+ MODEL

ARTICLE IN PRESS

GLOBAL-01229; No of Pages 9

Available online at www.sciencedirect.com

ScienceDirect

Global and Planetary Change xx (2007) xxx – xxx

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Historical and Holocene glacier–climate variations: General concepts and overview

O. Solomina [a], W. Haeberli [b], C. Kull [c,*], G. Wiles [d]

[a] *Russian Academy of Sciences, Institute of Geography RAS, Moscow, Russia*
[b] *Department of Geography, University of Zurich, Switzerland*
[c] *PAGES International Project Office, Bern, Switzerland*
[d] *Department of Geology, College of Wooster, Wooster, USA*

Keywords: glacier; climate; Holocene; variations

This special issue provides an overview of recent research activities concerning past to recent changes in the timing of glacier changes and their linkages to climate. The contributions are based on presentations from two "glacier–climate–cryosphere" sessions co-organized by the EU-funded GLOCHAMORE project (Global Change in Mountain Regions), PAGES (Past Global Changes) and the WGMS (World Glacier Monitoring Service) at the Open Science Conference on "Global Change in Mountain Regions" organized by the MRI (Mountain Research Initiative) and held in Perth Scotland, Oct. 2–6, 2005.

Covering a wide range of glacier-related topics, the conference sessions and this issue link studies and observations on the Late Quaternary to present in an attempt to bring together scientists and research results, which relate to the increasingly important issue of climate change. Results are presented from throughout the world, underscoring the important role that glacier-related research plays in assessing past and recent variations of the cryosphere and the climate system. Evidence from directly measured observations essentially covering the past century and the rapid and accelerating ongoing changes are collected and assessed by the WGMS. PAGES, on the other hand, maintains its focus on the variability in the more distant past. As shown by the successful sessions in Perth and now by this special issue, the respective communities have begun to communicate, linking their datasets to provide an important basis to assess ongoing climate and glacier change, and to develop realistic scenarios for future conditions and challenges in glacierised mountain regions.

1. Modern glacier observations in relation to pre-industrial variability ranges

Fluctuations of glaciers and ice caps have been systematically observed and measured for more than a century in various parts of the world (Haeberli, 2004). They are considered to be highly reliable indications of worldwide warming trends (cf. Fig. 2.39a in IPCC, 2001). Mountain glaciers and ice caps are, therefore, key variables to monitor for early-detection strategies of global climate-related observations.

Since the beginning of the internationally-coordinated collection of information on glacier changes was initiated in 1894 (Forel, 1895), various aspects have evolved in striking ways:

(1) Accelerating glacier shrinkage at the century time scale is now clearly non-cyclic, therefore there is little question that the originally envisaged

---

* Corresponding author.
E-mail address: kull@pages.unibe.ch (C. Kull).

0921-8181/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2007.02.001

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

"variations périodiques des glaciers" does not apply to ongoing developments;

(2) As a consequence of the growing influence of human impact on the climate system (enhanced greenhouse effect), dramatic scenarios of projected changes including complete deglaciation of entire mountain ranges must be taken into consideration (Haeberli and Hoelzle, 1995; Oerlemans et al., 1998; Zemp et al., 2006);

(3) Such future scenarios may be beyond the range of historical/Holocene variability and most likely introduce dramatic consequences (i.e., extent and rate of glacier melt and disequilibrium of glacier/climate relationships).

(4) The comparison of modern glacier retreat with the Holocene glacier variations provides important background information for our understanding of natural trends of, and human impacts on, climate change. In many regions glaciers have been shorter in the Early to Mid Holocene than at the end of the 20th century. Most probably, however, the reasons for such shrinkage were different than they are now and primarily related to the different orbital parameters of the Earth with a corresponding insolation regime;

(5) A broad portion of the global community today recognizes glacier changes as a key indication of regional and global climate, and environment change;

(6) Observational strategies established by expert groups within international monitoring programmes build on advances in understanding processes and now include extreme perspectives;

(7) These strategies make use of the rapid development of new technologies and relate them to traditional approaches in order to apply integrated, multilevel concepts (in situ measurements to remote sensing, local-process oriented to regional and global coverage), within which individual observational components (length, area, volume/mass change) fit together enabling a more holistic view of the cryosphere (Bishop et al., 2004).

Strategies for early detection of climate change aim at attributing causes and possible consequences of ongoing developments by considering information on (a) the rates and acceleration of change, (b) the spatial patterns of change and (c) their comparison with historical to Late Quaternary (i.e. pre-industrial) ranges of variability. Comparison with the historical and Late Quaternary glacier variability has become central to assessing the causes and possible future of the contemporary shrinking of glaciers. This is particularly the case in light of the increasing energetics of the climate system. The socio-economic and political significance of this public issue is such that careful argumentation and precise formulations are needed to reach safe conclusions and assessments. This especially concerns basic concepts of the process chain, which links climate change to glacier fluctuations.

A clear distinction must be made between change in thickness, volume or mass (the immediate "vertical" change) and change in length (the delayed "horizontal" change). Via the mass and energy balance, the volume change of glaciers is directly related to atmospheric conditions. The change in length of glaciers – advance and retreat of glacier tongues or lower ice margins – involves complex dynamic aspects of ice flow and, hence, is a delayed, filtered and enhanced consequence of direct changes in climate and glacier mass balance. The delay in time can be defined as: (a) the "reaction time" (the first change in the glacier terminus detected following a change in overall mass) and (b) the "response time" (the time needed for complete adjustment of the glacier to new equilibrium conditions). Reaction time can be empirically estimated from simultaneous observed mass and length changes of individual glaciers over time or approximated from (scientifically controversial) kinematic wave theory. Response time is a theoretical concept for an assumed step function in climate and best relates to characteristic thickness and ablation at the glacier tongue (Johannesson et al., 1989). Haeberli and Hoelzle (1995) explain the application of such concepts to simple inventory data (maximum/minimum height, area, length) of otherwise unmeasured glaciers. Response time primarily depends on slope (steep glaciers having short response times), is typically a few decades for mountain glaciers and about twice the reaction time of the same glacier. Comparison with rapid ongoing change requires a precise definition of time indicators. For example, the term "today" should be used with greatest care and not as a synonym of more diffuse terms like "modern", "present-day" or "recent". It must also be clear that the variable geometry of mountain glaciers results in widely varying sensitivities. The hypsography (area distribution with altitude) defines the local/individual sensitivity of glacier mass balance with respect to a given climate signal, and length, altitudinal extent and slope together govern the dynamic response of glacier tongues with respect to such individual mass balances. Correct interpretation of past changes in glacier length must take such individual components into account and assess it in relation to regional differences in climate change patterns.

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

An example from the European Alps illustrates basic aspects of these principles. After a transitional time of modest gain since the 1960s, mass balances become strongly negative after about 1980. Most glacier tongues have started to react to this signal but are still far from a full dynamic response. Today – here in the sense of the year 2005 – tongues of medium-sized valley glaciers still reflect climatic conditions towards the end of the past century. In the meantime, average volume loss of Alpine glaciers has increased to about 2 to 3% per year. For a full geometric adjustment to the climatic conditions of 2000–2005, most glacier tongues and ice margins would require a farther retreat of a kilometer or more; and with repeated conditions of the extreme summer of 2003, most glaciers would disappear completely. The (vertical) thinning of the glaciers has indeed become so fast that more and more glaciers have started changing from an "active retreat" — mode to downwasting and even collapse. Changes in glacier length are thus now increasingly becoming decoupled from mass balance and short-term atmospheric conditions. These key observations are vital for reconstructing and correctly interpreting past ice and climatic conditions from the rich glacial record now becoming exposed at lower ice margins in many regions of the world.

2. Glaciers in the past — progress in research

In recent decades our understanding of glacier fluctuations in the past had greatly improved due to a better understanding of modern climate–glacier relationships as well as to the rapid development of technologies and concepts in paleoclimatology. High-resolution climate reconstructions have provided quantitative parameters on past climatic changes for the Ocean and the land and made it possible to use similar methods for analysis and modeling as climatology does for modern processes, including synoptic meteorology (Wanner et al., 2000). Cumulative glacier length changes were recently used to model the global temperature variations over the last few centuries (Oerlemans, 2005) and equilibrium line reconstructions have shown to be useful for the investigation of long-term precipitation anomalies in the North Atlantic and the NAO oscillation (Dahl and Nesje, 1996; Bakke et al., 2005a,b, 2007-this issue; Nesje et al., 2005, 2007-this issue). Glacier fluctuations are a substantial part of many multi-proxy regional climatic and environmental reconstructions (e.g. Nesje et al., 2005) and interregional correlations (e.g. Luckman and Villalba, 2001). These records have to be taken into account in the discussion of long-term climatic trends, both at regional and global scales (Mann and Jones, 2003; Moberg et al., 2005).

Recent advances in dating techniques have begun to improve the chronologies of the glacial geological records, although the accurate moraine dating still remains a problem in many regions. Improvements in dating include several aspects. The calibration of 14C dates resulted in the use of the uniform calendar time scale for all types of dating. The development of long regional tree-ring chronologies (Villalba, 1994; Wiles et al., 2004; in press; Holzhauser et al., 2005; Yang et al., in press etc.) provided the opportunity to use the cross-dating of tree-ring samples to obtain precise calendar dates for advance and recession of glaciers. The use of more sophisticated and appropriate statistical approaches in lichenometry (Bull, 1996; Jomelli and Pech, 2004) allowed for more rigorous error estimate and higher accuracy. Major progress has also been made in the use of lacustrine sediments from proglacial lakes, which are used to reconstruct former glacier activity (Karlen and Matthews, 1992; Dahl et al., 2003), and have allowed the development of high-resolution quantitative continuous records both for glacier advance and retreats (Nesje et al., 2007-this issue; Bakke et al., 2007-this issue). In addition, strides made in cosmogenic dating over the past five years have significantly contributed to glacial chronology and promises to continue in importance (e.g. Gosse, 2005).

One of the last global review of Holocene glacier variations was published almost twenty years ago (Quaternary Science Reviews, 1988). Since then, many new detailed reconstructions of past glacier lengths in combination with high-resolution climatic records from ice cores, tree rings, lake sediments and speleothems have been produced in the Alps (Wanner et al., 2000; Hormes et al., 2001; Holzhauser et al., 2005; Joerin et al., 2006), Scandinavia (Nesje et al., 2005; Bakke et al., 2005a,b, 2007-this issue), Alaska (Wiles et al., 2004, 2007-this issue), Canadian Rockies (Koch et al., 2004; Menounos et al., 2004; Luckman and Wilson, 2005), Patagonia (Villalba, 1994; Glasser and Harrison, 2004), tropics of South America (Seltzer et al., 1995; Abbott et al., 1997, 2000, 2003), Tibet (Bao et al., 2003; Braeuning, 2006; Yang et al., 2007-this issue), the Arctic (Lubinski et al., 1999; Humlum et al., 2005; Miller et al., 2005) and Antarctica (Ingolfsson et al., 1998). A comprehensive review of Holocene glaciation presented in the extensive monograph of J. Grove "The Little Ice Ages" (Grove, 2004).

Analysis of Holocene glacier fluctuations is largely consistent with the reconstructions of climatic and environmental changes provided by other indicators.

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

General warming during the transition from the Lateglacial time period to the Early Holocene is clearly recorded by ice cores, tree-line shifts, pollen assemblages and lake sediments. After the end of the Younger Dryas (ca. 12,900 to 11,500 yr BP), this pronounced warming reduced the glaciers in most mountain areas to sizes which are comparable with conditions at the end of the 20th century (Grove, 2004). In northern Europe and western North America, which were influenced by the remnants of the great ice sheets, this process was delayed until the Mid Holocene. Several Early Holocene readvances, especially those in the North Atlantic (Nesje and Dahl, 2001; Miller et al., 2005) and North Pacific (Menounos et al., 2004) as well as possibly in the Alps (Joerin et al., 2006) cluster around the 8.2 ka event, and were likely to be triggered by the changes in the thermohaline circulation and subsequent cooling due to the lake Agassiz and Ojibway outbursts (Alley and Agustsdottir, 2005). This Early Holocene cooling has received much attention as it is important to track the 8.2 ka advances globally to spatially constrain the climatic effect of this event and further understand its global effect and possible causes.

During the Mid Holocene, most glaciers remained in a contracted stage (Grove, 2004), including those of the Southern Hemisphere in Patagonia (Glasser and Harrison, 2004), New Zealand (Gellatly et al., 1988) and the tropical Andes (Abbott et al., 2003). Although the temperature in the tropics was probably below the pre-industrial level in the Early–Mid Holocene (Rimbu et al., 2004), glaciers in this region were rather small or even absent likely due to increased aridity (Abbott et al., 2003).

It is difficult to assess precise glacier length during contracted stages, because the evidences may still be hidden underneath the present glacier. However, continued retreat of glacier tongues now provides important information about past phases of reduced glacier lengths. There are evidences that mountain glaciers were at least as short as in the 1980s–1990s during various periods of the Holocene and in many regions of both hemispheres (Nesje et al., 2007-this issue; Bakke et al., 2007-this issue; Wiles et al., 2007-this issue; Koch et al., 2004; Humlum et al., 2005, Hormes et al., 2001, 2004) including the tropics (Abbott et al., 2003), and subantarctic islands (Frenot et al., 1997). However these evidences must be interpreted with care if former glacier sizes are used in climatic terms. As mentioned above it is important to distinguish between the glacier thickness and length changes: for the second parameter a certain time lag has to be taken into account. For instance glacier tongues in the Alps are today (2005) still far more extended than an equilibrium with climatic conditions of the past decade would require. The finding of the Oetztal ice man in the uppermost part of a small glacier in the Austrian Alps clearly illustrates that Alpine glacier volumes (not lengths!) have become smaller now than during at least the past about 5000 years (Haeberli et al., 2004). Such findings are being confirmed from other sites on saddles and crests (for instant, Lötschenpass and Schneidejoch in the Bernese Alps, cf.Haeberli et al., 2004). In permafrost areas, specifics of glacier dynamics should be also taken into account: the melting of debris-covered glaciers slows down and even comes to a complete stop once the debris cover reaches the thickness of maximum thaw depth in summer — the permafrost active layer under periglacial conditions. As result in response of warming, the tongue retreat may not occur, but rather the surface of debris-free upper part of the glacier will be thinning (Etzelmüller, 2000). A further complication is the fact that glacier tongues on flat ground or with heavy debris input from surrounding rock walls tend to build up thick sediment beds (Maisch et al., 1999) and, hence, advance along steadily rising ground surfaces; as a consequence of the corresponding mass balance/altitude feedback and increasing lateral flow restriction, such glaciers are forced to a general and relatively long-term growth even with unchanged climatic conditions. In the case of Unteraar or Tschierva glaciers in the Swiss Alps, for instance, earlier reduced glacier lengths may at least partially be explained by such systematic long-term geomorphic effects.

Adjustment of glacier tongues by retreat, downwasting or even collapse lags ongoing rapid atmospheric warming by years to several decades. As a consequence, the extraordinary “vertical” mass losses during the past two decades (IUGG (CCS)/UNEP/UNESCO/WMO, 2005) cannot be recognized from the still too extended lower ice margins of glaciers. Some researchers even argue that many glaciers now (early 21st century) are already less extensive than they have been throughout the Holocene (Koch et al., 2004). Their arguments are based on the location of the trees and peat close to the modern glacier fronts, and the good preservation of the materials, which may preclude multiple past exposures. The retreat of maritime glaciers along the entire western Scandinavia over the last century is unprecedented at least during the entire Neoglacial period, which spans the last 5200 years (Bakke et al., 2007-this issue). In other regions some glacier tongues still seem to be longer than in the Mid and even some parts of Late Holocene.

Readvances of glaciers in the second half of the Holocene are recorded worldwide (Porter, 1981; Denton and Karlen, 1973; Grove, 2004). In many mountain areas the first Neoglacial advances are recorded about

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

6 ka cal BP, but in most locations the earliest advances are recorded much later, up to the last centuries (Snyder et al., 2000). The gradual re-appearance of the glaciers in the tropical Andes after 4 ka indicates an increase in humidity (Abbott et al., 2003).

The number of Neoglacial advances recorded in different mountain areas is highly variable. It depends on the preservation of the moraines especially in areas with extensive Little Ice Age advances, which may have destroyed the earlier glacial deposits (Spitsbergen, mid latitudes of North America). This potential loss of information makes it difficult to use data from glacial geomorphology for paleoclimatic reconstructions in some regions and for interregional comparisons.

In general the retreat of glaciers in the Early Holocene and the advances during the Neoglacial (Porter and Denton, 1967) (after 6 ka) are in line with orbital forcing (see Bakke et al., 2007-this issue), primarily with the decrease of summer insolation in the Northern Hemisphere. However the reduced length of glaciers of the Southern Hemisphere (e.g. New Zealand and Patagonia) in the first half of the Holocene cannot be attributed to the same cause, suggesting a potential large reorganisation of latitudinal heat transport involving the Ocean (Shulmeister, 1999). At the multi-centennial to multi-millennial scale, glacier lengths globally demonstrate general coherence, showing fast retreat after the Younger Dryas, reduced sizes in the Early to Mid Holocene, Neoglacial readvances after 6 ka cal BP, and contemporary retreat.

It is more difficult to assess the synchroneity or to examine other global patterns of multi-decadal glacial variations due to the low resolution of many glacial chronologies and the incomplete nature of the terrestrial glacier records. Broad synchroneity of glacier variations during the Holocene regionally was suggested by Denton and Karlen (1973), Mayewski et al. (2004) and Grove (2004). On the other hand, the expectations that advances should be globally synchronous may be unrealistic in view of the individual response characteristics and, especially, of the clear vision that regional modes of variability, such as NAO or ENSO, play a leading role with respect to decadal and multi-decadal variability of regional climates. It has been recently explained that some LIA advances in Scandinavia and in the Alps were not synchronous because of the NAO variability with its contrasting effect on the two regions (Nesje and Dahl, 2001). Glacier variations in Iceland do not show any correspondence with those in Scandinavia and in the Alps (Stoetter et al., 1999), and different parts of the Tibetan plateau show different patterns in the timing of glacier fluctuations during the Late Holocene (Yang et al., 2007-this issue). In contrast to such regional variability, a broad similarity of glacier fluctuations during the last millennium seems to exist in the areas of North and South America, which may be related to the dominating role of the tropical Ocean in the organization of the climatic system across the American Cordillera.

The solar (Denton and Karlen, 1973) or volcanic forcings (Porter, 1981) as potential triggers of glacier growth/retreat has long been proposed as a primary driver and potential explanation for globally synchronous glacier fluctuations. Indeed, in some regions such as Sweden (Karlen and Kuylenstierna, 1996), Alaska (Wiles et al., 2004, 2007-this issue), the Canadian Rockies (Luckman and Wilson, 2005) and the Alps (Holzhauser et al., 2005), solar irradiation minima coincide with increasing glacier lengths during the past few millennia. Furthermore a certain correspondence exists in the timing of major glacier advances at the interregional level for instance in the Alps (Holzhauser et al., 2005; Zumbühl et al., 2007-this issue), Alaska (Wiles et al., in press) and Southern Tibet (Yang et al., in press) during the last two millennia occurred around AD 200, 400, 600, 800–900, 1100, 1300 and in 17 though 19 centuries. A certain common external factor forcing the glacier growth and retreat in all these three remote regions should be suggested to explain this coherence.

Glacier recession after Little Ice Age maximum coincides with the increase in global atmospheric temperature since the middle of 19th century. General glacier shrinkage during 20th century is evident in most regions of the world, including the Southern Hemisphere. In northwestern Patagonia, for example, the drastic and widespread glacier recession observed by comparison of repeated photography is related to significant warming and decreasing precipitation in 1912–2002 (Masiokas et al., 2007-this issue). In South Georgia most glacier fronts had more advanced positions during the late 1800s than now. The rate of recession increased in the 1950s in response to a sustained atmospheric warming trend (Gordon, 2007-this issue). During the same time period, anthropogenic impacts on the climate system (aerosol concentration, greenhouse gases) are quite likely to have started overtaking the primary forcing. Since about the year 2000, glacier vanishing seems to have strongly accelerated in many regions of the world (many papers contributed to the International Symposium on Cryospheric Indicators of Global Climatic Change, Cambridge 2006). Consequences of continued drastic glacier changes in high-mountains are multiple and cause profound impacts on society. An example is the ongoing retreat of the tropical glaciers in Peru and Bolivia, which creates serious challenges for water supply and sustainable development in the region (Mark, 2007-this issue).

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

3. The value of new tools and interdisciplinary analyses — modeling, ice cores and remote sensing

The link between historical and past glacier variations and climate can be made through numerical models and similarly future variations in the cryosphere to climate change scenarios depend on models. Numerical models treat and sometimes integrate (a) the energy and mass balance at the glacier surface and (b) the dynamic response of glacier flow. In principle, this allows quantitative analyses of the glacier–climate relationship at different levels of complexity, depending on the desired results and available data. Such models can provide deeper insights concerning past climate and glacier dynamics (e.g. Haeberli and Penz, 1985; Oerlemans, 2001; Kull et al., 2002) and several studies in this issue have made use of modeling approaches to derive information related to climate change over different timescales from glacier variations (Zumbühl et al., 2007-this issue; Kerschner and Ivy-Ochs, 2007-this issue).

Some approaches link changes in key glaciological parameters such as the Equilibrium Line Altitude (ELA) or the Accumulation Area Ratio (AAR) and mass balance/altitude gradients to changes in climatic conditions (e.g. Kaser and Osmaston, 2002). More complex models attempt to simulate the dynamic response to imposed climatic forcing. A major obstacle that remains is to realistically model the basal sliding component of glacier flow and the effects of subglacial water pressure and variable thermal conditions within the ice (temperate, polythermal and cold glaciers). This deficiency can be overcome by looking at longer time intervals. Over periods corresponding to the dynamic response time (a few decades for relatively steep mountain glaciers) changes in glacier geometry are almost exclusively dominated by the principle of mass conservation rather than the details of glacier mechanics. This principle has been used to calculate average mass balances from observed and reconstructed cumulative length change worldwide during the 20th century (Hoelzle et al., 2003) and back in time (2000 years) for Aletsch Glacier in the Alps (Haeberli and Holzhauser, 2003). Based on advanced mathematical approaches (neural networks), glacier mass balance and corresponding dynamics can be modeled for historic times with a rather well defined climatic forcing (Steiner et al., 2005). An example of such a reanalysis for the Little Ice Age is presented in this issue by Zumbühl et al. (2007-this issue), which shows that Alpine glaciers did not uniformly respond to either a temperature or a precipitation forcing. In fact they responded to a complex interplay of favorable and less favorably synoptic weather patterns (Nesje et al., 2007-this issue).

The detailed application of models to changes in the more distant past therefore still poses a major challenge. Under different past mean climate conditions, glacier mass balance could have reacted with a different sensitivity to either a temperature or a precipitation change, as shown e.g. in modeling results for the Late Pleistocene glaciation in the Central Andes (e.g. Kull et al., 2003, in press). Modeling approaches may help sort out respective forcing factors and may provide a better view of past climatic conditions. Related examples are presented by Kerschner and Ivy-Ochs (2007-this issue).

Another important application of future modeling work links ice core sciences to mass balance — modeling approaches. Ice cores are records of past accumulation, which is a combination of local precipitation, avalanche, snow drift, melt and sublimation. Modeling and reconstructing the mass balance history from ice cores extracted from the accumulation area of a glacier could therefore help to model, validate and reconstruct past glacier variations as well as the prevailing local climate conditions. However, accumulation characteristics on wind-exposed, high-altitude peaks can strongly differ from those on more protected firn basins at lower altitude. Direct correlations between the two may be weak or even inverse (summer air temperature is positively correlated with accumulation of temperate firn but negatively with cold firn, cf. Haeberli and Alean, 1985). Variations in oxygen isotope concentrations, partly reflecting atmospheric temperature variations and variable circulation patterns may alternatively be used (Schotterer et al., 2003; Thompson, 2005). Today, ice core records exist from various places around the world and could be used more intensively in this context (e.g. Schwikowski, 2006; Ginot et al., 2006).

Addressing and observing the ongoing changes in the cryosphere benefits from the availability of remote sensing data (Bishop et al., 2004). Recent efforts make use of these technologies in order to derive rates of change not only from single glaciers but using the available data to construct a regional pattern of today's worldwide glacier retreat. The new glacier inventory for the Swiss Alps, or the altimetry studies in Alaska and Patagonia, for instance, clearly document the fast rate of glacier vanishing: surface lowering is even striking in the uppermost parts of many glaciers (Arendt et al., 2002; Rignot et al., 2003; Paul et al., 2004). This points to the fact that dynamic effects (flow adjustment, mass balance/altitude feedback) now started to overtake (Raymond et al., 2005) and to enhance the vanishing process far

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

beyond “horizontal retreat”. Related projects such as GLIMS (Global Land Ice Measurements from Space) are designed to monitor the world’s glaciers with respect to recent environmental change. Such efforts will certainly gain even more importance in the near future. They thereby help to expand the databases and knowledge but also providing an important basis for modeling approaches of past, ongoing and future changes in the glacier–climate system.

The papers compiled in this volume are based on various approaches of field techniques, analyses and modeling from a broad variety of regions both from Southern and Northern Hemispheres. We encourage the community to maintain the effort of deriving information on global change from changes in the glacier – climate system. These studies demonstrate the high value of the cryosphere system to indicate climate and environments on various timescales in the past and their relevance to understand recent and future changes.

References

Abbott, M.B., Binford, M.W., Brenner, M., Kelts, K.R., 1997. A 3500 14C yr high-resolution record of lake level changes in Lake Titicaca, Bolivia/Peru. Quaternary Research 47, 169–180.

Abbott, M.B., Wolfe, B., Aravena, R., Wolfe, A.P., Seltzer, G.O., 2000. Holocene hydrological reconstructions from stable isotopes and palaeolimnology, Cordillera Real, Bolivia. Quaternary Science Reviews 19, 1801–1820.

Abbott, M.B., Wolfe, B., Wolfe, A.P., Seltzer, G.O., Aravena, R., Mark, B.G., Polissar, P.J., Rodbell, R.T., Rowe, H.D., Vuille, M., 2003. Holocene paleohydrology and glacial history of the Central Andes using Multiproxy Lake Sediment Studies. Palaeogeography, Palaeoclimatology, Palaeoecology 194, 123–138.

Alley, R.B., Agustsdottir, A.M., 2005. The 8 k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.

Arendt, A., Echelmeyer, K., Harrison, W.D., Lingle, G., Valentine, V., 2002. Rapid wastage of Alaska Glaciers and their contribution to rising sea level. Science 297 (5580), 382–386.

Bakke, J., Dahl, S.O., Nesje, A., 2005a. Lateglacial and Early Holocene palaeoclimatic reconstruction based on glacier fluctuations and equilibrium-line altitudes at northern Folgefonna, Hardanger, western Norway. Journal of Quaternary Science 20 (2), 179–198.

Bakke, J., Dahl, S.O., Paasche, Ø., Løvlie, R., Nesje, A., 2005b. Glacier fluctuations, equilibrium-line altitudes and palaeoclimate in Lyngen, northern Norway, during the Lateglacial and Holocene. The Holocene 15 (4), 518–540.

Bakke, J., Lie, Ø., Dahl, S.O., Nesje, A., Bjune, A.E., 2007. Strength and spatial patterns of the Holocene wintertime westerlies in the NE Atlantic region. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.030.

Bao, Y., Brauning, A., Yafeng, S., 2003. Late Holocene temperature fluctuations on the Tibetan Plateau. Quaternary Science Reviews 22 (21), 2335–2344 (10).

Bishop, M.P., Olsenholler, J.A., Shroder, J.F., Barry, R.G., Raup, B.H., Bush, A.B.G., Copland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Kääb, A., Paul, F., Hall, D.K., Kargel, J.S., Molnia, B.F., Trabant, D.C., Wessels, R., 2004. Global land ice measurements from space (GLIMS): remote sensing and GIS investigations of the Earth’s cyrosphere. Geocarto International 19 (2), 57–84.

Braeuning, A., 2006. Tree-ring evidence of Little Ice Age glacier advances in southern Tibet. The Holocene 16 (2), 1–12.

Bull, W.B., 1996. Dating San Andreas faults earthquakes with lichenometry. Geology 24, 111–114.

Dahl, S.O., Nesje, A., 1996. A new approach to calculating Holocene winter precipitation by combining glacier equilibrium-line altitudes and pine-tree limits: a case study from Hardangerjokulen, Central Southern Norway. The Holocene 6 (4), 381–398.

Dahl, S.O., Bakke, J., Lie, O., Nesje, A., 2003. Reconstruction of former glacier equilibrium-line altitudes based on proglacial sites: an evaluation of approaches and selection of sites. Quaternary Science Reviews 22, 275–287.

Denton, G.H., Karlen, W., 1973. Holocene climatic variations – their pattern and possible cause. Quaternary Research 3, 155–205.

Etzelmüller, B., 2000. Quantification of thermo-erosion in proglacial areas — examples from Svalbard. Zeitschrift für Geomorphologie 44 (3), 343–361.

Forel, F.-A., 1895. Les variations périodiques des glaciers. Discours préliminaire. Archives des sciences physiques et naturelles. Genève XXXIV, 209–229.

Frenot, Y., Gloaguen, J.C., Van der Vijer, B., Beyens, L., 1997. Datation de quelques sédiments tourbeux holocènes et oscillations glaciaires aux iles Kerguelen. Ecologie 320, 567–573.

Gellatly, A.F., Chinn, T.J.H., Roethlisberger, F., 1988. Holocene glacier variations in New Zealand. Quaternary Sciences Reviews 7, 227–242.

Ginot, P., Kull, C., Schotterer, U., Schwikowski, M., Gäggeler, H., 2006. Glacier mass balance reconstruction by sublimation induced enrichment of chemical species on Cerro Tapado (Chilean Andes). Climate of the Past 1 (2), 155–168.

Glasser, N.F., Harrison, S., 2004. Late Pleistocene and Holocene palaeoclimate and glacier fluctuations in Patagonia. Global and Planetary Change 43 (1–2), 79–101.

Gordon, J.E., Haynes, V.M., Hubbard, A., 2007. Recent glacier changes and climate trends on South Georgia. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.037.

Gosse, J.C., 2005. The contribution of cosmogenic nuclides to unraveling alpine glacial histories in North and South America. In: Huber, U., Brugmannn, H., Reasoner, M. (Eds.), Global Change and Mountain Regions: An Overview of Current Knowledge, MRI. Kluwer Academics, Zurich.

Grove, J.M., 2004. Little Ice Ages: Ancient and Modern. Routledge, New York.

Haeberli, W., 2004. Glaciers and ice caps: historical background and strategies of world-wide monitoring. In: Bamber, J.L., Payne, A.J. (Eds.), Mass Balance of the Cryosphere. Cambridge University Press, Cambridge, pp. 559–578.

Haeberli, W., Alean, J., 1985. Temperature and accumulation of high altitude firn in the Alps. Annals of Glaciology 6, 161–163.

Haeberli, W., Hoelzle, M., 1995. Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Annals of Glaciology 21, 206–212.

Haeberli, W., Holzhauser, H., 2003. Alpine glacier mass changes during the past two millennia. Pages News 11 (1), 13–15.

Haeberli, W., Penz, U., 1985. An attempt to reconstruct glaciological and climatological characteristics of 18 ka BP Ice Age glaciers in and around the Swiss Alps. Zeitschrift für Gletscherkunde und Glazialgeologie 21, 351–361.

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

Haeberli, W., Frauenfelder, R., Kääb, A., Wagner, S., 2004. Characteristics and potential climatic significance of "miniature ice caps" (crest- and cornice-type low-altitude ice archives). Journal of Glaciology 50 (168), 129–136.

Hoelzle, M., Haeberli, W., Dischl, M., Peschke, W., 2003. Secular glacier mass balances derived from cumulative glacier length changes. Global and Planetary Change 36, 295–306.

Holzhauser, H., Magny, M.J., Zumbühl, H.J., 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. The Holocene 15 (6), 789–801.

Hormes, A., Muller, B., Schlüchter, C., 2001. The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. The Holocene 11 (3), 255–265 (11).

Hormes, A., Karlen, W., Possnert, G., 2004. Radiocarbon dating of palaeosol components in moraines in Lapland, northern Sweden. Quaternary Science Reviews 23, 2031–2043.

Humlum, O.E.B., Hormes, A., Fjordheim, K., Hansen, O.H., Heinemeier, J., 2005. Late-Holocene glacier growth in Svalbard, documented by subglacial relict vegetation and living soil microbes. The Holocene 15 (3), 396–407.

Ingolfsson, O., Hjort, C., Berkman, P.A., Bjork, S., Colhoun, E., Goodwin, I.D., Hall, B., Hirakawa, K., Melles, M., Moller, P., Prentice, M., 1998. Antarctic glacial history since the Last Glacial Maximum: an overview of the record on land. Antarctic Science 10 (3), 326–344.

IPCC, 2001. Climate change 2001 — the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IUGG(CCS)/UNEP/UNESCO/WMO, 2005. Glacier Mass Balance Bulletin No. 8 (2002–2003). World Glacier Monitoring Service, Zurich, Switzerland.

Joerin, U.E., Stocker, T.F., Schlüchter, C., 2006. Multi-century glacier fluctuations in the Swiss Alps during the Holocene. The Holocene 16, 697–704.

Johannesson, T., Raymond, C.F., Waddington, E.D., 1989. Time-scale for adjustment of glaciers to changes in mass balance. Journal of Glaciology 35 (12), 355–369.

Jomelli, V., Pech, P., 2004. Effects of the Little Ice Age on Avalanche Boulder Tongues in the French Alps (Massif des Ecrins). Earth Surface Processes and Landforms 29 (5), 553–564.

Karlen, W., Kuylenstierna, J., 1996. On solar forcing of Holocene climate: evidence from Scandinavia. The Holocene 6 (3), 359–365.

Karlen, W., Matthews, J., 1992. Reconstructing Holocene glacier variations from glacier lake sediments: studies from Nordvestlandet and Jostedalsbneen-Jotunheimen, southern Norway. Geografiska Annaler, Series A 63A, 273–281.

Kaser, G., Osmaston, H., 2002. Tropical Glaciers. Cambridge University Press, Cambridge.

Kerschner, H., Ivy-Ochs, S., 2007. Palaeoclimate from Glaciers: examples from the Eastern Alps during the Alpine Lateglacial and early Holocene. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.034.

Koch, J., Menounos, B., Clague, J., Osborn, G.D., 2004. Environmental change in Garibaldi Provincial Park, Southern Coast Mountains, British Columbia. Geoscience Canada 31 (3), 127–135.

Kull, C., Grosjean, M., Veit, H., 2002. Modelling modern and Late Pleistocene glacio–climatological conditions in the North Chilean Andes (29°S–30°S). Climate Change 53 (3), 359–381.

Kull, C., Hänni, F., Grosjean, M., Veit, H., 2003. Evidence of an LGM cooling in NW-Argentina (22°S) derived from a glacier climate model. Quaternary International 108, 3–11.

Kull, C., Imhof, S., Grosjean, M., Zech, R., Veit, H., in press. Late Pleistocene glaciation in the Central Andes: temperature versus humidity control—A case study from the eastern Bolivian Andes (17°S) and regional synthesis. Global and Planetary Change.

Lubinski, D.L., Forman, S.L, Miller, G.H., 1999. Holocene glacier and climate fluctuations on Franz Josef Land, Arctic Russia, 80°N. Quaternary Science Reviews 18 (1), 85–108 (24).

Luckman, B.H., Villalba, R., 2001. Assessing the synchroneity of glacier fluctuations in the Western Cordillera of the Americas during the last millennium. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, pp. 119–140.

Luckman, B.H., Wilson, R.J.S., 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised records. Climate Dynamics 24, 131–144.

Mark, B.G., 2007. Tracing tropical andean glaciers over space and time: some lessons and transdisciplinay implivations. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.032.

Maisch, M., Haeberli, W., Hoelzle, M., Wenzel, J., 1999. Occurrence of rocky and sedimentary glacier beds in the Swiss Alps as estimated from glacier-inventory data. Annals of Glaciology 28, 231–235.

Mann, M.E., Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophysical Research Letters 30 (15), 1820. doi:10.1029/2003GL017814.

Masiokas, M.H., Villalba, R., Luckman, B.H., Lascano, M.E., Delgado, S., Stepanek, P., 2007. 20th-century glacier recession and regional hydroclimatic changes in northwestern Patagonia. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.031.

Mayewski, P.A., Eelco, E., Rohling, J., Stager, C., Karle´n, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quaternary Research 62, 243–255.

Menounos, B., Koch, J.S, Osborn, G., Clague, J., Mazzucchi, D., 2004. Early Holocene glacier advance, southern coast mountains, British Columbia, Canada. Quaternary Science Reviews 23 (14–15), 1543–1550.

Miller, G.H.W., Brinera, A.P., Sauer, J.P., Nesje, P.E., 2005. Holocene glaciation and climate evolution of Baffin Island, Arctic Canada. Quaternary Science Reviews 24 (14–15), 1703–1721.

Moberg, A., Sonechkin, D., Holmgren, K., Datsenko, N., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution data. Nature 433, 613–617.

Nesje, A., Bakke, J., Dahl, S.O.,Lie, Ø., Matthews, J. A., 2007. Norwegian mountain glaciers in the past, present and future. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.08.004.

Nesje, A., Dahl, S.O., 2001. The Greenland 8200 cal. yr BP event detected in loss-on-ignition profiles in Norwegian lacustrine sediment sequences. Journal of Quaternary Science 16 (2), 155–166.

Nesje, A., Jansen, E., Birks, J.B., Bjune, A.E., Bakke, J., Andersson, C., Dahl, S.O., Kristensen, K., Lauritzen, S.E., Lie, O., Risebrobakken, B., Svendsen, J.-I., 2005. Holocene climate variability in the northern north Atlantic Region: a review of terrestrial and marine evidence. The Nordic Seas: an integrated perspective. Geophysical Monograph Series, vol. 158. AGU, pp. 289–322.

Oerlemans, J., 2001. Glaciers and Climate Change. Balkema, Rotterdam.

Oerlemans, J., 2005. Extracting a climate signal from 169 glacier records. Science 308 (5722), 675–677.

Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Johannesson, T., Knap, W.H., Schmeits, M., Stroeven, A.P., van de Wal, R. S.W., Wallinga, J., Zuo, Z., 1998. Modelling the response of glaciers to climate warming. Climate Dynamics 14, 267–274.

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., Haeberli, W., 2004. Rapid disintegration of Alpine glaciers observed with satellite data. Geophysical Research Letters 31, L21402. doi:10.1029/2004GL020816.

Porter, S.C., 1981. Recent glacier variations and volcanic eruptions. Nature 291, 139–141.

Porter, S.C., Denton, G.H., 1967. Chronology of neoglaciation in the Northern American Cordillera. American Journal of Science 265, 177–210.

Raymond, Ch., Neumann, T.A., Rignot, E., Echelmeyer, K., Rivera, A., Casassa, G., 2005. Retreat of Glaciar Tyndall, Patagonia, over the last half-century. Journal of Glaciology 51 (173), 239–247.

Rignot, E., Rivera, A., Casassa, G., 2003. Contribution of the Patagonia Icefields of South America to sea level rise. Science 302, 434–437.

Rimbu, N., Lohmann, G., Lorenz, S.J., Kim, J.H., Scheider, R.R., 2004. Holocene climate variability as derived from alkenone sea surface temperature and coupled ocean–atmosphere model experiments. Climate Dynamics 23, 215–227.

Schotterer, U., Grosjean, M., Stichler, W., Ginot, P., Kull, C., Bonnaveira, H., Francou, B., Gäggeler, H.W., Gallaire, R., Hoffmann, G., Poyaud, B., Ramirez, E., Schwikowski, M., Taupin, J.D., 2003. Glaciers and climate in the Andes between Equator and 30°S: what is recorded under extreme environmental conditions? Climatic Change 59, 157–175.

Schwikowski, M., 2006. Paleoenvironmental reconstruction from Alpine ice cores. Pages News 14 (1), 16–18.

Seltzer, G.O., Rodbell, D.T., Abbott, M., 1995. Andean glacial lakes and climate variability since the last glacial maximum. Bulletin de l'Institut Francais d'Etudes Andines 24, 539–549.

Shulmeister, J., 1999. Australasian evidence for mid-Holocene climate change implies precessional control of Walker Circulation in the Pacific. Quaternary International 57–58, 81–91.

Snyder, J.A., Werner, A., Miller, G.H., 2000. Holocene cirque glacier activity in western Spitsbergen, Svalbard: sediment records from proglacial Linne'vatnet. The Holocene 10 (5), 555–563.

Steiner, D., Walter, A., Zumbühl, H.J., 2005. The application of a nonlinear backpropagation neural network to study the mass balance of Great Aletsch Glacier. Journal of Glaciology 51 (173), 313–323.

Stoetter, J., Wastl, M., Caseldine, C., Haberle, T., 1999. Holocene palaeoclimatic reconstruction in northern Iceland: approaches and results. Quaternary Science Reviews 18 (3), 457–474 (18).

Thompson, L.G., 2005. In: Huber, U.M., Burgmann, H.K.H., Reasoner, M.A. (Eds.), Global Change and Mountain Regions (A State of Knowledge Overview). Springer, Dordrecht, pp. 225–234.

Wanner, H., Holzhauser, H., Pfister, C., Zumbuehl, H., 2000. Interannual to century scale climate variability in the European Alps. Erdkunde (Earth Science) 54, 62–69.

Wiles, G.C., Barclay, D.J., Calkin, P.E., Lowell, T.V., 2007. Century to millennial-scale temperature variations for the last two thousand years indicated from Glacial Geologic Records of Southern Alaska. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.036.

Wiles, G., D'Arrigo, R., Villalba, R., Calkin, P., Barclay, D.J., 2004. Century-scale solar variability and Alaskan temperature change over the past millennium. Geophysical Research Letters 31 (L15203).

Villalba, R., 1994. Tree-ring and glacial evidence for the Medieval Warm Epoch and the Little Ice Age in southern South America. Climatic Change 26, 183–197.

Yang, B., Bräuning, A., Dong, Z., Zhang, Z., Keqing, J., 2007. Late Holocene monsoonal temperate glacier fluctuations on the Tibetan Plateau. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.07.035.

Zemp, M., Haeberli, W., Hoelzle, M., Paul, F., 2006. Alpine glaciers to disappear within decades? Geophysical Research Letters 33, L13504. doi:10.1029/2006 GL026319.

Zumbühl, H.J., Steiner, D., Nussbaumer, S.U., 2007. 19th century glacier representations and fluctuations in the central and western European Alps: an interdisciplinary approach. Global and Planetary Change. doi:10.1016/j.gloplacha.2006.08.005.

Please cite this article as: Solomina, O. et al. Historical and Holocene glacier–climate variations: General concepts and overview. Glob. Planet. Change (2007), doi:10.1016/j.gloplacha.2007.02.001