Quaternary Science Reviews 149 (2016) 61–90

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Invited review

Glacier fluctuations during the past 2000 years

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ARTICLE INFO

Article history:
Received 31 May 2015
Received in revised form
2 April 2016
Accepted 12 April 2016

Keywords:
Late Holocene
Glacier variations
Neoglacial
Modern glacier retreat
Temperature change
Little Ice Age
Solar and volcanic activity

ABSTRACT

A global compilation of glacier advances and retreats for the past two millennia grouped by 17 regions (excluding Antarctica) highlights the nature of glacier fluctuations during the late Holocene. The dataset includes 275 time series of glacier fluctuations based on historical, tree ring, lake sediment, radiocarbon and terrestrial cosmogenic nuclide data. The most detailed and reliable series for individual glaciers and regional compilations are compared with summer temperature and, when available, winter precipitation reconstructions, the most important parameters for glacier mass balance. In many cases major glacier advances correlate with multi-decadal periods of decreased summer temperature. In a few cases, such as in Arctic Alaska and western Canada, some glacier advances occurred during relatively warm wet times. The timing and scale of glacier fluctuations over the past two millennia varies greatly from region to region. However, the number of glacier advances shows a clear pattern for the high, mid and low latitudes and, hence, points to common forcing factors acting at the global scale. Globally, during the first millennium CE glaciers were smaller than between the advances in 13th to early 20th centuries CE. The precise extent of glacier retreat in the first millennium is not well defined; however, the most conservative estimates indicate that during the 1st and 2nd centuries in some regions glaciers were smaller than at the end of 20th/early 21st centuries. Other periods of glacier retreat are identified regionally during the 5th and 8th centuries in the European Alps, in the 3rd–6th and 9th centuries in Norway, during the 10th–13th centuries in southern Alaska, and in the 18th century in Spitsbergen. However, no single period of common global glacier retreat of centennial duration, except for the past century, has yet been identified. In contrast, the view that the Little Ice Age was a period of global glacier expansion beginning in the 13th century (or earlier) and reaching a maximum in 17th–19th centuries is supported by our data. The pattern of glacier variations in the past two millennia corresponds with cooling in reconstructed temperature records at the continental and hemispheric scales. The number of glacier advances also broadly matches periods showing high volcanic activity and low solar irradiance over the past two millennia, although the resolution of most glacier chronologies is not enough for robust

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http://dx.doi.org/10.1016/j.quascirev.2016.04.008

statistical correlations. Glacier retreat in the past 100–150 years corresponds to the anthropogenic global temperature increase. Many questions concerning the relative strength of forcing factors that drove glacier variations in the past 2 ka still remain.

1. Introduction

Glaciers are sensitive climate proxies and variations in their length, area and volume provide insights into past climate variability, placing contemporary changes into a long-term context (Oerlemans, 1994, 2001; Hoelzle et al., 2003). A strong argument for the sensitivity and reliability of the glacier record is made by their relatively uniform retreat to contemporary warming (Vaughan et al., 2013).

A detailed analysis of Holocene glacier fluctuations from 17 regions and their relationship to potentially important forcing factors was presented in Solomina et al. (2015). Solomina et al. (2015) demonstrated a general trend of increasing glacier size from the early-mid Holocene to the late Holocene in the high and mid latitudes of the Northern Hemisphere and possible forcing by orbitally-controlled insolation. Glaciers advanced in the second half of the Holocene between 4.4 and 4.2 ka (ka = thousand years), 3.8–3.4 ka, 3.3–2.8 ka, at 2.6 ka, between 2.3 and 2.1 ka, 1.5–1.4 ka, 1.2–1.0 ka, and 0.7–0.5 ka. These ice expansions generally correspond with episodes of cooling in the North Atlantic and provide a record of cool summers with an approximate century-scale resolution.

Even though the quality and replication of data on Holocene glacier variations has dramatically improved in recent decades, the accuracy of dating advances and retreats is still limited. This dating uncertainty makes it difficult to draw firm conclusions about the synchronicity of glacial advances from different regions and therefore direct comparison with high-resolution proxy reconstructions is a challenge (Winkler and Matthews, 2010). The chronology of glacier fluctuations for the past two millennia is a more reliable climate proxy than earlier in the Holocene, as the ages of moraines are more precisely known, and the spatial coverage of the record is more dense. The possibility of dating advances to the calendar year with tree rings and historical data increases the resolution of the more recent portion of the records. Additionally, comparisons with high-resolution reconstructions of summer temperature and winter precipitation from tree rings, ice cores, and lake sediments helps identify potential climatic factors that may have driven glacier fluctuations. Glacier variations themselves can be used for low-frequency records of temperature and precipitation especially when they are combined with other proxies (e.g. Dahl and Nesje, 1996; Luckman and Villalba, 2001; Nesje et al., 2001; Nesje and Dahl, 2003) or associated with modelling studies (Leclercq and Oerlemans, 2011; Oerlemans, 2012; Leclercq et al., 2012; Marzeion et al., 2014).

Glacier variations of the past two millennia are usually considered in the context of Holocene glacier fluctuations as the latest part of the "Neoglaciation" (after ~4.5 ka) (Porter and Denton, 1967; special issues of Quaternary Science Reviews v. 7, issue 2, 1988 and v. 28, 2009 "Holocene and Latest Pleistocene Alpine Glacier Fluctuations: A Global Perspective"; Wanner et al., 2011). Two other terms are often used in the discussion of the environmental changes of the past two millennia: the "Medieval Climatic Anomaly" (MCA) or "Medieval Warm Period" and the "Little Ice Age" (LIA). Although there is little agreement in the literature on the definition of these terms, in this paper we will use the following approximate boundaries: ~950 to 1250 CE for the MWP/MCA and ~1250 to ~1850 CE for the LIA (IPCC AR5, 2013).

In this paper we will focus on the following questions:

- What were the periods of major glacier advances and retreats in key mountain regions over the past two millennia, and how synchronous were they regionally and globally?
- What was the magnitude of glacier fluctuations in the past two millennia and how does this compare with contemporary glacier retreat?
- How does the timing and magnitude of glacier variations relate to orbital, solar, volcanic and greenhouse gas forcings?

2. Approach, data, methods, accuracy of the records

The approach used here is generally the same as in Solomina et al. (2015) although it is applied to the past two millennia and focused on higher-frequency glacier variations. We provide a compilation of glacier fluctuations taking into account both continuous and discontinuous time series for both glacier advances and retreats of glaciers. We compile and analyze information about both individual glaciers and regional summaries (Table 1, Supplementary Materials (SM)). We selected the best-dated and most complete time series of glacier fluctuations with preference to those that extend the full two millennia. Periods of advances and retreats are identified by historical data, tree remains, ages of moraines—derived from dendrochronology, terrestrial cosmogenic nulcides and radiocarbon dating—as well as information from lake and marine sediments. In Solomina et al. (2015, SM) the reader can find a detailed description of the methods used for the reconstruction of glacier fluctuations. Below we briefly summarize the challenges related specifically to the past two millennia.

Historical data (maps, pictures, written documents) used for the reconstruction of glacier size is valuable and precise, but limited in time and to specific regions (Ladurie, 1971; Grove, 2004; Zumbühl et al., 2008; Masiokas et al., 2009a,b; Nussbaumer et al., 2011a,b; Nussbaumer and Zumbühl, 2012). In several mountain regions, for example Scandinavia, the earliest historical data are from the late 17th century. Information based on tree rings can also be of high quality and chronologically accurate. Unlike historical sources tree-ring data can cover longer periods, up to several millennia (e.g. Nicolussi and Schlüchter, 2012), and can be applied in areas where the historical descriptions of glaciers are absent. Trees growing on moraines provide minimum ages of these surfaces (McCarthy and Luckman, 1993; Wiles et al., 1995; Koch et al., 2009), whereas trees damaged or tilted by advancing glaciers can be used for more precise identification of the ages of glacial expansions (Koch et al., 2007b; Nicolussi and Patzelt, 2001; Nicolussi et al., 2006; Masiokas et al., 2009a,b; Bushueva and Solomina, 2012; Hochreuther et al., 2015; Solomina et al., 2015). Interesting results have also been obtained from wood buried in glacial or glacio-fluvial deposits, although the link between glacier activity and the death of a tree is not always clear (e.g. Nazarov et al., 2012).

Dendrochronologically-based calendar-dated glacier chronologies of high quality and accuracy are available now in several regions, such as Alaska (Wiles et al., 2011; Barclay et al., 2009a,b, 2013), the Alps (Nicolussi and Patzelt, 2001; Holzhauser et al.,