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AN INTRODUCTION TO MOUNTAIN GLACIERS AS CLIMATE INDICATORS WITH SPATIAL AND TEMPORAL DIVERSITY

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With 10 figures and 2 tables

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Summary: This article gives an introduction to the spatial and temporal diversity of mountain glaciers as climate indicators. Alongside some information about the present extent of mountain glaciation and available databases, some specific problems with the interpretation of mountain glacier changes are highlighted.

Zusammenfassung: Der Artikel ist als Einführung in die räumliche und zeitliche Differenzierung bei der Anwendung von Hochgebirgsgletschern als Klimaindikatoren konzipiert. Zusammen mit einigen Informationen über die Fläche der globalen Gebirgsvergletscherung und verfügbaren Datensammlungen werden einige spezielle Probleme bei der Interpretation der Veränderungen an Hochgebirgsgletschern aufgezeigt.

Keywords: Mountain glaciers: climate indicators, climate change, diversity

1 Introduction

Mountain systems are among the key areas of global climate change (Dikau et al. 2002; Huber et al. 2005; UNEP/GRID-Arendal 2009). Due to their dynamic natural character, the geo-ecosystems of mountain systems are especially sensitive and vulnerable to climate change (Messerli and Ives 1997; Ives and Messerli 2001). The alpine cryosphere, as part of the geo-ecosystems in mountain systems, is no exception (Slaymaker and Kelly 2007). Furthermore, regional climate models predict that the change of certain climate elements, e.g. air temperature, will be accelerated within mountain systems compared to predicted global means (Frei 2004; CIPRA 2006; IPCC 2007). At the same time, those mountain systems and their forelands are the living space for a considerable part of the global population. Therefore, any climate change that influences the hydrological cycle and increases the potential for natural hazards needs to receive high attention. To develop strategies of sustainable development (e.g. to ensure water supply and agricultural productivity) or natural risk management, it is crucial to understand recent glacier changes and estimate future variations (Huber et al. 2005).

During the past decade, 'diversity' has become a major focus within the research of causes and consequences of global climate change in mountain systems (Stadelbauer 2008). At first, this 'diversity' was mainly restricted to 'biodiversity' and its threats. However, even if the trend has moved onwards to consider additional aspects of this 'diversity' in related studies (Mountain Agenda 1998), the alpine cryosphere (mountain glaciers and permafrost) is usually not or only sparsely included (Burga et al. 2004; Huber et al. 2005; ICIMOD 2009). The natural spatial and temporal 'diversity' of mountain glaciers in their response to climate change has not yet received sufficient attention outside the glaciological community, although an impressive collection of recent publications has demonstrated the present knowledge on glaciers including their individualism (e.g. Nesje and Dahl 2000; Oerlemans 2001; Bamber and Payne 2004; Knight 2006; IPCC 2007; WGMS 2008a). In some cases, statements about the impact of glacier changes in specific regions were made without an adequate regional database or by inappropriate use of generalisations. The latter includes the unverified transfer of glacier models developed for different mountains and the application of 'global trends' that were never intended as guidelines for regional studies. Though glaciers are indeed key indicators of global climate change (IPCC 2007), their response to climate changes do not follow ubiquitous and simple rules.

There are many prominent examples as to why one should have a sound scientific database for the actual use of glaciers as key climate indicators.

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Numerous publications have recently reported an 'alarmingly' rapid glacier melt in the Himalayas and their possible disappearance by the year 2035 (e.g. Cruz et al. 2007). Many impact studies have followed in the wake of these conclusions stating that water availability for the more than 1.3 billion people depending on the Himalayan 'water towers' is in threat (e.g., Kehrwald et al. 2008; Eriksson et al. 2009; Kumar and Venkataraman 2009). However, taking a closer look at the available data, one finds that the Himalayas are among the regions that have comparably few glacier observations available and a lack of standardized long-term data series (cf. WGMS 2008a). The proposed rapid disappearance was the result of a serious misreading and serious methodological inadequacies (see Cogley et al. 2010). It could easily have been rejected using existing knowledge on present equilibrium line altitudes and elevation ranges of the corresponding mountain summits (cf. e.g., Owen and Benn 2005; Kayastha and Harrison 2008). Furthermore, the alleged importance of Himalayan glaciers for large-scale water availability has recently been questioned (Kaser and Grosshauser 2010). This most recent example verifies the effort made to increase our existing knowledge on glaciers and improve the related database.

This introductory paper is a supplement to the four detailed case studies collected in this issue (Huss et al.; Dykes et al.; Baumann and Winkler; Winkler et al. – all this volume). It should help to assess and classify their results. Our primary aim is to present a selection of the established knowledge of the diversity of glacier variations and indicate potential problems associated with the interpretation of glacier change data. Although we are aware that especially non-glaciologists and policymakers are in need of such interpretations, it is certainly an unachievable task to produce an overall review of the 'diversity' of mountain glaciers with this special issue. As the scientific field of investigating mountain glaciers as climate indicators is quite broad, we have decided to restrict our choice of cited examples mainly to those mid-latitude mountain systems with comparable good data available that are represented in this special issue.

Finally, note that in this study the term 'mountain glacier' is used in a descriptive and comprehensive way and synonymous with 'high mountain glaciers' or 'glaciers of mountain systems' (see Fig. 1). In conventional morphological classifications, like the one in use by the international glacier monitoring organisations (cf. UNESCO 1970; Rau et al. 2005) the term 'mountain glacier' includes small glaciers, e.g., cirque glaciers, niche glaciers, and hanging glaciers, but does not include the larger valley glaciers or outlet glaciers of mountain ice caps included in this work.

2 Global distribution of mountain glaciers and available datasets

2.1 Glaciers as climate indicators – different types of data

Any climate change or, strictly speaking, any variation of individual climatic elements, e.g., precipitation and air temperature, displays its impact at first in form of related changes of the glacier mass. If a glacier is simplified to an abstract budget-system (see Fig. 2), the relationship of input (accumulation, mass gain) and output (ablation, mass loss) in its response to the climate becomes obvious. This glacier mass input-output or glacier mass balance (or budget) is determined by the amount of accumulation (winter snow accumulation, summer snow accumulation, superimposed ice formation, positive contribution of snow/ice avalanches etc.) less the losses by ablation (ice/snow melt, calving, negative contribution of snow drift/avalanches etc.) over a given time interval, i.e., in most cases a single budget year (cf. descriptions of the principle of mass balance, e.g. Meier 1962; Østrem et al. 1988; Østrem and Brugman 1991; Liestøl 2000; Oerlemans 2001; Braithwaite 2002; Bamber and Payne 2004; Böhm et al. 2007; WGMS 2008a; Winkler 2009). The annual mass balance very sensitively summarises the health of a glacier over one budget year (which is displaced from the calendar year, being from the beginning of winter to the end of summer). Seasonal mass balance variability is often measured in temperate alpine glaciers in the Northern Hemisphere, which are mainly driven by accumulation and ablation during winter and summer seasons, respectively (Kuhn et al. 1999). However, this concept is not valid for low-latitude tropical glaciers where ablation occurs throughout the year and multiple accumulation seasons exist (Jordan 1979; Kaser 2001; Kaser and Osmaston 2002), for monsoonal glaciers of the Himalaya where the accumulation and ablation seasons occur at about the same time (Ageta and Fujita 1996), and for high-altitude and polar glaciers where any season can be the accumulation season (Chinn 1985).

Even if non-climatic factors such as glacier hypsography influence glacier mass balances, i.e., mass balance data of one individual glacier cannot

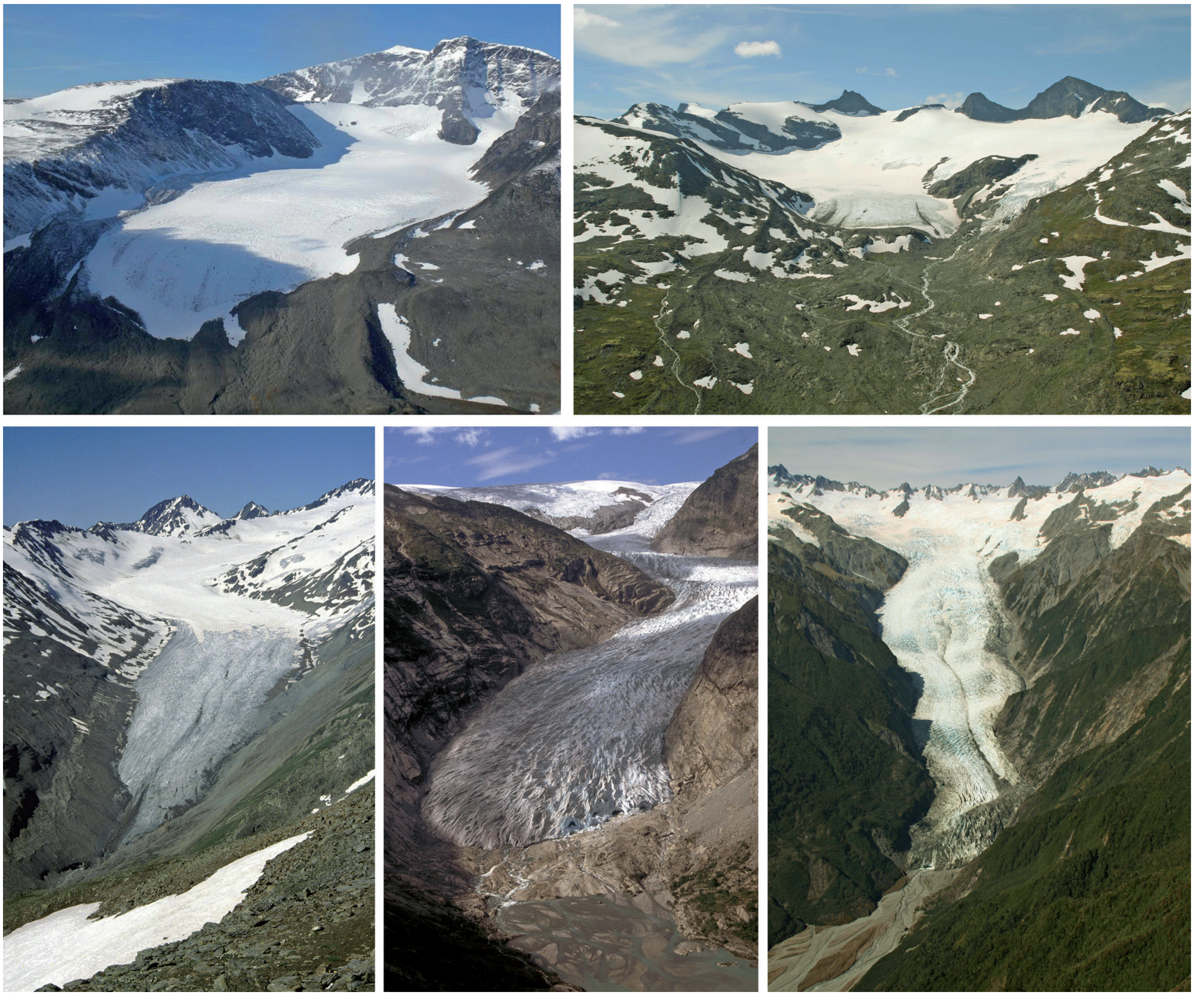

Fig. 1: Examples of mountain glaciers, showing their different size and morphology: Upper left: Storglaciären, Kebnekaise Mts., North Sweden (world's longest annual mass balance series since 1945/46; photo: T. Koblet 09.09.2008); upper right: Storbreen, Jotunheimen, Norway (photo: S. Winkler 26.07.2008); bottom left: Hintereisferner, Ötztal Alps, Austria (photo: S. Winkler 11.07.1994); bottom middle: Nigardsbreen, Jostedalen, West Norway (Photo: S. Winkler 24.08.2004); bottom right: Franz Josef Glacier, Southern Alps, New Zealand (Photo: S. Winkler 27.03.2007)

be labelled as purely representative of the climate, mass balance data will nonetheless deliver a more accurate climate signal compared to delayed and distorted length change information. It is, however, important to consider the actual methods used to collect this mass balance data. With the glaciological (direct, traditional) method, the mass balance is directly measured in the field on the glacier surface using ablation stakes, snow pits and snow probings (see Østrem and Stanley 1969; Østrem and Brugman 1991; Kaser et al. 2003 for technical details). Although time consuming, manpower-intensive, logistically demanding, and therefore only practicable for a limited number of glaciers, these direct mass balance measurements are irreplaceable for the understanding of climate impacts on glaciers as they provide direct, undistorted seasonal data. Another method of recording the changes of glacier volume is by geodetic mass balance measurements (e.g., Andreassen 1999). By terrestrial photogrammetric mapping or application of remote sensing techniques, the change in glacier geometry is calculated for longer time periods (usually > 10 years) and the related change in ice volume is deduced from these data. The accuracy of this method is closely connected to the quality of the (aerial) photographs and/or resolution of the satellite images, respectively. Glaciological (traditional, direct) mass balance measurements should be compared with the geodetic (volumetric) mass balance measurements in order to optimise the measurement design (e.g., number and distribution of stakes)

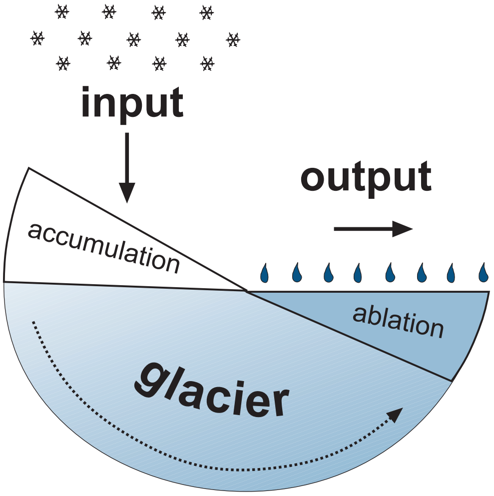

Fig. 2: Glaciers as input-output systems (modified after Winkler 2009)

and check their accuracy over longer time-periods (Krimmel 1999; Østrem and Haakensen 1999; Thibert et al. 2008; Huss et al. 2009; Zemp et al. 2010). However, even if the influence of systematic errors cannot be eliminated with the application of direct methods for mass balance measurements, the annual and seasonal resolution achieved is their greatest potential especially with the investigation of climate forcing (Dyurgerov and Meier 1999). Therefore, glaciological (in-situ) and volumetric mass balance measurements need to be recognized as having complementary character. Abermann et al. (2009) have clearly demonstrated the potential of high resolution LIDAR (light detection and ranging) DEMs (digital elevation models) as reliable methods to obtain changes in glacier area and volume in comparison with older glacier inventories for the Ötztal Alps (cf. similar studies using remote sensing approaches, e.g., Paul and Svoboda 2009; Svoboda and Paul 2009; Bolch et al. 2010). The expected developments in remote sensing techniques will further improve the application of volumetric mass balance studies in the future. They cannot replace traditional mass balance measurements, but high resolution seasonal and annual direct mass balance measurement records could be much better calibrated and assessed for their overall mass change, as seasonal volumetric mass balance measurements are yet another major methodological challenge. Additionally, the combined use of direct and remote sensing methods might help to judge the spatial and temporal representativeness of existing long-term measurement series in different mountain systems.

Changes in glacier length are driven by the changes of the glacier mass balance and modified by the related mass flux/glacier flow. In theory, each glacier tongue responds dynamically with a specific frontal time lag ('terminus reaction time') to any deviation from a steady-state mass flux (Oerlemans 2001; Hooke 2005). Therefore, glacier length changes should be treated as indirect, delayed and filtered signals (Haeberli and Hoelzle 1995). Under real conditions, a large number of factors might influence the response of the glacier terminus as well as the individual time lag/terminus reaction time. One might assume that glacier length changes are poor quality glacier data that should be avoided. However, length change data is simple to obtain and therefore the amount of information far exceeds that of mass balance data (see below). For some goals, e.g., risk assessment connected to potential GLOFs (glacier lake outburst floods), length change data is highly necessary. Length change measurements are much easier to perform than mass balance measurements, and they have been compiled much longer (see chapter 2.3). Additionally, length change data can be derived from historical documents as well as from mapping and dating of glacial geomorphological features like moraines in order to reconstruct the glacier chronology. Therefore, glacier length change data provide valuable information on climate impacts on glaciers.

2.2 International glacier monitoring – challenges and the status quo

As already pointed out, fluctuations of glaciers, especially those not influenced by thick debris covers, calving, surge instabilities, or other special conditions potentially veiling the climate signal (see chapter 3), are recognised as key indicators to climate forcing (Haeberli et al. 2007). Thus, they build one of the 'Essential Climate Variables' (ECV) within global climate-related monitoring programmes (GCOS 2004; WGMS 2008a). However, regional climate regimes and non-climatic factors influence glacier response changes and may lead to strongly diverse reactions between adjacent individual glaciers, even within the same catchment (Kuhn et al. 1985) or among the outlets of the same plateau ice cap (Winkler et al. 1997, 2009). Therefore, the systematic monitoring of glaciers on a global scale and the comprehensive compilation of glacier data is essential in order to build a substantial basis for the scientific community, as well as for policymakers and the general public.

Systematic worldwide collection of standardized data on glacier changes was initiated in 1894 with the foundation of the *Commission Internationale des Glaciers* in Zurich, Switzerland. Today, the World Glacier Monitoring Service (WGMS) continues the collection of standardised information on distribution and changes in glaciers, together with its cooperation partners (Haeberli 2004; Haeberli et al. 2007; WGMS 2008a). These are the US National Snow and Ice Data Center (NSIDC), and the Global Land Ice Measurements from Space (GLIMS) initiative (Haeberli et al. 2000; Braithwaite 2002; Kargel et al. 2005; Barry 2006; Raup et al. 2007). Recently, these three bodies strengthened their cooperation under the umbrella of the 'Global Terrestrial Network – Glaciers' (GTN-G). The GTN-G aims at providing quantitative and comprehensive information relevant to questions about ongoing processes, change detection, model validation and environmental impacts in an interdisciplinary context. The following datasets are available:

- Fluctuations of glaciers (e.g., changes in glacier length, area, mass and volume)
- World Glacier Inventory (details with up to 30 parameters for each glacier; e.g., glacier coordinates, location, area, morphological type)
- GLIMS inventory (e.g., glacier outlines, area, length, and elevation)
- Glacier Special Events (e.g., surges, GLOFs, ice avalanches)
- Glacier Maps
- Glacier Photo Collections

All data can be queried and ordered using a map search interface on the GTN-G website (http://www.gtng.org). In addition to the scientific data service, the GTN-G serves as an official contact for policy-makers, the media and the public. In order to link scientific process studies on the one hand with global coverage by satellite imagery and digital terrain information on the other hand, GTN-G provides observations at different levels. Firstly, extensive glacier mass balance and flow studies are conducted within major climatic zones in order to improve process understanding and calibration of numerical models. Secondly, glacier mass balances are determined using cost-saving methodologies within major mountain systems in order to assess the regional variability. Thirdly, long-term observations of glacier length change data and remotely sensed volume changes for large glacier samples are conducted within major mountain ranges for assessing the representativeness of *in-situ* measurements. Fourthly, glacier inventories are repeated at time intervals of a few decades by using remotely sensed data. This multi-level monitoring strategy across environmental gradients provides the basic datasets required for integrative studies and assessments of the distribution and changes of glaciers by combining *in situ*, remote sensing, and numerical modelling components.

2.3 Available datasets

From the given inventories, detailed information of about 100,000 glaciers and digital outlines of about 83,000 glaciers is available. The database on glacier fluctuations includes 36,240 length change observations from 1,803 glaciers as far back as the late 19th century AD, as well as about 3,400 annual mass balance measurements from 226 glaciers covering the past six decades (WGMS 2008a; Zemp et al. 2009). An extended overview of data on glacier changes in eleven glacierised macro regions (see Fig. 3) is given in WGMS (2008a). The macro regions were selected based on the amount of ice cover as well as on geographical characteristics described in Dyurgerov and Meier (2005). Most of these regions are characterised by mountain ranges, such as the Southern Alps in New Zealand or the Himalayas in Central Asia.

Regarding mass balance data, which represent the direct and un-delayed signal of a glacier reacting to atmospheric conditions (Haeberli and Hoelzle 1995, Haeberli et al. 2007; WGMS 2008a), about 90% of the available series come from the northern hemisphere, and 40% of this from Europe (see Fig. 4). An overview of available mass balance series and their attribution to the macro regions is given in table 1. The longest, continuous glacier mass balance series is the one from Storglaciären (Northern Sweden), starting in 1945 (Holmlund and Jansson 2005). Most of the (few) longer data series are located in the European Alps, Scandinavia, North America and High Mountain Central Asia. In the Canadian Arctic Archipelago as well as in High Mountain Central Asia, more than two-thirds of the series were discontinued by the end of the last century. Measurements in Northern Asia and Siberia, South America and of the individual glaciers surrounding the ice sheets in Greenland and Antarctica are seriously underrepresented within the network, especially in respect to the extent of the ice-covered areas in these regions (Zemp et al. 2009).

About 85% of all length change data (front variations) are measured on the northern hemisphere, with 42% from the 'Central Europe' macro region (comprising European Alps, Pyrenees, Caucasus; see Fig. 5). At the global scale, the average measurement

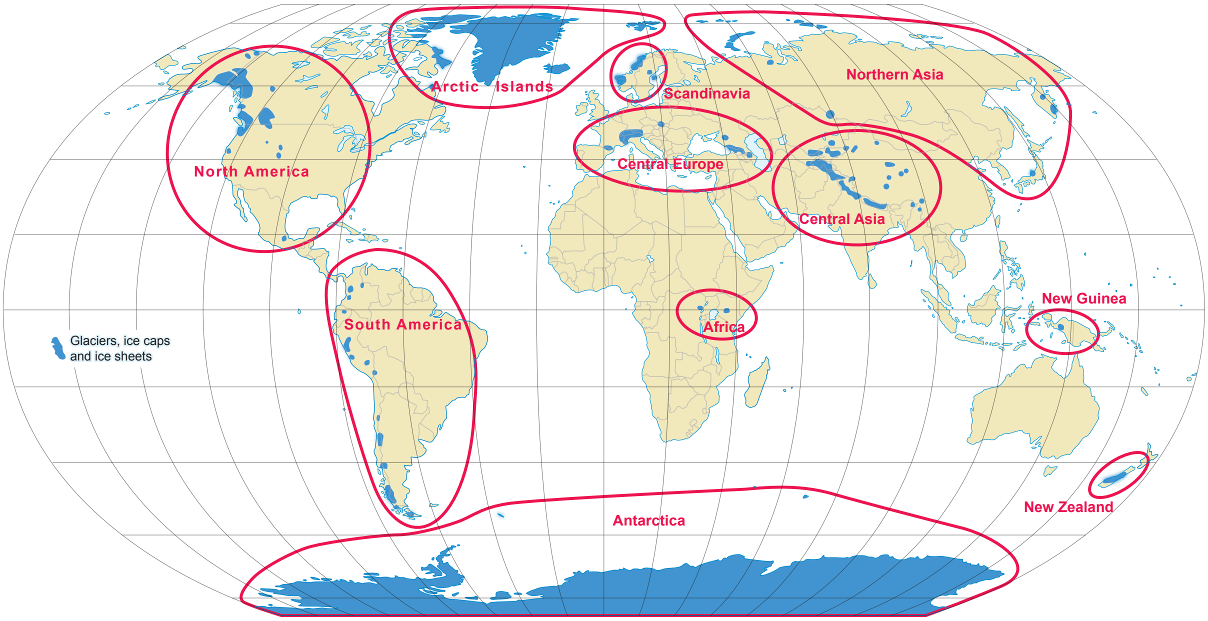

Fig. 3: The selected eleven glacierised macro regions (taken from WGMS 2008a)

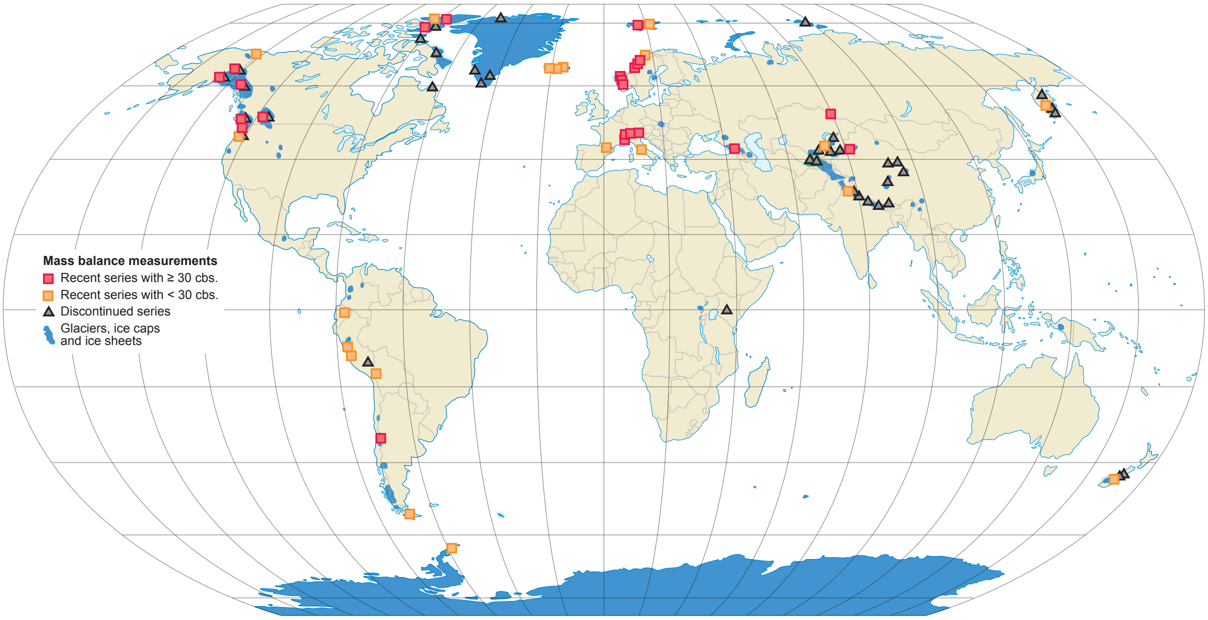

Fig. 4: Global distribution of mass balance measurements (taken from WGMS 2008a)

series covers a time range of 47 years with 20 observations (WGMS 2008a). The highest observation densities of spatial resolution are found in Central Europe (200 series per 1,000 km^2), followed by New Zealand (85 series per 1,000 km^2), Scandinavia (23 series per 1,000 km^2), and South America (three series per 1,000 km^2). However, one has to keep in mind that some measurements only have a qualitative character, i.e., they only indicate 'advance', 'retreat', or 'stationary position' (for example most of the series in the Southern Alps of New Zealand – WGMS 2008b). Earliest direct length change measurements started in the mid 19th century (e.g., Kleines Fleisskees, Austria). Some series have been extended by measuring distances to dated moraines that formed during the 'Little Ice Age', the period between the Middle

Tab. 1: Global and regional overview of the available length change (Tab. 1a) and mass balance observations (Tab. 1b). The data giving the status for 2005 exclude ice sheets and ice shelves, but include glaciers and ice caps around the ice sheets in Greenland and Antarctica (modified from WGMS 2008a)

a)

Macroregion (1)	Area (km^2)	Number of series	Number of series 21st (2)	First reference year	First survey year	Last survey year (3)	Average time range (4)	Average number obs. (4)	Series density (5)
New Guinea	3	3	0	1936	1941	1990	46.3	4.7	1000.0
Africa	6	14	11	1893	1899	2004	71.4	6.1	2333.3
New Zealand	1160	99	70	1879	1892	2005	14.4	6.2	85.3
Scandinavia	2940	67	45	1896	1899	2005	53.2	30.2	22.8
Central Europe	3785	764	417	1730	1815	2005	65.1	35.3	201.8
South America	25500	160	49	1830	1888	2005	36.4	4.1	6.3
Northern Asia	59600	24	11	1833	1895	2005	55.2	14.1	0.4
Antarctica	77000	48	7	1882	1883	2005	30.4	2.8	0.6
Central Asia	114800	310	16	1850	1893	2005	21.5	4.5	2.7
North America	124000	221	15	1720	1885	2005	36.9	5.2	1.8
Arctic	275500	93	49	1840	1886	2005	52.4	30.5	0.3
World	684294	1803	690	1720	1815	2005	46.7	20.1	2.6

b)

Macroregion	Area (km^2)	Number of series	Number of reference series (6)	Number of series 21st	First survey year	Last survey year	Average number observ.	Series density (5)
New Guinea	3	0	0	0				0.0
Africa	6	1	0	0	1979	1996	18.0	166.7
New Zealand	1160	3	0	1	1959	2005	2.7	2.6
Scandinavia	2940	39	8	23	1946	2005	16.3	13.3
Central Europe	3785	43	10	29	1948	2005	19.6	11.4
South America	25500	11	1	9	1976	2005	8.1	0.4
Northern Asia	59600	14	3	5	1962	2005	13.5	0.2
Antarctica	77000	1	0	1	2002	2005	4.0	0.0
Central Asia	114800	35	2	6	1957	2005	13.1	0.3
North America	124000	45	4	24	1953	2005	15.8	0.4
Arctic	275500	34	2	20	1960	2005	12.6	0.1
World	684294	226	30	118	1946	2005	15.0	0.3

(1) - Macro regions according to Dyurgerov and Meier (2005), see figure 3
(2) - Number of series continuing in 21st century, i.e. with last survey after 1999
(3) - Last survey year included in this overview, the surveys have continued since
(4) - Average time range and average number of observations per series, respectively
(5) - Series density: number of series per 1000 km^2
(6) - Number of 'reference' mass balance series with continuous measurements since 1976

Ages and the warming of the first half of the 20th century (Holzhauser and Zumbühl 1999; Grove 2004; Matthews and Briffa 2005; Nesje et al. 2008a). Concerning the length of the records, again Central Europe has the best coverage with an average time range of 65 years and a mean of 35 observations per series. Second is Scandinavia with 53 years and 30 observations. In South America, the average time range is 36 years with only 4 observations per series. Again, some macro regions or mountain systems, respectively, are highly underrepresented in the glacier-monitoring network.

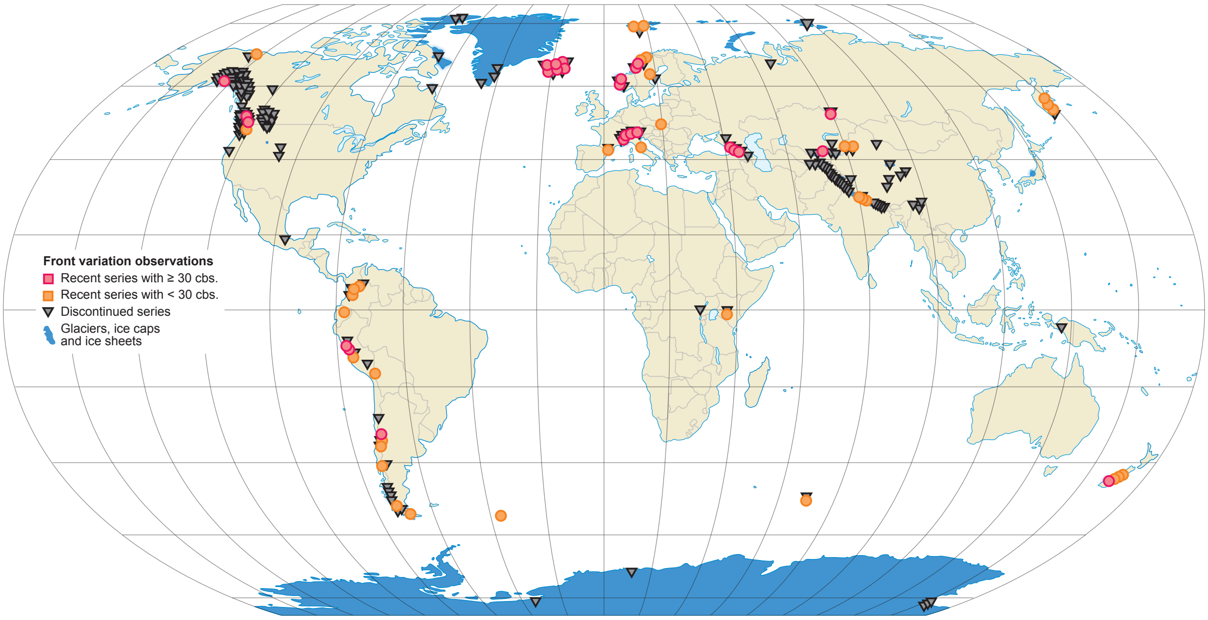

Fig. 5: Global distribution of length change observations (taken from WGMS 2008a)

2.4 Future tasks

In view of the incompleteness of inventory data in certain mountain regions (e.g., Andes, Himalayas) as well as the imbalance towards the northern hemisphere and Europe in particular, future monitoring of glaciers all over the world needs to consider the following strategy (cf. WGMS 2008a; Owen et al. 2009; Paul et al. 2009):

- Continuation of long-term fluctuation series (i.e., both length and mass balance changes) in combination with decadal determination of thickness/volume and length changes from geodetic methods in order to verify the annual field observations and hence, improve the understanding of ongoing process and response times.
- Re-initiation of interrupted long-term data series in strategically important regions.
- Expansion of the current monitoring network in those regions which are sparsely investigated (e.g., South America, North- and Central Asia).
- Compilation of a global inventory of glaciers.
- Repeated inventorying of defined key regions, where the glaciers are relevant to climate change and related impacts (i.e., sea level rise, hydrological changes, and natural hazards) and serve as sensitive indicators.

This strategy aims at addressing the discrepancy between the relevance of glacier data in the scientific argumentation of climate change impacts and the shortcomings of available datasets (Zemp et al. 2009). In order to reach these ambitious goals, newly developed technologies (e.g., remote sensing), resulting datasets (e.g., global digital elevation models) as well as numerical modelling approaches have to be applied systematically.

3 Mountain glaciers as climate indicators

3.1 Problems and restrictions

Can any mountain glacier be regarded as 'representative' for a whole mountain system? If not, how many glaciers are necessary to outline a significant trend for a whole mountain system? How can a 'key glacier' for the glacier chronology of a whole region be confidently chosen? Although important questions, they cannot be easily answered. It is quite obvious that any one individual glacier is very unlikely to act as 'representative' example for a whole mountain system (cf. Fountain et al. 2009). Furthermore, there are no general guidelines for judging the relative 'representativeness' of any individual glacier or sample of glaciers *a priori*, they have to be tested according to the aims of the related study. Even the 30 'reference' glaciers within the WGMS data base (Zemp et al. 2009) are not claimed to be 'representative' for their regions. However, some potential problems emerging with the study of glaciers as climate indicators can effectively be reduced by avoiding the study of some types of glaciers: surging glaciers, calving glaciers, and debris-covered glaciers (WGMS 2008a).

The detailed causes for glacier surges and their relation to the climate still remain unclear, in particular their typical periodicity. Although a disturbance of the mass transfer at predominately polythermal glaciers (ice velocity < balance velocity during quiescent phases) is frequently considered as the hypothesis for the occurrence of surges, the existing regional patterns of glacier surges cannot clearly be related to any climate trends (Lefauconnier and Hagen 1991). A recent decrease of advance distances within a surge phase attributed to climate change remains highly speculative (Hewitt 2005, 2007). Calving of glacier fronts into lakes or the ocean is a glacio-dynamical process not directly related to climate forcing. Warren and Kirkbride (2003) classified tidewater glaciers as being the least climate sensitive glaciers with lake-calving glaciers occupying an intermediate position between tidewater and the most sensitive non-calving glaciers. The formation of a proglacial lake is an important 'tipping point' in the process of glacier recession during a warming climate. Lake growth commences as soon as the terminus ice level drops below the meltwater stream outlet level, as shown at some recently calving glaciers in New Zealand (Warren and Kirkbride 2003; Chinn et al. 2005, 2008; Dykes et al. this volume). In addition to their inherent long response times, these large valley glaciers have also had a heavy debris mantle over their lower trunks that has caused the recession of these glaciers to lag behind the recession of the adjacent small clean glaciers by many decades. Because their debris-covered ice lies in deep valleys, these glaciers have "shrunk" by surface lowering rather than shortening, which can only commence once the proglacial lake growth commences (Nakawo et al. 2000). Once the glacier front commences calving into the lake, the glacier enters a catastrophic period of rapid retreat which is generally divorced from the climate (Warren and Kirkbride 2003) and is irreversible under the present climate regime. Even if debris-covered and/or lake-calving glaciers are regarded as poor climate indicators (WGMS 2008a), their common occurrence in some mountain systems (Karakoram, Himalaya, New Zealand) requires that they be considered with the investigation of glacier behaviours/chronologies. They might even be considered 'representative' to a certain degree in some locations, but one must in any case be aware of their limitations in comparative studies or regional correlations.

For many practical as well as theoretical studies of glaciers as climate indicators, modelling future glacier change is essential. The last two decades have seen a great step forward in this field of research. Today, a broad spectrum of different attempts of modelling covers parameterisation schemes (Hoelzle et al. 2007; Baumann and Winkler this volume) and simple degree-day models (e.g. Laumann and Reeh 1993; Braithwaite and Zhang 1999; Engeset et al. 2000), as well as energy-balance models (Kuhn et al. 1999; Oerlemans 2001, 2008) and even more sophisticated dynamic models (see summary in Marshall 2006). The most obvious limits of all models are the availability and quality of the necessary glaciological and meteorological input data. Simple models might not reflect the mass balance of a glacier in all details, but could be the best choice if the few data needed are available in good quality. More detailed models might represent the real mass balance of a glacier much better, but if several key data need to be estimated or if the available data are not really reliable, the model output might have a high degree of uncertainty. Modelling glacier length changes is a more difficult challenge than modelling the mass balance of a mountain glacier.

3.2 Spatial and temporal diversity

An obvious dilemma that needs to be solved is that, in theory and totally independent of the methodological approach, each single glacier should be treated as individual. This would, however, severely restrict its potential as a climate indicator on a local scale, impractical for most related studies. Generalisation seems necessary in this context. But as already mentioned, simple 'general' rules or 'global' trends are not an appropriate way either. A promising solution seems, therefore, to acknowledge the existing patterns of diversity of glacier changes. If the causes for distinct patterns of individual glacier changes (the 'diversity') on a regional scale are known, this knowledge could be used to detect the related climate forcing with greater reliability. With the concept of differentiation on regional and sub-regional levels, i.e., separating and classifying glaciers according to their maritime/continental climate conditions, size, hypsography (area-altitude distribution), percentage of supraglacial debris cover, or occurrence of proglacial lakes, the disadvantages of generalisation might effectively be reduced while the impracticability of individualistic approaches is avoided.

The diversity of glacier changes exists at different temporal and spatial scales. For example, both accumulation and ablation on a glacier surface during one budget year show specific spatial patterns, allowing the division into accumulation and ablation areas, respectively. Their extent normally varies from budget year to budget year as well as the equilibrium line altitude separating the accumulation area from the ablation area. These annual variations can be regarded as a form of temporal diversity. Changes of the net mass balance and length changes over consecutive years or decades often show a distinct regional pattern of spatial diversity, sometimes variable through time. It is this form of diversity alongside of regional patterns of glaciological characteristics that is highlighted here.

Glacier reaction to climate changes consists, in theory, of two different components: A regional climatic and a local topographic one. The regional climatic part, as it is mainly reflected in the mass balance gradient (Kuhn 1990), will create a spatial pattern of glacier variations according to the specific regional climate conditions. This kind of spatial diversity represents the original climate change and is relatively easy to interpret. The hypsography, i.e., the local or individual topographic part of glacier sensitivity, can, and does, lead to different responses of even adjacent individual glaciers within one region to an identical climate impact. It requires, therefore, a more detailed look into the glaciological conditions on a regional or even local scale. One major problem with individual glacier studies, as well as with investigations of any spatial differentiation, is the important question as to which one of these two components dominates when considering the interpretation of the glacier data. Furthermore, those two theoretical components of course interact in nature. They are, therefore, far away from being easily separated, especially if the different hypsographic characteristics exhibit a spatial diversity similar to those of the regional climate conditions and current trends. Additionally, the pattern of spatial diversity may not be consistent with time but subject to temporal or permanent changes, as some recent developments indicate (Winkler 2009; Winkler and Nesje 2009). As a consequence, any spatial differentiation applied to glacier change data should not be considered as *per se* independent from a potential additional temporal differentiation.

3.3 Examples of spatial and temporal diversity

3.3.1 Southern Norway

Among the best example for studying spatial patterns of glacier changes is given in southern Norway, where a long-term mass balance series that represents an E-W-profile and a strong continental-maritime climate gradient is available (Østrem et al. 1988; Andreassen et al. 2005). Typical characteristics of mass balance parameters, e.g., mass turnover or mean and extreme values of winter, summer, and net balances, follow this gradient in a set of clear trend surfaces sloping from maritime west to the continental east. (cf. Winkler and Nesje 2009; Baumann and Winkler this volume). The unambiguous and clear relation of this spatial differentiation to the impact of the general climate conditions on the mass balance is associated with the concept of relative importance of different climate forcing, e.g., the impact of variations of winter precipitation in relation to those of summer temperatures (see, e.g., Winkler 2009 for detailed description). For southern Norway, the influence of this spatial differentiation has already been demonstrated in a number of studies (e.g., Andreassen et al. 2005; Chinn et al. 2005; Nesje et al. 2008a). Most noticeable was the situation during the 1990s when the maritime glaciers experienced a large mass gain due to increased winter precipitation. Although winter precipitation increased simultaneously at the more continental glaciers and winter balances were above average in a number of years, no comparable mass gain was recorded at those glaciers, mainly because the increase in winter balance was in most years not large enough to compensate for the (slightly reduced) summer balance (Winkler and Nesje 2009; see Fig. 6). The spatial pattern of glacier change was not primarily related to different regional climate trends as the proportion of precipitation increase was identical along the entire profile and summer air temperatures were slightly above-average in whole southern Norway. Instead, it was to some extent a different response of glaciers depending on their specific sensitivity to changes of certain climate elements. This has also been demonstrated theoretically, e.g., by Laumann and Reeh (1993). Any spatial diversity like this one must therefore not be automatically interpreted as indication of different regionally climate trends.

3.3.2 Ötztal Alps (Austrian Alps)

Regular patterns of spatial diversity within one mountain system or between mountain ranges primarily caused by climatic conditions are relatively easy to detect and, therefore, of great value for the use of glaciers as climate indicators. By contrast, spatial differentiation on sub-regional (local) scales often encounters serious difficulties with interpretation. The main reason is the involvement of local glaciological factors such as irregular glacier hypsography. One famous example of different glacier

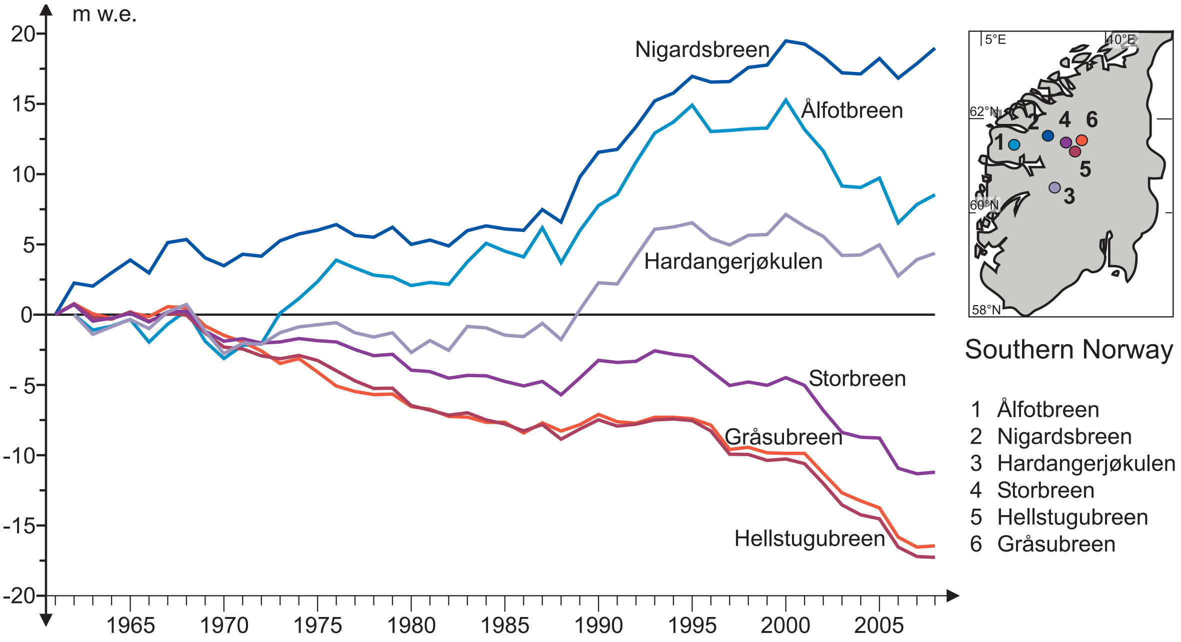

Fig. 6: Net mass balances (cumulative data) of six selected glaciers in southern Norway (data: NVE [Norges Vassdrags- og Energidirektoratet]; modified after Winkler and Nesje 2009)

behaviour within one catchment is described by Kuhn et al. (1985) from the Rofental in the Ötztal Alps. The different response to a short period of increased summer snowfall events in the 1970s and 1980s of two neighbouring glaciers (Hintereis- and Kesselwandferner) was a result of the different area-altitude distribution of those glaciers. Due to the concentration of its area at a comparably high altitude, Kesselwandferner benefited the most from this climate trend and showed a positive net mass balance, whereas the more-or-less evenly distributed Hintereisferner experienced no corresponding mass surplus (see Fig. 7). Other examples of different glacier response caused by the hypsography and size of individual glaciers might easily be found (e.g., the outlets of Jostedalsbreen in southern Norway, Winkler 1996a, b). With local knowledge and sufficient information, this type of basically "topographically determined diversity" might be considered and included in the interpretation. Without such information, however, misjudgements are sometimes difficult to avoid. Therefore, it is essential not only to order available glacier data from the accessible data basis, but also to obtain appropriate supplementary local/regional information. The lack of appropriate information enabling differentiation on a sub-regional level represents a prominent uncertainty, if individual glaciers are entitled 'key sites' or seen as 'typical' examples for a whole region.

3.3.3 Southern Alps (New Zealand)

Sometimes the plethora of different responses of glaciers to the same climate fluctuations is exacerbated by simple and erroneous comparison of two entirely different glacial systems. For example, the Southern Alps of New Zealand have a spectacularly steep west-east precipitation gradient expressed in a steeply tilted glacier equilibrium line altitude (ELA) trend surface. Yet despite this climatic differentiation, the annual mass balances of the glaciers on either side of the Alps have, rather surprisingly, had positive and negative balances in unison, indicating that the climate of the entire Southern Alps behaves as a single climatic unit (Clare et al. 2002; Chinn et al. 2005, 2008). This does not mean that the precipitation is the same everywhere, nor even a change in precipitation is distributed evenly; rather it means that the annual mass balance changes that affect the glaciers are similar throughout the Southern Alps. The long-term net balance monitoring by late summer snowline survey (Chinn 1995; Clare et al. 2002; Chinn et al. 2008) has revealed that annual and multi-annual trends are persistently uniform throughout the Southern Alps, especially if the most prominent and largest glaciers immediate west and east of the Main Divide in the vicinity of Mt Cook/Aoraki are compared. The net balance trend of Tasman Glacier during the past few decades was quite similar to. e.g..

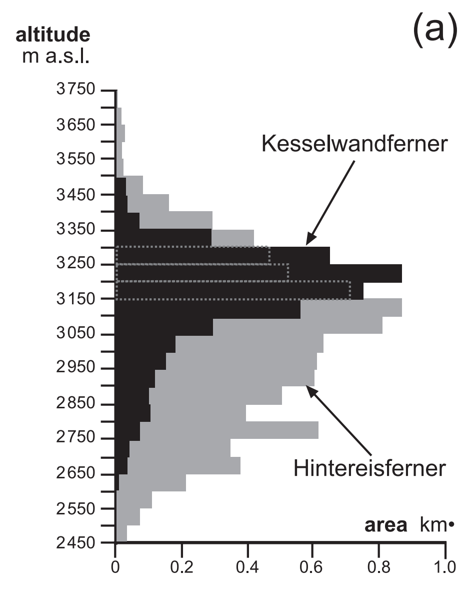

Fig. 7a: Area-altitude distribution (around 1985) of the neighbouring glaciers Hintereis- and Kesselwandferner, Ötztal Alps, Austria (modified after Kuhn et al. 1985)

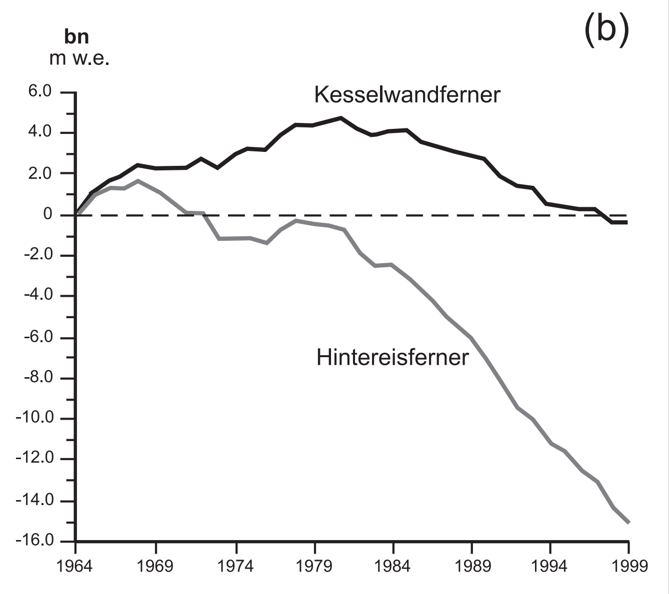

Fig. 7b: Cumulative net mass balances of the two glaciers during the second half of the 20th century. While Kesselwandferner advanced ca. 266 m between 1966 and 1985 in response to the recorded mass gain, Hintereisferner continued its retreat (data: WGMS; cf. Kuhn et al. 1985)

Franz Josef Glacier (Chinn et al. 2005). A negative mass balance in the arid east will be reflected by similar negative mass balances in the humid west. Thus, while there is no difference in annual gains and losses between eastern and western glaciers, there are obvious and spectacular differences in glacier activity due to individual glacier response times. The smaller, steeper mountain glaciers on both sides of the Alps have recently undergone minor readvances, while the large low gradient valley glaciers and other slow response glaciers have continued with their century of recession.

The climate leading to this mixture of glacier behaviours has been a century of warming with persistent and accelerating glacier wastage from the termination of the 'Little Ice Age' (AD 1850 to 1890 in this region) to the mid 1970's. This warming has lately been interrupted by 3 decades of near zero glacier mass balance throughout the New Zealand Southern Alps (Chinn et al. 2005). This period of oscillation about zero mass balance has permitted all of the fast response glaciers time to attain equilibrium sizes with the present climate, as indicated by minor readvances. Because the majority of the glaciers of the Southern Alps are steep and small to moderate in size, they have short response times and have had sufficient time to shrink to a new equilibrium area consistent with the current climate. However, the large sluggish debris-covered valley glaciers are still readjusting to the warming (WGMS 2008b). They have persistently maintained their 'Little Ice Age' areas for all but the last three decades. The relatively thick ice of the lower reaches of these glaciers was largely relict and insulated beneath thick protective mantles of debris. Ice loss was by slow downwasting (surface lowering) alone, with little to no terminus retreat. One after another, the terminus ice levels of these debris-mantled glaciers are reaching their 'irreversible tipping points' where ice level equals outlet stream level. This event triggers proglacial lake invasion of the terminus area. These lakes with their rapid expansion by both melt and glacier calving are now destroying the lower trunks of the large valley glaciers (Kirkbride and Warren 1999; Hochstein et al. 1998; Purdie and Fitzharris1999; Röhl 2006).

However, these differing responses are in danger of serious misinterpretation. The best known of the glaciers on the west of the Southern Alps are the Franz Josef and Fox Glaciers, two of the world's most climatically sensitive and reactive glaciers due to their high mass turnover and steep surface gradient (Andersen et al. 2008; Purdie et al. 2008). They have recently advanced (see Fig. 8), while on the dry eastern side and the best known glacier is the large debris covered Tasman Glacier, currently fast succumbing to proglacial lake decay. Because of their contrasting behaviour and their locations in different climate zones, the glacier behaviour on either

Fig. 8a: Franz Josef Glacier (Southern Alps, New Zealand) in 2003 (Photo: S. Winkler 11.03.2003)

Fig. 8b: Franz Josef Glacier in 2007. After advancing ca. 1200 m between 1984 and 1999, Franz Josef Glacier retreated until 2005 before it started to advance again, mainly due to increased precipitation (cf. Chinn et al. 2005, 2008; Photo: S. Winkler 03.03.2007)

side of the entire Southern Alps may erroneously be based on these few examples. Popular science publications and web blogs persistently continue to state that "the wet western glaciers are advancing and the dry eastern ones are retreating". Based on only 3 out of 3150 glaciers, this is patently untrue when each of the many hundred steep fast response glaciers on both side of the Alps have advanced, and all of the sluggish long response time glaciers on both sides of the Alps have receded (WGMS 2008b). In fact, this glacier behaviour is a result of response times and NOT climatic zones (Chinn et al. 2005, 2008; Winkler 2009; Dykes et al. this volume). There is no spatial pattern of the percentage of debris cover (Chinn 2001), but the two post prominent 'western' glaciers are (rare) examples of large and debris-free glaciers. This fact might be responsible for a second erroneous finding: That part of the contrasting behaviour arises from mainly debris-free 'western' glaciers versus debris-covered 'eastern' glaciers.

3.3.4 European Alps and Scandinavia – a comparison in historical context

Historical and proxy-records have documented a partly asynchronous evolution in temperature, precipitation and glacial variations in European regions during the 'Little Ice Age' (LIA; Nesje and Dahl 2003; Grove 2004; Matthews and Briffa 2005; Wanner et al. 2008). These findings underline the importance of spatial differentiation not only with the recent glacier fluctuations, but also with the reconstruction and interpretation of glacier chronologies for the 'LIA' (or the whole Holocene). Previously, the search for a parallel pattern of glacier variations was focus of many related studies (Furrer 2001). Even today, the need for spatial differentiation seems sometimes underrated, e.g., if 'hemispheric signatures' are applied (e.g., Schaefer et al. 2009). Despite their limitations, accurate measurements of glacier length fluctuations since the end of the 19th century (Rekstad 1904; Zumbühl and Holzhauser 1988) and historical methods can be used to reconstruct glacier behaviour during the preceding time of the LIA (e.g., Nussbaumer et al. 2007; Nesje et al. 2008a). A comparison between the Alps and Scandinavia allows an assessment of the spatial distribution of glacier fluctuations during the last few centuries. For these two areas, selected glaciers that are very well documented with temporally highly resolved reconstructions are presented here. Furthermore, spatial differentiations in glacier behaviour during the 20th century have previously been observed and related to climate (Günther and Widlewski 1986; cf. Winkler 1996a).

Historical descriptions of glaciers are accurate, but limited in space and time. Length changes can be determined by the interpretation of historical documents such as drawings, paintings, prints, photographs, maps and written sources. Historical material is only available in adequate quantity for those glaciers which drew the attention of travellers, scientists and artists through their reputation and scenic attraction, reflecting also the perception of glaciers at that time. A critical quality check of the documentary data is necessary in order to obtain reliable information on past glacier extents, and local circumstances need to be taken into account. Using these data, a resolution of decades or, in some cases, even individual years of ice margin positions has been achieved (Zumbühl and Holzhauser 1988).

The amount of historical material prior to 1800 highly depends on the elevation of the tongue, its dynamics as well as its distance to settlements and cultivated land.

In the Alps, existing glacier length records show advances around AD 1600, 1640, 1780, 1820 and 1850 (Zumbühl 1980; Zumbühl and Holzhauser 1988; Nicolussi 1990; Holzhauser et al. 2005; Nussbaumer et al. 2007). Results from outlet glaciers from south-western Norway indicate very different glacier behaviour compared to the Alps. According to the historical record, the maximum glacier extent occurred at Jostedalsbreen around 1750 (Nesje et al. 2008a). Figure 9 shows the length records based on historical evidence for selected glaciers in the Alps and in southern Norway (see also Tab. 2 for details on these glaciers). Due to the extraordinary low position of the terminus and its ease of access, the Unterer Grindelwaldgletscher is one of the best-documented glaciers in the Swiss Alps and likely in the world. Its cumulative length fluctuations, as derived from documentary evidence, covers the period 1535–2004, including the two well-known glacier maxima around 1600 and 1855/56 (Zumbühl 1980; Zumbühl et al. 2008).

The reconstruction for the Mer de Glace dates back to 1570, with a maximum glacier extent around 1644 (largest extent during the LIA), a slightly smaller maximum in 1821, and a second advance in 1852 (Nussbaumer et al. 2007). A comparison of the Mer de Glace length plot with that of the Unterer Grindelwaldgletscher depicts an astonishing simultaneity between the glaciers, despite their different settings in the western and central Alps. Small differences occur around 1850 (19th century maximum of the Unterer Grindelwaldgletscher) as well as between 1650 and 1750 (generally greater extension of the Mer de Glace with more variability). The Rhonegletscher shows similar behaviour: An advance around 1781, very well documented by Caspar Wolf (1735–1783), a Swiss painter of the early romantic and pioneering portraitist of the Alps. The advance of the 19th century (first culmination in 1818) is then documented by the drawings of Samuel Birmann (1793–1847) and by the outstanding photograph by Frédéric Martens (1806–1885) in 1856, at exactly the time of the glacier's 19th century maximum (Zumbühl and Holzhauser 1988; cf. Fig. 10).

There is reliable historic evidence for the impressive advance of Nigardsbreen in the first half of the

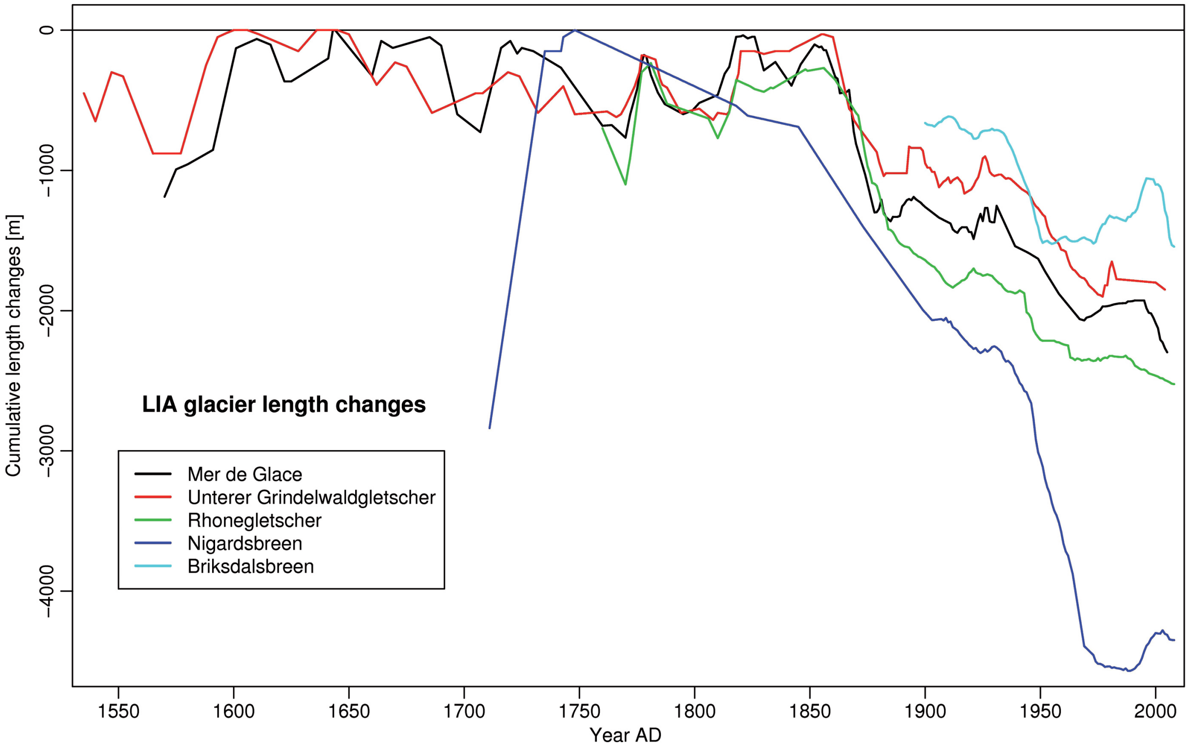

Fig. 9: Cumulative length variations relative to the LIA maximum extents of selected glaciers in the western and central Alps (data: Zumbühl 1980; Zumbühl and Holzhauser 1988; Nussbaumer et al. 2007; Zumbühl et al. 2008) and in southern Norway (data: Østrem et al. 1976; Nesje et al. 2008b; Kjøllmoen 2009)

Tab. 2: Topographical characteristics of the glaciers in the European Alps/Southern Norway with detailed historical evidence mentioned in the text (data: Mer de Glace: Nussbaumer et al. 2007; Unterer Grindelwaldgletscher: Steiner et al. 2008b; Rhonegletscher: Bauder et al. 2007; GLETSCHERBERICHTE 1881–2008; Nigardsbreen, Briksdalsbreen: Østrem et al. 1988)

Glacier	Geographical coordinates	Length [km]	Surface area [km²]	Head [m a.s.l.]	Terminus [m a.s.l.]
Mer de Glace	45°53'N 6°56'E	12.0	31.9	4072	1467
Unterer Grindelwaldgletscher	46°34'N 8°05'E	8.9	20.6	4107	1279
Rhonegletscher	46°37'N 8°24'E	7.9	16.5	3600	2197
Nigardsbreen	61°43'N 7°08'E	9.6	48.2	1950	355
Briksdalsbreen	61°39'N 6°55'E	6.0	11.9	1910	350

18th century. Contemporaneous accounts by the local priest, Matthias Foss (1714–1792) prove an advance of about 2700 m between 1711 and 1735. Between 1735 and the historically documented LIA maximum in 1748, the glacier advanced another 150 m (Nesje et al. 2008a). Briksdalsbreen, a fast reacting glacier, consistently observed since 1900, has been advancing since the 1950s, significantly since the late 1980s and culminating in 1996. From 1996 to 2008, Briksdalsbreen receded 487 m (Kjøllmoen 2009), mainly as an effect of high summer temperatures (Nesje 2005; Winkler and Nesje 2009).

In the Alps, positive mass balances and glacier length increases correlate quite well with low solar forcing plus rather high volcanic forcing activity (Wanner et al. 2008). Moreover, a negative NAO (North Atlantic Oscillation) regime might be a key feature of cold "Little Ice Age Type Events" *sensu* Wanner et al. (2000), causing glacier advances in Europe. However, glacier mass balances are also dependent on the hygric regime (precipitation and evaporation). Interpretation of glacier dynamics is thus difficult, since precipitation has been fluctuating strongly and is determined by the internal variability of the climate system and thus circulation changes on continental to local scale. Moreover, Steiner et al. (2008a) have shown that for selected advance and retreat periods, different combinations of seasonal temperature and precipitation patterns can explain these glacier variations.

Alpine winter precipitation is controlled by continental circulation dynamics (Wanner et al. 2003). In winter, the NAO is the dominant mode explaining the variability of the precipitation and temperature fields over this area, i.e., a mode with more zonal circulation with warm and wet westerly winds or with a blocking state with very cold and dry easterly winds. However, most favourable for positive mass balances in the Alps is a rather meridional circulation with a northern to north-westerly high altitudinal air flow, bringing cool weather with high precipitation. For instance, the major glacier advances in the Alps from 1820 to 1850 coincide with predominant north-westerly and northern weather situations (Jacobeit et al. 2003; Küttel et al. 2010). However, the question remains: What drives the amount of precipitation and the circulation dynamics in the Alps?

For glaciers in south-western Norway, influence by precipitation variation is much higher. Annual net mass balances of maritime (coastal) glaciers in southern Norway are largely controlled by the amount of winter precipitation from westerly air flow and thus mainly in phase with the winter NAO index (Nesje and Dahl 2003). On the other hand, annual mass balances of glaciers in the western and central Alps show quite complex relations to the NAO dynamics as shown above. According to Nesje (2005), the Briksdalsbreen record demonstrates that glacier variations not only respond to ablation-season (summer) temperature, but are also highly dependent on accumulation-season (winter) precipitation. Steiner et al. (2008a) showed that the 18th century advance of Nigardsbreen was largely controlled by winter and/or spring precipitation. This is in agreement with Nesje et al. (2008b) who state that, according to instrumental and proxy records, summer temperatures were not sufficiently low to explain glacier advances in that order in south-western Scandinavia. A prevailing positive NAO weather mode during the later part of the 17th century and the first half of the 18th century (Luterbacher et al. 2002) would explain increased winter precipitation with a large amount of snow (mild and humid winters) in south-western Scandinavia.

In summary, the exceptionally rich historical material on glacier fluctuations provides a valuable insight of glacier behaviour during the LIA. The cause for the different glacier behaviour and timing of LIA glacier maxima in western Scandinavia and in the Alps may be related to differences in temperature and precipitation distribution, which themselves are determined by changes in the large-scale atmos-

Fig. 10a: Rhonegletscher in 1856 in the valley floor at 1760 m a.s.l. as documented by Frédéric Martens. Alpine Club Library, London (Photo: H. J. Zumbühl)

Fig. 10b: Rhonegletscher in 2009. The arrow shows the current glacier terminus (Photo: S. U. Nussbaumer 22.07.2009)

pheric circulation over the northern North Atlantic/European and western Russian area, and possibly also by sea surface temperature (SST) changes at low frequency timescales.

4 Conclusions and outlook

The few examples presented and cited here, along with the case studies in this current issue of 'Erdkunde' comprise a subjective sample. Nevertheless, they provide valuable information to underline and emphasize the importance of spatial and temporal differentiation of the interpretation of the mass, volume, area, and length changes of mountain glaciers. For this important purpose, and to demonstrate the urgent need for including also glaciers in the existing focus on 'diversity' within the study-field of mountain ecosystems, those examples meet the target. As they are embodied in mountain systems/glacier regions with a comparably good data base and background knowledge, the need for further investigation is obvious. Having sufficient glaciological and meteorological data series available is far from being 'normal' for the majority of mountain systems on a global scale, which shows the need for future improvement.

Even if the spatial diversity of glacier changes is acknowledged and the related differences applied to any interpretations or predictions, there still is uncertainty about whether these patterns remain constant through time. Apart from some rather vague indications of 'regime shifts' that may have happened in the past, recent years have regionally brought situations without analogues in the historic and recent glacier chronologies (e.g., the record ablation in the European Alps during the 'centennial summer' of 2003, cf. Zemp et al. 2006, or the decoupling of length change and conventional net mass balance data series at the short outlets of Jostedalsbreen, cf. Winkler et al. 2009, Winkler and Nesje 2009). If these unprecedented situations continue to occur on a more regular basis in the future, the existing ways of explaining and modelling glacier changes might need to be modified or adjusted.

Considering the limits to knowledge of mountain glaciers and the need for spatial as well as temporal differentiation mentioned above, a number of summarizing statements on the potential and limit of glaciers as climate indicators can be stated:

- In the first instance, every individual glacier has to be treated as such. It is unrealistic to assume that single glaciers can be 'representative' for a whole mountain system and confirm regional or global trends.
- Considerable variability of several meteorological parameters on regional to local scale is typical for the climate of mountain systems. This 'climatological' spatial and temporal diversity is reflected in the determined glacier mass balance. Furthermore, several non-climatic factors such as glacier hypsography have an important impact on their individual responses to the climate. In some cases, the glacier response might be virtually decoupled from the climate due to non-climatic factors such as thick debris cover or calving and surge instabilities. These circumstances have to

be taken into account with any use of glacier data.

- There is no 'general' glacier model that could be ubiquitous and applied in any one mountain system. The transfer of models from one mountain system to another without previous regional verification should be avoided. If this is not possible, e.g., due to a lack of basic data, the procedure must explicitly be acknowledged and related uncertainties taken into account.
- In general, the status of accuracy, topicality, and representativeness of the glacier data used should always accompany the results of the scientific study, especially if the audience are the general public or scientists not familiar with glaciological research.
- Despite much improvement achieved during recent years, detailed knowledge about glacier response to climate change is still far from being satisfactory. Only for a few, well studied mountain systems such as the European Alps or Scandinavia has glaciological research reached a level to implement reliable impact scenarios. For most other mountain systems, unfortunately often those where strategies of sustainable development are desperately needed like the Central Asian mountain ranges or tropical/subtropical glacier regions in South America, the scientific base for glaciological predictions is poor, mainly due to the lack of glaciological and meteorological data.
- Even if remote sensing techniques are expected to considerably improve glacier studies in the near future, conventional mass balance and length measurements still need to be continued and extended. Therefore, the continuation and expansion of long-term monitoring programs has to be urgently stressed in the presence of policy makers and funding agencies. There is no alternative to meet the challenge of the significant spatial and temporal diversity of mountain glaciers with their response to climate changes.

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