its upper range margin in our study area and in other parts of the Scandes. However, this assertion could be weakened in the future by climate change effects leading to a warmer climate at higher elevations.

Climate change indication

Mountain environments are expected to react spontaneously to climate change, but ecosystem response to climate variations are hard to detect, since response to simultaneously occurring land use changes may superimpose the signals (Löffler *et al.*, 2004), thus making an interpretation more difficult. Overall, *M. frigidus* may be a valuable indicator species for climate change effects in alpine environments, as its imagoes are easily detectable and quite conspicuous. Thus, this species shows this clear advantage in comparison to the high number of other arthropod species occurring in alpine habitats which are also potentially answering to the climate change (expanding, retracting or shifting their range distribution). Especially in the Scandes, such eye-catching insects are relatively scarce. Furthermore, *M. frigidus* can be expected to be a temperature-sensitive insect, although various well established and founded mechanisms of climate indicator species have not been identified thus far. The species is broadly distributed in Fennoscandia and shows an upper distribution limit in the alpine belt. Population monitoring seems to be possible without exceptional effort, the monitoring occurring along altitudinal gradients, both being fundamental requisites for the detection of climate change effects (Sϕmme, 1993). A sufficient dispersal capacity along altitudinal gradients can be assumed, since the individuals are large and quite mobile within their habitat. Thus, we expect that a monitoring of *M. frigidus* will provide a more rapid and sensitive sensor of climate change effects than, for example, the distribution patterns of plants (Grabherr *et al.*, 1994; Hodkinson & Bird, 1998). Responses to climate change may be shifts in altitudinal distribution on a meso scale, small-scale changes of distribution patterns within single altitudinal belts, and/or changes in pattern of life history and abundance (e. g. Konvicka *et al.*, 2003). Nevertheless, having mentioned the advantages of this species as an indicator, one should note that it is not a host-specific insect. Thus it is not in accordance with the requisites of a potential indicator species in arctic and alpine environments as stated by Hodkinson and Bird (1998). However, Solbreck (1993) already noted that polyphages (like *M. frigidus*) are expected to disperse at high rates and thus may be faster than monophages in responding to climate change.

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5.8 Publikation VIII

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Growth-ring variations of dwarf shrubs reflect regional climate signals in alpine environments rather than topoclimatic differences.

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ORIGINAL ARTICLE

Growth-ring variations of dwarf shrubs reflect regional climate signals in alpine environments rather than topoclimatic differences

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ABSTRACT

Aim Our main aim is to determine if ring-width variations in *Empetrum hermaphroditum* reflect regional or local topoclimate signals in an alpine environment. In the case that topoclimate provides the dominant signal, a secondary aim is to link these to spatial distribution patterns of different vegetation types.

Location The study area is situated in the middle alpine belt in the Vågåmo region, Central Norwegian Scandes. Sampling sites cover different topoclimates: ridges, north-facing slopes and south-facing slopes.

Methods We constructed ring-width chronologies of *E. hermaphroditum* for each type of microsite for the common period 1951–2004. Climate data were prepared on an hourly, daily and growing-season time scale. Climate–growth relationships were evaluated using bivariate correlations and regression tree methods for continuous time-series analyses. In addition, extreme growth anomalies (pointer years) were compared with the climate conditions in those years. The impact of water supply on wood anatomy was determined by correlating the conductive area (percentage of vessel per growth ring) with a running mean (sum) of 10-day intervals for temperature and precipitation.

Results This study indicates that mean summer (June–August) temperatures determine the width of the growth rings of *E. hermaphroditum* irrespective of topoclimate. The length of the growing season, which is the most differentiating climatic factor between microsites, does not substantially alter the anatomical ring structure. Microsite differences in mean growth rates are attributed to the higher frequency of warm days. Extremely warm days limit ring-width development at south-facing slopes, while plants at ridges and north-facing slopes still benefit from higher temperatures. As a consequence, pointer years are not developed synchronously at all microsites. Vessel formation is affected by available moisture, especially in the later part of the growing season.

Main conclusions Topoclimate induces slight modifications of annual growth-ring increments of *E. hermaphroditum* at different microsites. In contrast to the distribution patterns of vegetation types that are determined by snow cover, growth-ring variations are related to summer temperature conditions, and the prominent regional climate signal is still reflected at all microsites. This offers the opportunity to reconstruct climatic change in alpine regions from dwarf shrub ring-width chronologies.

Keywords

Alpine vegetation, climate–growth relationships, dendroclimatology, dendroecology, *Empetrum hermaphroditum*, Norwegian Scandes, ring width, snow cover, wood anatomy.

INTRODUCTION

Dendroclimatology has been applied successfully in reconstructing climate in the boreal arctic (Briffa *et al.*, 1988, 1992; Jacoby & D'Arrigo, 1989; Wilson & Luckman, 2003). Dendroclimatological data serve as a resource for climate reconstructions, particularly in areas with no or only sparse meteorological station records (Beniston, 2002). However, beyond northern and alpine tree lines, other woody plants, such as dwarf shrubs, might be useful for dendroclimatological reconstructions. Only in recent years has the potential of dwarf shrubs for dendroecological studies been explored. Extremely small ring widths and numerous anomalies in tree-ring formation make the dendroecological analysis of dwarf shrubs difficult and time-consuming. In comparison with trees, additional steps of analysis are required to extract the common growth patterns of dwarf shrubs and thus the climate signal contained in their growth variations (Kolishchuk, 1990; Woodcock & Bradley, 1994; Bär *et al.*, 2007). Nevertheless, dwarf shrubs also attract research interest due to the large number of 'new' species for dendroecological analysis in areas without tree cover. For instance, growth increments derived from the internode length of *Cassiope tetragona* have been used as a climate proxy (Johnstone & Henry, 1997; Rayback & Henry, 2005, 2006). Furthermore, the radial growth of *Salix arctica* was used by Schmidt *et al.* (2006) to reconstruct snow regimes. Bär *et al.* (2006) were the first to succeed in constructing ring-width chronologies of *Empetrum nigrum* ssp. *hermaphroditum* Hagerup (henceforth *E. hermaphroditum*), thus showing the potential of this circumpolarly distributed species for climate reconstruction.

However, regional climate reconstructions might be affected by local site-specific topographic factors that are characteristic of alpine environments. In alpine regions, topography strongly controls microclimate (Barry, 1992; Löffler & Pape, 2004; Löffler *et al.*, 2006). As dwarf shrubs grow close to the soil surface, radial growth might primarily reflect these microclimatic conditions, rather than the climate of the free atmosphere. Microsite differences are represented mainly by (1) temperature patterns that result from differences in solar radiation input; and (2) the supply of moisture and the duration of the snow cover throughout the year. In winter, plants in alpine environments are usually protected against low temperatures by a persistent snow cover. Exceptions occur at ridge positions, which are exposed throughout the year. However, the benefit of the protective winter snow cover at some slope positions might be diminished by the fact that the growing season is shorter on slopes than on ridges, and north-facing slopes are generally cooler than ridges and south-facing slopes. Thus, snow distribution patterns are the most decisive factor for the spatial distribution of vegetation types in alpine environments (Dahl, 1987; Dierßen, 1996; Jones *et al.*, 2001). Moreover, interannual variations in snow cover distribution are probably reflected by growth rate differences between sites, as well as by interannual growth changes within a site. This can be studied best in a woody species with a wide ecological range that covers all microtopographic positions within a study area.

For this reason we selected *E. hermaphroditum*, which occurs at all microsite types. Our objective was to quantify the impact of microclimatic effects on annual growth patterns of *E. hermaphroditum*. Differences in microclimatic conditions at the sampling sites were quantified for different time scales. If it transpired that radial growth is altered by microclimate, we wanted to know if climate–growth relationships are site-specific and can be related to the differentiation of vegetation types. However, if radial growth was not significantly altered by microclimate, it might reflect a regional climate signal. In this case, *E. hermaphroditum* might have the potential to be used for reconstructing regional climate changes in alpine environments.

MATERIALS AND METHODS

Study area

The study area is located in the Central Norwegian Scandes near Vågåmo (61°53′ N; 9°15′ E). According to Moen (1999), this region has the most continental climate in Scandinavia. The valley floors receive an annual precipitation of 300–400 mm. The alpine zone stretches from the upper tree line at 1000–1050 m a.s.l. to the highest peak at 1618 m a.s.l., and comprises the lower and the middle alpine belts. The sampling sites are located in the middle alpine belt at 1450 m a.s.l., covering a set of topographic situations that result in different microclimatic conditions: ridges, north-facing slopes (16–19° inclination), and south-facing slopes (15–18° inclination). Although the vegetation cover is generally sparse, certain vegetation types can be assigned to these microsites: ridges are characterized by the chionophobous vegetation such as *Arctostaphylo–Cetrarion nivalis* Dahl 1956. *Cassiopo–Salicion herbaceae* Nordh. 1936 is a widespread snow-bed community at north-facing slopes, whereas south-facing slopes are dominated by *Phyllodoco–Vaccinion myrtilli* Nordh. 1936 (Dahl, 1987). At the study site, dwarf shrubs are close to their altitudinal distribution limit. To study the effect of microclimatic differences on the growth of *E. hermaphroditum*, samples were collected from ridges ($n = 17$), north-facing slopes ($n = 13$) and south-facing slopes ($n = 18$) (Fig. 1). For growth-ring analyses, we collected complete individuals including the root and branch systems.

Climate data

Climate data were obtained from (1) a meteorological station run by Det Norske Meteorologiske Institutt (DNMI), situated *c.* 40 km north-east of the sampling sites at 972 m a.s.l. (Meteorologisk institutt (eklima) 2006; #16600/16610 Fokstua); and (2) microclimate stations at each sampling site, which were set up for this study in 1998. They recorded hourly means of air temperatures at a height of 15 cm with shielded pt100 sensors and soil temperatures at a depth of 15 cm. In

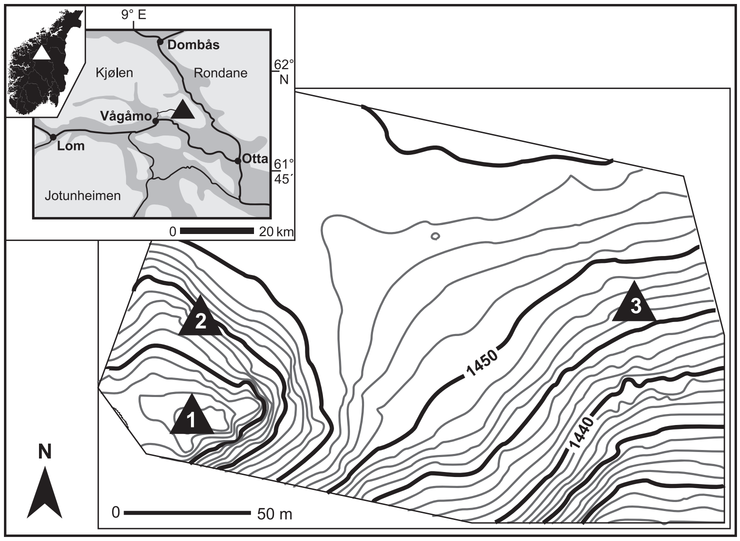

Figure 1 Location of the study area and sampling sites in Central Norway: (1) ridge; (2) north-facing slope; (3) south-facing slope.

addition, air temperatures, relative humidity, global irradiance, wind speed and precipitation were recorded at a height of 100 cm at the ridge position. These data (excluding data for precipitation) also served as input for a simple energy-balance model (Pape & Löffler, 2004) that was used to fill gaps caused by technical problems in the microclimate data of the north- and south-facing slopes between June and August (max. 21 days in 1999 and 40 days in 2000). For further analysis, daily means and sums for temperature and precipitation were calculated. Daily DNMI climate data are available for precipitation and temperature since 1923, snow cover data are available since 1969. How representative the DNMI data were for the study area was tested by calculating Pearson correlations with our microsite temperature data (Table 1). The differences between root mean square error values for the annual and snow-free periods underline the importance of snow cover for determining surface temperature conditions. Decadal and monthly means were calculated for temperatures, heat sums and precipitation sums of microsite data and DNMI data. Furthermore, the length of the growing season since 1969, and related mean temperatures and heat sums, were derived. Following Körner & Paulsen (2004), the growing season was defined as the time period of decadal (10-day intervals) air temperature means > 0°C.

Table 1 Correlation coefficients (r^2) and root mean square errors (RMSE) between elevation-corrected temperature data of DNMI meteorological station and micro-site temperature data for the whole year and for the snow-free period.

	Ridge	North-facing slope	South-facing slope
Annual mean			
Fokstua	0.944	0.897	0.922
RMSE	1.400	3.040	2.681
Snow-free period			
Fokstua	0.977	0.949	0.946
RMSE	1.351	1.989	0.880

Tree-ring data

For tree-ring analysis, microtome sections of complete dwarf-shrub stem cross-sections were prepared as described by Bär *et al.* (2006, 2007). Based on digital photographs of these sections, ring widths were measured on screen with a resolution of 0.01 mm using the software LignoVision (Rinntech, 2005). Afterwards, ring-width curves of all individuals from the same type of microsite were synchronized and checked for wedging rings and missing rings with the program TSAPWin (Rinntech, 2005). The synchronization procedure was based on the results of statistics (sign test) and the visual comparison of interannual growth-ring variations between single ring-width curves. Some samples could not be synchronized due to individual growth histories, and were excluded from further analysis. In a subsequent step, ring-width curves were standardized by fitting a 32-year smoothing spline in order to remove age-related growth trends. Standardization was performed using the program arstan (Cook, 1985). Finally, site chronologies were constructed as a mean of all standardized ring-width curves from the respective microsites. The common period covered by all microsite chronologies ranges from 1951 to 2004 (54 years). The signal strength within the site chronologies was determined by the standard deviation (SD), first-order autocorrelation (AC1), and mean interseries correlation (rbar). Similarities between all site chronologies of *E. hermaphroditum* were determined by computing Pearson's correlation coefficients.

Wood anatomy was analysed quantitatively using digital photographs with enhanced colour contrast between cell lumina and cell walls. Vessels were defined by cell lumen diameters > 10 μm^2 and were identified and measured automatically using the image analysis program WinCell (Régent Instruments Inc., 2004). The percentage of vessel area per tree-ring segment was determined for the 8-year period 1997–2004 for five individuals at each microsite.

Climate–growth analysis

Climate–growth relationships were evaluated using methods of continuous and discontinuous time-series analysis. For continuous time-series analysis, it was assumed that each tree ring contains a distinct climate signal that offers the possibility of reconstructing past climate for this variable. In contrast, the discontinuous time-series analysis focused on the biological impact of extreme climatic events (Schweingruber, 1996).

Ring-width series and monthly mean temperatures and precipitation sums from August of the year prior to growth until September of the growth year, as well as seasonal aggregates for the summer months (JJA), were subject to continuous time-series analysis for the period 1951–2004. The analysis was based on bivariate correlations with a two-tailed test of significance as well as on classification and regression tree methods (Breiman *et al.*, 1984; De'ath & Fabricius, 2000). Tree-based methods provide an alternative to common parametric approaches when the independent variables are suspected of interacting in a nested hierarchical fashion (Michaelsen *et al.*, 1987). Nonlinear and non-additive relationships, i.e. the effect of one independent variable that is conditioned by other independent variables, can be detected (Michaelsen *et al.*, 1994). Regression trees for each microsite were constructed using CART 6.0 (Salford Systems, 2006). To prevent overfitting, the optimal tree size was determined by cross-validation routines.

For discontinuous time-series analysis, site chronologies and climate data were normalized by *z*-transformation into deviations (in SD) from means. Extremely wide or narrow growth rings, so called pointer years, were extracted after Cropper (1979). First, the difference of the growth value of year i and the average of growth in the moving time window $i - 2$ to $i + 2$ was calculated. This value was then divided by the standard deviation of growth for the same time window. If the resulting pointer value exceeded a threshold of ±0.8 SD, the year was classified as a positive or negative pointer year, respectively. Subsequently, ring-width indices and corresponding climate data were selected for each pointer year ($t = 0$) following the epoch-analysing approach (Grissino-Mayer *et al.*, 2004). To detect the climatic triggers for extreme growth, positive and negative pointer years were analysed separately. As the number of positive (negative) pointer years (n = max. 7) was too small to obtain reliable climate-growth relationships. Thus, climate data were assessed assuming that their degree of deviation from average is linked to the importance for growth-ring variations.

As climate parameters did not exhibit extreme conditions in positive pointer years, we hypothesized a nonlinear relationship between ring width and temperature in July/August. This was tested by fitting second-order polynomial trend lines to the data. In addition, the simultaneous occurrence of positive pointer years and years with above-average summer temperatures were checked. The monthly temperature and precipitation anomalies for selected years were plotted to obtain a more comprehensive view of growth conditions.

We also analysed the impact of water supply and temperature on dwarf-shrub growth at a higher temporal resolution. Thus the conductive area of each growth ring was determined as the percentage of the vessel area. Then correlation coefficients between the conductive area and a running mean (sum) of 10-day intervals for temperature and precipitation were computed for the period from August to October prior to growth and the maximum length of the growing season (April to September) in the current year. We chose 10-day intervals because this is the minimum duration for vessel development and lignification (Suzuki *et al.*, 1996; García-González & Eckstein, 2003). For this analysis, we used the temperature data measured by the microclimate stations, because they directly reflect the local microclimatic conditions for dwarf-shrub growth. Therefore the period analysed was restricted to 1998–2004. Moreover, south-facing slopes were not considered, because exact snow-melt dates and the length of the growing season could not be determined due to missing data.

RESULTS

Climatic differentiation of sites

The microsite climate data reveal differences between the three topographic positions, mainly expressed by the length of the growing season (Fig. 2b–d). Snow melt on slopes is significantly later than on ridges, especially when the slopes receive less radiation input. Snow cover is important for the winter temperature conditions endured by the plants; while ridge positions are exposed to the lowest temperatures, slope positions are sheltered by snow. However, differences in microsites diminish when daily mean temperatures during the growing season are considered, as indicated by a very high correlation of $r = 0.89$ ($P < 0.01$). The absolute difference in temperature further diminished with decreasing time resolution, if decadal and monthly means are considered. Mean temperatures of the growing season at the three sites differ by only 0.5°C. Microclimatic differences become apparent only at shorter time scales. Regarding daily mean temperatures, ridges and the south-facing slopes are characterized by a similar number of days above 5°C (86/91), whereas only 73 days at north-facing slopes exceed this threshold (Fig. 2b–d). Differences in the diurnal temperature range at the three microsites are illustrated in Fig. 3. The daily temperature amplitude is highest at south-facing slopes (mean range 8.5°C), less pronounced at north-facing slopes (mean range 7.3°C) and lowest at ridge positions (mean range 6.9°C).

Characteristics of site chronologies

The three site chronologies are characterized by high mean interseries correlation (rbar values in Table 2). The interannual ring-width variation is high, which is expressed by low values

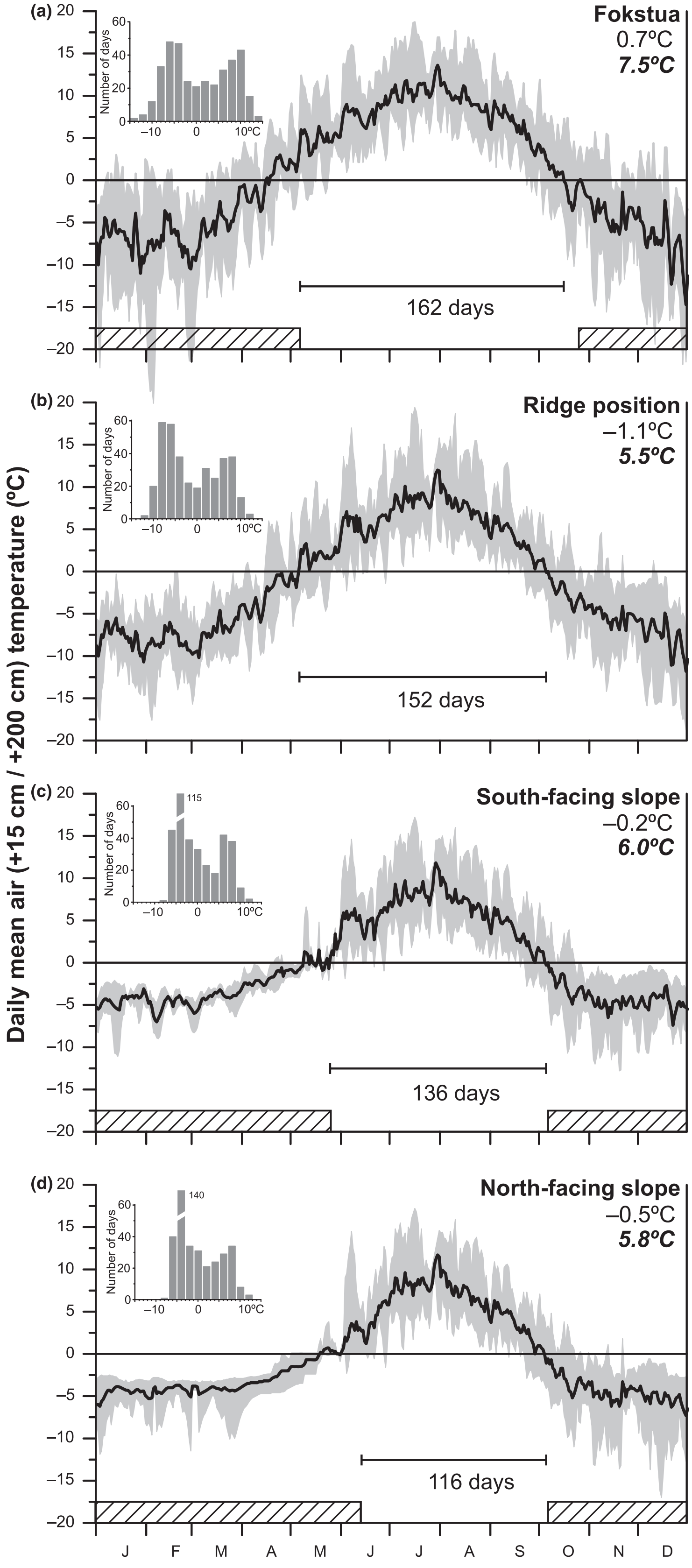

Figure 2 Annual temperature trends at the DNMI station (a) and three microsites (b–d). Solid line, daily mean temperatures over a period of 6 years (1999–2004); the range of minimum and maximum daily mean temperatures is shown in grey. Values for annual mean temperatures and mean temperatures for the growing season (bold) are given in the upper right corner of each diagram. Horizontal bars indicate the length of the growing season; hatched bars mark the duration of snow cover (> 10 cm thickness). Histograms in the upper left corner represent the frequency of daily mean temperatures.

of autocorrelation. Similarities between the chronologies are conspicuous; the correlation is highest between ridges and north-facing slopes ($r = 0.81$). South-facing and north-facing slopes are correlated with $r = 0.67$, and ridges and south-facing slopes are correlated with $r = 0.59$ (all correlation significant at $P < 0.01$). Despite these high correlations, which

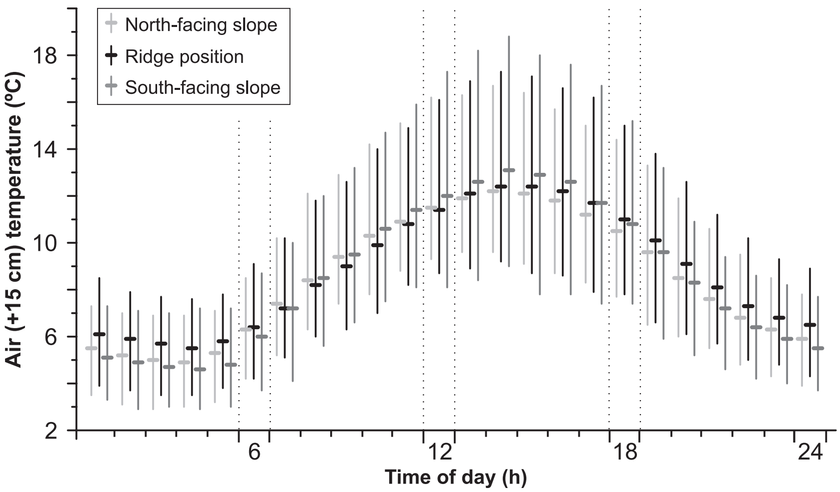

Figure 3 Diurnal course of temperatures at the three microsites. Mean hourly temperatures and their min–max range during the growing season (June to August) are illustrated.

Table 2 Statistical characteristics of *Empetrum hermaphroditum* chronologies from the three microsites.

Site chronology	N	Mean (mm)	SD	AC(1)	rbar
Ridge	11	0.09	0.26	−0.01	0.38
North-facing slope	10	0.07	0.32	−0.04	0.42
South-facing slope	13	0.11	0.27	−0.02	0.31

The analysis period is 1951–2004 (54 years). *N* = number of growth curves; mean = mean growth increment; AC(1) = first-order autocorrelation; rbar = mean correlation among all growth curves. Mean growth increments and SD were calculated from the measured raw values, all other values were calculated for ARSTAN standard chronologies.

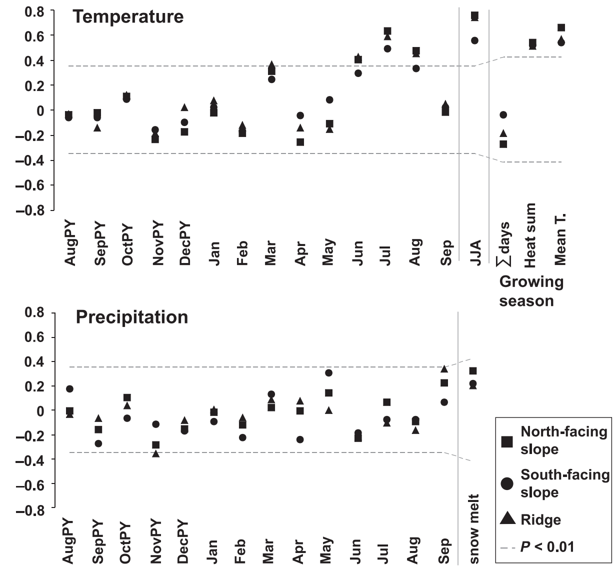

Figure 4 Correlation coefficients for site chronologies with monthly mean temperatures and various seasonal means, as well as monthly precipitation sums and snow melt.

point to the similarity of interannual growth patterns, the site chronologies differ in absolute growth increment rates. On average, mean increments are higher at south-facing slopes (0.11 mm year^{-1}) than at ridges (0.09 mm year^{-1}) or at north-facing slopes (0.07 mm year^{-1}).

Climate–growth analysis

Continuous time-series analysis

Bivariate correlations over the time period 1951–2004 indicate a strong positive effect of summer temperatures on growth rates of *E. hermaphroditum* at all microsites. Mean temperatures from June to August show correlations to ring widths of 0.74, 0.76 and 0.56 ($P < 0.01$ in all cases) for ridges, north-facing slopes and south-facing slopes, respectively (Fig. 4). In contrast, precipitation does not affect ring width significantly, except at the ridge positions, where the September precipitation shows a positive correlation with growth ($r = 0.34$; $P < 0.05$). A comparison with the time period 1969–2004, including additional data about the length of the growing season, cumulated heat sums and snow melt dates, reveals another interesting fact. Mean temperature during the growing season is still most important for ring width, followed by heat sums ($P < 0.01$ for both), whereas neither the length of growing season nor snow-melt dates show any significant correlation.

The results of the regression-tree analyses, all of which yield a proportional reduction in error > 0.75, support the findings of the correlation analysis. At all microsites, the first split between small and large ring widths is forced by mean summer temperature differentiating at a threshold of *c.* 9.1°C (Fig. 5). Any further differentiation in ring width is specific for each microsite. At ridges, a mean temperature below −4.9°C in March results in the strongest decline in ring width, whereas a supply of more than 55 mm rainfall in September results in the largest ring widths. At north-facing slopes, small ring widths are further differentiated by precipitation sums for the period from May to June. Exceptionally high temperatures in July lead

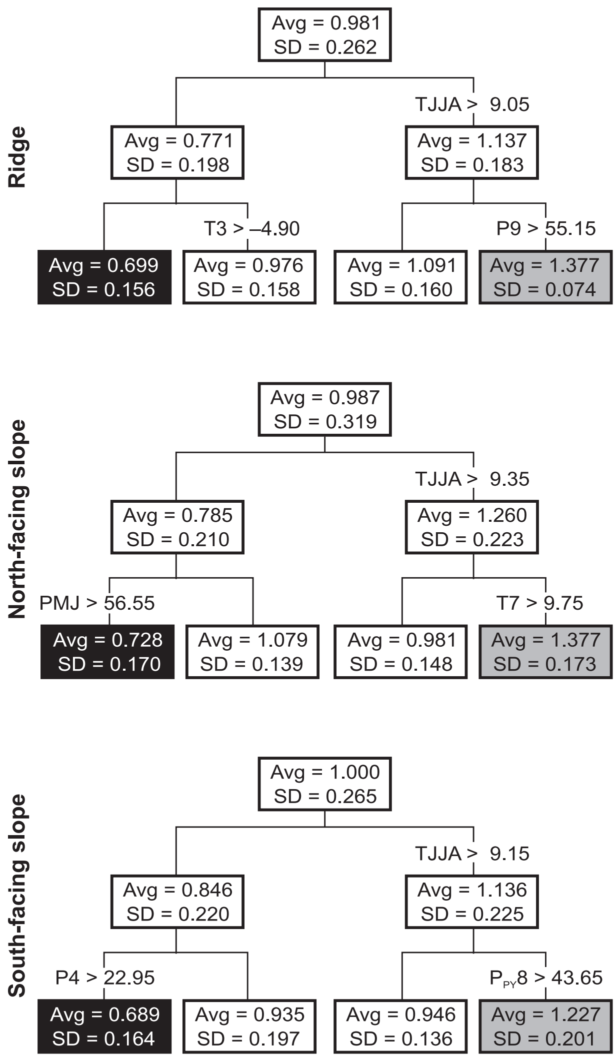

Figure 5 Regression-tree analysis for the three microsites. The average ring width (Avg) together with its SD is indicated by squares. The widest rings are indicated by grey squares and the narrowest rings by black squares. The differencing factor for the formation of wide and narrow rings is given for the first and second differentiation level, respectively. TJJA = mean temperature June–August; T3 = mean temperature in March; T7 = mean temperature in July; P4 = precipitation sum in April; P9 = precipitation sum in September; PMJ = precipitation sum in May–June; $P_{PY}8$ = precipitation sum in August prior to growth.

to the largest ring widths. At south-facing slopes, no further differentiation was possible. In conclusion, the regression-tree analyses suggest that interactions between different aggregations of summer temperatures in combination with precipitation are important for ring-width formation.

Discontinuous tree-ring analysis

Pointer-year analyses indicate that temperatures during the growing season exhibit the largest deviations from normal of all climate parameters and might thus determine extreme growth reactions in positive (negative) pointer years. However, temperature deviations in positive pointer years are not very pronounced (Table 3). The lack of exceptionally high temperatures in July and August, the main growing period, is obvious. Only at ridges, July temperature is significantly higher in years with wider rings. In contrast, high temperatures at the start of the growing season, which result in an overall higher heat sum, are more important at south-facing slopes. Negative pointer years occur mostly when temperatures during the growing season are significantly below average. This dependency is especially strong at north-facing slopes.

The impact of summer temperatures on ring width changes with increasing temperature. While at low temperatures the climate–growth relationships are still linear, this trend ceases with increasing summer temperatures (Fig. 6). This nonlinearity is most pronounced at south-facing slopes. This explains why extremely high summer temperatures do not necessarily lead to proportionally wider ring widths (positive pointer years).

Furthermore, pointer years do not occur simultaneously at all microsites in years characterized by high temperatures during the growing season. In years with a combination of high summer temperatures and contemporaneous low precipitation, we found pointer years only at ridges and north-facing slopes, as in 1991 and 1997 (Fig. 7, B1 and B2). At south-facing slopes, no pointer year occurs in any of these years. However, if above-average precipitation and higher temperatures occur simultaneously, south-facing slopes benefit most. For example, in 1980, a pointer year with a ring-width index of +1.68 SD occurred at the south-facing slopes (Fig. 7A).

Cell analysis

To analyse the interaction of temperature and precipitation on vessel formation, we computed moving correlations between these variables and the conductive tree-ring area. For both variables, the general patterns of influence on the conductive area are remarkably similar at all microsites, although the relative importance of temperature and precipitation varied greatly over time (Fig. 8). Temperature has a significant impact on vessel formation around 15 June, although the growing season at ridges usually starts around the beginning of May. There is an approximately 25-day delay at north-facing slopes due to late snow melt. However, this does not have a high impact on the conductive area. In the first half of June it is still cold and precipitation is low. At the end of July, during the warmest period, the temperature signal weakens temporarily and increases again at the end of the growing season. During the course of the main growing season, precipitation becomes increasingly important for the conductive area. Significant correlations occur first at the beginning of July at ridge sites, and later in August at both microsites. The previous year's climate conditions also influence vessel formation. For ridges, high temperatures in September and high precipitation in September/October affect growth positively in the following year. Similar patterns were found for north-facing slopes, with

Negative pointer years (climate parameter)	Deviation from long-term mean	Positive pointer years (climate parameter)	Deviation from long-term mean
Ridge			
Precipitation March	−0.70	Temperature July	0.65
Growing season (mean *T*)	−0.66		
Temperature June	−0.48		
North-facing slope			
Growing season (mean T)	−0.75	Snow-melt date	0.30
Temperature August	−0.73		
Growing season (heat sum)	−0.69		
South-facing slope			
Temperature May	−0.61	Growing season heat sums	0.96
Temperature July	−0.60	Precipitation May	0.65
		Temperature June	0.59

Climate variables were normalized to −1 <0 <+1 with 0 as mean value.

Table 3 Average deviation from the long-term mean in pointer years for the most important climate variables.

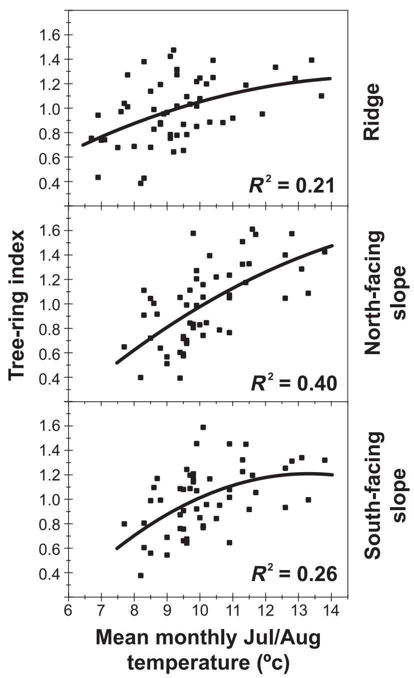

Figure 6 Scatter plots of ring width and mean monthly temperatures in July/August. Nonlinear regressions were determined by fitting with a second-order polynomial function.

temperature also having a greater effect during August of the year prior to growth.

DISCUSSION

Climate–growth relationships and their site-specific modifications in an alpine environment were analysed for the dwarf shrub *E. hermaphroditum* using different methods and temporal resolutions. Regarding near-surface temperature conditions *per se*, we found topoclimatic differences as described by Barry (1992) and Löffler *et al.* (2006) to be restricted primarily to time scales of hours during the snow-free season. However, the site differences are still visible in the daily means of meteorological data, but decline to *c.* 0.5°C when integrated over the whole growing season.

In view of these only slight differences in temperature regime, the significant correlations between the different microsite chronologies found by Bär *et al.* (2007) become understandable. We are now able to relate these observed similarities to two factors.

First, temperature is the limiting growth factor at all microsites. This is confirmed by regression-tree and negative pointer-year analyses. Regarding growth rates, mean summer temperatures (June–August) are the dominant factor. Therefore ring width can be regarded as a variable integrating temperature conditions during the main growing season. Microsite modifications of the temperature regime are small at this time scale; hence ring-width differences are also marginal.

Second, analysis of ring width and the percentage of vessel area verify that the length of the growing season, as well as the date of snow melt, which are the climatic factors showing the largest differences between microsites, do not substantially alter the anatomical ring structure. The gain in length of the snow-free period in spring at ridges compared with the slope positions is of minor relevance. The reasons for this are the low cell-division rates due to temperatures commonly below 5°C (Körner, 2003). Kudo *et al.* (1999) reported that *E. hermaphroditum* reacts to a shorter growing season with increasing leaf life span, rather than with shoot growth, except when the season is extremely short. Only under elevated temperatures does growth increase (Graglia *et al.*, 1997), supporting our results that the influence of temperature on growth dominates over that of growing-season length.

Nevertheless, different mean growth rates of *E. hermaphroditum* for north-facing slopes, ridges and south-facing slopes were reported by Bär *et al.* (2007). This suggests site-specific effects that might be attributable to the higher frequency of warm days, particularly in summer at the south-facing slope, as also revealed by the microclimate data.

Furthermore, we found that pointer years are not developed synchronously at all microsites. For instance, in years with exceptionally warm summers and low precipitation, positive

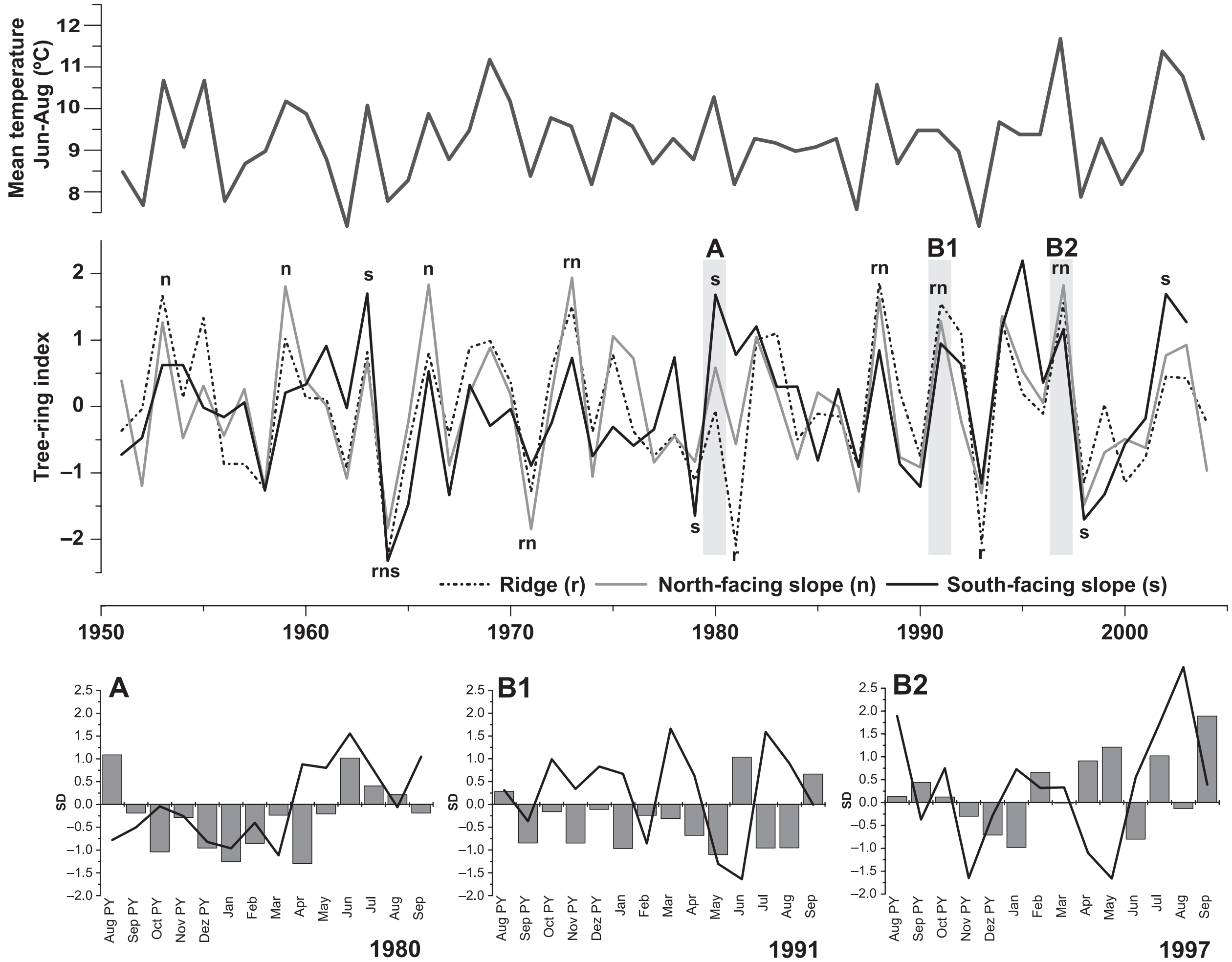

Figure 7 *Z*-transformed ring-width index chronologies with marked pointer years for the ridge (*r*), north-facing slope (*n*) and south-facing slope (*s*) (middle panel). Mean temperatures (Jun–Aug) are shown as the most important climate parameter for ring-width formation (upper panel). Variations of temperature (lines) and precipitation (bars) conditions in years with above-average temperatures (lower panel) with (a) above-average precipitation; (b) below-average precipitation during June to August based on monthly means and sums in SD.

pointer years are found only at ridges and north-facing slopes. While ring-width formation at ridges and north-facing slopes benefits from generally higher temperatures, such conditions obviously prevent the formation of positive pointer years at the south-facing slope. Although drought stress probably occurs rarely under average climatic conditions (Körner, 2003; Löffler, 2005), occasional water shortage associated with particularly high temperatures might occur at south-facing slopes. Under full solar radiation, temperatures might pass a critical physiological threshold that results in reduced net photosynthesis under insufficient water supply conditions (Körner, 2003). Recent studies also point to an increasing sensitivity of tree growth to microsite differences due to climate warming (D'Arrigo *et al.*, 2004; Wilmking *et al.*, 2005).

Quantitative analysis of wood anatomy revealed that the availability of moisture affects vessel formation, especially in the later part of the growing season when temperatures are highest. As sufficient moisture conditions are essential for growth, the distribution and amount of snow and its corresponding water equivalent becomes important. Thus, due to low precipitation amounts in spring, snow-free ridges might suffer from a lack of available water early in the growing season.

In summary, annual radial growth of *E. hermaphroditum* is determined primarily by summer temperatures at all microsites. Precipitation becomes temporally important, especially under extremely warm site conditions, while the date of snow melt does not show significant correlations. Linking these climate–growth relationships to the spatial distribution of vegetation types at the different microsites, it is evident that snow may not have the same importance for growth-ring variations of this individual species as for species composition of the vegetation. Thus it is not possible to draw conclusions from the distribution of vegetation types to growth reactions of *E. hermaphroditum*. As vegetation types are distinguished mostly by a combination of characteristic and/or dominant species, one certain species may be a part of several vegetation types as long as site conditions are not limiting.

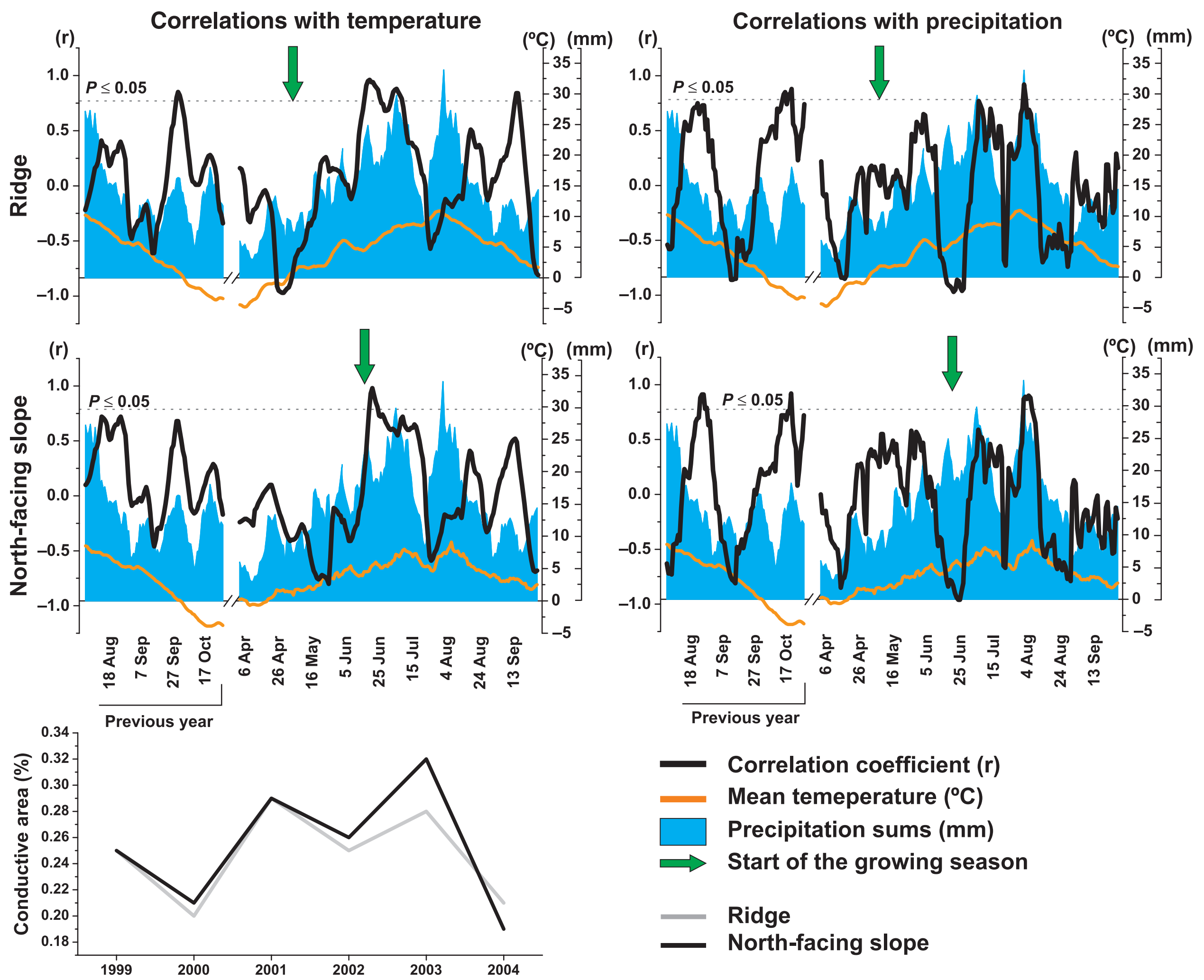

Figure 8 Running correlation coefficients between the conductive area per tree ring and mean temperature (precipitation sums) over 10-day intervals for the period 1998–2004. Results are presented for ridges and north-facing slopes. The analysis period covers the months from August to October prior to the growth year and the maximum length of the growing season (April–September) in the current year. For illustration, measured temperatures and precipitation sums are means of the period 1998–2004. Green arrows indicate the start of the growing season. The graph at the bottom illustrates the temporal variability of the conductive area between 1999 and 2004 for the ridges and the north-facing slopes.

Nevertheless, a higher potential impact than we found in our study of topography on growth variability due to differences in snow cover, moisture and temperature conditions is generally possible. Slopes in our study area showed inclinations between 15 and 20°. Steeper slopes might increase the contrast between microsites. In addition, we collected *E. hermaphroditum* individuals that were not directly at the thermal distribution limit of the species, which was determined at 5–6°C mean July temperature (Karlsen & Elvebakk, 2003). Under these conditions, the length of the snow-free period might also be more important for growth, as Kirdyanov *et al.* (2003) reported for tree growth in subarctic Eurasia and Schmidt *et al.* (2006) reported for the shrub *Salix arctica* in Greenland. At its thermal distribution limit, *E. hermaphroditum* is restricted to favoured microtopographic sites, such as south-facing slopes in Svalbard/Norway (Elvebakk & Spjelkavik, 1995). Under such extreme conditions, microtopography controls the distribution patterns of *E. hermaphroditum.*

The importance of canopy climate and the corresponding ability to create more favourable climatic conditions within a dense vegetation cover is stressed by many authors (Cernusca, 1976; Körner, 2003). However, its impact on growth-ring formation of dwarf shrubs remains unknown. Due to the sparse vegetation cover at our sampling sites, we assume that the influence of canopy climate can be neglected.

In conclusion, topoclimate induces slight modifications of annual growth-ring increments of *E. hermaphroditum*, but the prominent common growth pattern is still reflected at all microsites. Thus topoclimate only alters the absolute level of annual growth increments but does not outplay the regional climate signal. However, in contrast to the distribution patterns of vegetation types, which are primarily determined by snow cover variations, growth-ring differences are caused by summer temperature conditions. Hence, carefully synchronized and well replicated ring-width series of dwarf shrubs from alpine regions can be used as sensitive indicators for reconstructing past climate in vast regions beyond the polar and alpine tree limits.

ACKNOWLEDGEMENTS

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BIOSKETCH

Annette Bär studied for her PhD in landscape ecology at the University of Oldenburg, Germany, and is currently working at the Department of Geography at the University of Bonn, Germany. Her research activities focus on dendroecology, mountain ecology and landscape changes, with a regional focus on Fennoscandia.

Editor: Peter Linder

5.9 Darstellung des Eigenanteils an den Publikationen

Publikation I. *Löffler, J., Finch, O.-D., Naujok, J. & R. Pape (2001): Möglichkeiten der Integration zoologischer Aspekte in landschaftsökologische Untersuchungen von Hochgebirgen – Methodendiskussion am Beispiel ökologischer Prozesssysteme und Biozönosen. Naturschutz und Landschaftsplanung 33: 351-357.*

Die Idee für das Manuskript und dessen Konzeption geht auf die beiden Seniorautoren O.-D. Finch und J. Löffler zurück. Neben der Mitwirkung an dem Arbeitsprogramm hinsichtlich der Erfassung abiotischer Parameter, insbesondere des Energiehaushalts, geht in Absprache mit den Co-Autoren das „standörtliche Konzept- und Simulationsmodell als Prozess-Korrelationssystem“ auf meinen Entwurf zurück, in dem qualitativ die ökosystemaren Zusammenhänge zwischen Relief, Energie-, Wasser- und Stoffhaushalt sowie den Arten und Lebensgemeinschaften als Basis für eine weitere Modellierung dargestellt werden.

Publikation II. *Pape, R. & J. Löffler (2004): Modelling spatio-temporal near-surface temperature variation in high mountain landscapes. Ecological Modelling 178: 483-501.*

Die Konzeption des Manuskripts wurde zu etwa gleichen Teilen von beiden Autoren gemeinschaftlich erarbeitet. Der inhaltliche Hauptbestandteil der Publikation, das physikalisch basierte Modell zur standörtlichen Simulation der oberflächennahen Temperaturen wurde von mir entwickelt, angewendet und validert. Die entsprechenden textlichen Passagen wurden von mir verfasst, der übrige Teil gemeinschaftlich mit dem Co-Autor J. Löffler.

Publikation III. *Löffler, J. & R. Pape (2004): Across scale temperature modelling using a simple approach for the characterization of high mountain ecosystem complexity. Erdkunde 58: 331-341.*

Die Konzeption des Manuskripts wurde zu etwa gleichen Teilen von beiden Autoren gemeinschaftlich erarbeitet. Die Aufbereitung und Analyse der Daten sowie die Modellierung ist durch mich erfolgt. Die textlichen Passagen hierzu wurden von mir verfasst und in Abstimmung mit dem Co-Autor J. Löffler überarbeitet. Die Ergebnisse wurden gemeinschaftlich diskutiert und das weitere Manuskript gemeinschaftlich verfasst.

Publikation IV. *Löffler, J., Pape, R. & D. Wundram (2006): The climatologic significance of topography, altitude and region in high mountains – a survey of oceanic-continental differentiations of the Scandes. Erdkunde 60: 15-24.*

Alle drei Autoren waren etwa zu gleichen Teilen an der Konzeption des Manuskripts beteiligt. Die Aufbereitung und Analyse der Daten habe ich zusammen mit dem Co-Autoren D. Wundram vorgenommen, ein resultierender erster textlicher Entwurf der Ergebnisdarstellung wurde durch alle Autoren überarbeitet, die Diskussion der Ergebnisse und das Verfassen des Manuskripts erfolgte gemeinschaftlich durch alle Autoren.

Publikation V. *Pape, R. (2006): Klimadaten im Hochgebirge – Anspruch und Wirklichkeit. Norden 17: 45-50. Bremen.*

Idee, Konzeption und Umsetzung durch den Alleinautor.

Publikation VI. *Pape, R., Wundram, D. & J. Löffler (eingereicht): Modeling near-surface temperature conditions in high mountain environments – an appraisal. Climate Research.*

Das Manuskript wurde nach eigener Idee konzipiert. Die Modellweiterentwicklung, Anwendung und Validierung habe ich vorgenommen und das Manuskript selbst verfasst. Die Erfassung und Bearbeitung der Drachenluftbilder erfolgte durch D. Wundram. Ein erster Entwurf wurde mit den Co-Autoren diskutiert und entsprechend überarbeitet.

Publikation VII. *Finch, O.-D., Löffler, J. & R. Pape (2008): Assessing the sensitivity of Melanoplus frigidus (Boheman, 1846) (Orthoptera: Acrididae) to different weather conditions: A modeling approach focussing on development times. Journal of Insect Science (angenommen).*

Die Idee und Konzeption des Manuskripts geht auf den Erstautoren O.-D. Finch zurück. Daten zur Vegetation und generellen klimatischen Charakterisierung wurden durch den Co-Autor J. Löffler beigesteuert. Die Aufbereitung und Auswertung der habitatspezifischen Temperaturdaten erfolgte ebenso durch mich wie nach Vorgabe des Erstautors die Modellierung der Entwicklungszeit. Ein erster Entwurf des Manuskripts wurde durch alle Autoren diskutiert und entsprechend durch den Erstautoren überarbeitet.

Publikation VIII. *Bär, A., Pape, R., Bräuning, A. & J. Löffler (2008): Growth-ring variations of dwarf shrubs reflect regional climate signals in alpine environments rather than topoclimatic differences. Journal of Biogeography 35: 625–636.*

Der konzeptionelle Aufbau des Manuskripts beruht auf der Idee der Erstautorin A. Bär und wurde in Zusammenarbeit mit mir weiter ausgearbeitet. Die Bearbeitung des Zwergstrauchmaterials und die Auswertung der Klima-Wachstumsbeziehungen erfolgte durch die Erstautorin, ausgenommen der „regression tree analysis“, die durch mich durchgeführt wurde. Die Aufbereitung und Auswertung der Klimadaten erfolgte durch mich unter Mitarbeit der Erstautorin. Das Manuskript wurde gemeinschaftlich von der Erstautorin und mir verfasst, mit den beiden anderen Co-Autoren diskutiert und unter Berücksichtigung ihrer Korrekturvorschläge überarbeitet.

6 KRITISCHE BETRACHTUNG

An dieser Stelle seien die wesentlichen Aspekte dieser Arbeit einer kurzen kritischen Betrachtung unterzogen.

Die vorgenommenen Analysen der oberflächennahen Temperaturverhältnisse im Hochgebirge zeigen als ein neues Ergebnis deutlich die sehr stark ausgeprägte mikroskalige raum-zeitliche Differenzierung der Temperaturen, gegenüber der die bislang als übergeordnet angenommenen meso- und makroskaligen Einflüsse (vgl. z. B. Wallén 1970, Moen 1999) in ihrer Bedeutung zurücktreten. Generellen, auf Mittelwerten basierenden klimatologischen Gesetzmäßigkeiten, wie dem adiabatischen Temperaturgradient oder Ozeanitäts-Kontinentalitätsunterschieden (Barry 1992, Moen 1999), die auf diesen Skalenebenen wirken, soll damit jedoch keineswegs widersprochen werden. Vor dem Hintergrund der gezeigten raum-zeitlich hochaufgelösten Differenzierung der Temperaturverhältnisse muss allerdings die heutige gängige Praxis der Anwendung dieser Gesetzmäßigkeiten für Temperaturinterpolationen im Hochgebirge (Beniston 2003, Wang et al. 2006) unbedingt als kritisch angesehen werden. Dies gilt insbesondere, wenn diese Daten für ökologische Modellierungen verwendet werden (Dirnböck et al. 2003, Hamann & Wang 2006, Aitken et al. 2008), die eigentlich (vgl. Lookingbill & Urban 2003) auf der Mikroskala erfolgen müssten um die ökologisch relevanten Faktoren und Prozesse berücksichtigen zu können. Stattdessen werden makroskalige klimatische Gesetzmäßigkeiten eins zu eins auf feiner auflösende Skalen übertragen (vgl. insbesondere Wang et al. 2006), wobei lediglich die räumliche Auflösung, nicht aber auch die zwangsläufig damit verbundene inhaltliche Auflösung beteiligter Faktoren und Prozesse verbessert wird. Dieses Vorgehen wird nur vor dem Hintergrund der mangelhaften Datensituation in Hochgebirgen (vgl. Barry 1992, Price & Barry 1997) verständlich, in denen das Observationsnetzwerk zwar die makroskaligen Verhältnisse repräsentiert, nicht aber raum-zeitlich höher aufgelöste Phänomene. Eine für ökologische Modellanwendungen notwendige messtechnische Erfassung der mikroskaligen Differenzierung - wie im Falle dieses Forschungsprojektes - wird allerdings aufgrund des finanziellen und logistischen Aufwandes auf einzelne repräsentative Flächen oder Gebiete beschränkt bleiben müssen. Der für das gesamte Forschungsprojekt adaptierte hierarchische

Skalenansatz (Löffler 2002b) ermöglicht aber vor diesem Hintergrund wichtige inhaltliche und methodische Erkenntnisse.

Zur Schließung der Datenlücke für die Meso- und Mikroskala durch Modellierungs- und Interpolationsansätze konnte basierend auf dem vorliegenden Messkonzept zunächst ein geostatistisches Interpolationsverfahren für die erfolgreiche Verwendung im Hochgebirge angepasst werden. Weiterhin dienten die Daten für die Erstellung und Validierung statistisch basierter Modelle zur flächenhaften Modellierung der Oberflächentemperaturen auf den unterschiedlichen Skalenebenen. Darüber hinaus wurde ein neuer physikalisch basierter Modellansatz entwickelt und auf der Nanoskala gegen Messdaten validiert. Nachfolgend wurde dieser Modellansatz für eine räumliche Anwendung erweitert. Die gefundenen Ergebnisse belegen generell, dass eine Repräsentation der oberflächennahen Temperaturverhältnisse in hoher raum-zeitlicher Auflösung und ausreichender Genauigkeit mit diesen Ansätzen zu erzielen ist.

Allerdings offenbaren diese Ansätze auch methodische Schwächen, die hier zu diskutieren sind. So zeigt die Interpolation der Messdaten in Mittelnorwegen durch die Einbeziehung temperaturrelevanter Faktoren (für die Topographie vgl. Thomas & Herzfeld 2004) eine deutliche Verbesserung der Ergebnisse gerade im Hochgebirge gegenüber herkömmlichen Ansätzen (Hutchinson 1995, Martinez-Cob 1996). Für sich genommen, führt sie aber nicht zu den gewünschten mikroskaligen Erkenntnissen, da nur makroskalige Gesetzmäßigkeiten interpoliert werden. Diese Daten dienen vielmehr als Eingangsdaten für ein Downscaling (vgl. z. B. Benestad 2002, Miksovsky & Raidl 2005) auf der Meso- und Mikroskala, durch das die wichtigen Faktoren und Prozesse der jeweiligen Skalenebene integriert werden. Dies passiert im Rahmen der o.g. statistischen und physikalisch basierten Modellierung.

Trotz der gezeigten guten Ergebnisse der statistisch basierten Modellierung bleibt das Hauptproblem ihrer Anwendung (vgl. z. B. Duttmann 1999) jedoch die räumliche Übertragbarkeit, die bedingt durch die empirisch gefundenen Zusammenhänge auf vergleichbare Raumausschnitte limitiert ist. Allerdings trat diese Limitierung auch bei der Übertragung des Modells von West- nach Ostnorwegen bzw. umgekehrt bereits deutlich in Erscheinung. Steht eine räumliche Übertragung jedoch nicht im Fokus der Untersuchungen, so zeigen die Ergebnisse, dass die statistisch basierte Modellierung zurzeit ein probates Mittel zur flächenhaften Abbildung oberflächennaher Temperaturen darstellt. Damit befinden sich die Ergebnisse mit einem generellen Trend in der Klimamodellierung in Richtung statistisch basierter Modellansätze in Einklang (vgl. z. B. Joly et al. 2003, Chung & Yun 2004, Chung et al. 2006, Joly & Brossard 2007).

Physikalisch basierte Modellansätze unterliegen dagegen, wie gezeigt werden konnte, hinsichtlich ihrer räumlichen Anwendbarkeit noch größeren Limitierungen, obwohl eigentlich sie das größere Potenzial für eine räumliche Übertragbarkeit gegenüber den statistischen Modellen aufweisen (Duttmann 1999). Als Ursache für die Limitierung zeigte sich in dieser Arbeit die für eine flächenhafte Anwendung erforderliche Parametrisierung der beteiligten Prozesse. Die Parametrisierungen wurden für nicht-alpine Bereiche entwickelt (vgl. z. B. Beljaars & Holtslag 1991, Arola 1999, Liebethal & Foken 2007) und lassen sich daher, wie die vorliegenden Ergebnisse gezeigt haben, nicht ohne weiteres auf Hochgebirgslandschaften übertragen. Somit ist hier unbedingt ein erweiterter Forschungsbedarf zu konstatieren.

Die in der vorliegenden Arbeit neu entwickelten Modellansätze fokussieren bislang auf die Aperzeit. Wie die Ergebnisse des Forschungsprojekts allerdings gezeigt haben, bildet der

Faktor Schnee einen wichtigen Faktor in der Hochgebirgsökologie, insbesondere für die räumlichen Muster der Vegetation (Löffler 2003). Daher ist eine detailliertere Betrachtung der Schneeverhältnisse und der daraus resultierenden thermischen Bedingungen für eine ganzjährige Betrachtung der Ökosystemdynamik unbedingt notwendig. Da eine Schneedecke ab einer Mächtigkeit von 0,2 m effektiv gegen tägliche Lufttemperaturschwankungen isoliert (vgl. Oke 2001, Jones et al. 2001), verschiebt sich winterlich die Problematik von der Modellierung der bodenoberflächennahen Temperaturen hin zu einer räumlich expliziten Modellierung des Schneedeckenauf- und –abbaus. Diese Schneemodellierung ist neben der Temperaturmodellierung ein eigenes aktuelles Forschungsfeld (z. B. Winstral & Marks 2002, Strack et al. 2004, Liston & Elder 2006, Schmidt 2007) und hätte bei ihrer Berücksichtigung den Rahmen der vorliegenden Arbeit gesprengt. Für den Fortlauf des übergeordneten Forschungsprojektes sind Aspekte der Schneemodellierung (inklusive der Bereitstellung der hierfür erforderlichen Daten) allerdings unbedingt zu integrieren.

Die stellvertretend für die ökologische Relevanz oberflächennaher Temperaturen analysierten Zusammenhänge zum Habitat und der Entwicklung der Heuschrecke *M. frigidus* bzw. dem Jahrringwachstum der Zwergstrauchart *E. hermaphroditum* liefern für sich genommen wichtige Ergebnisse. Im Fall der Heuschrecke konnte erstmals eine Habitatbeschreibung vorgenommen werden, während die Ergebnisse der dendroökologischen Untersuchungen sogar forschungsmethodisch von herausragender Bedeutung sind. So konnte durch die Arbeit von Bär (2007) die Eignung von Zwergsträuchern für klimatische Rekonstruktionen belegt und damit das Forschungsfeld der Dendroökologie auf Bereiche jenseits der Baumgrenze ausgedehnt werden. Im Kontext des Forschungsprojektes liefern beide Fallbeispiele wichtige Erkenntnisse zur thermisch gesteuerten Ökosystemdynamik im Hochgebirge und belegen die Wichtigkeit einer multiskaligen Betrachtung dieser Systeme. Hinsichtlich der angestrebten Quantifizierung des Einflusses steuernder Größen im ökosystemaren Prozessgeschehen (Publikation I) wird mit diesen Untersuchungen ein erster Beitrag geleistet, allerdings ist eine Ausweitung der qualitativen und quantitativen Analysen auf die weiteren abiotischen (z. B. Wasserhaushalt) und biotischen (Arten und Gesellschaften) Kompartimente erforderlich, um eine ökosystemare Modellierung zu ermöglichen.

7 FAZIT

Vor dem Hintergrund eines langfristigen ökologischen Forschungsprojektes in den mittelnorwegischen Skanden wurden mit der vorliegenden Arbeit die oberflächennahen Temperaturverhältnisse entlang verschiedener Gradienten im Hochgebirge untersucht.

Die neue Erkenntnis über die übergeordnet steuernde Funktion der mikroskaligen Bedingungen stellt sowohl die gängige Praxis der Implementierung ökologischer Modelle, als auch Standardverfahren für Temperaturmodellierung und –regionalisierung im Hochgebirge in Frage. Aus dieser Konsequenz wurde ein neuer physikalisch basierter Modellierungsansatz entwickelt, sowie statistische Modellierungs- und Interpolationsverfahren für die Anwendung in Hochgebirgslandschaften modifiziert. Die Evaluation der Ergebnisse liefert den Beweis, dass eine angemessene räumliche Repräsentation der ökologisch relevanten oberflächennahen Temperaturen mit einfachen Mitteln möglich ist. Gleichzeitig zeigt sich aber gerade bei der physikalisch basierten Modellierung erweiterter Forschungsbedarf, da sich die bestehenden Parametrisierungen komplexer Prozesse hinsichtlich ihrer Anwendbarkeit im Hochgebirge als limitiert erweisen und somit zu ungenauen Modellergebnissen führen. Hier sind zukünftig angepasste Parametrisierungsverfahren zu entwickeln um eine adäquate Wiedergabe der Temperaturen insbesondere für ökologische Folgeanwendungen zu gewährleisten.

Die Untersuchung der ökologischen Bedeutung der oberflächennahen Temperaturen ergab eine starke Abhängigkeit zwischen thermischen Bedingungen und der Biotik und liefert damit einen wichtigen Beitrag für die im Rahmen des übergeordneten Forschungsprojekts angestrebte Quantifizierung ökosystemarer Prozesse. Darüber hinaus unterstreicht sie einmal mehr die Notwendigkeit, die Wechselwirkungen unterschiedlicher Skalenebenen berücksichtigen zu müssen und liefert exemplarische Beweise für eine Indikatorfunktion der Hochgebirge hinsichtlich des Klimawandels.

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Oldenburg, 17.03.2008

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ERKLÄRUNG

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Oldenburg, 17.03.2008

Roland Pape

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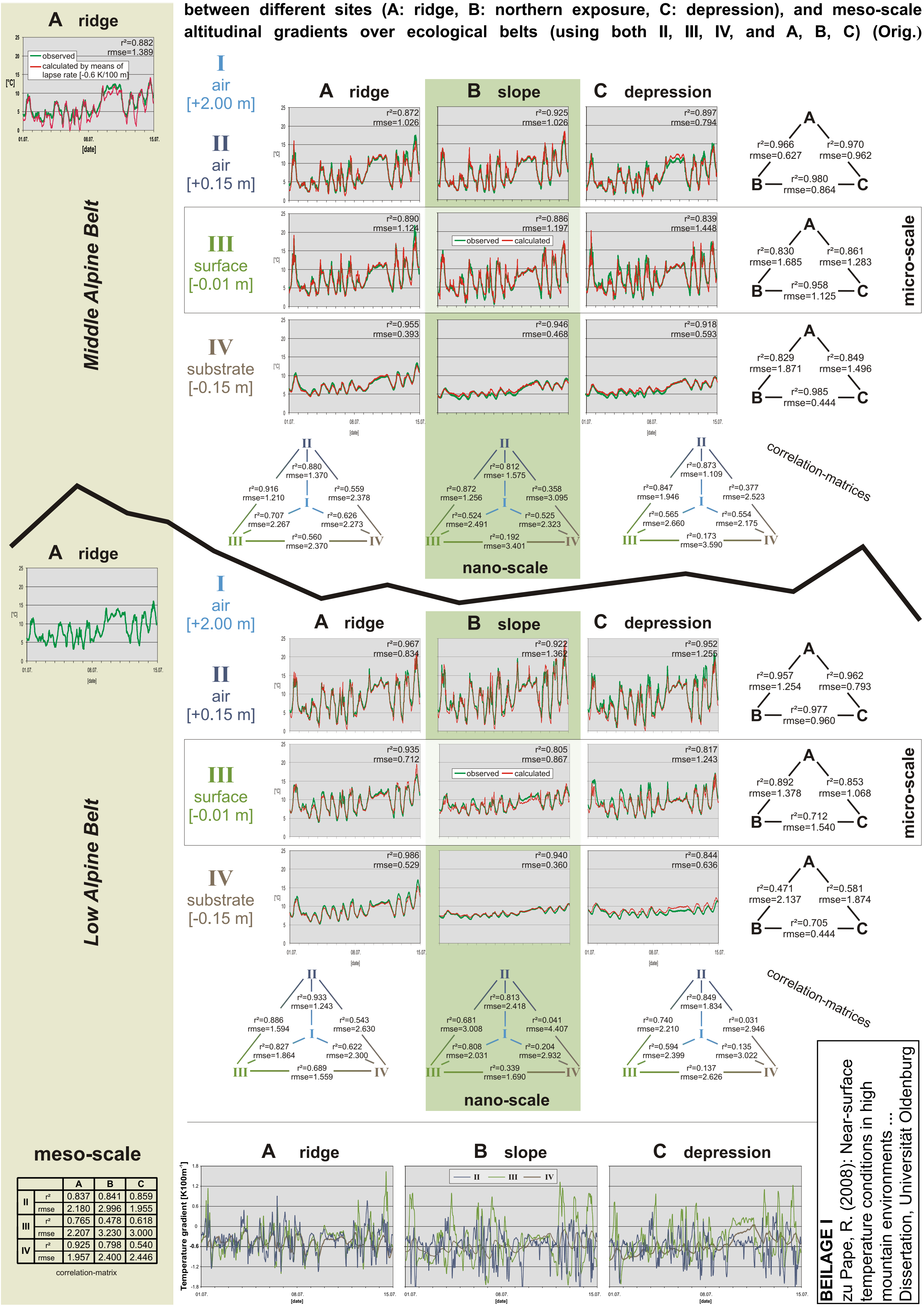
Scale-specific matrices for the evaluation of temperature variation along nano-scale vertical profiles at single sites (I: T+200, II: T+15, III: T-1, IV: T-15), micro-scale topographical gradients between different sites (A: ridge, B: northern exposure, C: depression), and meso-scale altitudinal gradients over ecological belts (using both II, III, IV, and A, B, C) (Orig.)



		A	B	C
II	r²	0.837	0.841	0.859
	rmse	2.180	2.996	1.955
III	r²	0.765	0.478	0.618
	rmse	2.207	3.230	3.000
IV	r²	0.925	0.798	0.540
	rmse	1.957	2.400	2.446

correlation-matrix

BEILAGE I
zu Pape, R. (2008): Near-surface temperature conditions in high mountain environments ... Dissertation, Universität Oldenburg

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The climatologic significance of topography, altitude and region in the Scandes

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