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Alpine climate during the Holocene: a comparison between records of glaciers, lake sediments and solar activity

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ABSTRACT: The European Alps are very sensitive and vulnerable to climate change. Recent improvements in Alpine glacier length records and climate reconstructions from annually laminated sediments of Alpine Lake Silvaplana give the opportunity to investigate the relationship between these two data sets of Alpine climate. Two different time frames are considered: the last 500–1000 years as well as the last 7400 years. First, we found good agreement between the two different climate archives during the past millennium: mass accumulation rates and biogenic silica concentration are largely in phase with the glacier length changes of Mer de Glace and Unterer Grindelwaldgletscher, and with the records of glacier length of Grosser Aletschgletscher and Gornergletscher. Secondly, the records are compared with temporally highly resolved data of solar activity. The Sun has had a major impact on the Alpine climate variations in the long term, i.e. several centuries to millennia. Solar activity varies with the Hallstatt periodicity of about 2000 years. Hallstatt minima are identified around 500, 2500 and 5000 a. Around these times grand solar minima (such as the Maunder Minimum) occurred in clusters coinciding with colder Alpine climate expressed by glacier advances. During the Hallstatt maxima around 0, 2000 and 4500 a, the Alpine glaciers generally retreated, indicating a warmer climate. This is supported by archaeological findings at Schnidejoch, a transalpine pass in Switzerland that was only accessible when glaciers had retreated. On shorter timescales, however, the influence of the Sun cannot be as easily detected in Alpine climate change, indicating that in addition to solar forcing, volcanic influence and internal climate variations have played an important role. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: Alpine climate; glacier fluctuations; Holocene; European Alps; lake sediments; solar activity.

Introduction

Improved understanding of long-term, natural climate variability on different spatial and temporal scales is crucial to put the recent climate change in a longer-term context (e.g. Jones and Mann, 2004; Osborn and Briffa, 2006). For example, it is important to know whether comparably warm periods occurred earlier during the Holocene and what was forcing these changes (see Wanner *et al.*, 2008, for a comprehensive overview of different archives and forcing factors).

Because glaciers are considered important climate indicators (Lemke *et al.*, 2007) understanding of past and present glacier variations is a key task for evaluating current climate change. According to Denton and Karlén (1973), the Holocene experienced alternating intervals with differing intensity of glacier expansion and recession, the strongest advances occurring around 200–330, 2800 and 5300 cal a BP in North America and northern Europe. Other strong glacier advances possibly occurred around 1400 and 3800 cal a BP (Wanner *et al.*, 2008). Past treeline data from the eastern Alps, as well as radiocarbon and dendrochronologically dated wood fragments from glacier forelands in the Swiss and Austrian Alps, point to persistent periods during the Holocene during which glaciers were even smaller than during the late 20th century (Ivy-Ochs *et al.*, 2009). Other archives such as pollen and plant macrofossils (e.g. Bjune and Birks, 2008) and lake sediments (e.g. Nesje, 2009) also reveal decadal- to centennial-scale climate variations during the Holocene.

The question remains whether these climate variations have been triggered by solar variability, volcanic activity or internal variability of the climate system (Bond *et al.*, 2001; Wanner *et al.*, 2008). Here we investigate whether the influence of solar activity was a determining forcing factor on regional climate. Among the different archives reflecting past climate variations, glacier records and lake sediments from the Alps have proven potential; Alpine glaciers are highly sensitive indicators of climate changes and their fluctuations directly reflect the climatic conditions during the Holocene (Holzhauser, 2007). Lake sediments, on the other hand, are valuable palaeoclimate archives, but they are underrepresented in the data series used for quantitative regional, global or inter-hemispherical comparisons, and for quantitative, annually resolved multi-proxy climate reconstructions (Grosjean *et al.*, 2009).

The climate of the Earth is determined to a large extent by the radiative energy it receives from the Sun and its latitudinal distribution (Beer *et al.*, 2008; Gray *et al.*, 2010). Due to orbital forcing, the latitudinal distribution of solar energy has varied on long timescales, i.e. on several 10,000 years (known as Milankovitch cycles; Laskar *et al.*, 2004). It is widely accepted that changes in orbital forcing have been responsible for the regular changes between glacials and interglacials (e.g. Jansen *et al.*, 2007; Clark *et al.*, 2009).

Compared with the timescales of the orbital forcing, the variation of energy emitted by the Sun takes place on shorter

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timescales, i.e. years to millennia. The measure describing the amount of incoming solar electromagnetic energy at the mean Sun–Earth distance is called total solar irradiance (TSI). The average solar activity during the past 50 years has been high (high TSI values). In the past, however, TSI has been very low during some periods, called grand solar minima. The influence of the Sun on the Earth's climate shows up in several climate reconstructions from all over the world on different timescales (e.g. Magny, 1993; van Geel *et al.*, 2000; Bond *et al.*, 2001; Wang *et al.*, 2005a; Eichler *et al.*, 2009; Nicolussi *et al.*, 2009) as well as in modelling studies (e.g. Cubasch and Voss, 2000; Renssen *et al.*, 2005; Wagner *et al.*, 2007; Spangehl *et al.*, 2010).

One example is the Little Ice Age (LIA), a period with generally cold climate conditions, lasting from the Late Middle Ages until the mid-19th century in the Alpine region (Grove, 2004). This time period coincides with a cluster of grand solar minima. One of those grand solar minima is the well-known Maunder Minimum in the years 1645–1715 (Eddy, 1976). Compared with the most recent 50 years, solar activity was very low during the Maunder Minimum, characterized by an almost complete absence in sunspots, and lower TSI values (Wang *et al.*, 2005b; Krivova *et al.*, 2007; Steinhilber *et al.*, 2009).

Two time frames are considered within this study: the last 500–1000 years and the last 7400 years. Hence, different types of climate archives are used, with the quality and temporal resolution of the data varying. Information and methodological considerations on the corresponding archives and climate indicators are given in the next section.

Data and methods

The different records used in this study are Alpine glacier reconstructions based on historical sources (Mer de Glace, Unterer Grindelwaldgletscher) as well as dendrochronology and radiocarbon dating of changes of Grosser Aletschgletscher and Gornergletscher, lake sediment cores from Lake Silvaplana (Engadine, Switzerland), and polar ice cores whose cosmogenic radionuclides were measured and used to determine solar activity (TSI). Figure 1 shows the locations of the Alpine study sites.

Glacier reconstructions

Glacier length changes during the Little Ice Age

If sufficient in quality and quantity, written documents and pictorial historical records (drawings, paintings, sketches, engravings, photographs, chronicles, topographic maps, reliefs) provide a detailed picture of glacier fluctuations over the last few centuries. Using these data, a resolution of decades can be achieved or, in some cases, even individual years of ice margin positions are known (Zumbühl and Holzhauser, 1988; Holzhauser *et al.*, 2005).

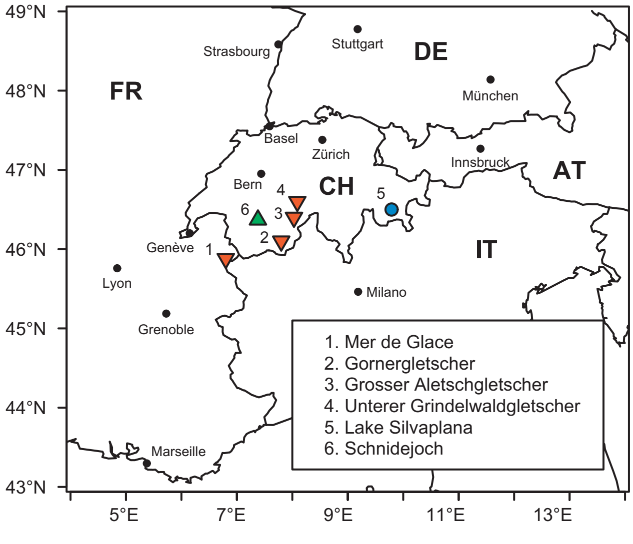

Figure 1. Locations of the study sites in the European Alps. This figure is available in colour online at wileyonlinelibrary.com.

The evaluation of historical sources, the so-called historical method, has to fulfil the following conditions to provide reliable results concerning former glacier extents (Zumbühl and Holzhauser, 1988). First, the date of the document has to be known or reconstructed. Secondly, the glacier and its surroundings have to be represented realistically and be topographically correct, which requires certain skills of the corresponding artist. Thirdly, the artist's topographic position should be known. The historical glacier reconstructions presented here include the Mer de Glace, located on the north flank of Mont Blanc (France), and the Unterer Grindelwaldgletscher in the Bernese Alps (Switzerland). The Mer de Glace (45°53′N, 6°56′E) is a compound valley glacier, 12.0 km long and covering a surface of 31.9 km^2, with the glacier terminus at 1467 m a.s.l. (data for 2001; Nussbaumer *et al.*, 2007). The Unterer Grindelwaldgletscher (46°34′N, 8°05′E) is a valley glacier 8.9 km long and covering a surface of 20.6 km^2. Today the glacier terminates at 1297 m a.s.l. in a narrow gorge (data for 2004; Steiner *et al.*, 2008b). The Mer de Glace is the longest and largest glacier of the western Alps. During the LIA, the glacier reached the bottom of the valley of Chamonix at 1000 m a.s.l., similar to the Unterer Grindelwaldgletscher which was then also threatening inhabitants of the valley. For both the Mer de Glace and the Unterer Grindelwaldgletscher, there is a wealth of historical (pictorial) documents (Zumbühl, 1980; Nussbaumer *et al.*, 2007).

The record of cumulative length fluctuations of the Mer de Glace extends back to AD 1570, with a maximum glacier extent around 1644 (largest extent during the LIA), and a slightly smaller maximum in 1821 with a second advance in 1852 (Nussbaumer *et al.*, 2007). The reconstruction of the Unterer Grindelwaldgletscher covers the period AD 1535–2004 including the two well-known glacier maxima about 1600 and 1855/1856 (Zumbühl, 1980; Zumbühl *et al.*, 1983, 2008). Comparison between the Mer de Glace length curve with that for the Unterer Grindelwaldgletscher depicts a generally synchronous development of the two glaciers with time. Correlation between these two glacier records is $r = 0.81$ ($P < 0.05$) when setting a 1-year lead of the Mer de Glace relative to the Unterer Grindelwaldgletscher.

Glacier reconstructions for the Holocene

Major glacier advances are reflected in moraines in the glacier foreland (proglacial area), where also fossil soils (palaeosols) and trees may be found once the ice has retreated. For both the Grosser Aletschgletscher and Gornergletscher, numerous fossil soils and *in situ* fossil wood pieces were found and dated by Holzhauser *et al.* (2005) using dendrochronology and the radiocarbon method.

The Grosser Aletschgletscher (46°30′N, 8°02′E) is the largest glacier in the Alps, with a length of 22.8 km and a surface area of about 81.7 km^2 (1998), terminating at 1565 m a.s.l. Since reaching its last maximum in AD 1859/1860, the glacier has receded by 4 km (Holzhauser, 2009). The length record for the Grosser Aletschgletscher spans the last 3500 years and can be considered as the most complete for Alpine glaciers, as it is based on the dendrochronologically absolute dating of fossil trees found *in situ* in the older segment, and in the most recent segment, based on archaeological, historical and glaciological evidence (Holzhauser *et al.*, 2005; Holzhauser, 2007).

Gornergletscher (45°58′N, 7°48′E), the second largest glacier in the Alps, covers a surface of about 50 km^2 and has a length of 12.3 km, with the tongue at 2240 m a.s.l. (Holzhauser, 2010). The glacier reached its maximum extension in AD 1859 as the third of three peaks during the LIA, similar to Grosser Aletschgletscher. The glacier's history is very well documented by written and pictorial documents, but in particular also by dendrochronological dating of fossil trees from the glacier foreland (Holzhauser *et al.*, 2005; Holzhauser, 2007, 2010).

A third glacier curve spanning the last 7400 years is based on findings from dendrochronology and radiocarbon dating from different glacier forelands in the Swiss Alps (Holzhauser, 2007). Note that these three long-term glacier reconstructions have a lower temporal resolution (decadal to centennial scale) than the curves solely based on historical documents for the Mer de Glace and Unterer Grindelwaldgletscher.

Lake Silvaplana

Sediment analysis

Biogenic silica and mass accumulation records from the annually laminated, proglacial Lake Silvaplana (46°27′N, 9°48′E; 1791 m a.s.l.) are available back to the year AD 1177 (Trachsel *et al.*, 2010). The chronologies rely on ^{210}Pb, ^{137}Cs and on varve counts corroborated by known flood events (Caviezel, 2007).

The annual sediment mass accumulation rate (MAR) was calculated from varve thickness accounting for water and organic matter content following Berner (1971) and Niessen *et al.* (1992). For further details see Blass *et al.* (2007b). Biogenic silica (bSi) concentration in the sediment was determined using wet alkaline leaching (Mortlock and Froelich, 1989) and inductively coupled plasma optical emission spectrometry (ICP-OES). Data were corrected for lithogenic Si according to Ohlendorf and Sturm (2007). bSi is an indicator of primary production (silicious algae) in the lake and can be influenced by both temperature and nutrient input. In Lake Silvaplana, nutrient level is stable prior to AD 1950 (Bigler *et al.*, 2007).

Comparison with glacier records

Since changes in glacier extent only influence sedimentation on multi-decadal timescales (e.g. Leonard, 1997) we applied a 50-year loess filter (locally weighted smooth regression) to the MAR prior to comparison. To compare the one-dimensional changes in glacier length with MAR influenced by the sub-glacial area (two-dimensional), we applied the square root to the MAR signal. Fifty-year loess-filtered MAR and bSi concentration were then compared with the glacier reconstructions based on historical data from the western Alps (Zumbühl, 1980; Nussbaumer *et al.*, 2007) back to AD 1535/1570. Note that glacier length is an indirect, filtered and delayed response to climate change (Oerlemans, 2001).

For Lake Silvaplana a larger glacier extent in the catchment is expected to result in increased MAR (Leemann and Niessen, 1994; Ohlendorf *et al.*, 1997; Blass *et al.*, 2007b). In general, bSi concentration is expected to show a negative correlation with glacier fluctuations because bSi is diluted ('matrix effect') by increased sedimentation during large glacier extents (e.g. Nesje *et al.*, 2001). bSi concentration is heavily affected by human-induced eutrophication after 1950 (Blass *et al.*, 2007a). We therefore restrict the comparison of bSi with glacier extents to the period prior to 1950.

Back to AD 1177 we compare the sediment-derived records with the length reconstructions of two large Alpine glaciers (Grosser Aletschgletscher and Gornergletscher; Holzhauser *et al.*, 2005). As these two glaciers have an increased response time and smoothed fluctuations, we apply a 100-year loess filter to the sediment-derived data (MAR, bSi) prior to comparison.

Solar activity

The amount of incoming solar electromagnetic energy measured at 1 astronomical unit (mean Sun–Earth distance) outside of the Earth's atmosphere is termed TSI. We use the reconstruction of TSI mainly based on the cosmogenic radionuclide ^{10}Be measured in the GRIP ice core, Greenland (Steinhilber *et al.*, 2009). To understand how TSI has been determined we briefly give a summary of how TSI was reconstructed.

Cosmogenic radionuclides such as ^{10}Be and ^{14}C are produced by nuclear reactions between cosmic ray particles and atmospheric gases. Before the cosmic ray particles reach the Earth's atmosphere they are modulated by the variable solar activity and the geomagnetic field. After their production in the atmosphere ^{10}Be and ^{14}C are transported to the ground where they can be measured in polar ice (^{10}Be) and trees (^{14}C). ^{10}Be is almost immediately (within a few years) transported to the ground and therefore directly reflects production changes due to solar and geomagnetic activity. In contrast to ^{10}Be, ^{14}C oxidizes to CO$_2$ and is involved in the carbon cycle, including exchanges between atmosphere, biosphere and the oceans. Thus, the ^{14}C signal measured in tree rings is a damped and shifted signal, implying that neither the ^{14}C signal nor the detrended ^{14}C signal can be directly used as a measure of solar activity. Even if the effect of the carbon cycle is removed from the ^{14}C signal the strong effect of the geomagnetic field has to be removed.

The geomagnetic field also has to be removed from ^{10}Be. Besides the geomagnetic and solar components climatic effects are found in the ^{10}Be signal. To remove this high-frequency climatic noise, a 40-year low-pass filter was applied. The ^{10}Be signal has then been combined with a reconstruction of the geomagnetic field intensity (Yang *et al.*, 2000) and production calculations (Masarik and Beer, 1999), from which the strength of the open solar magnetic field could be determined (Steinhilber *et al.*, 2010). The open solar magnetic field correlates with TSI during the 11-year solar cycle minima (Fröhlich, 2009), which enabled Steinhilber *et al.* (2009) to obtain TSI values from the ^{10}Be record. The application of a 40-year low-pass filter implies that the reconstruction can be used to study the solar–terrestrial relationship in the long term (multi-decadal and longer) but not in the short term (annual). The reconstruction covers the past 9300 years and it is therefore well suited to search for the solar fingerprint in the Alpine climate reconstructions during the Holocene.

Note that in the following text the term 'solar activity' is used with the same meaning as the term 'TSI'. Long-term changes in TSI and their influence on climate are then analysed for the last 500 years and for the past 7400 years.

Records of glaciers, lake sediments and solar activity during the last millennium

Results

We first compared the MAR from Lake Silvaplana with the glacier length record of nearby Tschierva glacier (Vadret da Tschierva) available back to AD 1934, to examine if the glacier extent correlates with the MAR in a proglacial lake. In addition to the visual agreement (Fig. 2) we find a correlation of $r = 0.68$ ($P = 3 \times 10^{-4}$). MAR smoothed with a 50-year low-pass filter (loess) yielded the best optical and statistical ($r = 0.97$, $P = 0.002$) agreement between the two records. We therefore

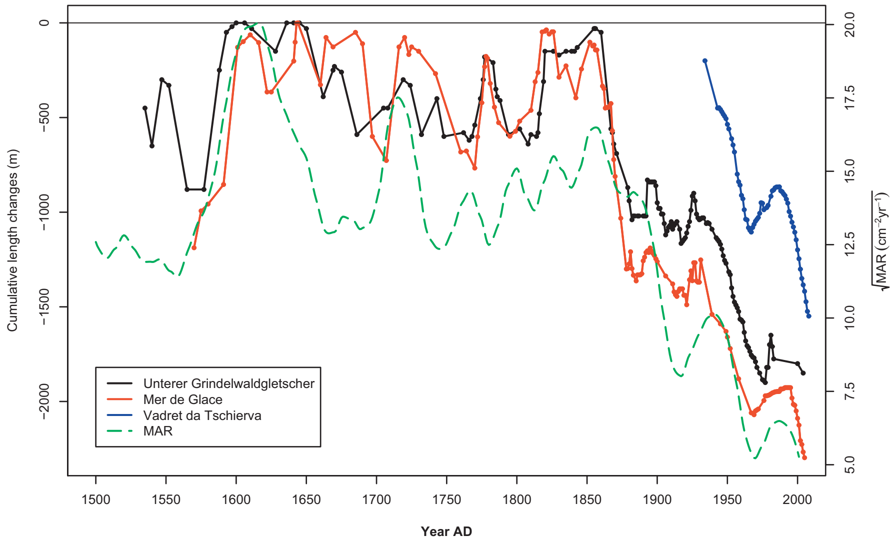

Figure 2. Comparison of Alpine glacier length changes (dots: reconstructed/measured values; lines: linear interpolation; Zumbühl, 1980; Zumbühl *et al.*, 1983; Nussbaumer *et al.*, 2007; Gletscherberichte, 1881–2009) and mass accumulation rates (MAR) in Lake Silvaplana (50-year loess-filtered; Blass *et al.*, 2007b; Trachsel *et al.*, 2010) during the past 500 years. Vadret da Tschierva (glacier length record available back to AD 1934) is in close vicinity to Lake Silvaplana. This figure is available in colour online at wileyonlinelibrary.com.

use a 50-year low-pass filter to smooth the MAR record for further comparison with glacier records.

Back to 1580 the MAR from Lake Silvaplana is in accordance with the length records of Mer de Glace and Unterer Grindelwaldgletscher (Fig. 2). In particular, the major glacier advances in the 1590 s, around AD 1710 and during the final phase of the LIA between 1810 and 1850, are clearly recorded in the lake sediment. Disagreement is found between 1750 and 1800 where the glacier reconstructions and the MAR are inversely related. Despite the large accordance in the structure, the peaks of the compared records differ. The Alpine glacier reconstructions show their maximum advances in the 17th and 19th centuries, whereas the maxima in the MAR record occur around 1620 and 1730.

We further compared MAR with the reconstructions of the two larger glaciers Grosser Aletschgletscher and Gornergletscher back to the Middle Ages (Fig. 3). MAR is increased in the 14th century, i.e. the time period when large advances of the Grosser Aletschgletscher and Gornergletscher are recorded. The timing of the advances are in very good accordance with an advance of the Unterer Grindelwaldgletscher, which is dendrochronologically dated to 1338 based on a rooted tree overrun in that year (Holzhauser *et al.*, 2005). The MAR record indicates a two-phased glacier advance in the 14th century: the first and larger one around 1340, and a second minor one in the late 14th century. An increased MAR is also found for the last two decades of the 15th century, when a small advance of the Grosser Aletschgletscher is recorded.

We find a strong inverse relationship between the bSi concentration in the sediments and the glacier reconstructions (Fig. 4). A striking feature when comparing these records is the lead of bSi concentration compared with the glacier fluctuations. The lead is not constant but varies between 8 years (in 1780) and 15 years (as in 1820). As in the MAR results, bSi and glacier records differ in the relative changes. However, the amplitudes are closer to each other than between the MAR and the glacier records. bSi concentration is higher prior to 1550 compared with 1600–1850, and prior to 1600 no general agreement between bSi concentration and glacier length changes could be detected (Trachsel *et al.*, 2010).

From the TSI reconstruction, two distinct solar minima are visible (Fig. 5), the Late Maunder Minimum from 1675 to 1715, and the Dalton Minimum between 1790 and 1830. The solar minimum at 1700–1705 is followed by a rapid advance of the Mer de Glace between 1707 and 1720. The Unterer Grindelwaldgletscher shows a less pronounced advance that

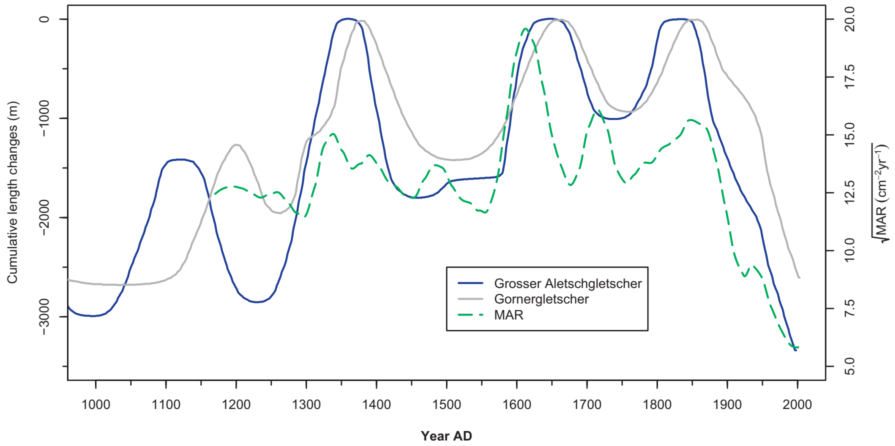

Figure 3. Comparison of long-term glacier length variations (Holzhauser *et al.*, 2005) with mass accumulation rates (MAR) in Lake Silvaplana back to AD 1170 (100-year loess-filtered; Blass *et al.*, 2007b; Trachsel *et al.*, 2010). This figure is available in colour online at wileyonlinelibrary.com.

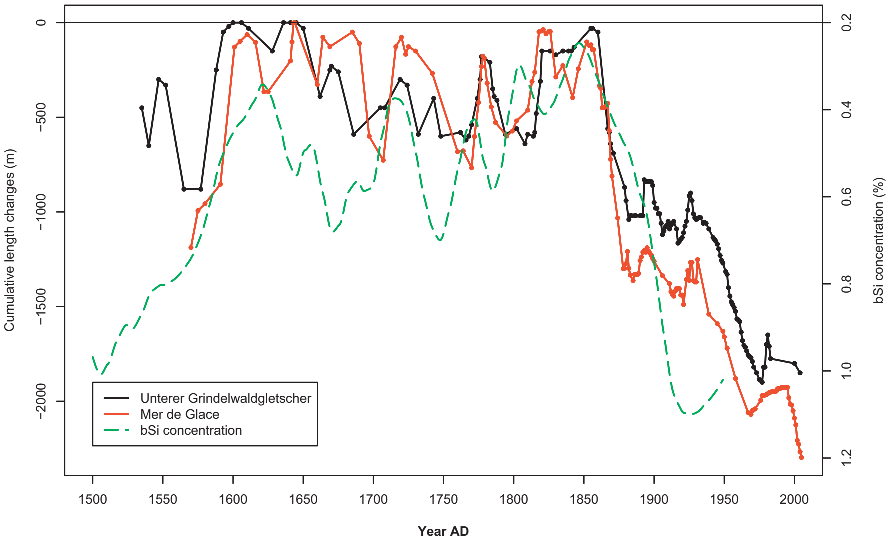

Figure 4. Comparison of glacier length changes relative to the LIA maximum (Zumbühl, 1980; Zumbühl *et al.*, 1983; Nussbaumer *et al.*, 2007) and biogenic silica (bSi) concentration in Lake Silvaplana (50-year loess-filtered; Blass *et al.*, 2007a; Trachsel *et al.*, 2010) during the past 500 years. Note that bSi is plotted on a reversed scale. This figure is available in colour online at wileyonlinelibrary.com.

lasts from about 1700 to 1719. During the Dalton Minimum the Mer de Glace and Unterer Grindelwaldgletscher glaciers are advancing rapidly. During the massive glacier retreat at 1860–1880 the Sun is in a more active state, although solar activity is not exceptional compared with other activity maxima in the last 500 years. The largest glacier advance in the last 500 years started before the end of the 16th century with the culmination points around 1600 and 1640 (Unterer Grindelwaldgletscher) and 1643/1644 (Mer de Glace). During these years solar activity is generally high, and there is no clear relationship between changes in solar irradiance and glacier lengths in the central and western Alps.

Discussion

Correlation between glacier changes and lake sediment records

The relationship between glacier extent in the catchment of a proglacial lake and the sedimentation rate is complex (e.g. Leonard, 1997; Jansson *et al.*, 2005; Hodder *et al.*, 2007). However, increased sedimentation rates often go hand in hand with increased glacial cover (Hallet *et al.*, 1996; Leonard, 1997; Nesje *et al.*, 2001; Hodder *et al.*, 2007; Menounos and Clague, 2008). This increased sedimentation is mainly explained by the increased area of sub-glacial erosion (e.g. Leonard, 1997; Menounos and Clague, 2008). For Lake Silvaplana this argument has been used by Leemann and Niessen (1994) to explain changes in sedimentation rates throughout the entire Holocene, and by Ohlendorf *et al.* (1997) and Blass *et al.* (2007b) to explain the increased sedimentation rates during the LIA. As MAR is directly related to the glacier area, its delayed response to a climate perturbation is the same as for the glacier length signal.

Increased sedimentation is found for phases with rapid glacier advances or rapid glacier retreats (Leonard, 1997; Menounos and Clague, 2008). Processes governing sedimentation rates are reviewed in detail by Hodder *et al.* (2007), including those related to climate, the glacial system,

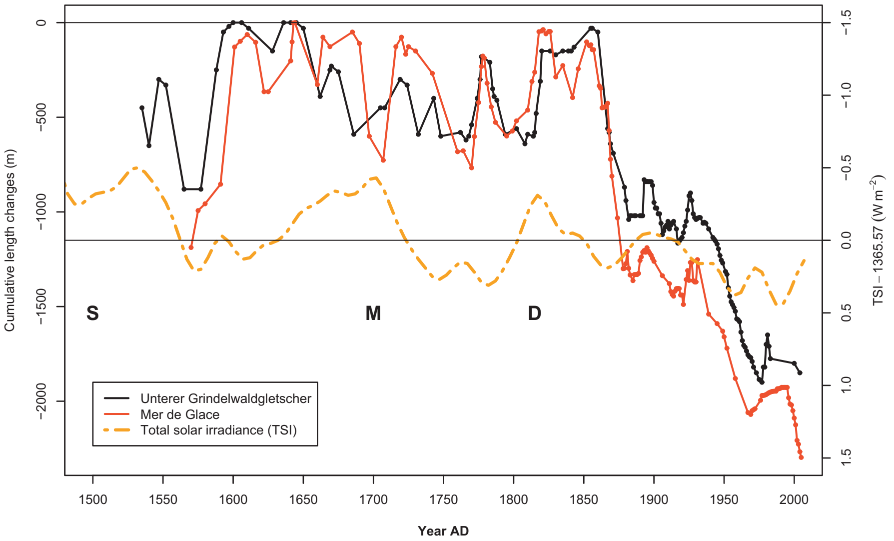

Figure 5. Comparison of glacier length changes relative to the LIA maximum (Zumbühl, 1980; Zumbühl *et al.*, 1983; Nussbaumer *et al.*, 2007) and solar activity (total solar irradiance; TSI; Steinhilber *et al.*, 2009) during the past 500 years. Grand solar minima are indicated by upper-case letters: S (Spörer), M (Maunder), D (Dalton). Note that TSI is plotted on a reversed scale. This figure is available in colour online at wileyonlinelibrary.com.

geological and geomorphological settings, and terrestrial and fluvial systems. Menounos and Clague (2008) emphasize lags between sediment formation and sediment delivery to lakes and thus changes in the sediment storage in the glacier system as resulting in non-linear relationships between glacier extent and sedimentation rate.

The comparison of MAR with the length changes of the nearby Tschierva glacier (see Fig. 2) is a good example of the combination of sediment availability and transport. The overall trend is similar, which can be clearly attributed to changes in sediment availability. Mass loss of Alpine glaciers was very high in the 1940 s (Huss *et al.*, 2009). The decrease in MAR is more pronounced between 1950 and 1970 than the retreat of the Tschierva glacier. This might be explained by the decrease in summer temperatures between 1950 and 1978 (Begert *et al.*, 2005). The decreasing summer temperatures reduce glacier melt, inducing reduced runoff, thus reducing sediment transport as well, amplifying the reduction of MAR already caused by reduced sediment availability.

For the reduction of MAR between 1900 and 1915 the process of reduced sediment transport through runoff because of reduced summer temperatures is even more important. Between 1900 and 1915 MAR decreases although the glaciers remain stable. When looking at the summer, i.e. June, July and August temperatures, the years between 1910 and 1915 are the coldest in the instrumental record spanning back to 1864 (Begert *et al.*, 2005). Although the sediment availability can be expected to be stable, the low summer temperatures reduce glacier melt, and thus less runoff is generated for transporting sediment to the lake. Hence the MAR is decreasing because of the same climate conditions that are, by contrast, allowing the glaciers to remain stable. This is supported by the findings of Blass *et al.* (2007b) which show a significant correlation between average May–September temperature and MAR in the high-frequency domain. The agreement between MAR and glacier reconstructions confirms the findings of Leemann and Niessen (1994), Ohlendorf *et al.* (1997) and Blass *et al.* (2007b) who attributed the increased sedimentation during phases with larger glacier extents to increased sub-glacial erosion. The major disagreement between MAR and the glacier reconstructions in the late 18th century might be explained by a glacier collapse in 1793 (Vadret dal Corvatsch; Caviezel, 2007). A large, former sub-glacial area was exposed to precipitation, which was then available to supply sediment for transportation to the lake, inducing the increase in MAR lasting from 1793 to 1800. The highest values of MAR occurring in the early 17th century are probably caused by the advance of the glacier in areas where it had previously not been advancing for longer periods, which resulted in a non-linear increase of erosion (Nesje *et al.*, 2001). This is again a good example for non-linearities in the relationship between glacier extent and sedimentation rate.

The increase of MAR in the late 14th and in the late 15th centuries highlights the potential of sediment-based glacier reconstructions to increase the temporal resolution of long-term glacier reconstructions based on dating of fossil wood. For example, minor advances closely following major glacier advances and thus glaciers not advancing in vegetated areas can be detected. The increased MAR in the late 14th century might indicate a minor glacier advance 40 years after the major advance. This minor advance cannot be detected in glacier reconstructions based on findings of fossil wood because 40 years is too short a time period to allow major vegetation (i.e. tree) growth. A minor glacier advance in the second half of the 15th century is in line with the reconstruction of the Grosser Aletschgletscher (Holzhauser *et al.*, 2005) and lower summer temperatures in the Alpine region around 1460 (Büntgen *et al.*, 2006; Trachsel *et al.*, 2010).

The accordance between bSi concentration or, more generally, the concentration of organic compounds and glacier extent has been widely discussed in the literature (e.g. Nesje *et al.*, 2001), and follows the same arguments as mentioned above. A large glacier erodes more material which in turn leads to more sediment transported to the lake. The increased input of clastic material dilutes the organic mater produced in the lake ('matrix effect'; e.g. Nesje *et al.*, 2001), or in our case, of biogenic silica; hence, lower bSi concentrations are expected with an extended glacier.

Studies in which the organic matter content was used to determine glacier size have a far coarser temporal resolution than we have in our study. Hence in our study an additional interesting effect can be detected: the annual bSi concentration values are not only influenced by dilution but are also dependent on the temperatures of the actual year, which partly define the primary production in the lake (Blass *et al.*, 2007a). We thus have two different processes operating on different timescales influencing the bSi concentration: dilution depends on the input of clastic sediment, which was shown to be controlled by the glacier extent, and the primary production in the lake. The glacier extent is delayed compared with summer temperature (e.g. Haeberli and Hoelzle, 1995) whereas primary production of the lake operates immediately (inter-annual timescale). The combination of these two different timescales explains the lead of bSi concentration compared with glacier fluctuations. The lead of bSi varies between 8 and 15 years compared with the glaciers, as can be seen in Fig. 4.

The primary production in the lake is even more complex than the formation of clastic sediment and is thus influenced by a greater number of processes. After 1950, bSi concentration is no longer related to climate due to human-induced eutrophication (Bigler *et al.*, 2007; Blass *et al.*, 2007a). Prior to AD 1550 the bSi concentration is higher than from 1600 to 1850 (Trachsel *et al.*, 2010), possibly indicating generally reduced glacier extents and smaller MAR values. During such phases the importance of dilution, compared with other processes such as primary production mainly driven by climate conditions and nutrient availability, is reduced (Trachsel *et al.*, 2010) explaining the low accordance between bSi concentration and glacier extents.

To study discontinuities and changes in the frequency or magnitude of time series over time, we used the Morlet wavelet for the continuous wavelet transform (Torrence and Compo, 1998). Besides the striking visual agreement between the fluctuations of the Mer de Glace and Unterer Grindelwaldgletscher, wavelet analysis suggests that the frequency content of the records has varied with time and reveals a similar behaviour of these two glaciers in the time/frequency domain (Fig. 6a). Intermittent and high wavelet power in the record of the Mer de Glace is found at periods centred at about 40 and 60 years during AD 1600–1700, and at 40 years during AD 1780–1900, respectively. High and significant (95% confidence level) wavelet power in both glacier records is found at periods between about 70 and 100 years, and around 40 years, respectively, after AD 1780. Differences are greatest from AD 1650 to 1800, especially at periods below about 50 years (Fig. 5).

On the other hand, wavelet analysis of MAR in Lake Silvaplana shows a significant frequency signal centred at about 100 years as well as at about 210 years (Fig. 6b). The spectral coincidence with the solar ~90-year Gleissberg cycle and the 208-year Suess cycle (de Vries cycle) might point to a solar influence.

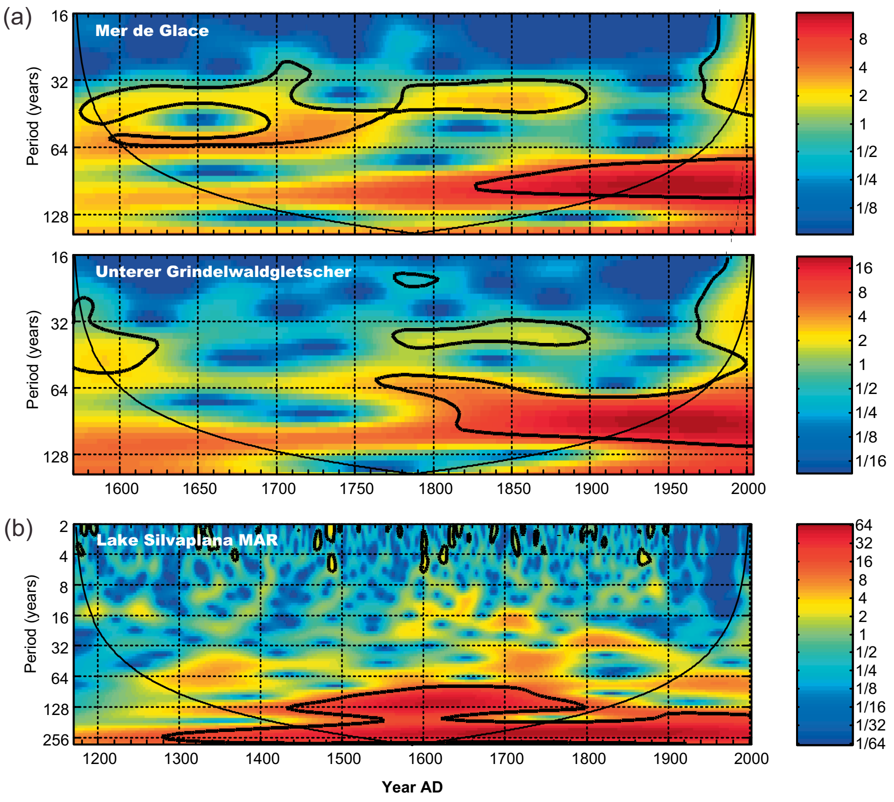

Figure 6. Wavelet power spectrum (Morlet wavelet) for (a) the Mer de Glace und Unterer Grindelwaldgletscher, and (b) MAR in Lake Silvaplana. Occurrence of the periods with respect to the time is given. Thick black contours designate the 95% confidence level. The region below the curved black line is the cone of influence (COI), where edge effects become important.

Glacier changes and solar activity

There are time periods for which accordance between the solar signal and glacier behaviour can be detected (Fig. 5): glacier advances around AD 1720, 1780 and 1820 follow, with a characteristic delay of 10–20 years, periods of low solar activity. As mass balances of Alpine glaciers are to a large degree affected by summer temperatures (Oerlemans and Reichert, 2000; Huss *et al.*, 2010), lower solar forcing reduces glacier melt during the summer season. High solar activity around 1950 and an increased anthropogenic greenhouse effect coincide with an overall retreat of the glaciers studied.

The pronounced retreat of both the Mer de Glace and Unterer Grindelwaldgletscher by the end of the 17th century coincides with low solar activity during the Maunder Minimum. Luterbacher *et al.* (2001) showed that during the Late Maunder Minimum (1675–1715), more frequent blocking situations were connected with cold air outbreaks towards central and eastern Europe, leading to very low winter temperatures together with easterly winds that bring little snowfall (Wanner *et al.*, 2000).

There are, however, periods such as the early 17th century when there is no accordance between the solar and glacier signals. The Mer de Glace and Unterer Grindelwaldgletscher reached their maximum LIA extent at that time, which may have been induced by enhanced (mainly winter) precipitation and/or reduced summer temperatures due to other processes (including internal variability).

Besides changes in solar forcing, the climate response to a given forcing is also strongly dependent on dynamic effects and on feedback mechanisms connected with clouds, water vapour, ice-cover, albedo, and atmospheric and ocean circulation (Beer *et al.*, 2000). For example, volcanic activity and its related aerosols can significantly reduce incoming solar radiation, leading to episodic cooling events characteristic of the climate during the LIA (Wanner *et al.*, 2000).

Volcanic eruptions that had a large impact on climate occurred in 1809 (unknown location) and 1815 (Tambora), leading to summer cooling and winter warming in Europe (Fischer *et al.*, 2007). These eruptions were responsible for low temperatures in the Northern Hemisphere from 1810 to 1819, which was probably the coldest decade during the past 500 years or longer (Cole-Dai *et al.*, 2009), including the 'year without a summer' in 1816 (Pfister, 1999). Superimposed on low solar activity during the Dalton Minimum, volcanic forcing additionally led to climate conditions favourable to positive glacier mass balances. This is in agreement with Steiner *et al.* (2008a) who showed that low summer temperatures were crucial for the 1810–1820 advance of the Unterer Grindelwaldgletscher.

We thus conclude that a combination of low solar forcing, frequent and strong volcanic eruptions, and dynamic effects due to internal variability of the climate system led to the prominent glacier advances during the LIA. This has also been demonstrated by modelling studies (Ammann *et al.*, 2007; Jansen *et al.*, 2007; Wanner *et al.*, 2008). For instance, Reichert *et al.* (2001) found a high correlation between decadal variations in the North Atlantic Oscillation and the mass balance of the Rhonegletscher (central Swiss Alps). This mechanism is due to internal variations in the climate system. Generally, differences in temperature and precipitation distribution in the Alps are determined by changes in the large-scale atmospheric circulation over the northern North Atlantic/European area and Eurasia, and by sea surface temperature changes at low frequency timescales, reflected in changes of the Atlantic Multidecadal Oscillation (Huss *et al.*, 2010).

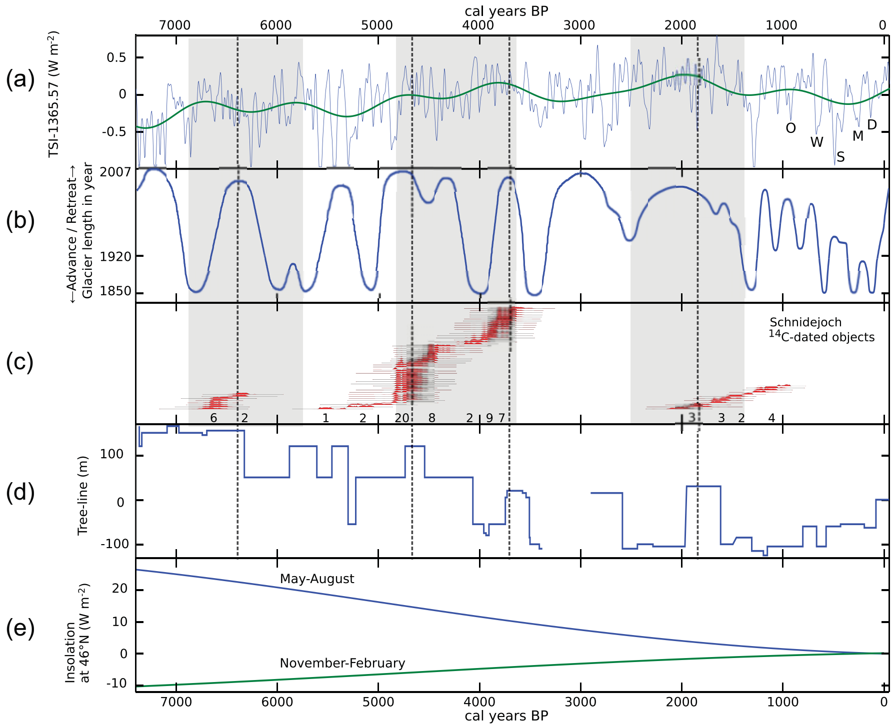

Figure 7. Comparison of different Holocene climate indicators. Grey bars: Hallstatt cycle maxima (see text). Hallstatt cycle maxima are observed around 6200, 4500 and 2000 a, and today. (a) Total solar irradiance curves of Steinhilber *et al.* (2009); bold line: low-pass filtered 1000 years; thin line: low-pass filtered 40 years. Grand solar minima for the past 1000 years are indicated by upper-case letters: O (Oort), W (Wolf), S (Spörer), M (Maunder), D (Dalton). (b) Alpine glacier length curve, calibrated (Holzhauser, 2007). Note that the *y*-axis is reversed compared with previous figures. (c) Archaeological findings at Schnidejoch: calibrated radiocarbon dates given as probability distributions and number of samples (Suter *et al.*, 2005; Hafner, 2009). (d) Treeline in the central eastern Alps relative to today (Nicolussi *et al.*, 2005). Today the treeline is at 2245 m a.s.l. (e) Mean orbital insolation at 46°N in the boreal summer (May–August) and winter (November–February) relative to today (Laskar *et al.*, 2004). This figure is available in colour online at wileyonlinelibrary.com.

Solar activity and glaciers during the Holocene

Results

The Sun and its influence on the long-term climate changes in the Alpine region during the past 7400 years is analysed in the following by using the TSI record of Steinhilber *et al.* (2009) and the Holocene glacier curve of Holzhauser (2007) (Fig. 7a, b). Three other records are shown in Fig. 7(c–e). One data set (Fig. 7c) shows radiocarbon-dated archaeological objects found at Schnidejoch in Switzerland (Suter *et al.*, 2005; Hafner, 2009). The record in Fig. 7(d) is the treeline variability in the Kauner valley, which is located in the central eastern Alps (Nicolussi *et al.*, 2005). Finally, the third record shown in Fig. 7(e) is the mean insolation at 46°N (approximate latitude of the Alps) in the boreal summer and winter months due to changes in orbital parameters (Laskar *et al.*, 2004).

The Schnidejoch transalpine pass (46°22′10″N, 7°23′17″E) at 2756 m a.s.l. connects the Rhone valley in the south with the Bernese Oberland in the north (see Grosjean *et al.*, 2007, for a detailed geographical description). On the northern slope, a small ice field below the pass has rapidly melted in the last years. During cold periods, the ice field has been connected with the larger Tungelgletscher situated nearby (north-west of Wildhorn). The size of the Tungelgletscher determines whether the transalpine route is passable. This has been the case during some periods in the past (Grosjean *et al.*, 2007), as suggested by the radiocarbon-dated archaeological objects.

Discussion

Comparison of the Alpine glacier curve and radiocarbon-dated archaeological findings at Schnidejoch from different periods reveals a strong correlation. When the Alpine glaciers were retreated, people were able to cross the Schnidejoch and apparently lost things or left belongings at the site. Only from periods when the Alpine glacier curve indicates glacier recession can objects be found at the Schnidejoch (Fig. 7b,c; Grosjean *et al.*, 2007). However, there are periods for which no objects have yet been found at Schnidejoch, although the Alpine glacier curve indicates recession (e.g. at 3000 cal a BP).

As can be seen in Fig. 7(b), Alpine glacier advances and retreats have occurred several times during the Holocene. There have been ‘heavier’ and more prolonged glacier advances in the near past, i.e. 600–100 cal a BP (AD 1350–1850) than in the mid-Holocene, i.e. 6000 cal a BP. This is in agreement with several studies (Hormes *et al.*, 2001, 2006; Joerin *et al.*, 2006), which suggest that glaciers have retreated more often in the mid-Holocene than in the recent past. This long-term variability can be explained by changes in insolation due to changes in orbital parameters. The high insolation in the Northern Hemisphere is reflected by the so-called Holocene Climate Optimum (Renssen *et al.*, 2009). As shown in Fig. 7(d), the orbital insolation at 46°N was about 25 W m^{-2} higher in the boreal summer 7000 years ago, and about 10 W m^{-2} lower in winter. Thus, in the past more solar energy was available at 46°N in the boreal summer than today, suggesting higher summer temperatures at this latitude. This implies a more intense melting and consequently shorter glacier lengths, i.e.

more distinct glacier recessions. In addition to Alpine glaciers the treeline of the Alpine region has been influenced by the change in orbital insolation. The treeline has retreated in step with the summer insolation at 46°N. The increase in winter insolation is not reflected in the treeline record as the vegetation growth period is restricted to the warm season.

Besides this long-term behaviour, shorter-term fluctuations can be seen in the glacier length records, the Schnidejoch findings as well as in the treeline data. These are unlikely to be due to the very smooth changes in orbital insolation. Thus, other mechanisms must be responsible for these shorter-term fluctuations, for example volcanic eruptions, changes in solar activity such as TSI or internal variability.

From the 1000-year low-pass filtered TSI curve (Fig. 7a), it can be seen that TSI varies with a 2000- to 2400-year cycle, also called the Hallstatt cycle (Damon and Sonett, 1991). Hallstatt cycle maxima, marked with grey bars, are observed around 6200, 4500 and 2000 a, and today. The minima in between are called Hallstatt cycle minima. The amplitude of TSI between Hallstatt minima and maxima is about $0.2\,\mathrm{W\,m^{-2}}$, which is about five times smaller than the amplitude of TSI observed between the 11-year cycle minima and maxima. Although the Hallstatt cycle amplitude in TSI is only small, glacier recessions and advances occur more or less simultaneously with the Hallstatt cycle maxima and minima. Agreement between the two is best for the most recent times and worst at 7400 cal a BP.

The thin line in Fig. 7(a) is the 40-year low-pass filtered TSI of Steinhilber *et al.* (2009). Comparing this curve with the 1000-year low-pass filtered TSI curves (bold line) shows that grand solar minima occurred more frequently during the Hallstatt cycle minima than maxima. As can be seen from the TSI record, a typical grand solar minimum lasts several decades and is characterized by a decrease in TSI of approximately $1\,\mathrm{W\,m^{-2}}$ compared with the mean value of the most recent 30 years. Hence, during a grand solar minimum the Sun emits less energy that can be received by the Earth, leading to a deficit in energy. The longer a grand solar minimum lasts, the greater is the deficit in energy. This deficit is even larger when several grand solar minima occur in a row with only little time in between, which occurred during the Hallstatt cycle minima.

In summary, the climate and glacier response to changes in TSI mainly depends on: (i) the amplitude of the change in TSI, and (ii) how long the period of changed TSI persists. The TSI record shows that during the Hallstatt cycle minima, both conditions are fulfilled, and thus solar activity could leave its (solar) fingerprint on the Alpine climate. However, although the solar imprint can be seen clearly in the Alpine climate on the long-term 2000-year Hallstatt cycle, this does not imply that the Sun is the dominant forcing factor on shorter timescales. For example, the presently observed Alpine glacier length recession is probably due to an enhanced greenhouse effect by anthropogenic greenhouse gas emissions, and not due to volcanic and solar activity.

Conclusions and outlook

We have presented a new compilation of temporally highly resolved data sets: the Mer de Glace and Unterer Grindelwaldgletscher are among the historically best-documented glaciers in the world, and Lake Silvaplana has one of the best-studied sediment records and represents a situation where glacier input is reflected in lake sediments. There is very good agreement between the glacial signal extracted from Lake Silvaplana sediment records and the independently reconstructed glacier variations for the last millennium. Finally, the recent reconstruction of Holocene solar activity by Steinhilber *et al.* (2009) allowed the assessment of solar imprint on the Alpine climate.

The relationship between solar forcing and glacier variations is clearly visible on the long-term, millennial-scale fluctuation during the mid- to late Holocene. Alpine glacier advances in the late Holocene were stronger and more prolonged due to reduced orbital insolation in the boreal summer (changed orbital forcing as an important background effect). On a short-term scale such as during the LIA, the influence of solar activity is not unequivocal and other forcing factors have to be considered, i.e. volcanoes or internal variability, e.g. the influence of the North Atlantic Oscillation. Moreover, the behaviour of glaciers depends on the sum of complex interactions due to climatic parameters (e.g. temperature, precipitation, solar radiation) but also topographical conditions.

There is need for high-resolution climate model runs using TSI as input parameter to quantify its influence on climate. This will reveal in more detail how summer and winter temperatures in the Alpine regions have been influenced by changes in solar forcing over the Holocene.

Regarding present climate change, it is also important to discern between natural forcings such as solar and volcanic, and anthropogenic greenhouse gas forcing. It remains unclear whether, without anthropogenic forcing, we would now be faced with a LIA-type climate due to orbital forcing.

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Abbreviations. bSi, biogenic silica; LIA, Little Ice Age; MAR, sediment mass accumulation rate; TSI, total solar irradiance.

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