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Introduction

# Holocene and latest Pleistocene alpine glacier fluctuations: a global perspective

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ABSTRACT

Alpine glacier fluctuations provide important paleoclimate proxies where other records such as ice cores, tree rings, and speleothems are not available. About 20 years have passed since a special issue of *Quaternary Science Reviews* was published to review the worldwide evidence for Holocene glacier fluctuations. Since that time, numerous sites have been discovered, new dating techniques have been developed, and refined climatic hypotheses have been proposed that contribute to a better understanding of Earth's climate system. This special volume includes 12 papers on Holocene and latest Pleistocene alpine glacier fluctuations that update the seven review papers from 1988.

Major findings of these 12 papers include the following: many, but certainly not all, alpine areas record glacier advances during the Younger Dryas cold interval. Most areas in the Northern Hemisphere witnessed maximum glacier recession during the early Holocene, with some glaciers disappearing, although a few sites yield possible evidence for advances during the 8.2 ka cooling event. In contrast, some alpine areas in the Southern Hemisphere saw glaciers reach their maximum post-glacial extents during the early to middle Holocene. In many parts of the globe, glaciers reformed and/or advanced during Neoglaciation, beginning as early as 6.5 ka. Neoglacial advances commonly occurred with millennial-scale oscillations, with many alpine glaciers reaching their maximum Holocene extents during the Little Ice Age of the last few centuries. Although the pattern and rhythm of these glacier fluctuations remain uncertain, improved spatial coverage coupled with tighter age control for many events will provide a means to assess forcing mechanisms for Holocene and latest Pleistocene glacial activity and perhaps predict glacier response to future impacts from human-induced climate change.

## 1. Introduction

The papers in this volume originate from a session titled, "Holocene and latest Pleistocene alpine glacier fluctuations: A global perspective" organized by us for the XVII INQUA Congress in Cairns, Australia, in August 2007. Much new information has become available on the ages of alpine glacier fluctuations throughout the world since a special session dedicated to Holocene glacier fluctuations was convened at the XII INQUA Congress during July 1987 in Ottawa (Davis and Osborn, 1988). Abrupt Younger Dryas cooling at the end of the Pleistocene, for example, is now recognized in many areas around the globe, and a cooling episode about 8200 years ago also caused glaciers to advance at several alpine sites. In addition, some studies indicate that Neoglaciation began earlier than previously believed, perhaps as far back as about 6.5 ka.

Alpine glaciers provide important paleoclimate proxies for comparison with recent climate changes that are likely anthropogenic (Oerlemans, 1994, 2005; Lowell, 2000; Meier et al., 2007; Barry, 2006; Owen et al., 2009). Continued retreat of alpine glaciers throughout the world provides a valuable opportunity to recover organic material, such as *in situ* sheared tree trunks, for $^{14}$C dating. Advances in cosmogenic nuclide exposure dating now allow high-precision measurements of moraine boulders and glaciated bedrock surfaces of Holocene and latest Pleistocene age. Higher resolution records from glacial lake sediments and related proxies, such as ice cores, tree rings, varves, corals, and speleothems, suggest decadal to multi-centennial Holocene climatic fluctuations, culminating with the Little Ice Age (Mayewski et al., 2004). Given the sensitivity of alpine glaciers to climate forcing (Schmidt et al., 2004) and the probable human-induced global warming over the

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past few decades (Intergovernmental Panel on Climate Change, 2007a, b), an understanding of naturally occurring climatic forcing over the past 10 to 12 millennia is more important than ever.

In the preface to an earlier special volume of Quaternary Science Reviews titled “Holocene glacier fluctuations,” Davis and Osborn (1988) stated: “Studies of Holocene glacier fluctuations may have practical applications, with relevance to, for example, water resources, mining and engineering operations, and agricultural endeavors in high mountain regions, and to dwelling and shipping in coastal areas. However, the broadest and most valuable application of alpine glaciers concerns their use as a proxy indicator of climatic change, as small glaciers are very sensitive to slight fluctuations in summer temperature and mean annual precipitation. Alpine glaciers are also surprisingly widely distributed, from polar latitudes to equatorial regions; thus they allow climatic comparisons to be made between many different geographic settings. An understanding of Holocene glacier fluctuations and the prediction of future climate are of obvious value to society, with consequences for food and water supply, energy production and use, and sea level change.”

Our words in the paragraph above are as important today as they were over two decades ago. The vulnerability of water resources to warming climate and glacier retreat has become a critical, global issue (cf., Gleick, 2003, 2008; Vörösmarty et al., 2000; Peterson et al., 2002; Mark and Seltzer, 2003; Barnett et al., 2005; Milly et al., 2005; Singh et al., 2005; Bradley et al., 2006). Reduced meltwater from glacier and winter snowpack is also predicted to have a significant impact on agriculture (Schindler and Donahue, 2006; Lobell et al., 2008). Glacier recession and thawing permafrost also create geotechnical hazards and engineering problems in the mountain environment (Haeberli, 1992; Harris et al., 2001; Oppikofer et al., 2008) and myriad other hazards (Grove, 1987). Besides a wide array of health hazards related to global warming and glacier recession (Ebi et al., 2007), perhaps the most catastrophic health risk is the danger from glacier outburst floods (Watanabe et al., 1994; Walder and Costa, 1996; Clague and Evans, 2000; Richardson and Reynolds, 2000; Kattelmann, 2003; Huggel et al., 2004; Cary, 2005; O’Connor and Costa, 2004; Harrison, 2006). Melting of alpine glaciers has significantly contributed to global sea-level rise over the past century, and it is projected that sea-level rise could potentially displace millions of people over the next few decades (Nicholls et al., 1995, 1999; Titus and Narayanan, 1996; Gregory and Oerlemans, 1998; Nicholls and Mimura, 1998; Klein and Nicholls, 1999; Dyurgerov, 2003; Walsh et al., 2004; Meier et al., 2007; Edwards, 2008; Bahr et al., 2009). Although rapidly shrinking alpine glaciers reveal archeological treasures (Spindler, 1994; Fowler, 2001; Dixon et al., 2005), their demise is also a major aesthetic loss (Wilson, 2003; Kennedy and Hanson, 2006; Cary, 2007).

Our objective for this special volume of *Quaternary Science Reviews* is provision of the most up-to-date datasets on alpine glacier moraine ages for paleoclimate reconstruction and modeling. The data provided in a previous special volume on Holocene glacier fluctuations organized by Davis and Osborn (1988), for example, led Nesje and Johannessen (1992) to suggest that a combined effect of volcanic aerosols and summer insolation variations forced climate over the past 10 ka. A better understanding of the spatial distribution of lateglacial moraines may also allow more meaningful testing of hypotheses concerning the cause of Younger Dryas cooling (Taylor et al, 1997; Alley, 2000, Broecker, 2003, 2006; Firestone et al., 2007; Lowell and Kelly, 2008; Bakke et al., 2009; Kennett et al., 2009). More precise and robust dating of Little Ice Age and Neoglacial moraines throughout the world may allow testing of hypotheses for Holocene climate variability (Bond et al., 1997, 2001; Broecker, 2000; Denton and Broecker, 2008).

## 2. Methods

Radiocarbon dating remains the primary method for constructing Holocene and latest Pleistocene alpine glacier chronologies. Over the past couple of decades, lichenometric dating of pre-Little Ice Age glacial chronologies (Benedict, 1973: Denton and Karlén, 1973) is less common than it was in the 1970s and 1980s, although lichens are still useful for distinguishing advances of the past few hundred years. Dendrochonology, especially using fossil wood, has continued to contribute many high-resolution chronologies, especially for moraines dating to the last couple of millennia in areas such as coastal Alaska and British Columbia. Optically stimulated luminescence (OSL) dating also has been pioneered for dating Holocene moraines at a few select sites. However, the most important advance over the past two decades for dating alpine glacier moraines is that provided by cosmogenic radionuclides (CRNs), especially $^{10}$Be formed in situ on exposure surfaces such as moraine boulders.

In general, $^{14}$C ages are considered to be only minimum-limiting if derived from basal sediments obtained from bogs and ponds behind moraines within glacial forefields. However, even this interpretation requires careful analysis in the field, as fossil organic materials are not always removed by overriding ice (Andrews et al., 1976; Thompson et al., 2006; Anderson et al., 2008). Radiocarbon ages on fossil organic materials such as tree trunks or soil A horizons situated beneath or within tills, such as in a lateral moraines (cf., Röthlisberger, 1986), are generally considered to be only maximum-limiting for the advance that buried the organic material. However, $^{14}$C ages on sheared *in situ* stumps are a special case that may more closely date a glacier advance. In some cases where multiple tills are exposed, the possibility exists that one $^{14}$C age on buried organics at an unconformity could provide a minimum-limiting age for an advance represented by an underlying till and a maximum-limiting age for an advance represented by an overlying till.

Widely distributed and well-dated tephra also may be useful for obtaining minimum- and maximum-limiting ages of moraines, in similar fashion to that described for $^{14}$C-dated fossil organic materials above. Mazama and Glacier Peak tephra, which were distributed over many of the mountainous areas of western United States and Canada, can be readily fingerprinted geochemically and are now more precisely dated than they were two decades ago (Hallett et al., 1997; Zdanowicz et al., 1999; Kuehn et al., 2009).

Interpretation of upvalley glacier activity by clastic sedimentation in alpine lakes was pioneered by Karlén (1976) and Leonard (1986a, b) and continues to be a useful proxy for reconstructing paleoclimate, although some studies suggest that the climate signals may be more complex than previously believed (Bakke et al., 2005; Jannson et al., 2005). Nevertheless, lake sediment core proxies for glacier activity lend themselves to $^{14}$C dating and are more continuous than moraine chronologies, and have been summarized in some of the papers in this special volume.

In the past two decades since publication of a previous volume on Holocene glacier fluctuations (Davis and Osborn, 1988), cosmogenic radionuclide (CRN) exposure dating has become an important tool in dating moraines around the globe (Nishiizumi et al., 1989; Hallet and Putkonen, 1994; Dunai, 2000; Gosse and Phillips, 2001; Putkonen and Swanson, 2003). Where available, most authors in this volume report cosmogenic radionuclide (CRN) ages ($^{10}$Be and $^{26}$Al) in ka and recalibrated some ages in the literature using the CRONUS-Earth (**C**osmic-**R**ay pr**O**duced **NU**clide **S**ystematics on Earth) online calculator [Version 2.2, available at http://hess.ess.washington.edu/math/al_be_v22/al_be_multiple_v22.php; full documentation is provided by Balco et al. (2008) with time-dependent scaling methods of Lal (1991) and Stone (2000) to provide consistency for comparisons between field areas]. More recently determined $^{10}$Be production rates (cf., Balco et al., 2009) were not used in the papers in this volume.

We encouraged authors of all the papers in this volume to report ages in both radiocarbon years ($^{14}$C yr BP) and calibrated years before 1950 AD (ka, for "thousands years ago"), following Rose (2007) in his editorial concerning the use of time units in *Quaternary Science Reviews*. Most authors calibrated $^{14}$C years using CALIB version 5.0.2 (available online at http://calib.qub.ac.uk/calib/; documentation is provided by Stuiver et al., 2005).

Authors for the papers in this volume follow the most recent time definition for the lower boundary of the Holocene at 11.7 ka, as determined from the NGRIP ice core (Walker et al., 2008). The age of the Pleistocene/Holocene boundary thus remains at 10,000 $^{14}$C yr BP, as proposed by Mercer (1972). Geologic-climate terms such as early, mid- and late Holocene, Climatic Optimum (Antevs, 1938), Hypsithermal (Deevey and Flint, 1957), Neoglacial (Moss, 1951; Sharp, 1960; Birkeland, 1964; Richmond, 1965; Porter and Denton, 1967), and Little Ice Age (Matthes, 1935, 1941; Ladurie, 1971; Denton and Karlén, 1973; Grove, 1988, 2004) are used in a generic fashion without exact time boundaries (cf., Clague et al., 2009).

## 3. Global regions

In this volume, 10 papers cover five of the same areas summarized in the 1988 *Quaternary Science Reviews* special volume (Davis and Osborn, 1988), along with five new regions. Barclay et al. (2009) provide an update on Calkin (1988) for Alaska, and Menounos et al. (2009) expand upon Osborn and Luckman (1988) by including the Yukon previously covered by Calkin (1988). A follow-up paper on Davis (1988) for the American Cordillera (lower 48 states) by D.H. Clark and P.T. Davis could not be completed in time for this volume, but a general summary and some key recent references are offered below. The papers by Briner et al. (2009), Kelly and Lowell (2009), and Geirsdóttir et al. (2009) fill in major gaps in the 1988 special volume, namely the eastern Canadian Arctic, Greenland, and Iceland, respectively. Nesje (2009) provides an update to Karlén (1988) on Holocene glacier fluctuations in Scandinavia. Ivy-Ochs et al. (2009) and Owen (2009) provide important summaries and updates to Röthlisberger (1986) for the Alps and the Himalaya/Tibet region, respectively, also not represented in the 1988 special volume. A follow-up paper by J.M. Schaefer and others on Holocene glacier fluctuations in New Zealand (Gellatly et al., 1988) could not be completed in time for this volume, but we provide a general summary for that region below, including a recent paper by Schaefer et al. (2009). The review paper on Holocene glacier fluctuations in South America and Antarctica by Clapperton and Sugden (1988) is brought up to date in two separate papers on the Andes by Rodbell et al. (2009) and Antarctica and the Subantarctic Islands by Hall (2009). Although a follow-up paper on Holocene glacier fluctuations in Africa (Mahaney, 1988) is not included in this volume, we note important review papers on Quaternary glaciations in East Africa by Rosqvist (1990), Shanahan and Zreda (2000), and Mark and Osmaston (2008), and in the tropics overall by Benn et al. (2005) and Hastenrath (2009). We also recognize that Mount Kilimanjaro has become the poster child for rapid ice retreat from its summit area over the past few decades (Osmaston, 1989; Hastenrath and Greischar, 1997; Vershuren et al., 2000; Thompson et al., 2002; Kaser et al., 2004; Mölg and Hardy, 2004). Finally, a paper on nomenclature and resolution in Holocene glacial chronologies by Clague et al. (2009) concludes this volume.

### 3.1. Alaska

Volume changes in the large glacier complexes of southern Alaska over the past few centuries have affected global sea level (cf., Meier et al., 2007), as well as local glacioisostatic depression and rebound. In their paper on Holocene glacier fluctuations in Alaska, Barclay et al. (2009) update reviews by Calkin (1988), Calkin et al. (2001), Mann et al. (1998a), and Wiles et al. (2008), and distinguish three main types of glaciers in Alaska: 1) land-based valley and cirque glaciers whose termini have been mostly controlled by climate throughout the Holocene, 2) tidewater glaciers in southern Alaska whose iceberg-calving termini have been primarily affected by non-climatic forcings, and 3) large foreland glaciers in the Chugach and St. Elias ranges whose terminal positions reflect both climatic and non-climatic factors.

Moraines in at least two areas are coeval with the Younger Dryas (Briner and Kaufman, 2008); afterwards glaciers throughout Alaska retreated and remained behind their modern marginal positions until the beginning of Neoglaciation (Barclay et al., 2009). Lake sediment cores in some areas suggest an increase in glacial activity as early as 5 ka, followed by Neoglacial advances by 4.1 ka in the Brooks Range (dated by lichenometry) and glacier expansions elsewhere by 3.3 ka, with advances at 3 and 2 ka (dated by $^{14}$C). Tree-ring cross-dating of killed and damaged trees in southern Alaska suggest synchronous advances between 500 and 700 AD, followed by the Little Ice Age advances that began in the 1200s to early 1300s, with two maxima in the 1600s to mid-1700s and mid- to late 1800s. Expansions of tidewater glaciers appear to be asynchronous with non-climatic forcings, although warming probably triggers rapid iceberg-calving retreat such as that going on today (Barclay et al., 2009).

### 3.2. Western Canadian Cordillera

Since the review on Holocene glacier fluctuations in western Canada by Osborn and Luckman (1988), much new work is reported by Menounos et al. (2009), who also include a summary of fluctuations of the Cordilleran ice sheet during the latest Pleistocene. The lateglacial Crowfoot moraine at its type locality in the Canadian Rockies defined by Luckman and Osborn (1979) was dated to the Younger Dryas by bracketing $^{14}$C ages on sediments from Crowfoot Lake (Reasoner et al., 1994). Menounos et al. (2009) note that by ~11.0 ka glaciers in the Canadian Cordillera receded to positions no greater than those of the late 20th century.

Menounos et al. (2009) report that some glaciers in the Coast Mountains began to advance again by ~7.4 ka, which they define as the beginning of Neoglaciation. Fossil wood from glacier forefields in western Canada provide $^{14}$C ages for glacier advances at ~8.59 to 8.18 ka, ~7.36 to 6.45 ka, ~4.40 to 3.97 ka, ~3.54 to 2.77 ka, ~1.71 to 1.30 ka, as well as during the last millennium (Menounos et al., 2009). They define glacier advances beginning in the 11th century as the initiation of the Little Ice Age (LIA), which culminated with maximum Holocene glacier advances during the early 18th to mid-19th centuries.

The identification of numerous additional glacier advances during the early and middle parts of Neoglaciation led Menounos et al. (2009) to expand the time frames of the "Garibaldi Phase" and Tiedemann Advance as initially defined in the southern Coast Mountains by Ryder and Thomson (1986) and the Peyto Advance as described in Canadian Rockies by Luckman et al. (1993). Moreover, the recently identified greater complexities and earlier beginnings to Neoglaciation and the LIA in western Canada led Clague et al. (2009) to question the appropriateness of terms such as Garibaldi Phase, Tiedemann Advance, Peyto Advance, and Little Ice Age.

### 3.3. Western American Cordillera

Davis and Osborn (1987) and Osborn et al. (1995) suggested that many outer cirque moraines in the North American Cordillera were formed during the Younger Dryas (YD) rather than during Neoglaciation as summarized by Burke and Birkeland (1983). Much work has been completed in cirques of the western conterminous United States since a summary paper was published by Davis (1988). Indeed, many outer cirque moraines appear to be YD in age, such as the type Titcomb Lakes moraine in the northern Wind River Range of Wyoming [based on $^{10}$Be dating of moraine boulders (Gosse et al., 1995) and $^{14}$C dating of lake sediments (Davis et al., 1998)], a moraine upvalley from Sky Pond in the northern Colorado Front Range [based on $^{14}$C dating of lake sediments (Menounos and Reasoner, 1997)], the type Rat Creek moraines in the Icicle Creek drainage in the Washington Cascades [based on $^{36}$Cl dating of moraine boulders (Porter and Swanson, 2008)], and moraines within 1 km of cirque headwalls in the San Bernardino Mountains in southern California [based on $^{10}$Be dating of boulders (Owen et al., 2003)].

Other alpine glacier moraines, such as the type Recess Peak in the Sierra Nevada of California appear to be older than the YD [based on $^{14}$C dating of lake sediments (Clark and Gillespie, 1997)], and the type McNeeley moraines at Mount Rainier in the Washington Cascades appear to be older and younger than the YD [based on $^{14}$C dating of lake sediments (Heine, 1998)]. Taken at face value, $^{14}$C dating of sediments from Rapid Lake suggest a pre-YD age for the type outer Temple Lake moraine in the southern Wind River Range of Wyoming; however, Zielinski and Davis (1987), Fall et al. (1995), and Reasoner and Jodry (2000) suggest that these $^{14}$C ages may be too old by a couple of millennia and that the moraine is correlative to the YD. Benson et al. (2007) used $^{10}$Be dating of boulders to suggest a YD age for a suite of moraines at Lower Chicago Lake on Mount Evans in the Colorado Front Range, but recalibration of these ages using accepted $^{10}$Be production rates indicate a pre-YD age. In the Sangre de Cristo Range of northern New Mexico, $^{14}$C dating of clastic lenses in a bog suggested to Armour et al. (2002) that cirque moraines upvalley are YD and Neoglacial in age, but both moraines were recently dated pre-YD by $^{10}$Be analyses of boulders (S.A. Marcott, unpublished data).

On the north side of Mount Baker in the Washington Cascades, $^{14}$C dating of fossil logs in lateral moraines of the Middle Fork and charcoal in outwash in the North Fork of the Nooksack valley suggested to Kovanen and Easterbrook (2001) that alpine glaciers advanced 25 to 45 km from their sources during the YD; however, advances of such length with the required ELA depression are unlikely in this timeframe. Osborn and Bevis (2001) proposed that some moraines veneered with Mazama tephra in the Great Basin might be good candidates for YD-age alpine glacier advances, but acknowledged that the tephra only provides a minimum-limiting age. Based on $^{14}$C-dating of lake sediment cores, all cirques in the Uinta Mountains in northern Utah were ice-free by YD time (Munroe, 2002). All moraines formed by a northern Yellowstone ice cap in south-central Montana [based on $^{3}$He and $^{10}$Be dating of boulders (Licciardi et al., 2001)] and in the Greater Yellowstone and Teton Range in northwestern Wyoming [based on $^{10}$Be dating of boulders and bedrock (Licciardi and Pierce, 2008)] are pre-YD in age. Three boulders that lie on bedrock, rather than a moraine crest, in Lake Solitude cirque in the Teton Range are dated by $^{10}$Be to about 12.8 ± 0.6 ka (Licciardi and Pierce, 2008). Based on $^{14}$C ages on sediment cores from tarns, glaciers in some cirques in the Colorado Front Range were confined just beyond their Little Ice Age limits since before the YD (Davis et al., 1992). Finally, the type Satanta Peak moraine in the Colorado Front Range may be pre-date the YD based on an unpublished 11,700 ± 60 $^{14}$C age (collected by J.B. Benedict, by Dethier et al., 2003).

Besides the possible early Holocene age of the inner type McNeeley moraine on Mount Rainier (Heine, 1998), Thomas et al. (2000) and Kovanen and Slaymaker (2005) proposed that early Holocene glacier advances occurred on the south slope of Mount Baker and in a cirque southwest of Mount Baker. However, Davis et al. (2006, 2007), Osborn et al. (2007a, b), and Clark et al. (2007) found evidence to the contrary, supporting the arguments against early Holocene alpine glacier advances in the North Cascades summarized by Davis and Osborn (1987) and Reasoner et al. (2001). Marcott et al. (2009) used minimum-limiting $^{14}$C ages and Mazama tephra from bog cores to suggest early Holocene or latest Pleistocene glacier advances at Three Sisters and Broken Top volcanoes in the Oregon Cascades. Licciardi et al. (2004) present a case for a minor glacial advance in Wallowa Mountains in southeastern Washington at about 10.6 ka, but acknowledge that the limited number of $^{10}$Be analyses on moraine boulders makes this age inconclusive. Benson et al. (2007) used $^{10}$Be dating of boulders in Butler Gulch in the Colorado Front Range to argue for an early Holocene glacier advance, but these boulders are very small and may have been considerably shielded by till or snowpack to explain their young age.

Many outer cirque moraines in the western American Cordillera at one time were believed to be Neoglacial age, but are now known to be late Pleistocene in age. Thus, Little Ice Age (LIA) moraines commonly represent the most extensive alpine glacier advances during the Holocene. Although pre-LIA Neoglacial moraines now appear to be rare in the western United States, Neoglacial rock glaciers are recognizable in many cirques by their moderate lichen cover and steep proximal slopes well above the angle of repose, likely indicating extant ice cores. Some good examples of Neoglacial rock glaciers occur in the Sierra Nevada, California (Clark and Gillespie, 1997; Konrad and Clark, 1998), Stoud Basin on the eastern side of the southern Wind River Range, Wyoming (Dahms, 2002), and upvalley of Sky Pond (Menounos and Reasoner, 1997) and in Arapaho cirque (Benedict, 1973) in the Colorado Front Range. However, $^{14}$C dating of lake sediment cores in Temple Lake valley on western side of the southern Wind River Range, Wyoming, suggests that rock glaciers there have been inactive throughout the Holocene, consistent with their smaller size and more subdued forms (Zielinski, 1989).

Although multiple Holocene tills are rarely found in the western American Cordillera, recent $^{14}$C dating of fossil wood within lateral moraines at Mount Baker indicates that Easton Glacier on the south side advanced as early as 6.6 to 5.9 ka, retreated, then advanced again around 1430 to 1630 AD to its maximum LIA position (Davis et al., 2006; Osborn et al., 2007a); that Coleman Glacier on the north side advanced about 1000 to 1210 AD to its maximum LIA position (Davis et al., 2007); and that Deming Glacier on the west side advanced soon after 1.8 ka, retreated, then advanced again around 1420 AD to its maximum LIA position (Osborn et al., 2007b).

### 3.4. Eastern Canadian Arctic (Baffin Island)

As is the case for Alaska, melting ice caps and alpine glaciers on Baffin Island and elsewhere in the eastern Canadian Arctic have been major contributors to sea-level rise during the 20th century. But, unlike Alaska, deglaciation of the Laurentide Ice Sheet (LIS) was globally the largest contributor to sea-level rise during the early to mid-Holocene as its margins retreated to the present-day Barnes Ice Cap on Baffin Island. Briner et al. (2009) review the key patterns and chronologies for LIS retreat, as well as advances and retreats of ice caps and alpine glaciers during the Holocene. They note that the LIS on Baffin Island underwent two periods of rapid retreat from ~12 to 10 ka as outlet glaciers rapidly calved in deep sounds and fiords and again at ~7 ka when the ice sheet collapsed over Foxe Basin. Thus, both of these rapid retreat episodes were driven in part by non-climatic factors. In some areas, such as Cumberland Sound, LIS outlet glaciers were still grounded in fiords during the YD, when the margins of nearby alpine glaciers were less extensive than during the LIA.

Some alpine glaciers on Baffin Island apparently survived the early Holocene thermal maximum, although data for alpine glacier margins during this time are limited. However, alpine glaciers began to advance by ~6 ka, as indicated in $^{14}$C-dated lake sediment cores, reaching their LIA positions by ~3.5 to ~2.5 ka, dated by $^{14}$C and lichenometry. Multiple Neoglacial moraine sets, revealed in a few key locations not overrun by the generally more extensive LIA ice advances, suggest sub-millennial-scale fluctuations with maxima at ~3.5 ka, ~2.3 ka, ~500 AD, ~900 AD, ~1350 AD, ~1600 AD, and ~1900 AD (Briner et al., 2009). Warming during the past few decades has exposed fossil organic materials underlying melting ice caps that provide $^{14}$C ages supporting the view that some ice caps have persisted since ~900 AD, through the Medieval Warm Period (Andrews et al., 1976; Anderson et al., 2008).

### 3.5. *Greenland*

Rapid temperature shifts revealed in Greenland ice cores indicate that the YD was ~15 °C colder than the mean annual temperature today, yet alpine glacier fluctuations throughout the world generally indicate only ~3 to 6 °C cooler temperatures in the YD than today's value. Kelly et al. (2008) tested the seasonality hypothesis of Denton et al. (2005) by $^{10}$Be exposure dating of boulders in the Scoresby Sund area of East Greenland to determine that two sets or moraines were formed prior to and at the end of the YD. After making adjustments for isostatic rebound (Hall et al., 2008), Kelly et al. (2008) suggested that these moraines indicate a summertime cooling of ~3.9 to 6.6 °C compared with today's value, and that that the extreme YD cooling seen in Greenland ice cores was largely the result of wintertime rather than summertime temperature.

In this volume, Kelly and Lowell (2009) summarize research on local glacier fluctuations in Greenland, namely data for ice caps and alpine glaciers separate from the Greenland Ice Sheet (GIS). In nearly all areas of Greenland, local glaciers were smaller than at present or may have disappeared completely following advances during Lateglacial or early Holocene time, such as the advances dated to the end of the YD in the Scoresby Sund area (Kelly et al., 2008). Morainal evidence has not been found for the prominent 8.2-ka cooling event that is registered in multiple ice cores from Greenland. Moreover, Neoglacial moraines formed by small ice caps and alpine glaciers predating Historical time (~1200 to 1940 AD, i.e., the LIA) occur only in a few locations in western and south-eastern Greenland. In general, local glacier advances in Greenland during the LIA are the most extensive since Lateglacial or early Holocene time. In all areas with the exception of North Greenland, local glaciers are retreating from their maximum LIA extents (Kelly and Lowell, 2009).

### 3.6. *Iceland*

Iceland's location within the central North Atlantic Ocean is strategically situated to evaluate changes in atmospheric and ocean circulation on a variety of time scales.

Geirsdóttir et al. (2009) note that during retreat of the Iceland Ice Sheet (IIS) from its margins on the continental shelf during the Last Glacial Maximum, regional advances or still stands occurred during the late Alleröd to early YD and again during the PreBoreal. During this time, glaciers terminated in deep fiords and bays. But, by 10.3 ka the IIS was in rapid retreat, with the Holocene thermal maximum occurring after 8 ka when the island became mostly ice-free. Although morainal evidence for the 8.2-ka cooling has not been found in Iceland, marine and lacustrine sediment proxy records indicate a cooling episode between 8.5 and 8 ka. Neoglacial cooling began after 6 ka with glacier advances occurring between 4.5 and 4.0 ka, and then again between 3.0 and 2.5 ka. The Medieval Warm Period is not strongly present in Icelandic paleoclimate records, although the landscape apparently was reasonably stable from 0 AD to 1200 AD (Geirsdóttir et al., 2009). Numerous studies report on LIA moraines and other proxy records dating between 1250 and 1900 AD in Iceland (cf., Grove, 1988, 2004), which represent the most extensive glacial advances since deglaciation in the early Holocene (Geirsdóttir et al., 2009).

### 3.7. *Scandinavia*

The Fennoscandian Ice Sheet (FIS) advanced during the YD cold interval and deposited moraines that have been mapped just about everywhere around the perimeter of the former ice sheet (Andersen, 1995a, b; Mangerud, 2004). Many of these classic moraines, such as the Salpausselkä I moraines in Finland, have been dated to the YD by $^{10}$Be analysis of morainal boulders (Rinterknecht et al., 2004, 2006). Therefore, the record of alpine glacier fluctuations in Scandinavia begins after retreat of the FIS from its YD marginal positions.

Nesje (2009) provides an update to the review on Holocene alpine glacier fluctuations in Scandinavia by Karlén (1988). Increased freshwater inflow into the North Atlantic is invoked as a mechanism for driving abrupt Lateglacial and early Holocene glacier fluctuations in Norway, with the most prominent advances at ~11.2, ~10.5, ~10.1, ~9.7, ~9.2, and ~8.4 to 8.2 ka, the latter being part of a cooling episode known at the Finse Event dating 8.5–8.0 ka in Norway, so a broader event than the 8.2-ka cooling event in Greenland ice cores. Following maximum Holocene warming in Norway between 6.6 and 6.0 ka, when some glaciers may have disappeared, glaciers advanced during Neoglaciation with peaks at ~5.6, ~4.4, ~3.3, ~2.3, ~1.6 ka, and during the mid-18th century (the LIA). Many of these advances are interpreted from $^{14}$C-dated minerogenic layers in sediment cores in lakes down valley of glaciers. Although most Norwegian glaciers have been in retreat since the mid-18th century, some began to advance in the 1950s and others in the 1990s in response to increased winter accumulation (Nesje, 2009), but all have experienced rapid retreat during the past decade.

In northern Sweden, where Karlén (1976) pioneered radiocarbon dating minerogenic layers in sediment cores down valley from glaciers, inferred clastic intervals relate to glacier advances that occurred ~8.5 to 7.9, 7.4 to 7.2, 6.3 to 6.1, 5.9 to 5.8, 5.6 to 5.3, 5.1 to 4.8, 4.6 to 4.2, 3.4 to 3.2, 3.0 to 2.8, 2.7 to 2.0, 1.9 to 1.6, 1.2 to 1.0, and 0.7 to 0.2 ka, with glaciers reaching their maximum LIA extents during the late 17th and early 19th centuries (Nesje, 2009). However, the chronology of alpine glacier advances in northern Sweden has been challenged by Snowball and Sandgren (1996), who suggest that some glaciers may have disappeared during the early Holocene until 3.3 ka, after which they reformed during Neoglaciation. Likewise, Rosqvist et al. (2004) did not find evidence for glacier advances between 8.0 and 6.0 ka, although they interpreted minerogenic sediments in Lake Vuolep Allakasjaure (cf. Karlén, 1976) to indicate glacier advances at ~4.3, 3.1, 2.2, 1.8 ka, and during the last 1300 years, with peak LIA advances at ~0.3 to 0.2 ka.

### 3.8. *European Alps*

The large majority (81%) of glaciers in the Alps are small (<0.5 km$^2$), and therefore sensitive to climate change (Zemp, 2006). Ivy-Ochs et al. (2009) expand on their earlier work (Ivy-Ochs et al., 1999) and that of Röthlisberger (1986) and many others in their summary of latest Pleistocene and Holocene glacier fluctuations in the European Alps. The outer Egesen moraine in Julier Pass, Switzerland, dates ~12.2 ka, based on $^{10}$Be analyses of surface boulders, thus is believed to have formed as a response to YD cooling (Ivy-Ochs et al., 1999). Final stabilization of moraines during the Egesen stadial occurred by ~11.3 ka, as shown by $^{10}$Be dating of moraines at four sites across the Alps. Exposure $^{10}$Be ages indicate that glaciers advanced at ~10.8 ka in the northern Tyrol, Austria, where stabilization of rock glaciers occurred by ~10.5 ka. Thus, cold climate conditions lingered in the Alps into the early Holocene.

From ~10.5 ka until ~3.3 ka, climate was too warm for significant glacier expansion in the Alps (Ivy-Ochs et al., 2009), with most glaciers probably smaller than they were during the late 20th century. Although a moraine in the Kromer valley, Austria, is dated by $^{10}$Be analyses of boulders to ~8.4 ka and was believed by Kerschner et al. (2006) to be correlative with the 8.2-ka cooling event in Greenland ice cores, Ivy-Ochs et al. (2009) advise caution in this interpretation, as they do for a few other sites in the Alps, such as the Pasterze Glacier in Austria where Nicolussi and Patzelt (2000) suggested an advance at ~8.8 ka based on $^{14}$C-dated fossil wood fronting the glacier. Ivy-Ochs et al. (2009) offer that perhaps small glaciers may have advanced to near their LIA extents between ~10.5 and ~3.3 ka, but that cold intervals were too short for large glaciers to advance.

After ~3.3 ka, climate conditions deteriorated in the Alps to allow large glaciers, such as Grosser Aletschgletscher, to advance at ~3.0 to 2.6 ka, ~600 AD, and during the LIA. During the LIA, glaciers in the Alps reached their maximum extents during the 14th, 17th, and 19th centuries, with the final 1850–1860 AD advance being the greatest (Ivy-Ochs et al., 2009). Satellite monitoring data indicate that Swiss glacier area loss from 1985 to 1999 increased by a factor of seven compared to the period from 1850 to 1973 (Paul et al., 2007).

### 3.9. Himalaya and Tibet

Owen (2009) provides an update to earlier summaries on Holocene glacier fluctuations in the Himalaya and the Karakoram by Röthlisberger (1986) and Röthlisberger and Geyh (1985), in western China by Zhou et al. (1991), and in Tibet by Yi et al. (2008), all primarily based on $^{14}$C dating. Cosmogenic radionuclide exposure dating studies are beginning to provide a chronology for glacier advances during the late Pleistocene in the Himalaya and Tibet (Owen, 2009), whereby $^{10}$Be data on moraine boulders suggest that the youngest Lateglacial advances occurred ~16 to 15 ka, with moraines dating to the YD not identified in the Himalaya.

Röthlisberger and Geyh (1985) used $^{14}$C ages on fossil wood and soils in lateral moraines to suggest substantive glacier advances at ~8.3, 5.4 to 5.1, 4.2 to 3.3, 2.7 to 2.2 ka, with lesser advances at ~2.6 to 2.4, 1.7 to 1.4, 1.3 to 0.9, 0.8 to 0.55, and 0.5 to 0.1 ka in the Himalaya and the Karakoram. In northwestern China, Zhou et al. (1991) suggest that glaciers advanced ~9.3, 6.4, 4.5, and 0.5 ka, whereas in southeastern Tibet they indicate that glaciers advanced ~3.1, 1.9, 0.9, and 0.3 ka. In Tibet, Yi et al. (2008) identified glacier advances dating at ~9.4 to 8.8, 3.5 to 1.4, and 1.0 to 0.13 ka. In westernmost Tibet, Seong et al. (2009) used $^{10}$Be exposure ages for moraine boulders to date glacier advances at ~11.2, 10.2, 8.4, 6.7, 4.2, 3.3, 1.4 ka, and the last few hundred years before present. Thus, alpine glaciers apparently advanced and retreated numerous times throughout the region, with especially large moraines formed during the early Holocene.

Glacier advances during the mid- and late Holocene in the Himalaya were generally less extensive than those during the early Holocene. In the Khumbu Himal, Finkel et al. (2003) used $^{10}$Be analyses on boulders to date Neoglacial moraines to ~3.6 ka. Younger Neoglacial moraines in the Khumbu area have been dated at ~1.0, 0.5, and 0.4 ka by a variety of workers using $^{14}$C, OSL, and $^{10}$Be analyses, but LIA moraines in the region are in general poorly constrained by numerical ages (Owen, 2009). Finally, recent glacier retreat in the Himalaya is already affecting runoff (Singh et al., 2005), and according the Intergovernmental Panel on Climate Change (2007a), glaciers in the Himalaya are melting back faster than those in any other part of the world and may disappear by 2035 AD if their current rates of recession continue.

### 3.10. New Zealand

Reviews on alpine glacier fluctuations in New Zealand published by Gellatly et al. (1988) and Röthlisberger (1986) did not include the latest Pleistocene; however, much of the work concerning whether the YD cooling event is recorded in New Zealand has been published only in the past two decades. Following earlier efforts by Wardle (1978) and Mercer (1988), Denton and Hendy (1994) $^{14}$C-dated 25 pieces of fossil wood from Canavans Knob and suggested that the Waiho Loop moraine of Franz Josef Glacier is YD in age. These studies are summarized by Fitzsimons (1997).

Turney et al. (2007) carried out additional $^{14}$C dating of fossil wood from Canavans Knob and suggested that the Waiho Loop predates the YD, and falls within the latter part of the Antarctic Cold Reversal. A pre-YD age for the Waiho Loop moraine is supported by proxy records from sediment cores that also suggest precipitation was more important than temperature as a climate forcing (Singer et al., 1998; Newnham and Lowe, 2000; Turney et al., 2003). Anderson and Mackintosh (2006) designed a numerical model to suggest that the advance of Franz Josef Glacier that formed the Waiho Loop moraine was driven by temperature rather than precipitation change.

Barrows et al. (2007, 2008) measured $^{10}$Be from 10 surface boulders on the Waiho Loop and suggested that the moraine is post-YD in age; however, Applegate et al. (2008) reinterpret these data and suggest an 1100-year older exposure age for the moraine, placing it at the end of the YD. Lowell and Kelly (2008) further discuss why $^{14}$C ages on fossil wood and $^{10}$Be exposure ages on moraine boulders might vary for a given glacial deposit. Finally, Tovar et al. (2008) made a detailed study of till clast lithology and shape from several sections in the Waiho Loop to suggest that the moraine has a landslide origin, making its climatic significance questionable. At Arthur's Pass, a higher elevation site than the Waiho Loop in the Southern Alps, Ivy-Ochs et al. (1999) measured $^{10}$Be from five boulders to suggest an YD exposure age for the Lake Misery moraines, which they suggest was deposited at the same time as the Egesen moraines at Julier Pass in Switzerland (Ivy-Ochs et al, 2009).

Much recent work also has been published on Neoglacial moraines in the Southern Alps. Fitzharris et al. (1992, 1997) compared glacier mass balance of New Zealand glaciers over the past 130 years with atmospheric fluctuations. Chinn (1996, 1999) summarized glacier fluctuations in New Zealand over the past century and two decades, respectively, and Chinn et al. (2005) note that many glaciers in New Zealand recorded positive mass balances from the early 1980s to about 2000 AD, after which all glacier mass balances returned to the negative. Hoelzle et al. (2007) note a 49% decrease in glacier area between 1850 and the mid-1970s.

Winkler (2000, 2004, 2005) used lichenometry and Schmidt hammer tests to refine the chronology for LIA moraines of the Mueller and Tasman Glaciers on the east side of Mount Cook. Tasman Glacier, in particular, has drawn much attention as it has rapidly downwasted during the past few decades (Hochstein et al., 1995), leading to the formation of large proglacial lakes that have accelerated downwasting by calving of the snout (Kirkbride, 1993; Kirkbride and Brazier, 1998; Purdie and Fitzharris, 1999).

In Westland, McKinzey et al. (2004) provide a revised LIA chronology and Goodsell et al. (2005) examine outburst flooding events for Franz Josef Glacier, respectively. Winkler (2009) suggests that the onset of Neoglaciation at Strauchon Glacier in Westland began about 5.5 ka, provides $^{10}$Be ages of 2.5–2.4 ka, 1.7 ka, and 1.1–1.0 ka for subsequent Neoglacial advances, and dated LIA moraines by lichenometry.

The Southern Alps of New Zealand are one of the key areas for testing whether changes in North Atlantic thermohaline circulation during the Holocene force climate in the Southern Hemisphere (Denton and Broecker, 2008). Hence, the precise timing of LIA and earlier Neoglacial advances as well as the YD in New Zealand are important for assessing late Pleistocene and Holocene bipolarity of millennial-scale climate change in the northern and southern polar regions. An extensive project using $^{10}$Be exposure dating of Holocene age moraines in New Zealand is underway, with the first part recording high-frequency Neoglacial fluctuations of the Mueller, Hooker, and Tasman Glaciers on the east side of Mount Cook (Schaefer et al., 2009). In this study, Schaefer et al. (2009) sampled 74 moraine boulders with some of the youngest and most precise $^{10}$Be exposure ages yet recorded; all ages are consistent with moraine position, with the exception of only four outliers. Moraine $^{10}$Be ages for Mueller Glacier are: $160 \pm 30$ ($n = 3$), $220 \pm 10$ ($n = 2$), $270 \pm 50$ ($n = 10$), $400 \pm 70$ ($n = 9$), $570 \pm 70$ ($n = 12$), $1840 \pm 130$ ($n = 7$), $2000 \pm 150$ ($n = 2$), $3230 \pm 220$ ($n = 4$), and $6370 \pm 760$ ($n = 1$) yr B.P. Moraine $^{10}$Be ages for Hooker Glacier are: $810 \pm 70$ ($n = 1$), $1020 \pm 70$ ($n = 5$), and $1370 \pm 180$ ($n = 6$) yr B.P. Moraine $^{10}$Be ages for Tasman Glacier are: $1040 \pm 100$ ($n = 1$), $1650 \pm 110$ ($n = 3$), and $6550 \pm 370$ ($n = 5$) yr B.P. Schaefer et al. (2009) note that their $^{10}$Be ages compare well with $^{14}$C ages from fossil wood buried by tills in lateral moraines as summarized by Burrows (1980, 1989) and suggest that $^{14}$C ages record glacial advances whereas $^{10}$Be ages register glacial terminations. Thus, Schaefer et al. (2009) combine $^{14}$C and $^{10}$Be data to suggest that glaciers advanced and then terminated at ~6.5 ka, 3.65 to 3.20 ka, 2.30 ka, 2.00 to 1.65 ka, 1.40 ka, 1.00 ka, 0.85 to 0.80 ka, 0.65 to 0.57 ka, 0.40 ka, and 0.27 to 0.10 ka. They also note that Mount Cook glaciers respond to summer temperature, based on a nearby tree-ring chronology; were further advanced ~6.5 ka than at any time later in the Holocene; advanced during warm intervals in the Northern Hemisphere; and advanced earlier within the LIA than in the Northern Hemisphere. Schaefer et al. (2009) conclude that Mount Cook glacier chronologies are neither completely synchronous nor completely asynchronous with those in the Northern Hemisphere; thereby the records do not support a singular explanation for global forcing of Holocene climate such as changes in solar irradiance or thermohaline circulation.

### *3.11. South America*

Rodbell et al. (2009) updated the first part of the review paper by Clapperton and Sugden (1988) by subdividing South America into three areas: 1) temperate mid-latitude glaciers of Chile and Argentina, 2) glaciers in the dry subtropical Andes, and 3) tropical Andean glaciers. They note that glaciers in these three regions along a 68-degree meridional transect likely respond differently to disparate atmospheric circulation and regional moisture patterns and are skeptical that glaciers throughout the Andes respond synchronously as suggested by Clapperton and Sugden (1988). Despite these different settings, some similar patterns of glacier fluctuations in the three areas occurred during the Lateglacial, ~16.7 to ~11.5 ka. However, based on the best-dated moraines, glacier fluctuations in the southernmost Andes appear to correlate better with the Antarctic Cold Reversal (~15.2 to 12.2 ka), whereas farther north towards the Equator glacier fluctuations may correlate with the YD cold interval, although much more work is needed to clarify this spatial pattern (Rodbell et al., 2009).

There is a substantial amount of evidence for early to mid-Holocene glacier advances in most areas of South America except for the dry subtropical Andes; in some cases these glacier advances are the most significant during the Holocene, with the exception of northern Bolivia and southern Peru where maximum Holocene ice expansion occurred during the last millennium. There is also good evidence for Neoglacial advances in many areas of South America dating between ~2.5 and ~1.0 ka. The climatic significance of some early Neoglacial advances has been questioned by Porter (2000). Moraines dating between ~1.0 and ~0.5 ka are also found in a few areas, but LIA moraines are ubiquitous throughout the Andes, most dating to the past 450 years. The rapidity of recent glacial recession in the Andes, as in many other mountainous areas of the world, is a threat to future water supplies (Bradley et al., 2006).

### *3.12. Antarctica and the Subantarctic Islands*

Hall (2009) provide new information on both ice sheet and alpine glacier fluctuations in Antarctica and the Subantarctic islands during the Holocene in their update to the second part of the review paper by Clapperton and Sugden (1988). Although not included in their review, the presence of an YD signal in Antarctic ice cores remains elusive, with the exception of an ice core from Taylor Dome (Steig et al., 1998). However, the Antarctic Cold Reversal that pre-dates the YD by ~1.8 ka is recognized in many ice cores on the continent (Blunier et al., 1997; Morgan et al., 2002). Ice cores also record an early Holocene climate optimum between ~11.5 and 9.0 ka, with a secondary optimum between ~7.0 and ~5.0 ka in the Ross Sea region and a late optimum in eastern Antarctica between ~6.0 and ~3.0 ka (Masson et al., 2000).

Hall (2009) note that ice extent was less extensive than at present during the mid-Holocene in several areas of Antarctica, with the exception of the West Antarctic Ice Sheet where recession has continued throughout the Holocene. Neoglacial advances occurred as early as ~5.0 ka in many areas of Antarctica, although advances in the western Ross Sea region during this time frame have not been recognized. Several locations on the Antarctic Peninsula and the adjacent South Atlantic islands record alpine glacier advances ~8.0 to 7.0 ka, ~5.0 to 4.5 ka, ~2.0 ka, and ~1.4 to 1.1 ka (Hall, 2009). Since ~0.7 ka, glaciers in nearly all areas of Antarctica have experienced renewed growth, followed by recession in the past 50 years. This recession is highest for glaciers on the Antarctic Peninsula where recent warming has been more extreme than elsewhere in Antarctica. On the Antarctic Peninsula, some ice shelves reformed after collapsing in response to mid-Holocene warming (Hall, 2009), whereas Larsen B ice shelf was in existence throughout the Holocene until its recent collapse (Domack et al., 2005).

## 4. Discussion

Historical and geologic records of alpine glacier fluctuations were among the first proxy records used to establish the history of Holocene climate change, and these records continue to be valuable to assess current and future changes induced by human activities (Alley et al., 2003; Mayewski et al., 2004; Intergovernmental Panel on Climate Change, 2007a, b). The spatial coverage of these records is now global with firm dating constraints for many of the Holocene glacier advances. Better spatial coverage coupled with tighter age control for many events provide a means to assess forcing mechanisms for Holocene glacier activity that include changes in solar irradiance (Denton and Karlén, 1973; Denton et al., 1986; Bond et al., 2001), volcanic aerosols (Porter, 1986; Nesje and Johannessen, 1992), ice sheets (Bond et al., 1993; Clark et al., 1999), greenhouse gases (Mann et al., 1998b), thermohaline circulation (Bond et al., 1997; Broecker, 2000, 2003; Denton and Broecker, 2008), orbital variations (Kutzbach and Liu, 1997; Ruddiman, 2003), internal atmosphere–ocean interactions, such as ENSO (Haug et al., 2001), and events such as the Younger Dryas (Alley, 2000; Broecker, 2003) or the 8.2-ka Agassiz flood (Alley et al., 1997; Schmidt et al., 2004).

### 4.1. The Lateglacial, deglaciation of cirques, and the Younger Dryas cooling event

Pronounced warming following the Last Glacial Maximum caused widespread recession of alpine glaciers and decay of Northern Hemispheric ice sheets. In northern Europe, cirques probably became ice free before YD cooling caused glaciers to reform (Mangerud et al., 1974). Davis and Osborn (1987) suggested that many outer cirque moraines in western North America, initially believed to be Neoglacial in age, probably formed during the YD; their hypothesis was later confirmed by some studies (Reasoner et al., 1994; Gosse et al., 1995; Menounos and Reasoner, 1997), but not others, where some outer cirque moraines in the western United States appear to be pre-YD in age (Clark and Gillespie, 1997; Heine, 1998).

Advances of ice sheets and alpine glaciers during the YD are also recognized in many other parts of the world, including Alaska (Barclay et al., 2009), Baffin Island (Briner et al., 2009), British Columbia and Washington (Menounos et al., 2009), Iceland (Geirsdóttir et al., 2009), Scandinavia (Andersen, 1995a, b; Mangerud, 2004; Rinterknecht et al., 2004, 2006), and the Alps (Ivy-Ochs et al., 2009). Whether alpine glaciers globally responded to the YD (Peteet, 1995; Osborn et al., 1995) remains controversial in many areas, such as South America (Blunier et al., 1998; Rodbell, 2000; Lowell and Kelly, 2008; Rodbell et al., 2009), New Zealand (Denton and Hendy, 1994; Barrows et al., 2007, 2008; Applegate et al., 2008), and Greenland (Hall et al., 2008; Kelly et al., 2008; Kelly and Lowell, 2009).

### 4.2. The Early Holocene and the 8.2-ka cooling event

Davis and Osborn (1987) and Reasoner et al. (2001) disputed the evidence of significant glacier advances during the early Holocene in western North America as originally proposed by Beget (1983). A similar debate continues for glacier activity on Mount Baker in the Washington Cascades where reports of extensive, early Holocene glaciers (Thomas et al., 2000; Kovanen and Slaymaker, 2005) have been challenged by others (Davis et al., 2006; Osborn et al., 2007a, b; Clark et al., 2007). However, in other parts of the Northern Hemisphere there is evidence for minor glacier advances correlative with the 8.2 ka cooling event (Alley et al., 1997), such as the western Canadian Cordillera (Menounos et al., 2004, 2009), Scandinavia (Nesje and Dahl, 2001; Nesje, 2009), and possibly the Alps (Kerschner et al., 2006; Ivy-Ochs et al., 2009). By contrast, in the Southern Hemisphere (Rodbell et al., 2009; Schaefer et al., 2009; Hall, 2009) and the Himalaya (Owen, 2009), some alpine glaciers were more extensive during the early Holocene than any time later.

### 4.3. Neoglaciation and the Little Ice Age

In some parts of the world, alpine glaciers disappeared during the Hypsithermal (Deevey and Flint, 1957) before re-forming during Neoglaciation (Porter and Denton, 1967). Recent data from many areas suggest that Neoglaciation began earlier than suggested by Porter and Denton (1967), typically by 6.5 ka (Davis et al., 2006), and perhaps as early as 7.4 ka in western Canada (Menounos et al., 2009; Clague et al., 2009). The timing and causes of millennial-scale fluctuations of alpine glaciers during the Holocene remain big questions. Denton and Karlén (1973) and Denton et al. (1986) suggested that alpine glaciers advanced and retreated on a 2500-yr cycle in tune with solar variation, whereas Röthlisberger (1986) countered that alpine glaciers responded on a shorter time scale, closer in length to the proposed 1500-yr North Atlantic thermohaline cycle (Bond et al., 1993, 1997).

The Little Ice Age (LIA), once defined as the re-growth of glaciers during the past few millennia of the postglacial (Matthes, 1935, 1941), is now commonly used in reference to glacier advances from about the mid-1400s to late 1800s AD, during the latest Neoglacial (Grove, 1988, 2004). However, Clague et al. (2009) note that in many areas, including the western Canadian Cordillera, LIA advances began hundreds of years earlier. Questions remain whether alpine glaciers fluctuated globally in unison during Neoglaciation and whether LIA advances are somehow different in comparison to earlier Neoglacial advances (Broecker, 2000; Denton and Broecker, 2008). In many areas of the Northern Hemisphere, LIA advances are the most extensive during the entire Holocene, in contrast with most areas of the Southern Hemisphere. Only recently have detailed records of alpine glacier fluctuations on decadal to centennial time scales become available through dendrochronology (cf. Barclay et al., 2009), proglacial lake sedimentation (cf. Menounos et al., 2009; Briner et al., 2009; Geirsdóttir et al., 2009; Nesje, 2009), or cosmogenic nuclide exposure dating (cf. Schaefer et al., 2009).

### 4.4. Future work

A large array of chronological methods with improved accuracy and precision are now available for dating alpine glacier moraines and related deposits. Ideally multiple methods for dating moraines, such as combining $^{14}$C dating of fossil wood in lateral moraine stratigraphy and $^{10}$Be dating of moraine surface boulders, should be used to yield comprehensive chronologies for a particular glacier or alpine region. Better yet, in combination with moraine dating strategies, glaciers should be chosen with downvalley lakes to provide continuous proxies for upvalley glacier activity. Additional insight into the exact timing of events and climate forcing may be provided by targeting future work in glacier forefields in close proximity to high-resolution climate records provided by tree rings, speleothems, and ice cores from mountain ice caps.

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