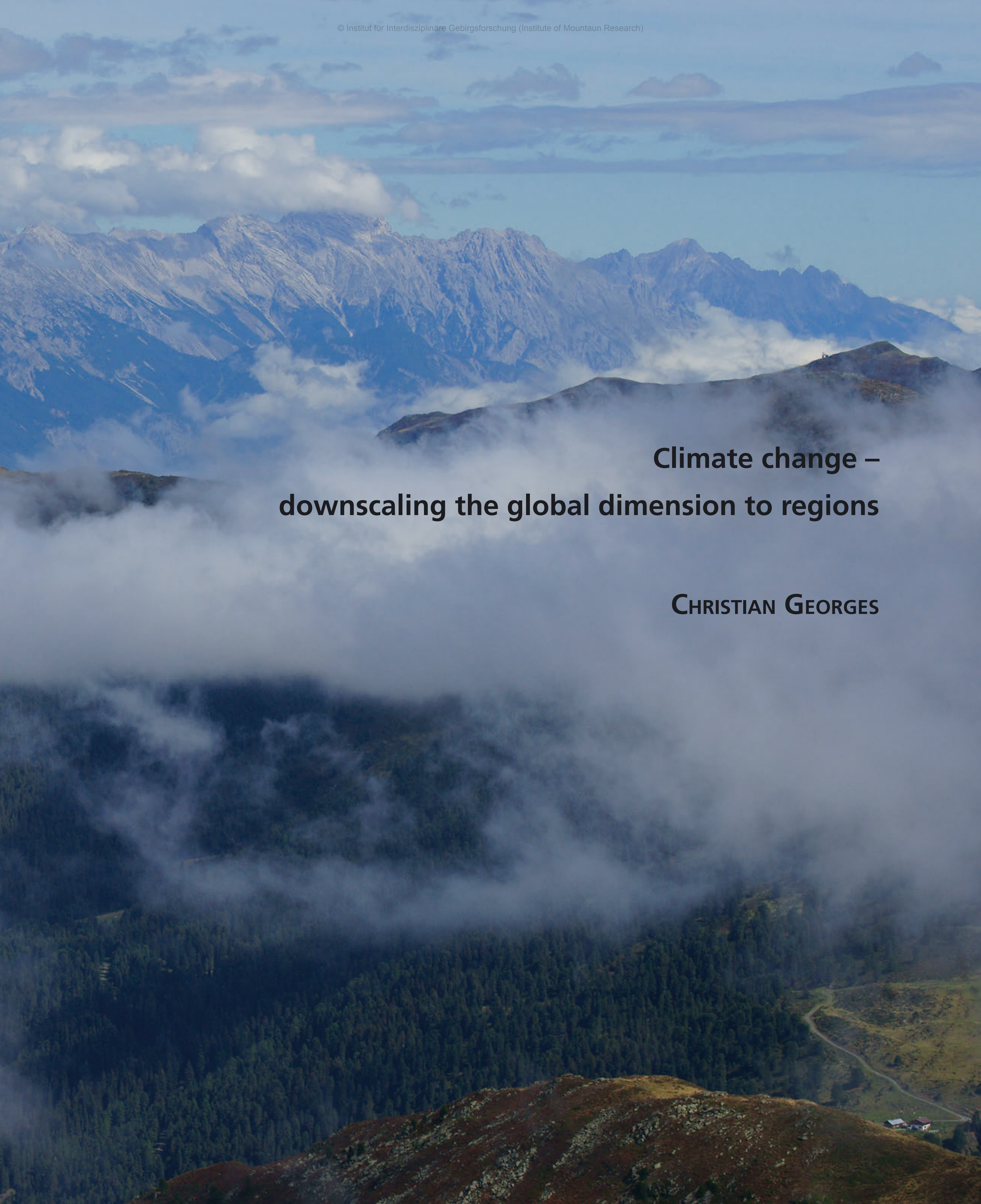

Climate change – downscaling the global dimension to regions

Christian Georges

Introduction

In 2007, the Intergovernmental Panel on Climate Change (IPCC, Solomon et al. 2007) presented its 4th Assessment Report. Recent changes in the climate system, evident from multitudinous observations, have been identified to be unequivocal. The substantial effect of human activities on climate change has been pointed out more clearly than ever. Projections of future changes in climate indicate significant modifications of temperature, rainfall and circulation patterns with wide-ranging consequences for human societies and ecosystems. A recent update report (Allison et al. 2009) concluded that several important aspects of climate change are already occurring at the high end, or even beyond, the expectations of just a few years ago. High mountain areas such as the Alps are especially affected. Local impact studies for such regions are highly desirable since they provide baseline information for adaptation and mitigation strategies (e. g. Georges et al. 2008).

Climate projections have been obtained from Global Climate Model (GCM) simulations driven by idealized greenhouse gas emission (or concentration) scenarios. GCM-derived climate projections as presented by the IPCC draw a large-scale and long-term picture on a global perspective. As a result, those simulations cannot be used for local impact studies. GCM simulations can be made meaningful for specific regions by downscaling (Wilby & Wigley 1997). For a region such as the Alps, which is characterized by complex topography, downscaling of GCM output is particularly important for assessing regional climate change. In this study, a pattern (down-)scaling approach (Mitchell 2004) has been applied to generate local climate projections for the region of Tyrol. The resulting datasets may be used for local socio-economic and environmental impact studies of changes in regional climate. This paper summarizes the downscaling approach and presents projections of local climate for the beginning, mid- and late 21st century.

Sources of uncertainty in climate projections

Uncertainties in future climate projections basically result from two different sources:

- the future development of greenhouse gas emissions and
- the modelling approach of the GCM (physics, parameterization, etc.).

Magnitudes of future changes in climate mainly depend on the future emissions of greenhouse gases. Corresponding emission scenarios have been developed and discussed in an IPCC Special Report (Nakićenović & Swart 2000). The Special Report on Emission Scenarios (SRES) provides a comprehensive set of 40 socio-economic futures based on four storylines (Fig. 1), and presents details on the consequences of anthropogenic emissions of greenhouse gases and pollutants. Illustrative so-called SRES marker scenarios characterize fundamentally different futures in terms of energy and consumption behaviour. For the approach used here, I considered four illustrative scenarios. Scenario A1FI describes a future world of fuel-intensive rapid economic growth; scenario A2 is another economy-oriented future albeit in a more heterogeneous world; scenario B1 stands for a future world of global growth with reductions in material intensity and the use of clean and resource-efficient technologies; scenario B2 is a future world with an emphasis on local solutions. These four represent 68% of the range of uncertainty in emissions published by SRES as compared to the full set of 40 SRES scenarios.

The other important source of uncertainty in global climate projections arises from differences in physics and parameterizations between climate models. This uncertainty has been addressed by using and comparing four different GCMs in this study. The GCMs and their spatial resolution are presented in Table 1. Fundamentals on the GCMs are provided in the following references: CGCM2 – Flato and Boer (2001); CSIRO2 – Gordon and O'Farell (1997); HadCM3 – Mitchell et al. (1998); PCM – Washington et al. (2000).

Economic emphasis

Global integration

Regional emphasis

A1 storyline **World**: market-oriented **Economy**: fastest per capita growth **Population**: 2050 peak, then decline **Governance**: strong regional interactions; income convergence **Technology**: three scenario groups: • A1Fi: fossil-intensive • A1T: non-fossil energy sources • A1B: balanced across all sources	**A2 storyline** **World**: differentiated **Economy**: regionally oriented; lowest per capita growth **Population**: continuously increasing **Governance**: self-reliance with preservation of local identities **Technology**: slowest and most fragmented development
B1 storyline **World**: convergent **Economy**: service and information-based; lower growth than A1 **Population**: same as A1 **Governance**: global solutions to economic, social and environmental sustainability **Technology**: clean and resource-efficient	**B2 storyline** **World**: local solutions **Economy**: intermediate growth **Population**: continuously increasing at lower rate than A2 **Governance**: local and regional solutions to environmental protection and social equity **Technology**: more rapid than A2; less rapid, more diverse than A1 / B1

Environmental emphasis

Fig. 1: Summary characteristics of the four SRES storylines (based on Nakićenović & Swart 2000).

Pattern-scaling approach

The approach by Mitchell (2004) refines the quite coarse outputs from GCMs in the space domain to obtain feasible data for investigations on the regional scale. Following the principle idea of Mitchell (2003) of pattern (down-)scaling, regional climate data are linked to GCM outputs. In addition to GCM outputs (monthly, 2001–2100), the approach requires two further data sources:

- observed climatology (monthly, 1961–1990) and
- observed time-series (monthly, 1901–2000).

Table 1: Acronyms of GCMs used for the climate scenarios. Resolution refers to the spatial resolution of the GCM in the bottom layer of the atmosphere. Acronyms: CGCM2 – Canadian Global Climate Model version 2, CSIRO2 – Commonwealth Scientific and Industrial Research Organisation GCM mark 2, HadCM3 – Hadley Centre Coupled Model version 3, PCM – National Centre for Atmospheric Research Parallel Climate Model.

GCM	Resolution [degree]
CGCM2	73.8 by 3.8
CSIRO2	103.2 by 5.6
HadCM3	232.5 by 3.75
PCM	302.8 by 2.8

The GCM data represent time series of global warming and the patterns of change in the mean. Thus, the GCM data is treated as basic information for possible future mean climates. The observed datasets are based on long-term measurements (Fig. 2), which have been homogenized and compiled to spatially finer grained, gridded information on regional climate[1]. They provide input to the computation of the patterns, which take into account the spatial variation and sub-centennial variability in regional climate. Based on these spatial

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[1] All datasets were kindly provided by the Climatic Research Unit, University of East Anglia (see http://www.cru.uea.ac.uk for details and original authors of the datasets).

Fig. 2: Local weather observations provide fundamental data to establish the link between GCM output and local climate (source: Matthias Monreal).

patterns, the GCM outputs were downscaled to 10 arc minute grids. The finer resolution is particularly crucial in mountain regions due to the great spatial variability.

The pattern-scaling approach was applied to 16 climate change scenarios of temperature and rainfall, which represent all combinations of the four emissions scenarios and the four global climate models (GCMs) described above. The resulting scenarios (10 arc minute grids, monthly, 2001–2100) cover 93% of the range of uncertainty in global warming in the 21st century as published by the IPCC (Mitchell 2004). The 16 scenarios should be treated as equally likely. Thus these scenarios allow assessing the implications for climate impacts of some of the major sources of uncertainty in future climate.

For local impact studies and comparability, it is more reasonable to use a pattern-scaled dataset than to use direct model outputs. There is complete consistency between the emissions scenarios and climate models used here. The direct model outputs are generally available only on the native grids, which vary between models. The net effect of these advantages is that it becomes much easier to conduct systematic investigations.

Results

The climate projections are presented in 30-year climatologies. Three future periods have been defined:

- early 21st century (2011–2040)
- mid-21st century (2041–2070) and
- late 21st century (2071–2100)

For these periods, I compiled maps and annual cycles of temperature and precipitation for all 16 scenarios. The figures below are shown as differences between the respective future period and the observed period 1960–1990.

Maps of rise in surface temperature [ΔK] in the mid-21st century (2041–2070) are shown in Figure 3. Largest increases are projected for the fuel-intensive emission scenario A1Fi, slight ones for B1 and moderate rises for B2 and A2. This order has been derived from all four GCMs. However, magnitudes of the rise in temperature differ for the GCMs, with HadCM3 projecting highest values in general. There is little spatial variation in the rise in surface temperature. Still, each of the four GCMs gives a slightly different spatial pattern, which persists for all emission scenarios.

Changes of annual cycles of temperature and precipitation for the three future periods and all scenarios are presented in Figure 4 and Figure 5.

The rise in annual mean temperature in the early 21st century, compared with the late 20th century, is projected as 1.5 to 2.0 K (Fig. 4, left column). Annual cycles of the changes show distinct but moderate characteristics with smaller values in winter and larger ones in summer. The winter seasons (Dec–Feb) will be 1.2 to 1.5 K warmer, the summer seasons (Jun–Aug) 1.8 to 2.5 K. Temperature rise at the end of the winter season (Mar / Apr), which is significant for alpine winter tourism, is projected to be 1.5 to 2.0 K warmer. This value corresponds to a rise of the average snowline of 100 to 150 m. Annual precipitation is projected to increase by 60–80 mm or about 10% in the early 21st century, compared with the late 20th century (Fig. 5, left column). The annual cycles of change in precipita-

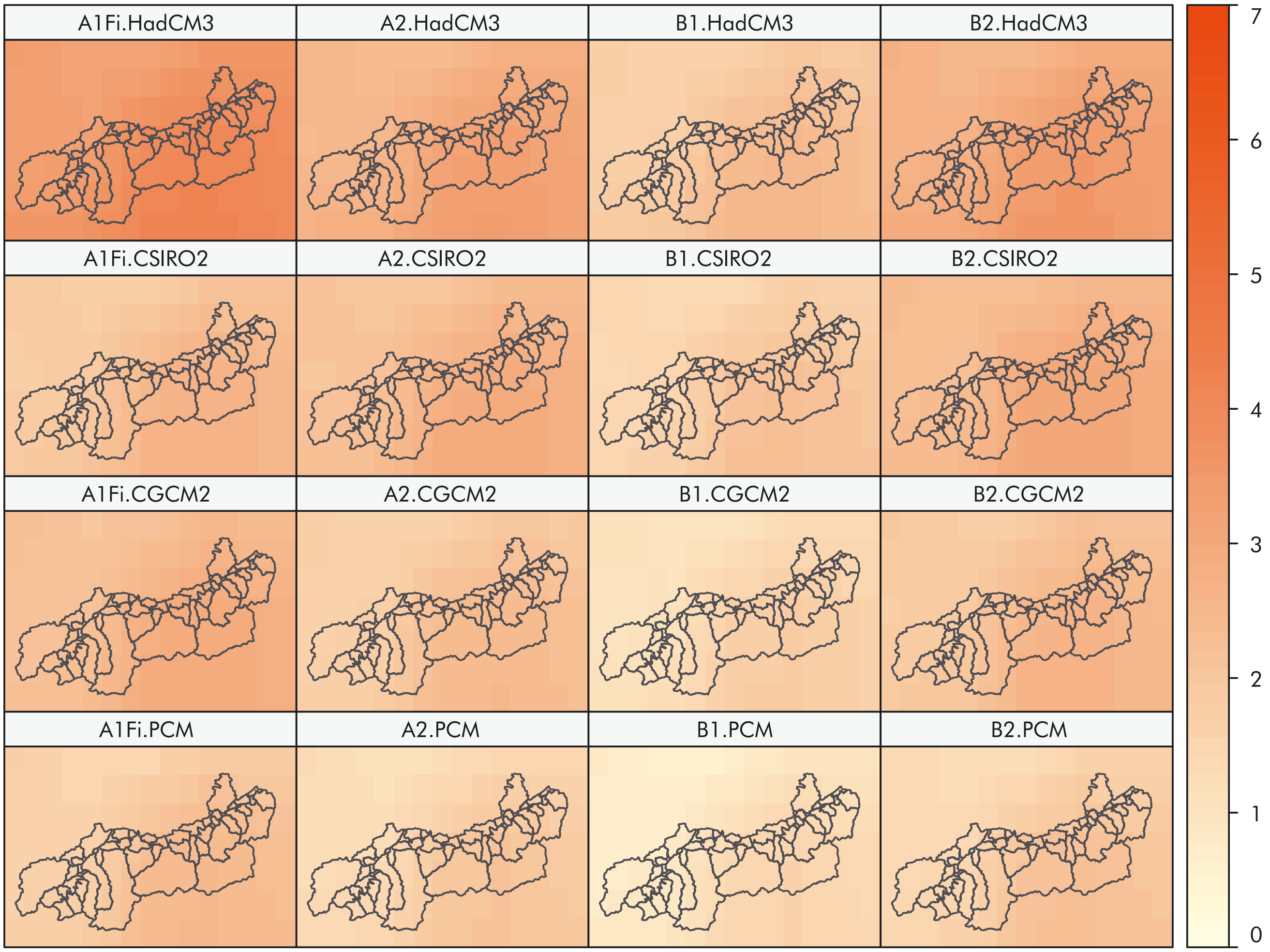

Fig. 3: Rise in surface temperature [ΔK] in Tyrol in the mid-21st century (2041–2070), compared to the observed period 1961–1990, based on four SRES emission scenarios (A1Fi, A2, B1, B2) and computed by four GCMs (CGCM2, CSIRO2, HadCM3, PCM). Black lines represent tributary catchments for the Tyrolean Inn.

tion are pronounced. The summer seasons will become drier, all other seasons wetter. Monthly precipitation in winter will increase by 15–20 mm or 20–30%. In contrast, monthly rainfall in summer will decrease by 10–15 mm or about 10%. Likewise, daily temperature amplitudes in summer will increase slightly. Variations of change between the emission scenarios are small for both temperature and precipitation in the early 21st century. Large intra-seasonal deviations (e.g. temperature in August) are due to the pattern-scaling method and an anomaly of the 20th century climate rather than a realistic projection.

All described features of climate change become more pronounced in the mid-21st century with larger ranges and uncertainties. The annual mean temperature change rises to 2.1–3.7 K (Fig. 4, middle column). Seasonal changes of +1.3 to +2.6 K are projected for winter and +2.5 to +4.5 K for summer. The end-of-winter season rise in temperature will be +2.0 to +3.9 K, equalling a +150 to +250 m rise of the snow line. The climate will be drier than during the early 21st century: changes in annual precipitation totals will only range from +10 to +50 mm (Fig. 5, middle column). This is caused by the summer dry period expanding into May and

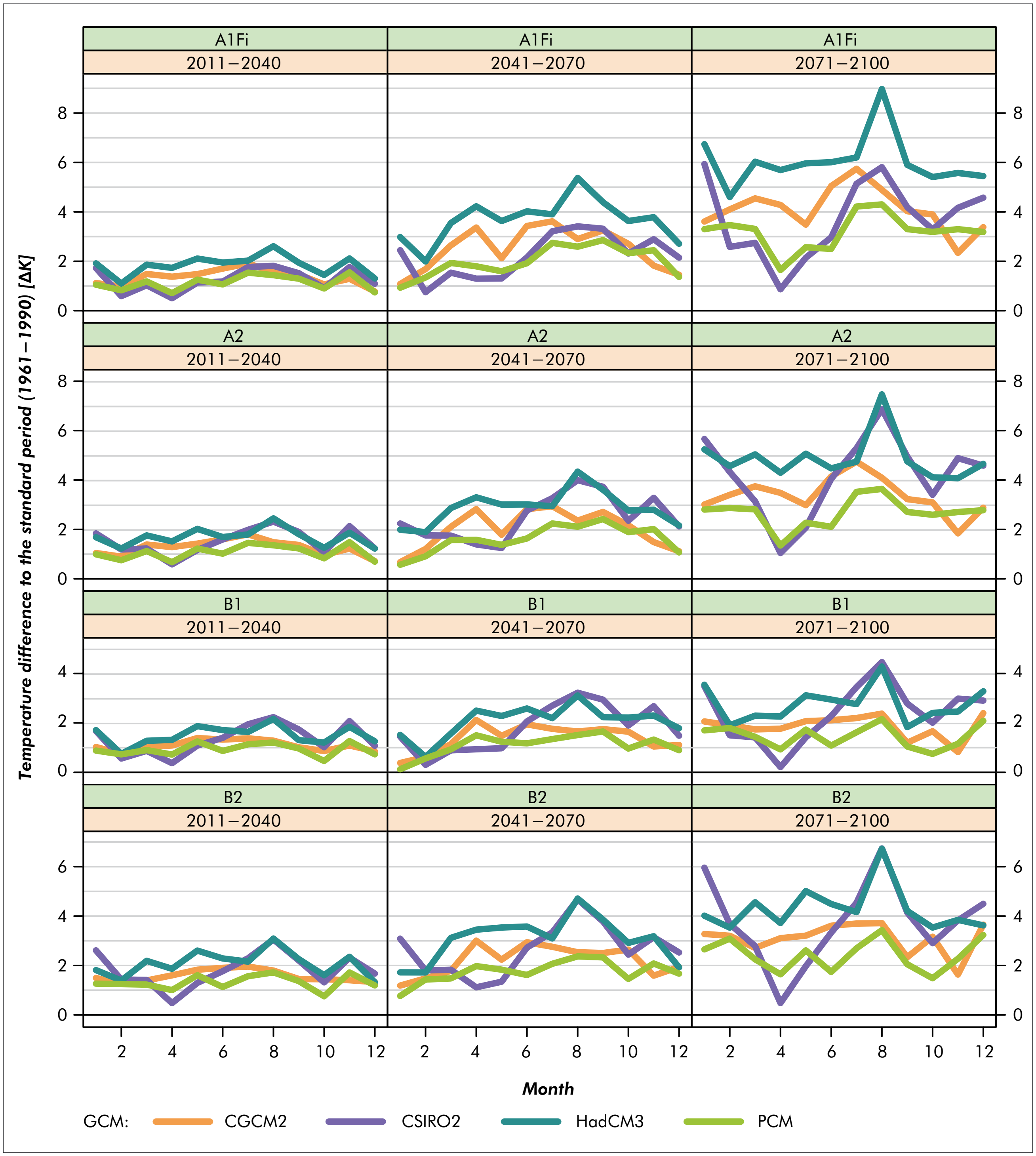

Fig. 4: Changes of annual cycles of temperature [ΔK] in the early (2011–2040), mid- (2041–2070) and late 21st century (2071–2100), based on four SRES emission scenarios (A1Fi, A2, B1, B2) and computed by four GCMs (CGCM2, CSIRO2, HadCM3, PCM), compared with the observed period 1961–1990 for the western part of Tyrol.

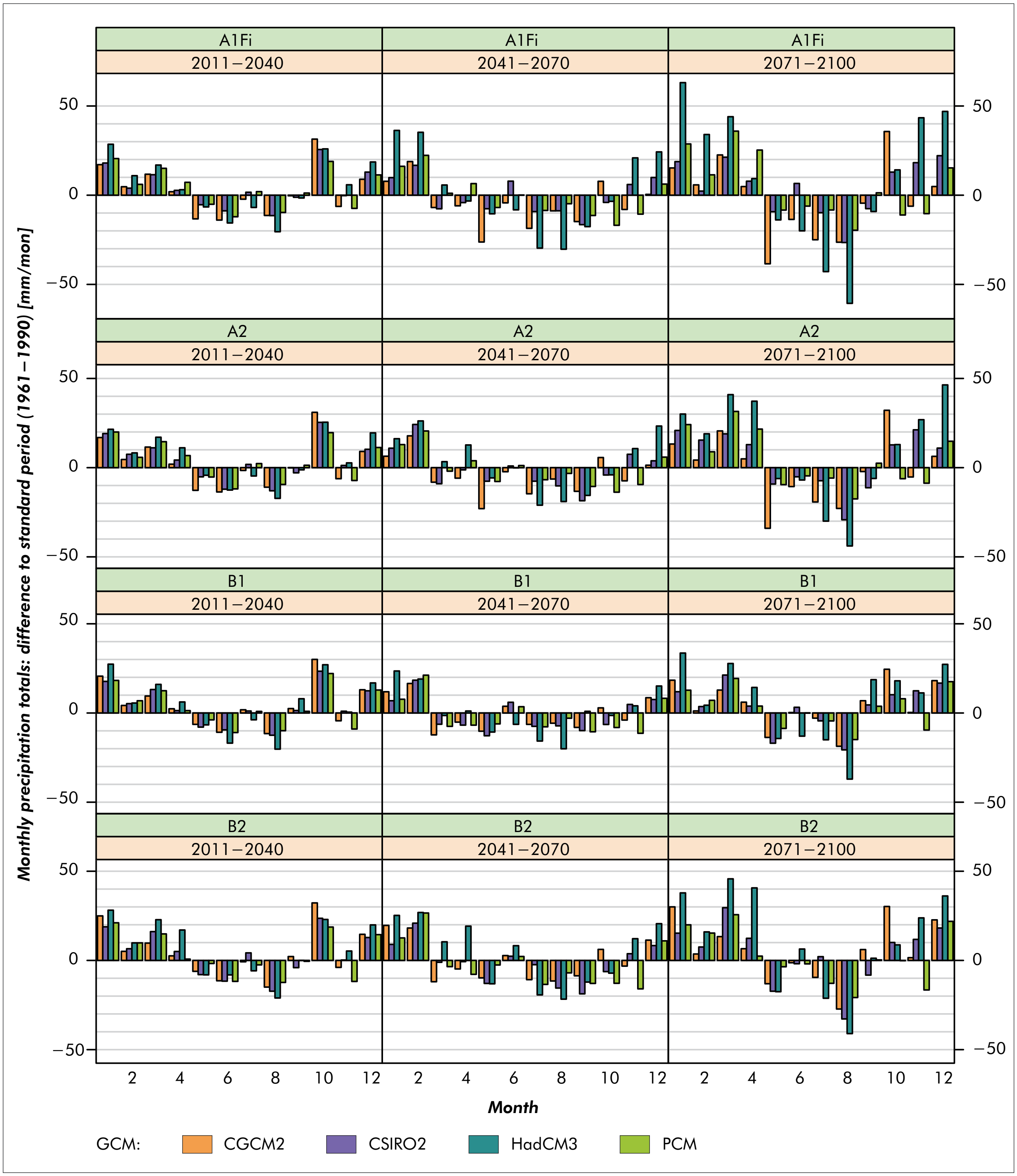

Fig. 5: Changes of annual cycles of precipitation in the early (2011–2040), mid- (2041–2070) and late 21st century (2071–2100), based on four SRES emission scenarios (A1Fi, A2, B1, B2) and computed by four GCMs (CGCM2, CSIRO2, HadCM3, PCM), compared with the observed period 1961–1990 for the western part of Tyrol.

Table 2: Changes in temperature, precipitation and snow line elevation in Tyrol for the early, mid- and late 21st century.

Variable			**Early 21st cent.**		**Mid-21st cent.**		**Late 21st cent.**	
			(2011–2040)		(2041–2070)		(2071–2100)	
			min	max	min	max	min	max
Temperature	year	°C	+1,5	+2,0	+2,1	+3,7	+2,8	+6,0
	winter	°C	+1,2	+1,5	+1,3	+2,6		
	end of winter	°C	+1,5	+2,0	+2,0	+3,9		
	summer	°C	+1,8	+2,5	+2,5	+4,5		
Precipitation	year	mm/a	+60	+80	+10	+50	+75	+135
	winter	mm/mon	+15	+20	+20	+30		
	summer	mm/mon	–10	–15	–10	–20		
Snow line	end of winter	m	+100	+150	+150	+250		

Winter = December–February, end of winter = March–April, summer = June–August. For further details see text.

October. In this period, monthly precipitation sums of –10 to –20 mm (–10 to –15%) are expected, whereas monthly precipitation in the shortened winter season will be +20 to +30 mm (+30 to +45%). Differences for the emission scenarios are much more distinct for both temperature and precipitation changes.

The magnitude of climate change in the late 21st century largely depends on greenhouse gas emissions during the 21st century. This becomes clear when you compare the changes of annual mean temperature of the four emission scenarios (Fig. 4, right column): values range from +2.8 K (B1) and +4.3K (B2) and +4.9 K (A2) up to +6.0 K (A1Fi). Still, the seasonal variation of temperature prevails as in the mid-21st century. Likewise, changes of annual precipitation are linked to emissions (Fig. 5, right column): +75 mm (B1), +135 mm (B2), +120 mm (A2), +110 mm (A1Fi). The annual cycle of changes in precipitation will persist but the contrasts deepen, depending on emission scenario: +20 to +50 mm (winter months), –20 to –40 mm (summer months). More definite interpretations of the late 21st century data do not seem feasible due to the uncertainty of the development in greenhouse gas emissions during the 21st century.

Summary

Downscaling of GCM-derived climate projections is necessary to obtain adequate regional-scale data for local impact studies. In this study, a pattern-scaling technique was applied to obtain projections of the local climate for Tyrol. Pattern-scaling enhances the GCM output with the spatial footprint of the observed data. Uncertainties resulting from future greenhouse gas emissions and GCM physics are tackled by the use of four different emission scenarios and four GCM integrations, which results in 16 climate projection scenarios.

Projections of the local climate for Tyrol show increases in temperature throughout the year with higher values in summer and lower increases in winter. In contrast, changes of yearly cycles of rainfall are more accentuated. Whereas precipitation in the winter season will increase considerably, summer rainfall will decrease. These trends are projected to prevail throughout the 21st century. However, the magnitude of the changes in temperature and precipitation largely depend on future greenhouse gas emissions.

Regional-scale climate projections as shown provide essential inputs for environmental and socio-economic studies. Methods and data presented here serve as inputs for an Austrian Academy of Sciences funded impact study on peak runoff in alpine catchments, which is currently conducted at the alpS – Centre for Climate

Change Adaptation Technologies, Innsbruck (Monreal & Veulliet 2010 in this volume) and the University of Innsbruck. Based on existing hydrological models (Achleitner et al. 2008), future peak runoff is derived from the pattern-scaled rainfall projections. Results are expected to serve as vital information for political decision makers as well as flood hazard experts, both responsible for the public safety.

Acknowledgements

This study was supported by the Austrian Academy of Sciences programme "International Strategy for Disaster Reduction (ISDR)". The author wishes to thank Matthias Monreal and Dieter Schäfer for providing high-quality photographs.

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Zeitschrift/Journal: Sonderbände Institut für Interdisziplinäre Gebirgsforschung (Institute of Mountain Research)

Jahr/Year: 2014

Band/Volume: 2

Autor(en)/Author(s): Georges Christian

Artikel/Article: Climate change - downscaling the global dimension to regions 31-39