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Invited review

Holocene glacier fluctuations

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ABSTRACT

A global overview of glacier advances and retreats (grouped by regions and by millennia) for the Holocene is compiled from previous studies. The reconstructions of glacier fluctuations are based on 1) mapping and dating moraines defined by ^{14}C, TCN, OSL, lichenometry and tree rings (discontinuous records/time series), and 2) sediments from proglacial lakes and speleothems (continuous records/time series). Using 189 continuous and discontinuous time series, the long-term trends and centennial fluctuations of glaciers were compared to trends in the recession of Northern and mountain tree lines, and with orbital, solar and volcanic studies to examine the likely forcing factors that drove the changes recorded. A general trend of increasing glacier size from the early–mid Holocene, to the late Holocene in the extra-tropical areas of the Northern Hemisphere (NH) is related to overall summer temperature, forced by orbitally-controlled insolation. The glaciers in New Zealand and in the tropical Andes also appear to follow the orbital trend, i.e., they were decreasing from the early Holocene to the present. In contrast, glacier fluctuations in some monsoonal areas of Asia and southern South America generally did not follow the orbital trends, but fluctuated at a higher frequency possibly triggered by distinct teleconnections patterns. During the Neoglacial, advances clustered at 4.4–4.2 ka, 3.8–3.4 ka, 3.3–2.8 ka, 2.6 ka, 2.3–2.1 ka, 1.5–1.4 ka, 1.2–1.0 ka, 0.7–0.5 ka, corresponding to general cooling periods in the North Atlantic. Some of these episodes coincide with multidecadal periods of low solar activity, but it is unclear what mechanism might link small changes in irradiance to widespread glacier fluctuations. Explosive volcanism may have played a role in some periods of glacier advances, such as around 1.7–1.6 ka (coinciding with the Taupo volcanic eruption at 232 ± 5 CE) but the record of explosive volcanism is poorly known through the Holocene. The compilation of ages suggests that there is no single mechanism driving glacier fluctuations on a global scale. Multidecadal variations of solar and volcanic activity supported by positive feedbacks in the climate system may have played a critical role in Holocene glaciation, but further research on such linkages is needed. The rate and the global character of glacier retreat in the 20th through early 21st centuries appears unusual in the context of Holocene glaciation, though the retreating glaciers in most parts of the Northern Hemisphere are still larger today than they were in the early and/or mid-Holocene. The current retreat,

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however, is occurring during an interval of orbital forcing that is favorable for glacier growth and is therefore caused by a combination of factors other than orbital forcing, primarily strong anthropogenic effects. Glacier retreat will continue into future decades due to the delayed response of glaciers to climate change.

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1. Introduction

The retreat of glaciers worldwide recorded in all mountain systems, in the Arctic and in Antarctica, over the past century provides some of the most striking evidence in support of current human-induced global climate change (IPCC, 2007, 2013). A primary conclusion, based on an evaluation of Holocene glacier variations, formulated in the Fourth Asessment Report, which was generally confirmed in the recent AR5 states: "*Glaciers in several mountain regions of the Northern Hemisphere retreated in response to orbitally forced regional warmth between 11 and 5 ka, and were smaller (or even absent) at times prior to 5 ka than at the end of the 20th century. The present day near-global retreat of mountain glaciers cannot be attributed to the same natural causes, because the decrease of summer insolation during the past few millennia in the Northern Hemisphere should be favourable to the growth of the glaciers*." (IPCC, 2007, page 436). This conclusion supports most of the other findings reported in the IPCC Assessments, however, it is clear that many specific questions regarding the dynamics of glacial systems, specifically temporal and spatial variability, remain unanswered (Wanner et al., 2008, 2011). A main limitation for a more detailed understanding and conclusion is the lack of well-defined and detailed Holocene glacial chronologies, especially for the Southern Hemisphere (SH), Central Asia and Antarctica as well as a comprehensive global synthesis and review.

Retreating glaciers are releasing wood, soils, plant detritus and archaeological artefacts that were buried beneath the ice. Dating of these remains using radiocarbon or tree-ring techniques is providing exciting and important information on the scale, timing and duration of former Holocene glacier oscillations, as well as providing additional information about periods when the glaciers were close to or smaller than their present sizes (Hormes et al., 2001; Miller et al., 2005; Koch et al., 2007; Ivy-Ochs et al., 2009; Agatova et al., 2012; Goehring et al., 2012; Nesje et al., 2011; Nesje and Matthews, 2012; Margreth et al., 2014) (see also *"Data and methods of reconstructions of glacier variations" in the Supplementary materials").*

Studies of Holocene glacial geomorphic and sedimentological records provide the most direct means of determining the extent and timing of glacier oscillations. Until recently it has been difficult to define the ages of moraines in many regions because of the lack of appropriate dating techniques. Radiocarbon has been the most widely used and in some cases optically stimulated luminescence (OSL) dating has been implemented, but in most cases these can only be utilized to provide maximum and/or minimum ages on moraines by dating organic-rich deposits that are buried beneath moraines/tills, beyond the glacial limit (maximum ages), on top of moraines, or within the glacial limit (minimum ages). The development of terrestrial cosmogenic nuclide (TCN) dating, however, has provided a direct method of dating moraines and has lead to a plethora of studies that are shedding new light on the nature of Holocene glacier fluctuations (Douglass et al., 2005; Kerschner et al., 2006; Benson et al., 2007; Glasser et al., 2009; Licciardi et al., 2009; Ivy-Ochs et al., 2009; Schaefer et al., 2009; Kaplan et al., 2010; Jomelli et al., 2011; Putnam et al., 2012; Schindelwig et al., 2012; Schimmelpfennig et al., 2012a,b; Balco et al., 2013; Badding et al., 2013; Briner et al., 2013; Young et al., 2013; Dortch et al., 2013; Kelly et al., 2013; Briner et al., 2014; Owen and Dortch, 2014; Murari et al., 2014). TCN dating has its own challenges, which are discussed in more detail below (see also*"Data and methods of reconstructions of glacier variations" in the Supplementary materials").*

Continuous reconstructions of glacier size variations based on lake sediments provide information on glacier oscillations (Leemann and Niessen, 1994; Karlen et al., 1999; Leonard and Reasoner, 1999; Abbott et al., 2003; Levy et al., 2004; Anderson et al., 2005; Thomas et al., 2010; Bowerman and Clark, 2011; Nesje et al., 2014) and may allow quantitative reconstructions of equilibrium-line altitudes (ELAs) and analyses of the frequency of the Holocene glacier oscillations (Dahl and Nesje, 1994; Nesje et al., 2000; Bakke et al., 2005a,b,c, 2010, 2013; Matthews et al., 2005; Matthews and Dresser, 2008). Additionally, the size and stability of ice-shelves can be assessed by examining glaciomarine sediments (Pudsey and Evans, 2001; Antoniades et al., 2011; Hodgson, 2011). Ice core records (Koerner and Fisher, 2002; Thompson et al., 2006; Buffen et al., 2009; Herren et al., 2013) and, in some circumstances, speleothem-based reconstructions (Luetscher et al., 2011) are also useful for estimating the timing and extent of former glaciers.

Descriptions of the local and regional patterns of Holocene glacier oscillations have been presented in numerous papers over the past decade, including special issues in *Global and Planetary Change* (v. 60, 2008, "*Historical and Holocene Glacier-Climate Variations*") and in *Quaternary Science Reviews* (v. 29, 2009, "*Holocene and Latest Pleistocene Alpine Glacier Fluctuations: A Global Perspective*"), and a special volume in the *Developments in Quaternary Science* series (v. 15, 2011, *Quaternary glaciations-extent and chronology: a closer look*). These recent advances, including the greater number of detailed local and regional reconstructions of the Holocene glacier oscillations present an opportunity to undertake a comprehensive global review of Holocene glaciation. This paper therefore aims to review the global Holocene glacial and associated geomorphic and sedimentological record to help define the general trends in Holocene glacier oscillations and evaluate potential forcing mechanisms. This information is important for understanding and modeling past, present and future climate and associated cryospheric changes.

We focus on the following questions:

1. What were the long-term trends in Holocene glacier variability?
2. What were the periods of major glacier advances in key mountain regions in the Holocene and how synchronous were they regionally, throughout each hemisphere, and globally?
3. What is the magnitude of the most pronounced glacier retreat during the Holocene in different regions, and when did it happen? Moreover, was this comparable with the glacier retreat being experienced at the end of 20th–early 21st century? In addition, when and where were the glaciers smaller than at the end of 20th–early 21st century, and what were the possible forcing mechanisms?

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