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HOLOCENE MOUNTAIN GLACIER FLUCTUATIONS: A GLOBAL OVERVIEW

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Since one century mountain Holocene glacier fluctuations are considered as proxies of climate changes. Starting from the Alps, studies in all the mountain regions from poles to the equator revealed a multitude of high-frequency glacier fluctuations, mainly related to local-regional climate variability. On the long trend at the millennial scale, a more coherent pattern of glacier advance/retreat phases is emerging, if not worldwide at least at the hemispheric level.

In the northern hemisphere mountain glaciers at the beginning of the Holocene were still retreating from Late Glacial positions, but 10 thousand years ago they were already reduced to the present size. From 10 to 5-6 thousand years ago mountain glaciers of the northern hemisphere were mainly reduced to their minimum size, and locally they even entirely disappear.

During the last 5-6 millennia mountain glaciers re-expanded, recording several phases of advances, more and more extended and long-lasting, collectively referred to as *Neoglaciation*. During the last of these phases, known as Little Ice Age (XIV-XIX centuries), mountain glaciers of the northern hemisphere generally reached their maximum extent. As in the previous neoglacial phases, the Little Ice Age consisted of several advances, not exactly comparable (in time and extent) in the different mountain areas.

In the southern hemisphere the knowledge is more scanty, with significant differences in humid and in dry areas. Largest advances occurred during the early-mid Holocene, while the Little Ice Age moraines are ubiquitous but often not the more external.

During the last century mountain glaciers are retreating all over the world (with some exceptions) at a rate accelerating in the last decades. A few small glaciers are presently reduced to pre-neoglacial size, while larger glaciers, due to decades-long response time, are not yet in equilibrium with present climate conditions.

KEY WORDS: Holocene, Mountain glacier fluctuations, Italian Alps.

MOUNTAIN GLACIERS AND CLIMATE CHANGE

Mountain glaciers, being largely composed of ice at the melting point, are highly sensitive to climate changes, responding with mass and size variations and changes of flow dynamics. This is particularly true for the temperate glaciers of the humid regions such as the Alps, characterized by a high turnover (high snow accumulation and intense summer melting) and consequently by a relatively fast flow. The small temperate mountain glaciers (e.g. the cirque glaciers) respond almost immediately, feeling the effects even of the annual variability. The medium size valley glaciers respond with years of delay to multiannual/decadal climate changes, while the largest composite valley glaciers respond uniquely to multidecadal/secular climate changes, with dozens of years of delay. Therefore mountain glaciers terminating on land, which are widely distributed and present even at the equator, have long been considered as proxies of climate changes, and reconstructions of their fluctuations were among the first records used to unravel the history of the Holocene climate (Davis & *alii*, 2009). However glacier/climate interactions are quite complex and differ from high to low latitudes and from humid to arid regions. A large number of studies have been done to disentangle the effects of the various climatic parameters on present glaciers (e.g. Hoinkes, 1968; Kuhn, 1981; Ohmura & *alii*, 1992; Kaser, 2001, Winkler & *alii*, 2010) and an even more large literature is growing on glaciers and climate change (e.g. Oerlemans, 2001, 2005; Zemp, 2006).

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RECENT AND ONGOING GLACIER FLUCTUATIONS

The easiest way to monitor glacier variations is the repeated measurement of length and volume changes. Systematic measurements of glacier frontal fluctuations began on the Alps at the end of the XIX century and since the late fifties of the past century glaciers fluctuations in many mountain areas are monitored under the coordination of the World Glacier Monitoring Service (http://www.geo.uzh.ch./wgms).

Continuous records of glacier length variations are therefore available from many parts of the world and, more recently and for a limited number of glaciers, of yearly mass balance data. These records clearly show the global effects of the warming during the last three decades, with a general trend of rapid, if not accelerating, glacier shrinkage, even though a high variability is observed in the individual fluctuations series (Zemp & van Woerden, 2008). Furthermore, a recent analysis on Swiss glaciers showed that at least part of the ongoing phase of glacier mass loss in the Alps may be ascribed to the natural multidecadal climate variability (Huss & *alii*, 2010).

For a few glaciers of the Alps, historical documents, pictures, maps and engravings allow a reconstruction of the frontal fluctuations since the XVIII century, or, for a larger number, since the first half of the XIX century, when glaciers lastly reached their maximum extent at the end of that multicentury phase of glacier growth, in the second millennium, known as Little Ice Age (Grove, 2004). For this period, documents can be compared with field evidence: in this way the recent and past history of glaciers can be connected, the latter being based only on geologic and geomorphic studies.

GEOLOGIC EVIDENCE OF PAST GLACIER FLUCTUATIONS

Mountain glaciers leave in the surrounding environment direct traces of their past presence and activity, thus allowing the reconstruction of the history of their changes in length, volume, morphology, flow dynamics, temperature, hydrology, mass balance, etc. If non-climatic forcing can be excluded, those changes record the glacier reaction to climate fluctuations.

The most common, direct features left by glaciers are the marks of their past maximum extent or of nested minor and later advances, such as marginal moraines, drift limits and trim lines (Orombelli, 2005). Older phases of glacier activity, exceeded by larger later advances, can be recognized on the base of stratigraphic evidence (Porter & Orombelli, 1985). Past glacier fluctuations can also be reconstructed with studies of trees and vegetation (Pelfini, 1999) or of lacustrine sediments from glacier-fed lakes (Karlen & Matthews, 1992; Bakke & *alii*, 2005), while vegetation changes recognized in pollen diagrams from nearby peat bogs not necessarily reflect glacier fluctuations.

Various dating methods are available to determine the age of sediments, soils, rock surfaces, blocks, stratigraphic sequences related to past glacier fluctuations, ranging from numerical techniques (among the most used: radiocarbon, cosmogenic isotopes, dendrochronology, lichenometry, varve counting, etc.) to relative dating methods (geomorphic, paleobiologic, paleosols, etc.). In this way it is possible to reconstruct a chronologic sequence of glacier advance and retreat phases, more or less strictly bracketed by dates, and for the advance phases it is also possible to evaluate length, surface, volume, equilibrium line altitude for a single glacier or groups of glaciers. On the other hand, information on glaciers extent in the retreat phases is much more scanty and approximate. In general the geologic evidence produces a discontinuous and poor time-resolved record of glacier fluctuations, with the high frequency variations often obscuring the long trend/millennial changes.

STUDIES ON THE HOLOCENE GLACIER FLUCTUATIONS IN THE ALPS AND IN OTHER MOUNTAIN REGIONS

Geologic studies on the Holocene glacier fluctuations started on the Alps in the second half of the XIX century, when moraines were in a phase of active construction at the margins of valley glaciers, and could be compared with nearby older, stabilized and vegetated moraines. Starting from the end of the XIX century, in several separated Alpine districts, and often independently, a sequence of Holocene glacial events or phases was gradually reconstructed and named with a local terminology. An increasing number of glacial advance/retreat phases were recognized so that the Holocene on the Alps became almost entirely saturated by overlapping glacier events, which could not be clearly separated. This was due to insufficient time-resolution dating, to the widespread use of indirect stratigraphic evidence, and to many other sources of errors.

The evolution of knowledge can be followed in the last decades in the schemes proposed by Patzelt (1977), Röthlisberger (1986), Furrer & *alii* (1987), Grove (1988), Maisch (2000), mainly concerning the Austrian and Swiss Alps.

More recently the interest moved towards the past phases of glacier minima, evidenced by the finding of organic remains in recently deglaciated areas, such as peat or logs, *in situ* or reworked by melt water streams, and of archaeological remains (Nicolussi & Patzelt, 2000, 2001; Hormes & *alii*, 2001; Joerin & *alii*, 2008; Hormes & *alii*, 2006; Grosjean & *alii*, 2007, Ivy-Ochs & *alii*, 2009). These findings ignited a discussion weather the present extent of glaciers on the Alps is entirely new for the Holocene or phases with glacier reduction greater than now (the «green Alps») were also common in the past ten thousand years.

On this point it must be remembered the findings, on the Italian Alps, of peat near the front of the Ruitor Glacier at 2510 m, since 1957 (Peretti & Charrier, 1967; Charrier & Peretti, 1972, 1975; Armando & *alii*, 1975; Armando

& Charrier, 1985; Porter & Orombelli, 1985; Burga,1991, 1993, 1995; Orombelli,1998) and of the «iceman» in the upper accumulation area of the Giogo Basso (Niederjoch) Glacier (Baroni & Orombelli, 1996), clearly indicating a phase of glacier contraction during the middle Holocene, in the Italian Alps, with glaciers much more reduced than now.

Beside the Alps, studies on Holocene glacier fluctuations covered many mountain regions, particularly Scandinavia, the Western Cordillera of North America, the Himalayas, the Andes and New Zealand. Several attempts to global/hemispheric synthesis were produced, with review papers and collection of papers in volumes or special issues of journals (Denton & Karlen, 1973; Röthlisberger, 1986; Porter, S.C., 1986; Clapperton & Sugden, 1988; Davis & Osborn, Ed., 1988; Grove, 1988; Frenzel & *alii*, 1997; Porter, S.C., 2000; Koch & Clague, 2006; Jansen, Overpeck & *alii*, 2007; Solomina & *alii*, 2008; Wanner & *alii*, 2008; Davis & *alii*, 2009). In the pioneering paper by Denton & Karlen (1973) three major phases of worldwide glacier advance were recognized in the last 6 000 years, peaking at about 5 300, 2 800 and 200-330 calendar year BP. A less extensive advance phase culminating at 8 000 years BP was reported in the Swedish Lapland.

Since the papers by Porter & Denton (1967) and Denton & Porter (1970), the phases of glacier advance in the second part of the Holocene, after the time of maximum warmth (Hypsithermal), were often collectively referred to as *Neoglaciation,* reserving the name *Little Ice Age* only to the last phase of advances during the last millennium.

In the following decades the increasing wealth of data obscured this first scheme with a host of glacier fluctuations, mainly reflecting the high frequency glacier variability, without a filter on the merely local histories and without a distinction among large, far-reaching advances, and minor oscillations. But in the last reviews a more coherent pattern is emerging, recognising different Holocene glacier histories in the two hemispheres.

HOLOCENE GLACIER FLUCTUATIONS IN THE ITALIAN ALPS

The southern slope of the European Alps hosts nearly a thousand glaciers, the majority of which are very small (Orombelli, 2003). Only a limited number of the Italian glaciers have a surface larger than 5 km^2. Most Italian glaciers are entirely above the tree line and their fluctuations did not affect wood and trees. Therefore organic remains suitable for ^{14}C dating are rarely found within Holocene glacier deposits. For this reason the majority of data on glacier variations on the Italian Alps are the historic ones, referring to the last oscillations of the Little Ice Age.

After the last phases of Late Pleistocene advances, referred to the Egesen Stadial, and dated with exposure ages in Italy in the Maritime and in the Central Alps at the end of the Younger Dryas (Federici & *alii*, 2008; Hormes & *alii*, 2008), glaciers on the southern side of the Alps were reduced to their present size or possibly to a much smaller extent. La Mare Glacier (Ortles Group, Central Alps) at 10.4-10.1 ka ([1]) terminated certainly up valley of its max LIA advance (Speranza & *alii*, 1996), Ruitor Glacier (Western Alps) at 10.3-9.9 ka was much more retreated than now (2010). The max LIA end moraine deposited by Scerscen Glacier (Bernina Group, Central Alps) rests with its right terminal part upon an undisturbed peat sequence dated at the base 9.9-9.5 ka BP and at the top 0.5-0.3 cal BP (Orombelli, Baroni, Ravazzi, unpublished), recording that the LIA advance in this glacier was the maximum advance since the Early Holocene (Boreal).

For the time interval 10 to 5 ka about, very few data concerning glacier activity in the Italian Alps are available. But one locality deserves a special mention: near the present front of Ruitor Glacier, at the elevation of 2510 m, a peat section is preserved beneath glacigenic sediments. The sequence is glaciotectonically deformed, but locally portions of stratigraphically continuous sediments are preserved, documenting that peat was deposited, with only minor interruptions of sand-fine gravel sedimentation, near the present front of the glacier from about 9.5 to 7 ka.

A short episode of glacier advance, but not reaching the site of the peat sequence, possibly occurred between 7 and 6.7 ka. Ten ^{14}C dates from reworked blocks and clasts of peat contained in the covering glacigenic sediments (outwash gravel and till) are uniformly distributed between about 6.7 to 5.6 ka. In conclusion, although minor glacial advances cannot be excluded, environmental conditions favourable to peat deposition prevailed at the present front of the Ruitor glacier in the 9.5-5.6 ka time interval (Orombelli, 1998). During this long and protracted contraction phase of the Ruitor Glacier, a few evidence of advance phases are reported from the Italian Alps as, for instance, in the Adamello Group (Baroni & Carton, 1991, 1992).

During the last 5-6 millennia, there is evidence of Neoglacial advances in the Italian Alps. A first signal of glacier re-growth is given by the mummy of the so called «Iceman», buried in snow on ice-free ground at about 5.2 ka and since then continuously preserved in cold ice at the upper edge of the Giogo Basso Glacier, in the Eastern Alps, near the Italian/Austrian boundary (Baroni & Orombelli, 1996). In the Western Alps the Miage Glacier, descending from Monte Bianco, advanced and dammed the trunk valley (Val Veny), for the first time after the Late Glacial, at least since about 5-4.6 ka (Deline & Orombelli, 2005).

Advance phases are recorded at about 3-2.5 ka for a few glaciers in the Central and Western Alps (Orombelli & Mason, 1997). In particular the Forni Glacier, one of the largest in Italy, reached a frontal position a few metres outside of the subsequent maximum LIA moraine, at around 3-2.7 ka (Orombelli & Pelfini, 1985). Another phase of advance is recorded at a few glaciers in the Western and Central Alps in the Early Middle Ages around 770-960 AD (Orombelli & Mason, 1997).

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(1) All B.C. dates are reported as thousand cal. years (ka) before present.

The Little Ice Age (LIA) moraines are well preserved at the forefield of the Italian glaciers, where they generally represent their Holocene maximum advance. In the Italian Alps the LIA moraines are mainly dated to the last phase of advance in the XIX century. Earlier phases are recorded by historic documents of the Ruitor floods. When in an advanced phase, the Ruitor Glacier dammed a lake, which produced repeated outburst floods. First floods are reported at the end of the XIII century and in the first decades of the XV century (Le Roy Ladurie, 1967) while better documented floods occurred each year from 1594 to 1598, in 1630, 1640, 1646, 1679, 1680, 1751, and the last one in 1864. As already observed by Sacco (1917), the outburst floods occurred when the Glacier reached a critical size, a bit smaller than the maximum size shown by the more external moraines left in the first half of the XIX century.

A few moraines and advance phases have been dated to the first decades of the XVII century (Deline, 1999; Strada, 1987; Pelfini, 1999), but the best documented part of the LIA is in the first half of the XIX century. In the Western Alps many glaciers reached their maximum extent in 1818-1820. After a retreat in the 1830s a second largest advance occurred in 1845-1860 (e.g. Orombelli & Porter, 1982). In the Central Alps the Forni glacier reached its maximum size in 1859 (Pelfini, 1987). Since the second half of the XIX century the Italian glaciers are retreating, with only minor re-advance phases around 1890-95, 1920-25 and 1965-1985, on more and more retreated positions.

HOLOCENE GLACIER FLUCTUATIONS IN THE ALPS

A review on «Latest Pleistocene and Holocene glacier variations in the European Alps» was recently published by Ivy-Ochs & *alii* (2009), mainly dealing with Swiss and Austrian Alps. At the beginning of the Holocene, during the Preboreal, glaciers were still retreating from the maximum extent reached with the Egesen Stadial (Younger Dryas), with minor fluctuations, locally named Kartell Stadial.

From around 10.5 ka to about 3.3 ka alpine glaciers «were smaller than today for most of the time», with only a few short phases of re-advance, when small glaciers could reach approximately their subsequent LIA extent, while the largest remained well behind. These short advance phases are reported mainly from the Austrian Alps, but they partly coincide with glacier recession periods in the Swiss Alps.

After 3.8 ka small glaciers started to re-advance with a first advance phase (Löbben oscillation, 3.8-3.4 ka). The great Swiss glaciers (Aletsch, Lower Grindelwald, Gorner) advanced between 3.0 and 2.6 ka, during the Göschener I oscillation, recorded by many glaciers in the Alps during the Iron Age. After a period of glacier recession during Roman times, another phase of advance is well recorded by the Aletsch and by many other alpine glaciers in the Early Middle Ages (Göschener II oscillation). Archaeological remains indicate glacier contraction during IX and X century AD. A minor advance occurred at the Aletsch and Gorner glaciers in the XI-XII century. Finally, from the XIV to the XIX century, during the Little Ice Age, all the glaciers of the Alps advanced, generally reaching their maximum extent. Three major phases are clearly recorded by the Aletsch Glacier, peaking at 1360-90, 1600-50 and 1820-60 (Holzhauser & *alii*, 2005).

HOLOCENE GLACIER FLUCTUATIONS IN THE WORLD

From the most recent general reviews quoted above, a global coherent pattern at the millennial time scale is emerging from the studies of Holocene mountain glacier fluctuations, whereas, at the secular/decadal time scales, regional and local variability prevails. This is possibly due to real local factors and/or to often insufficient time resolution of the dating methods. During the last millennium a broad similarity of glacier activity is recognized, with high coherence during the last century and especially in the last decades.

At the millennial time-scale, mountain glaciers of the northern hemisphere, during large part of the first half of the Holocene were more reduced than now, while during the last six millennia glacier advanced several times, reaching their maximum extent (Neoglaciation). On the contrary in the southern hemisphere (and in Himalaya and Tibet), where data are more scanty, mountain glaciers most significantly advanced in the first half of the Holocene, but advances are also reported in the last 2-3 millennia, particularly in the LIA (Davis & *alii*, 2009).

In the northern hemisphere, after the Younger Dryas (and possibly early Holocene) advances, mountain glaciers retreated behind their modern marginal positions in Alaska, Western Canadian and American Cordilleras, Baffin Island, Greenland; the Iceland Ice Sheet was in rapid retreat by 10.3 ka and after 8.ka the island was mostly ice free. Early Holocene advances (Preboreal and Boreal) are reported from Scandinavia. Glacier advances occurred at around 8.4 to 8.2 ka in Scandinavia, 8.6 to 8.2 and 7.4 to 6.4 ka in the Western Canadian Cordillera.

The Neoglaciation started at around 6.0 ka in Scandinavia, Baffin island, Iceland and at 5.0 ka in Alaska. Neoglacial advance phases are reported from 4.5 to 4.0 ka in Western Canadian Cordillera and in Iceland, at about 3.5 to 2.5 ka in Alaska, Western Canadian Cordillera, Baffin Island, and Scandinavia. Early Middle Ages advances are reported from Western Canadian Cordillera, Baffin Island and Scandinavia. The Little Ice Ages moraines are very often the best preserved and imposing Holocene moraines, marking the largest glacier advance since the Late Glacial (Western Canadian and American Cordilleras, Baffin Island, Greenland, Iceland). The LIA initiated as early as the XI century (Western Canadian Cordillera) or most often by the XIII-XIV centuries (Alaska, Greenland, Iceland, Scandinavia). Most prominent phases of advance occurred at the XIV century (Baffin Island), XVI-XVIII centuries (Alaska, Baffin Island, and Scandinavia), XIX century (Alaska, Western Canadian Cordillera, Baffin Island).

In conclusion the Holocene history of mountain glaciers of the northern hemisphere can be broadly subdivided in three main periods:

- a first period (11.7 ka to ~ 9 ka BP), corresponding to Preboreal-Boreal chronozones, with (large) mountain glaciers retreating (with minor re-advances) from the positions reached during the latest Pleistocene stadial, back to frontal positions comparable to the present ones;
- a second period (~ 9 ka to 5-6 ka), roughly corresponding to the Atlantic chronozone, and sometimes indicated as *Hypsitherml*, with mountain glaciers for most of the time in a reduced size, if not smaller than now;
- a third period (the last 5-6 ka) corresponding to the Subboreal-Subatlantic chronozones, and often referred to as *Neoglaciation* or *Neoglacial*, characterized by a renewed glacier activity with at least 3-4 major multisecular phases of advance, culminating at around 5.0 ka, 3.0-2.5 ka, 1.7-1.3 ka and 0.7-0.1 ka (LIA).

In the southern hemisphere Holocene mountain glacier fluctuations were studied in the Andes, New Zealand and local glaciers in Antarctica. In the Andes, south of the equator, Holocene glacier fluctuations were significantly different between the arid subtropical, and the humid tropical and mid latitude zones (Rodbell & *alii*, 2009).

In South America (except the arid subtropical Andes) and New Zealand there is evidence for early to mid Holocene substantial advances, in many cases reaching the most extensive positions. Neoglacial advances are reported at about 6.5 ka in New Zealand, as early as 5.0 ka in Antarctica, at 3.7 to 3.2 ka in New Zealand, from about 2.3 to1.7 ka in New Zealand and in South America. Several advance phases are reported from New Zealand from the Early Middle Ages to the LIA.

The most complete and recent record of Holocene glacier fluctuations (Schaefer & *alii*, 2009) shows that they were not in phase with those of northern hemisphere glaciers, except for the Early Middle Ages and LIA advances.

The Little Ice Age moraines are ubiquitous in the Andes, and mostly date to the past 450 years. LIA advances were not the most extensive during the Holocene, except in the arid Andes, surrounding the Bolivian Altiplano. Finally LIA advances were also reported from Antarctic local alpine glaciers (Baroni & Orombelli, 1994; Hall, 2009).

PATTERN AND CAUSES OF HOLOCENE GLACIER FLUCTUATIONS

As discussed above, during the Holocene mountain glaciers have been affected by repeated phases of multisecular glacier expansion, each composed of numerous distinct frontal advance and retreat episodes, and separated by longer time intervals of glacier contraction.

Cyclicity in Holocene glacier fluctuations and, more generally, in climate variations has been the topic of many papers. Denton & Karlen (1973) first suggested, for the Holocene and the Late Glacial, a recurrence of major phases of glacier advance with a periodicity of about 2500 years. Referring to the Denton & Karlen's paper, but on the base of evidence from deep sea and Greenland ice cores, Bond & *alii* (1997) recognized a pervasive cyclicity of about 1500 years, which they connected to the variations of the solar output, over the Last Glaciation and the Holocene. Since then a 1500 years cycle has been frequently reported in many Holocene records (Mayewski & *alii*, 2004; Wanner & *alii*, 2008). Shorter solar cycles have been compared with shorter (multidecadal to multiannual) glacier advance/retreat phases (Holzhauser & *alii* (2005), but, according to Wanner & *alii* (2008), except for the 1500 years Bond cycles, there is «scant evidence for consistent periodicities» in the last 6 ka.

In a number of papers (e.g. Mayewski & *alii*, 2004) rapid climatic changes, not comparable in magnitude to those of the last glaciation but occurring in a few decades, have been indicated in the Holocene. Were the glacier fluctuations connected to these rapid changes? Small glaciers respond quickly to climate forcing. Time-distance curves obtained from yearly length variations for many alpine glaciers in the last century reveal sharp (one to few years) turning points from advancing to retreating episodes and vice versa. Larger glaciers, on the other hand, as shown by the time-distance curve of the great Aletsch glacier, do not show any sudden relevant change (Herren & Bauder, 2008). On a longer time scale, the reconstructed time-distance curve of the Great Aletsch Gl. shows transition from advancing to retreating episodes lasting a few decades (Holzhauser & *alii*, 2005).

A rapid climate change has been suggested by Baroni & Orombelli (1996) at about 5300-5050 ka for the millennial persistent snow burial of the «Iceman» over ice-free ground. A major widespread climatic change is also reported at this time by Magny & Haas (2004). A rapid climate change at around 2650 ka, possibly in relation to a glacier advance in the Alps, has been indicated by Van Geel & *alii* (1996). Minor glacier advances have been correlated to the 8.2 ka short cooling event (Davis & *alii*, 2009) but no evidence of the 8.2 ka advance has been found in other well dated glacier fluctuations records.

The problem of the causes of Holocene glacier fluctuations has been discussed in many papers (e.g. Denton & Karlen, 1973; Porter, 1986; Holzhauser & *alii*, 2005; Koch & Clague, 2006; Wanner et al. 2008). Following Clague et al. (2009) it is convenient to distinguish between long term and short term causes.

If we consider the long trend of glacier variations along the entire Holocene (last 11.7 ka), we can recognize in the northern hemisphere a general increase of mountain glacier activity, in terms of frequency, duration and surface extent of glacier advances (with the exception of the early Holocene local inheritance of Late Pleistocene advances). This long term trend has been attributed to the precessional decrease of summer insolation at mid-high latitude in the northern hemisphere: mean June insolation at 60° N decreased from about 520 W/m^2 at 11.0 ka to the present minimum value of 475 W/m^2 (Koch & Clague, 2006; Orombelli, 2007).

The low summer insolation in the southern hemisphere at 60 °S during early-mid Holocene, increasing to a maximum value at 4-3 ka and subsequently declining, on the contrary, could explain the larger extent reached by the Andean and New Zealand mountain glaciers in the early-mid Holocene and the subsequent late Neoglacial advances.

At a shorter time-scales (millennial to multisecular), the repeated (quasiperiodic?) major phases of glacier advances have been attributed to different causes. If these major phases of glacier advances can be considered broadly worldwide synchronous, the variations of solar radiation, as deduced from changes in production rates of the cosmogenic nuclides carbon-14 and beryllium-10, have been proposed as a possible cause by Denton & Karlen (1973), Mayewski & *alii* (2004), Holzauser & *alii* (2005), Koch & Clague (2006). Whether or not these major phases of glacier advance are synchronous in the two hemispheres is still debated (Schaefer & *alii*, 2009): if not, as possibly for Late Glacial stadials, a connection with thermohaline circulation variations has been discussed (Denton & Broeker, 2008).

At a still shorter time-scale (secular to decadal) mountain glacier variations have been attributed to solar activity (Holzhauser & *alii*, 2005), to volcanic explosive activity (Porter, 1986), or to internal oscillations of the coupled ocean-atmosphere system (such as ENSO, NAO, etc.), as discussed by Huss & *alii* (2010) for recent mass balance variations in the Swiss Alps.

It has also been suggested that glacier and climate variations have been caused by a combination of different causes (Wanner & *alii*, 2008).

FREQUENTLY ASKED QUESTIONS

Mountain glaciers are considered among the clearest evidence of the effects of climate change and global warming. People living or frequenting mountain areas during the summer season can directly observe, year after year, the retreat of the glaciers, comparing their present extension to that in the recent past, as fixed in photos or postcards, or recognize in the landscape the large areas recently abandoned by glaciers. Therefore there are no doubts to associate the glacier retreat to the recent general increase of temperature and duration of the ablation season (Zemp & *alii*, 2006).

What is not clear to the public opinion is whether the present glacier condition is natural and common or represents an anomalous and new fact. In other words, are the present glaciers less extended than in the past centuries and millennia or, better, in any time of the present interglacial (the Holocene)? Is the present rate of mountain glacier retreat unusual? Is the present phase of retreat/collapse attributable to the human forcing on climate?

Mountain glaciers during the Holocene have been certainly much more reduced than now. For the northern hemisphere this is generally true for the time interval from 10 to 5-6 ka, but locally also more recently up to 3.3 ka and, for short episodes, also later. On the other hand there is local evidence in the Alps of small glaciers at present more reduced than in any time over the past 5 ka. Large glaciers (such as the great Aletsch Gl.) were possibly smaller than now during Bronze Age and Roman times (Holzhauser & *alii*, 2005), but they are not yet in equilibrium with the present climatic conditions, due to a long (several decades) estimated response time (Haeberli, 1996).

There are some considerations suggesting that the present state of mountain glaciers is unusual and unexpected. First the present (last decades) phase of marked glacier retreat, with few exceptions, is a worldwide and simultaneous fact, differing from previous phases of retreat characterized by a large space and time variability. Second the rate of retreat and volume decrease of mountain glaciers accelerated in the last three decades (Zemp & Van Woerden, 2008), and it is considered 10 times faster than the average rate of volume decrease during the last deglaciation, which lasted 7 ka. In many glacier groups this phase of decrease is described as an accelerated glacier shrinkage if not a glacier collapse (e.g. Paul & *alii*, 2004). Third, if we consider the long trend (last millennia) of glacier fluctuations in the northern hemisphere (most probably controlled by the declining insolation), characterized by progressively greater (in extent and duration) phases of glacier advance and by shorter and faint phases of glacier retreat, the present marked retreat phase appears unusual and difficult to model when referring only to natural causes. The retreat of mountain glacier since their maximum LIA extent can be well correlated with the increase of the global mean annual air temperature since the mid 19th century, which is considered most likely human-induced for the most part (UNEP-WGMS, 2010). At the scale of decades, natural climatic oscillations may produce glacier fluctuations superimposed over the long trend (Huss & *alii*, 2010): it is therefore reasonable to think that the present phase of accelerated retreat of mountain glaciers is the result of intertwined natural and human-induced causes.

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