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Nomenclature and resolution in Holocene glacial chronologies

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ABSTRACT

Most Quaternary research in Canada during the first half of the twentieth century focused on Pleistocene glaciation. Given the dramatic shifts in climate during the Pleistocene, it is not surprising that the Holocene was viewed as a time of benign climate. Holocene climate variability was first recognized around the middle of the century when paleoecologists found evidence that the early part of the epoch was warmer and drier than the later part. In 1970s and 1980s, another generation of geologists, geographers, and botanists began to recognize more complexity in Holocene climate and vegetation in western Canada. Several millennial-scale glacier "advances" postdating the early Holocene warm interval were defined, including the Garibaldi Phase (6.9–5.6 ka), the Tiedemann–Peyto Advance (3.5–1.9 ka), and the Little Ice Age (AD 1200–1900). Subsequently, application of dendrochronological techniques and stratigraphic studies in glacier forefields showed that the Little Ice Age was itself more complex than previously thought. During that 700-year period, glaciers repeatedly advanced and retreated in response to climatic variability on time scales ranging from centuries to decades. Recent work shows that the glacier record of the Garibaldi Phase and the Tiedemann and Peyto advances are similar in complexity to the Little Ice Age, with multiple advances of glaciers separated by intervals of more restricted ice cover. Researchers have also identified other times in the Holocene when glaciers expanded from restricted positions – 8.20, 4.90–3.80, and 1.70–1.40 ka. Continued research undoubtedly will reveal additional complexities, but with what is currently known the appropriateness of terms such as "Tiedemann Advance," "Peyto Advance," and "Little Ice Age" can be questioned. Only short periods of time separate these episodes as currently defined, and it seems likely that intervals of restricted glacier cover within each of these millennial-length intervals are just as long as the intervals separating them.

1. Introduction

The Holocene is viewed by some as a time of benign climate that contrasts markedly with the highly variable climates of the late Pleistocene. Average regional temperature during the Holocene did not vary by more than 2 °C, a fraction of the range in the global average temperature during the Pleistocene. However, as more complete, continuous proxy records of Holocene climate have been developed, it has become apparent that climate has varied continuously over the past 11.8 ka[1] (O'Brien et al., 1995; Mayewski et al., 2004), with sudden changes that have impacted societies. For example, severe cold and wet intervals during the Little Ice Age (AD 1200–1900) caused famine and disease in Europe (Grove, 1988).

Although the Little Ice Age is the best known of the cold intervals of the Holocene (Grove, 1988; Mann et al., 1998; Bradley et al., 2003), it is not unique – there were other cold, wet intervals of comparable duration during the latter half of the epoch. The Laurentide ice sheet, the largest of the late Pleistocene ice sheets in the Northern Hemisphere, also persisted, albeit in a much reduced state, for the first several thousand years of the Holocene (Dyke and Prest, 1987), and global sea level remained well below its present datum until the middle Holocene (Fairbridge, 1989). These persisting effects of late Pleistocene glaciation must have influenced global and regional climates well into the Holocene.

Terminological difficulties can arise when ongoing research and new methods allow better temporal resolution. Western Canada's well-documented Holocene glacial chronology (Menounos et al., 2009) provides a prime example of such difficulties. Here we focus on that example to demonstrate changing scientific attitudes about Holocene glacial activity and climate variability. This paper is not

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[1] 'ka' denotes thousands of calendar years ago.

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a literature review, but rather a discussion of nomenclature that has been applied to Holocene alpine glacier activity in western Canada in the context of our evolving understanding of that activity. These attitudinal changes are paralleled by similar developments elsewhere in the world, and the western Canadian problems raised here are generally applicable in many other regions.

Our interest in this topic derives from questions about the appropriateness of present nomenclature applied to late Holocene glacial events in western Canada that arise from our improved understanding of glacier fluctuations and climate change. For example, does the continued use of terms such as the "Little Ice Age" and "Neoglaciation" to describe Holocene glacier fluctuations help or hinder the establishment of regional glacier chronologies and the critical appraisal of regional and global synchronicity of glacial events and probable forcing mechanisms? Can, and if so, how does one define the start, duration, and end of an "advance," a term commonly used for expansion of alpine glaciers in North America? How, for that matter, does one gauge the magnitude of the advance? Are terms that have been applied in the past helpful in understanding the causes of Holocene glacier fluctuations? We argue here that some terms, coined at a time of nascent awareness of the complexity of Holocene climate, condition scientists to force their evidence into "boxes" that may be inappropriate today. Dating techniques have improved, and events of interest can now be dated, in many instances, with decadal or better resolution. We argue that these improvements are increasingly rendering existing terminology archaic.

2. Early developments

The first evidence that the Holocene was a time of variable climate in western Canada was gathered by paleoecologists and glacial geologists in the 1940s and 1950s. Henry Hansen and William Mathews made especially notable contributions. Hansen (1940, 1947, 1950a, b, 1955) published pollen diagrams spanning the Holocene for several sites in British Columbia and western Alberta. From them, he inferred that climate during the early Holocene was warmer and drier than today. By inference, climate cooled and became wetter later during the Holocene. Mathews (1951), working in Garibaldi Provincial Park in the southwest Coast Mountains, was the first geologist to report that glaciers advanced during the Little Ice Age in western Canada. This term was coined a decade earlier by Matthes (1939, p. 520) to describe glacier inception or growth in the Sierra Nevada, California, during the late Holocene. Similar pioneering work was carried out in the Canadian Rockies by Heusser (1955, 1956, 1960). These studies were remarkable for their time and set the stage for broader recognition that glaciers, and consequently climate, in western Canada fluctuated markedly during the Holocene.

The moraines that Matthes attributed to the Little Ice Age were later recognized as a product of a long period of "Neoglaciation" (Porter and Denton, 1967) that comprised several intervals of glacier expansion. Neoglaciation followed the period of maximum Holocene warmth, referred to as the Hypsithermal (Deevey and Flint, 1957). The term "Little Ice Age" now refers only to the latest part of Neoglaciation, during the past millennium (Grove, 2001a, b).

A second generation of glacial geologists, physical geographers, and paleoecologists, trained in the 1950s, 1960s, and 1970s, refined the record of climate and glacier change in western Canada using the same methods that had been used by Hansen, Mathews, and Heusser. Paleoecologists focused on the transition from Lateglacial time to the Holocene. They reconstructed early postglacial vegetation, which rapidly changed following the first colonization of deglaciated landscapes by plants (Mathewes, 1973, 1985; Hebda, 1983; Heusser et al., 1985). Like Hanson, they recognized a warmer, drier interval in the early Holocene that contrasted with the cooler, wetter climate of the past 5–6 ka. They did not focus on climate change on time scales of centuries or less, largely because the temporal resolution of the cores they studied precluded such detail and because vegetation did not respond that quickly.

Evidence that climate fluctuated significantly during the latter half of the Holocene was provided by research in the 1980s in the Coast Mountains (Ryder and Thomson, 1986; Ryder, 1987) and in the Rocky and Purcell Mountains (Luckman and Osborn, 1979; Osborn, 1986; Osborn and Karlstrom, 1988, 1989; Osborn and Luckman, 1988). Ryder and Thomson (1986) presented evidence for a major advance of Tiedemann Glacier between about 3.5 and 1.9 ka, an event they called the "Tiedemann Advance" (Fig. 1). At about the same time, Osborn (1986), Osborn and Karlstrom (1988, 1989), and Osborn and Luckman (1988) reported a similar event in the Rocky and Purcell Mountains. They argued that the event consisted of two advances with an intervening period of retreat. Luckman et al. (1993) later termed this event the "Peyto Advance." The Tiedemann and Peyto advances significantly postdate climate cooling in the middle Holocene inferred by paleoecologists, suggesting that the assumption of monotonic climate cooling during the late Holocene was incorrect. Ryder and Thomson (1986) also identified an earlier interval of glacier expansion in Garibaldi Park about 6.9–5.6 ka, which they called the "Garibaldi Phase."

3. Greater complexity

An awareness of greater complexity in Holocene climate and glacier activity emerged with new dendroclimatological and dendroglaciological studies. Researchers used new tree-ring and lichenometric data to better constrain the ages of glacier advances in the Rocky Mountains (Luckman, 1994, 1995, 1996, 2000; Luckman et al., 1993, 1997), the southern Coast Mountains (Larocque and Smith, 2003) and on Vancouver Island (Smith and Laroque, 1996; Smith and Desloges, 2000; Lewis and Smith, 2004). They also developed proxies for precipitation and temperature over the past several hundred years from tree-ring series (Fig. 2). Most recent research has been on Little Ice Age events, but researchers also have contributed to recognition of earlier glacier advances. What stands out from this body of research is the previously unrecognized variability of climate during periods when glaciers were generally extensive, such as the Little Ice Age. The Little Ice Age was not a period of uniformly cool climate, but rather included cold or wet events lasting from a decade or less to more than a century, separated by relatively warm or dry conditions. Perhaps, it should come as no surprise that climate during the Little Ice Age was also variable, as shown by many reconstructions of Northern Hemisphere temperatures during the past millennium (Mann et al., 1998). Awareness of climate variability during the past millennium has forced a reassessment of the value of the term "Little Ice Age" (Matthews and Briffa, 2005), as discussed below. The implications of this reassessment for earlier, less well-documented intervals of cooler climate and glacier advance are only now being considered.

The numerous high-resolution proxy climate records that have become available in the past few decades show that climate varied through the Holocene and cannot be easily divided into simple units. The nomenclature that we discuss and criticize was based on an older view of climate, one underpinned by assumptions of slow and discontinuous climate change.

Our emerging understanding of complex Holocene glacier activity has been paralleled by recognition of the importance of several climate forcing mechanisms that are effective on different time scales. Orbital solar forcing probably has driven successively more extensive Northern Hemisphere glacier advances throughout the Holocene. Glacier fluctuations on century and millennial time

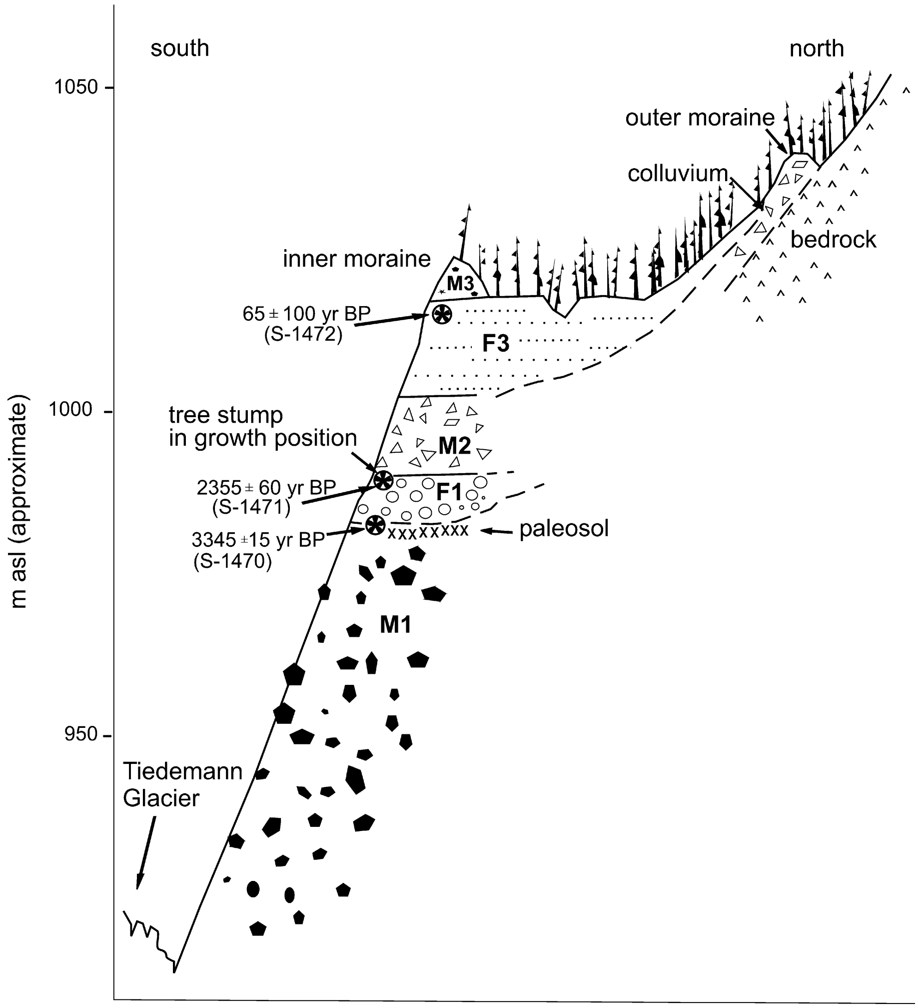

Fig. 1. Stratigraphy of north lateral moraine of Tiedemann Glacier as presented by Ryder and Thomson (1986). This stratigraphy provides evidence for the Tiedemann Advance.

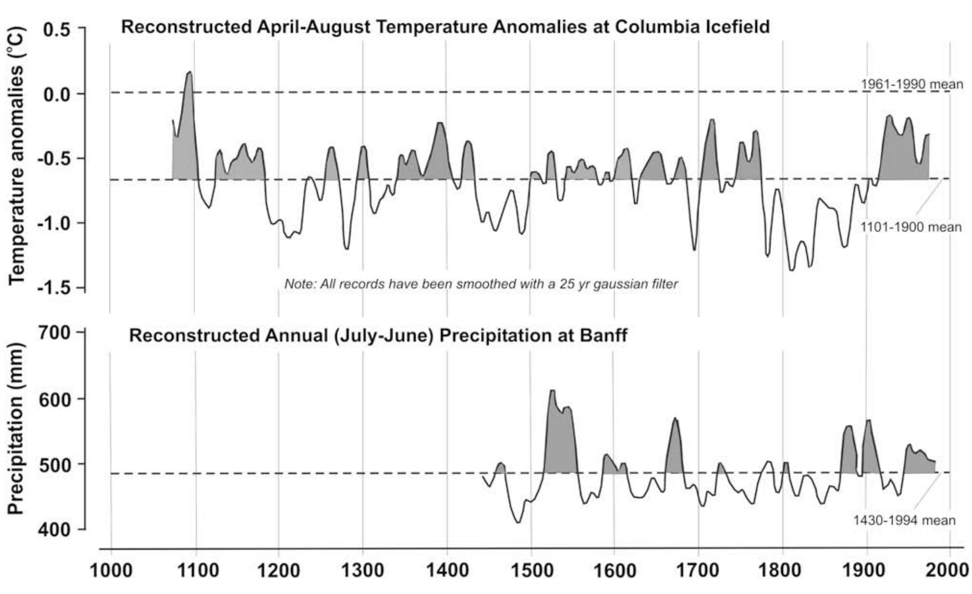

Fig. 2. Temperature and precipitation reconstructions for the Columbia Icefield area of the Rocky Mountains based on tree-ring series derived from old living trees and cross-dated snags (after Luckman, 2000).

scales appear to be influenced by changes in solar irradiance (Denton and Karlén, 1977; Karlén and Kuylenstierna, 1996) and modulated by atmospheric or feedback effects. In addition to these normal climate forcings, exceptional events with terrestrial triggers, such as the 8200-year cold event (Alley et al., 1997) and anthropogenic greenhouse forcing of the past century, events have had climatic effects on a global scale (Intergovernmental Panel on Climate Change, 2007).

Equally important to understanding the complexity of Holocene glacier activity are regional and altitudinal differences in climate, which may vary with time. British Columbia's climate is dominated by moist air masses that move eastward from the North Pacific Ocean across the province. North Pacific climate, in turn, is closely linked to the Pacific Decadal Oscillation (PDO), a long-term El Niño-like pattern of North Pacific climate variability, with phases that persist for decades (Mantua and Hare, 2002). The positive, or warm, phase of the PDO is characterized by cooler-than-average sea-surface temperatures near the Aleutian Islands and warmer-than-average sea-surface temperatures along the California coast. El Niño-like conditions are enhanced during the positive phase of the PDO. The negative, or cool, phase of the PDO enhances La Niña conditions in the Northern Hemisphere (Mantua and Hare, 2002). The cyclicity, strength, and spatial pattern of the PDO may have changed through the Holocene as climate warmed or cooled. If so, glaciers in different areas may have responded differently to climate forcing at different times in the past. Likewise, altitudinal differences probably introduce complexity in glacier activity over time. When climate cools, glaciers with large, high accumulation areas might respond differently from small glaciers at similar elevations. Similarly, the seasonal distribution of snowfall and temperatures may change through time, affecting glaciers in some regions differently than in others.

4. Relevance of "Little Ice Age" as a term

In her comprehensive review, Grove (2004, p. 1) defined the Little Ice Age in terms of glacier extent, stating that it began in the thirteenth or fourteenth century and culminated between the mid-sixteenth and mid-nineteenth centuries. This definition is not universally accepted, largely because the Little Ice Age has also been associated with climate different from today's, for example a notable "cold period" (Lamb, 1977). Today, climate is the focus of much of the discussion about the Little Ice Age, rather than glacier extent, which is the basis for its original definition. The mixed use of the term has created confusion (Matthews and Briffa, 2005), leading some to recommend that the term be avoided (Jones and Mann, 2004) or allowed to disappear from use (Ogilvie and Jónsson, 2001).

That glaciers were more extensive during the past several centuries than today is an undeniable fact (Grove, 2004), but the usefulness of the term "Little Ice Age" for this period is called into question by several issues (Matthews and Briffa, 2005). First, scientists contest the time of onset and the end of the Little Ice Age. Second, the degree of synchroneity of glaciers in different mountain ranges, or even within ranges, remains uncertain. Third, no consensus exists over the causes of glacier change during the Little Ice Age, which is essential if the term is to be properly defined and used. We consider each of these issues in turn, in part because they also apply to earlier periods of glacier expansion in the Holocene that are similar to the Little Ice Age but are much more poorly understood.

Grove (2001a, b) concluded that the Little Ice Age began before the fourteenth century based on evidence that glaciers were advancing between the twelfth and fourteenth centuries. Regions with the best temporal resolution, such as the Swiss Alps (Holzhauser, 1997), reveal a complex history. Grosser Aletsch Glacier, for example, expanded at the end of the twelfth century, marking the onset of the European Little Ice Age. However, the greatest advances of Grosser Aletsch Glacier, at about AD 1350, 1650, and 1850, were little more extensive than those at about AD 450 and 800, prior to the Little Ice Age (Fig. 3).

The question of synchroneity of Little Ice Age advances must be considered in relation to the time scale of interest. Synchronous advance and retreat of glaciers, even within a single mountain range, should not be expected on time scales of less than a decade, as is evident from glacier activity in the twentieth century. Even within a region of relatively homogenous climate, glaciers may fluctuate differently due to their different topographic contexts, hypsometry, and the relative effects of summer temperature and winter precipitation. Non-climatic factors appear to play an important role in the behavior of tidewater glaciers. Asynchronous glacier behavior becomes even more obvious when considered worldwide, because many glaciers in the Southern Hemisphere, notably New Zealand, advanced at times in the twentieth century when Northern Hemisphere glaciers retreated (Grove, 1988). On time scales of several decades to centuries, however, a different picture emerges – the vast majority of alpine glaciers in both hemispheres retreated in the twentieth century due to well-documented climate warming. Furthermore, according to Grove (2004, p. 560), there is "a striking consistency in timing of the main advances" of the Little Ice Age worldwide. Her statement is consistent with Porter's (1981) conclusion that late Little Ice Age advances throughout the Northern Hemisphere were broadly synchronous on a multi-decadal time scale.

Researchers also disagree on when the Little Ice Age terminated, mainly because they have used different criteria. In many areas, glaciers receded during the second half of the nineteenth century after advances earlier in that century. Some authorities thus place the end of the Little Ice Age in the late 1800s, or for simplicity around AD 1900 (Dyurgerov and Meier, 2000; Bradley et al., 2003). In western Canada and elsewhere, significant glacier recession did not begin until the early to mid-twentieth century. Matthews and Briffa (2005) thus have suggested that the mid-twentieth century might be a more appropriate end point for the Little Ice Age.

5. Little Ice Age-like "events" earlier during the Holocene

The same issues that confound use of the term "Little Ice Age" also apply to earlier Holocene glacier advances. As our

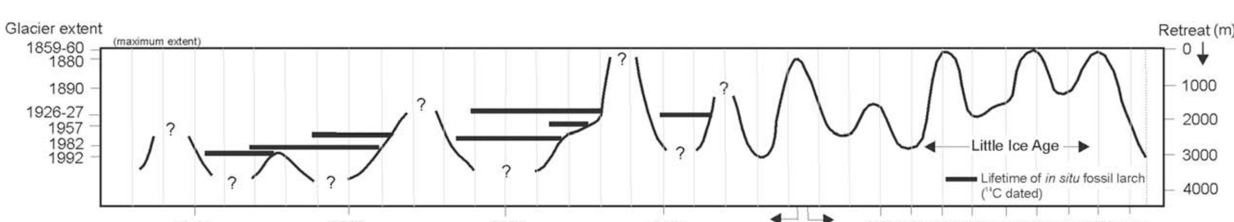

Fig. 3. Variations in the extent of Grosser Aletsch Glacier in the Swiss Alps over the past 3000 years based on documentary and proxy evidence (after Holzhauser, 1997).

understanding of these earlier, Little Ice Age-like episodes has improved, we have recognized that at least some of them are of similar duration to, and have all the complexity of, the Little Ice Age. In this section, we summarize the evidence for this assertion. We refer readers to the paper by Menounos et al. (2009) for additional details on the chronology of Holocene glacier fluctuations in western Canada.

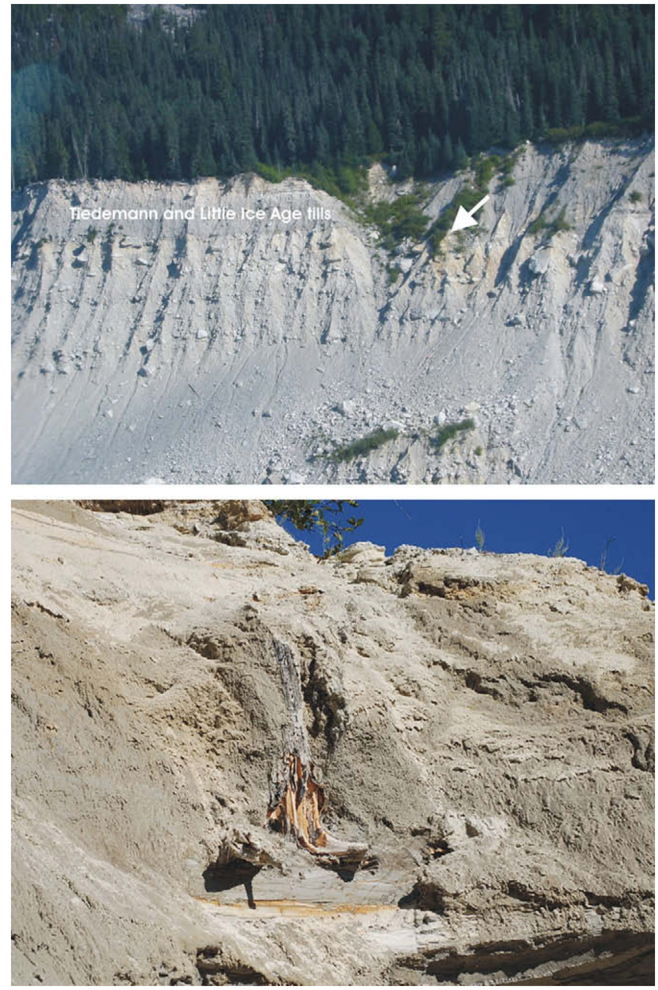

Fig. 4. (Top) North lateral moraine of Tiedemann Glacier and (bottom) *in situ* stump within a sequence of sand and silt. Outermost rings of the stem gave a radiocarbon age of 2660 ± 50 ^{14}C yr BP (2.72–2.87 ka). The stratified sediments were deposited by a stream flowing along near the margin of Tiedemann Glacier when it was more than 100 m thicker at this site than today. They are overlain successively by Tiedemann and Little Ice Age tills.

5.1. Tiedemann–Peyto Advance

The Tiedemann Advance was defined by Ryder and Thomson (1986) for an advance of Tiedemann Glacier in the southern Coast Mountains between about 3300 and 1900 ^{14}C yr BP (3.5–1.9 ka). The evidence includes lateral moraines outside the Little Ice Age limit, as well as the radiocarbon-constrained stratigraphy of the composite, north-lateral, Little Ice Age moraine (Fig. 4). Other researchers subsequently reported glacier activity within the period of the Tiedemann Advance at many other sites in western North America. Some of Ryder and Thomson's evidence, however, is enigmatic. Notably, Tiedemann Glacier is the only site in British Columbia where Neoglacial moraines with firm chronologic control lie outside Little Ice Age moraines, and it is unclear why Tiedemann Glacier would behave differently from other glaciers.

The Tiedemann Advance was originally thought of as a single expansion of glaciers. Indeed, a single, continuous expansion of glaciers is implicit in the use of the word "advance," which in its singular form means "a moving forward." Yet, later work at Lillooet Glacier by Reyes and Clague (2004), in Garibaldi Park by Koch et al. (2007), and elsewhere demonstrated that the Tiedemann Advance comprises two or more separate advances separated by marked recession. A picture has emerged of a millennial-length period during which alpine glaciers were generally more extensive than today, but with repeated advances and retreats on much shorter time scales (decades to centuries), similar to Little Ice Age advances and retreats.

Glaciers in the Purcell and Rocky Mountains expanded during the Peyto Advance (Osborn and Karlstrom, 1988, 1989; Osborn and Luckman, 1988; Luckman et al., 1993), which is broadly synchronous with the earlier part of the Tiedemann Advance, identified farther west. Bugaboo Glacier in the Purcell Mountains advanced between 3390 ± 80 and 3070 ± 120 ^{14}C yr BP (3.7–3.2 ka) and again shortly after about 2500 ^{14}C yr BP (2.6 ka).

A long, but complex period of more extensive glacierization around 3.7–2.6 ka is supported by records derived from sediment cores collected from proglacial lakes in southwest British Columbia. Clastic sediment delivery to Green Lake, interpreted by Menounos (2002) to be a proxy for ice cover in Garibaldi Park directly to the east, increased abruptly about 3230 ± 50 ^{14}C yr (3.6–3.4 ka) and peaked about 2.6 ka (Osborn et al., 2007). This rapid increase is superposed on the general increase in clastic sediment delivery to the lake from the early Holocene to the present, which reflects the greater extent of glaciers during each successive millennial-scale glacial phase.

5.2. Garibaldi Phase

Although not as well documented as the Tiedemann Advance, the Garibaldi Phase, dated to between 6.9 and 5.6 ka, is another period when glaciers repeatedly advanced. The term "Garibaldi Phase" was coined by Ryder and Thomson (1986) on the basis of *in situ* stumps of coniferous trees in subalpine environments in glacier forefields in Garibaldi Park. Koch et al. (2007) reported additional radiocarbon ages on *in situ* stumps and detrital wood from the park that suggest the Garibaldi Phase was not a single advance, but a series of advances spanning more than a millennium. The radiocarbon ages from Garibaldi Park, which Koch et al. (2007) argued closely delimit times of local glacier advances, range from 6360 ± 80 to 5130 ± 40 ^{14}C yr BP (7.3–5.8 ka). An independent proxy for an advance of glaciers during the Garibaldi Phase is the clastic sediment record in proglacial lakes in the southern Coast Mountains. Menounos (2002) and Osborn et al. (2007) noted an abrupt increase in sediment delivery to Green Lake about 5040 ± 50 ^{14}C yr (5.9–5.7 ka), which they attributed to increased ice cover in Garibaldi Park.

It is noteworthy that Ryder and Thomson (1986) used the word "phase" to describe the period of extended alpine glacierization in the middle Holocene. "Phase" does not suffer the disadvantage of suggesting a single forward movement of glaciers, implicit in the word "advance." "Phase" connotes cyclicity – its definition is "a stage or form in any *series* or *cycle* of changes, as in development" (Webster's New World Dictionary). The cyclicity of Holocene glacial episodes is discussed later in this paper.

5.3. Other events

The complexity of the Holocene glacial record in British Columbia has become clearer in recent years with the discovery of other periods of extended glacier cover. First was recognition of an

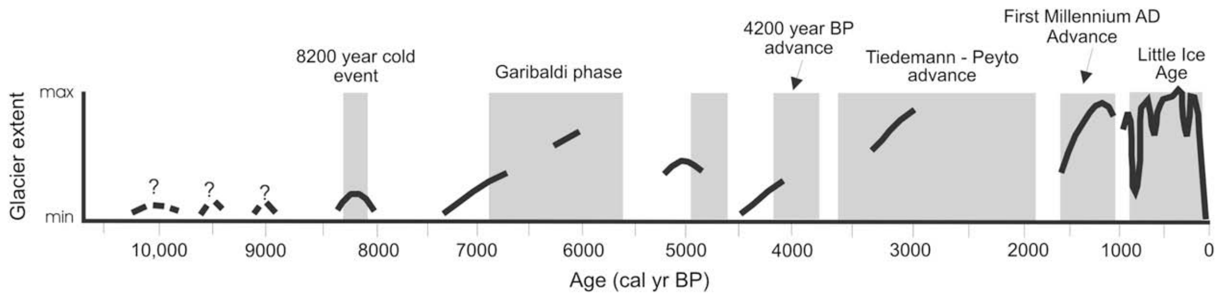

Fig. 5. Generalized activity of Holocene glaciers in western Canada during the Holocene. Grey blocks are named "advances." Diagram was compiled from sources mentioned in the text.

advance at the time of the 8200-year cold event, originally recognized in Greenland ice cores and in areas bordering the North Atlantic (Alley et al., 1997). This cold event was attributed to disruption of thermohaline circulation due to the final drainage of Lake Agassiz into the North Atlantic via Hudson Bay and Hudson Strait (Barber et al., 1999; Alley and Ágústsdóttir, 2005). Menounos et al. (2004) provided the first evidence that glaciers in western North America responded to the 8200-year cold event – clastic sediment delivery to Green Lake and nearby lower Joffre Lake increased and glaciers overrode forest in Garibaldi Park about 8.1 ka. They argued that this advance was small and of short duration compared to later glacier advances. Wood of the same age also washed out of the front of retreating Athabasca Glacier in the Canadian Rockies in the mid-1980s (Luckman, 1988).

Reyes et al. (2006) documented a short-lived period of extended glaciers between about 1.7 and 1.4 ka, which they termed the "First Millennium AD Advance." The evidence includes glacially overridden, radiocarbon-dated stumps and dated paleosols overlain by till in lateral moraines.

No regional glacier advances between about 5 and 3 ka have been recognized in western Canada, although a number of isolated cases have been reported (e.g. Gardner and Jones, 1985; Koch et al., 2007). Recently, however, Menounos et al. (2008) presented new evidence that many glaciers in British Columbia advanced into forest between about 4.9 and 3.8 ka. An advance about 4.9 ka was followed by retreat and then, about 4.2 ka, by a more extensive advance that may have lasted a few centuries.

In summary, our knowledge of Holocene glaciation in western Canada is far more detailed than it was even a decade ago. Our sharpened view reveals considerable complexity that formerly was not known (Fig. 5), including repeated, millennial-length periods of greater ice cover, but within which glaciers fluctuated on decadal and centennial time scales (Garibaldi, Tiedemann–Peyto, Little Ice Age, and the period between ca 4.9 and 3.8 ka). New data reveal other, previously unrecognized events, including an advance about 8.1 ka and another about 1.7 ka. Other advances and additional complexity probably will be found in the future.

6. Problems with existing terminology

We assert that the word "advance" is inappropriate for an event as complex and long as the Tiedemann Advance. Other related issues are worthy of discussion. Pigeonholing events with phrases such as "Garibaldi Phase," Tiedemann Advance," and "Little Ice Age" may mask the true complexity of Holocene glacier activity. As an example, consider the commencement of the Little Ice Age. Some researchers have argued that the beginning of the Little Ice Age be linked to the start of the most severe climates of the past millennium, around AD 1550 (Lamb, 1963, 1966; Bradley and Jones, 1992a, b). This definition corresponds to what Ogilvie and Jónsson (2001) called the "orthodox" or "classical" view (Lamb, 1977). However, this view is based on climate, not on the glacial record, and we argued earlier for restricting the term to the latter. Even so, some climatologists argue that the Little Ice Age began in the early thirteenth century (Jones and Mann, 2004). In general, definitions based on climate are potentially problematic and should be eschewed. Landsberg (1985, p. 62) captured the widespread dissatisfaction among climatologists with the idea of a Little Ice Age climate in stating the obvious – climate during this period "was not uniformly cold in space or time."

Defining the beginning of the Little Ice Age at say AD 1200 is, however, not without its problems. We have suggested that climate continuously varies, which in itself may make such an exercise fruitless. Further, glaciers throughout western North America advanced between 1.7 and 1.4 ka (AD 300–600). This advance began less than 600 years before the first advance of the Little Ice Age, around AD 1200. Given that some glaciers in western North America were as extensive at AD 600 as they were 600 years later (Reyes et al., 2006), why not include this event in the Little Ice Age?

Similar problems arise with the Tiedemann Advance. Ryder and Thomson (1986) stated that the Tiedemann Advance ended about 1900 years ago, only 200 years before the beginning of the First Millennium AD Advance. Again, the latter may record a more extensive advance, at least locally, than the former, thus the rationale for separating the two is problematic.

We recommend restricting the term "advance" to a single, major, well-dated expansion of glaciers to a limit, without significant intervening retreats, an event that commonly is difficult to document based on landform and stratigraphic evidence alone. Long intervals when glaciers were generally extensive, but which contained several periods of advance separated by glacier retreat, are perhaps better termed glacial "phases," but this term should be used informally. In general, however, the focus of effort should be on dating glacier margins as accurately as possible, not on defining or applying terms that force the complex activity of glaciers into century- and millennial-scale "boxes."

The "Little Ice Age" remains a useful term and, in any case, is entrenched in the psyche of researchers and likely will never be abandoned. The term should, however, be applied to glacier activity and not used in a climatic context.

7. Conclusions

An earlier simplistic scenario of Holocene glaciation in western Canada is being replaced by one that features far more complexity and is characterized by variability in glacier activity comparable to that of the historic period. Researchers originally pictured the Holocene as having two phases, an early warm dry interval followed by a period of cooler climate broadly similar to that of today.

The current view involves three levels or tiers of climate complexity with different principal forcings.

The first level is millennial-length periods of glacier expansion, each more extensive than its predecessor. Long periods of extended ice cover date to about 6.9–5.6, 4.9–3.8, 3.5–1.9, and 0.8–0.1 ka in western Canada. The trend towards successively greater extent of glaciers in western Canada during the Holocene is likely the result of the continuous reduction in solar insolation during summer in the Northern Hemisphere over this period.

On the second level are the fluctuations of glaciers on time scales of decades and centuries within each of the millennial-length periods. These fluctuations may have periodicities, but high-resolution, continuous records from tree-rings, ice cores, or annually laminated lake sediment cores are required to test this assertion. Forcings may include changes in solar irradiance, volcanic activity, or other factors.

On the third level is glacial activity on very short time scales of a decade or less. This activity is controlled by local and regional climate and modulated by non-climatic factors such as topography, glacier hypsometry, and elevation.

The natural human tendency to categorize and box "events" may impede achieving a full understanding of the complexity of climate and glacier systems. Scientists, of course, require labels to communicate with one another, but there is a danger in forcing evidence of past glacier activity into previously named events, such as the Tiedemann Advance and the Garibaldi Phase. A further concern arises around the appropriateness of some terms now used to identify highly complex periods of greater ice cover, notably the word "advance." We recommend more careful use of these terms and greater focus on dating Holocene glacier activity with the greatest precision possible.

Acknowledgements

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