'Our ice dependent world'

A paleoenvironmental perspective

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1 Introduction

Our world is changing. The climate is warming and glaciers are melting. The rate of global oceanic and atmospheric warming observed over the past two decades is unprecedented (Lemke *et al.*, 2007), and in the Arctic this rate of warming is 1.9 times greater than the global average (Serreze and Barry, 2011). We know that this rate of warming is unprecedented because we can compare today's climate with past climates that are archived in the paleo-record. These records include marine and ice cores that preserve an isotopic history of past environmental change, such as precipitation and temperature. Understanding how the climate has changed in the past – its timescales, dynamics, and sensitivities – allows modern climate change to be placed into a better-understood long-term context. This long-term context has shown that the climate of the Arctic has always been changing, and that change is perfectly natural. We know, for example, that during the last interglacial ~120,000 years ago that the Canadian Arctic was approximately 4°C warmer and sea levels were ~6m higher than today (Kaufman and Brigham-Grette, 1993). What is disconcerting about modern climate change is the *rate* of change, not the change itself.

Although the climate will continue to change, and the ice will continue to melt, we can look to the paleo-record to provide insights into *how* and *when* this melt will happen. The western Canadian Arctic preserves a rich history of past environmental and glacial change and can provide a wide range of relevant analogues for contemporary glaciers and ice sheets. These analogues can provide crucial tools for the effective planning and mitigation of global ice melt and its far-reaching environmental, social, and economic repercussions.

This paper will discuss: 1) The history of glacial reconstructions in the western Canadian Arctic, 2) Research into the glacial history of Banks Island, western Canadian Arctic, 3) The wider implications of this research on Banks Island 4) Analogues from south Banks Island that are relevant to modern glacier change, and 5) The importance of a paleoenvironmental perspective when tackling the issue of 'our ice dependent world'.

2 The glacial history of the western Canadian Arctic

The climate and environment of the western Canadian Arctic (Figure 1) have fluctuated dramatically over the last 2.6 million years. Over the course of this period, known as the Quaternary, huge ice sheets repeatedly inundated the region. These ice sheets acted as major agents of landscape modification – scouring and deepening marine channels, eroding and smoothing upland peaks, and depositing and shaping many of the landforms that are so ubiquitous in the Arctic today. Each major ice advance occurred during a glacial period that lasted approximately 100,000 years, superseded by a much shorter interglacial period that lasted 10,000 years (Benn and Evans, 2010). These interglacial periods were characterised by abrupt climate warming and an associated migration of more temperate flora and fauna into the high-latitudes. We are currently nearing the end of one of these interglacial periods, known as the Holocene, which began 10,000 years ago after the termination of last glacial episode, known as the Wisconsinan. The Wisconsinan Glaciation was punctuated by three glacial maxima (distinct ice advances) that correspond to colder peaks in the climate. The Wisconsinan Glaciation culminated in a period of global maximum ice extent between 25,000-10,000 years ago, known as the Late Wisconsinan. The chronology, configuration, and dynamics of the major ice sheets that occupied and influenced the western Canadian Arctic during the Late Wisconsinan have remained a matter of fascination and debate for over a century (e.g. Hobbs, 1945; Jenness, 1952).

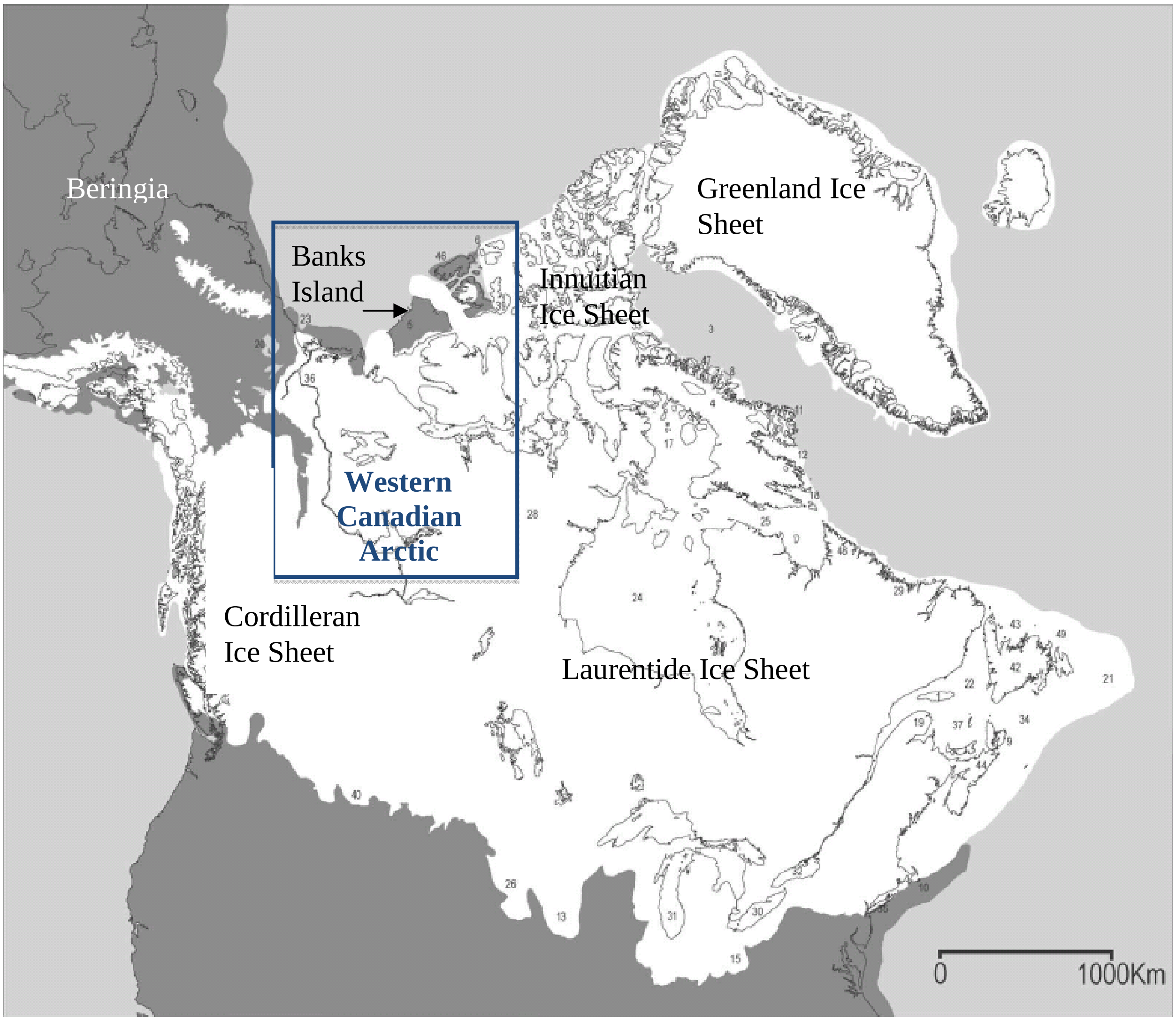

Figure 1: North America during the Late Wisconsinan. Dyke *et al.*, 2002

Over the past century, pendulum swings have been witnessed in the prevailing minimalist (restricted ice) versus maximalist (extensive ice) paradigms of the western Canadian Arctic (e.g. Prest, 1969; Hughes, 1972; Vincent, 1982; Sharpe, 1984). Fundamental discrepancies between glacial reconstructions have arisen because of limited fieldwork, poor chronological control, and subjectivity by researchers that have served to polarise and politicise the community. However, such polarisation has also been paramount in generating interest in the glacial history of the western Canadian Arctic. Consequently, a concerted research effort in the region over the past decade has led to the consensus that ice was extensive and pervasive (thereby supporting the maximalist paradigm) during the Late Wisconsinan (e.g. Kristoffersen *et al.*, 2004; Bromwich *et al.*, 2004; Stokes *et al.*, 2005; England *et al.*, 2009).

3 Banks Island

3.1 Previous Quaternary model

Vincent (1982, 1983) established the seminal and widely cited Quaternary model for Banks Island, in accordance with the minimalist paradigm. According to this model, ice sheets sourced from mainland Canada terminated on Banks Island on three occasions during the Quaternary, each separated by an interglacial and associated with a marine transgression and regression: 1) >780,000 years ago during the earliest and most extensive Banks Glaciation that trimmed a purported 'never-glaciated' landscape on the northwest corner of the island. The Banks Glaciation was followed by the Morgan Bluffs Interglaciation; 2) Between 780,000-120,000 years ago when the intermediate Thomsen Glaciation covered the eastern half of Banks Island and reached tidewater in at least two fiords on the north coast. The Thomsen Glaciation was followed by the Cape Collinson Interglaciation (Sangamonian); 3) 85,000-60,000 years ago when the restricted M'Clure Stade of the Amundsen Glaciation (Early Wisconsinan) terminated less than 50 km inland of the south, east, and north coasts of Banks Island. According to Vincent (1982, 1983) during the most recent Russell Stade of the Amundsen Glaciation (Late Wisconsinan) a floating ice shelf impinged on the far northeast corner of Banks Island, leaving the rest of the island ice-free.

The discovery of a single mammoth fragment on the northwest coast of Banks Island, dated to 22,000 years ago, ostensibly supports the argument for ice-free terrain on Banks Island during the Late Wisconsinan (Harrington, 2005). This mammoth fragment has been used to suggest that Banks Island constituted the northeastern extremity of Beringia – a biologically viable ice-free refugium extending from Siberia to the Yukon (Figure 1).

3.2 Revised Quaternary model

The glacial model of Vincent (1982, 1983) remained problematic due to a lack of chronological control on till sheets, glacial landforms, and associated relative sea levels ascribed to each glaciation. These chronological uncertainties – indeed the very originally-proposed field evidence – have been contradicted by the recent mapping and dating of Late

Wisconsinan desposits on the opposing coastlines of northern Banks Island and southern Melville Island (England *et al.,* 2009 – Figure 2). Air photo mapping and widespread fieldwork on northern Banks Island indicates complete glaciation during the Late Wisconsinan, and the seperation of land-based ice and marine-based ice during deglaciation (England *et al.,* 2009). The elevations of raised marine shorelines across the opposing coastlines of northern Banks Island and southern Melville Island are also compatible with the presence of a grounded ice stream with a thickness of at least 760 m occupying the channel to the north of Banks Island (M'Clure Strait) prior to deglaciation (Stokes *et al*., 2005, 2006, 2009; England *et al.,* 2009). AMS radiocarbon dates from shells collected from deglacial marine deposits along the opposing coastlines indicate that this ice stream thinned and retreated as a floating ice shelf ~11,500 years ago (England *et al.*, 2009). This new evidence has warranted a fundamental revision of the previous ice-free model, amalgamating the multiple glaciations of Vincent (1982, 1983) into a single Late Wisconsinan glaciation (Figure 2).

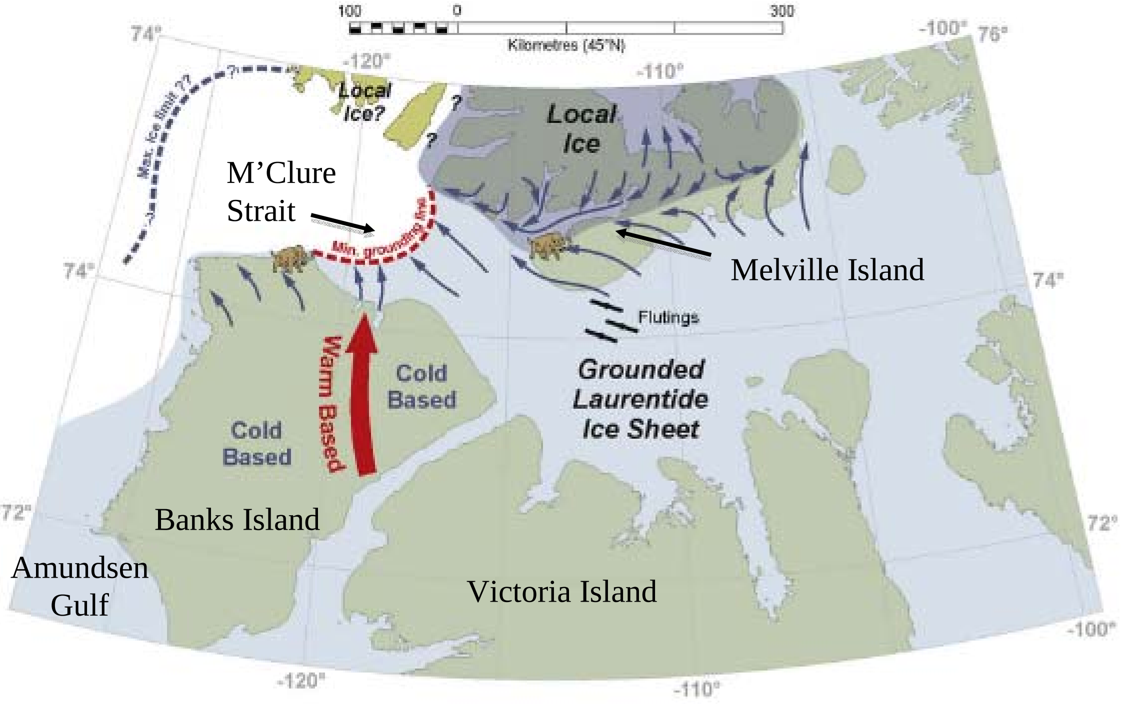

Figure 2: Proposed revision of the northwest Laurentide Ice Sheet during the Late Wisconsinan. England *et al* (2009).

The proposed revision for extensive Laurentide Ice on Banks Island during the Late Wisconsinan is in agreement with widespread fieldwork on central and southern Banks Island by Lakeman and Vaughan (Dr. England's research group at the University of Alberta).

Collectively, the University of Alberta research group have over eighty AMS radiocarbon dates on Banks Island that constrain the timing of glaciation to the Late Wisconsinan. Further support for the revised glacial model of England *et al. (*2009) includes evidence that the Laurentide Ice Sheet reached its all time Quaternary maximum to the south in the Richardson Mountains (Yukon) where large proglacial lakes were impounded (e.g. Duk-Rodkin and Hughes, 1991; Bateman and Murton, 2006), and to the north in the Queen Elizabeth Islands where the Innuitian Ice Sheet coalesced with the Greenland and Laurentide ice sheets during the Late Wisconsinan (England *et al.*, 2006, 2009).

Marine evidence is also compatible with the revised glacial model of Banks Island (England *et al.,* 2009). Glacigenic bedforms at depths of up to 1000 m below sea level mapped on the Chukchi Borderland (Jakobsson *et al.*, 2005; Polyak *et al.*, 2007) have been tentatively dated to the Late Wisconsinan and purportedly record the passage of an enigmatic ice shelf sourced from the western Canadian Arctic (Engels *et al,* 2008; Polyak *et al.,* 2007). Such an ice shelf necessitates an extensive northwest Laurentide Ice Sheet. Furthermore, episodic ice streams reconstructed from remotely sensed data are hypothesised to have operated in M'Clure Strait and Amundsen Gulf during the Late Wisconsinan (Stokes *et al.,* 2005, 2006, 2009). The revised glacial model of Banks Island (England *et al.,* 2009) provides the first direct geological evidence confirming the existence and timing of the M'Clure Strait Ice Stream, and research on southern Banks Island by Vaughan supports the existence of thick marine ice occupying Amundsen Gulf.

4 Implications of a revised Banks Island model

During the Late Wisconsinan much of the northern hemisphere was experiencing its most intense cold interval. In North America, the Laurentide Ice Sheet attained its largest dimensions, and is now known to have advanced as far west as the continental shelf beyond Banks Island in the western Canadian Arctic (England *et al*., 2009).

Scientifically, the reconstruction of dynamic, largely cold-based ice (ice that is frozen to its bed) crossing the interior of Banks Island, flanked by thick ice-streams operating in the surrounding marine channels is compatible with new evidence for expansive ice elsewhere in the western Canadian Arctic during the Late Wisconsinan. Recently, the glacial history of the region has been indirectly reconstructed using Arctic Ocean sediment cores (e.g. Darby *et al*., 2002). It is logical to predict that major export events (huge volumes of sediment, ice, and meltwater evacuated into the ocean) hypothesised to have been sourced from the western Canadian Arctic during the Late Wisconsinan (e.g. Darby *et al.,* 2009) would be manifested by major landform generating events on land, such as the development of megascale glacial lineations during ice streaming episodes. Therefore, until the events depicted in the Arctic Ocean sediment cores can be correlated with glacial geology and geomorphology – they must be treated as entirely speculative. Consequently, the direct dating and mapping of Laurentide Ice Sheet margins and landforms on Banks Island by Dr. England and his research group at the University of Alberta provides an independent test on the Arctic Ocean sediment core reconstructions. A more extensive Laurentide Ice Sheet margin in the western Canadian Arctic would also provide support for recent evidence of deep draft glacial erosion on the Polar Continental Shelf (e.g. Polyak *et al.*, 2007). Thicker ice occupying the western Arctic islands and adjacent marine channels would deliver large icebergs (megabergs) to the Arctic Ocean and/or supply ice to a floating ice shelf that could cause significant erosion on the eustatically depressed Polar Continental Shelf. Megabergs or large ice shelves occupying the continental shelf would have implications for paleoceanic circulation and sedimentation patterns in the Arctic Ocean Basin. Furthermore, extensive ice in the western Canadian Arctic has implications for the nature and magnitude of Wisconsinan and Holocene relative sea level change. The greater volume of ice now recognised to have existed in the Canadian Arctic requires quantification in order to understand the volume of water that the Laurentide Ice Sheet contributed to sea level change. Accurately quantifying the volume, location, and effects of meltwater release from the Laurentide Ice Sheet during the Late Quaternary is crucial for ongoing comparisons between this ice sheet and the contemporary Greenland and Antarctic ice sheets.

Environmentally, extensive ice on Banks Island would necessitate the revision of the northeast extremity of ice-free Beringia (e.g. Harrington, 2005). Redefining the limits of Beringia has significant implications for the history of northern flora and fauna, including the evolutionary and migratory patterns of endemic or now extinct species that are crucial for the reconstruction of northern paleoenvironments. Furthermore, thick ice cover on Banks

Island would support the split jet-stream hypothesis (Bromwich *et al.,* 2004), which provides a mechanism for transporting moisture to an area long-thought to have been hyper-arid (e.g. Vincent, 1982). The split-jet stream hypothesis proposes that the imposing dimensions of the Wisconsinan Laurentide Ice Sheet perturbed the northerly mid-latitude jet stream, causing it to split into two branches; one skirting the southern edge of the ice sheet and one skirting the northern edge. The northern branch supplied moisture from the Pacific Ocean to the western Canadian Arctic and permitted the Laurentide Ice Sheet to advance farther west. Therefore, redefining the limits of Beringia and extending the margin of the Laurentide Ice Sheet westward has significant implications for paleoatmospheric circulation patterns and phenomenon. These past relationships provide important insights into how the changing configurations and dimensions of modern ice sheets will continue to influence atmospheric circulation patterns.

Socially, a revised and better-constrained glacial history of Banks Island bears directly upon ongoing relative sea level rise that is adversely impacting northern communities, such as Sachs Harbour on Banks Island. Current relative sea level rise is directly tied to past glacial loading patterns and the migration of the glacial forebulge (an area of positive relief peripheral to glaciated areas) back towards the centre of ice loading (Hudson Bay). This forebulge has recently migrated across Banks Island, and as a result the land is now subsiding. This subsidence is producing regionally higher sea levels that are combining with eustatically higher sea levels (related to global warming) to amplify local relative sea level rise. Therefore, a good understanding of the glacial history of a region is imperative when predicting and planning for future sea level change.

Economically, the western Canadian Arctic has recently been opened up for resource exploration. An increased interest in the area stems from greater accessibility to the Northwest Passage (due to reduced summer sea ice coverage), from territorial and sovereignty disputes, and from a renewed emphasis on frontier basin exploration by hydrocarbon and mineral companies searching for new target sites to exploit. The effective prospecting of economically attractive resources rests on an accurate understanding of the geological and glacial history of the area. Specifically, past ice flow determines the sedimentary foundation of the Canadian Arctic marine channels and Polar Continental Shelf where hydrocarbon prospecting is ongoing. Past ice flow also disperses indicator mineral anomalies across the Arctic Islands that can be traced back to their potentially exploitable source areas. Therefore a revised glacial history of Banks Island will have substantial implications for the economy and self-sufficiency of the western Canadian Arctic.

5 Relevant analogues from South Banks Island

Extensive mapping and dating of glacial landforms and sediments on south Banks Island by Vaughan has led to the reconstruction of largely cold-based ice crossing the island with thick ice grounded in Amundsen Gulf to the south during the Late Wisconsinan. From this body of research, two relevant analogues for contemporary ice sheets will be presented.

5.1 Rapid retreat of marine ice

In the Canadian Arctic, shorelines that record former sea level since deglaciation tend to be raised relative to the modern shoreline as a result of glacioisostatic rebound. These shorelines frequently yield fossils of organisms and organics that previously inhabited the sea. Raised marine deposits along the south and far southwest coasts of Banks Island, however, are unfossiliferous. A possible explanation for these unfossiliferous shorelines is that ice grounded in Amundsen Gulf retreated *prior* to the resubmergence of Bering Strait at ~11,500 years ago (England and Furze, 2008). During this earlier interval of deglaciation, marine molluscs were unavailable to invade the coastal areas of south and southwest Banks Island. After the arrival of molluscs when Bering Strait was resubmerged (~11,500 years ago), the oldest shorelines may have been raised up to 40 m above sea level by glacioisostatic uplift, leaving only the younger, lower shorelines habitable. These lower, younger shorelines may now be submerged beneath present sea level due to late Holocene and ongoing submergence of Banks Island. Therefore, only the older, unfossiliferous shorelines remain exposed.

The evidence for early deglaciation of Amundsen Gulf suggests that retreat would have been rapid. Marine ice would have been destabilised by rising sea levels *and* warming temperatures. Once the ice in Amundsen Gulf was thin enough, it would have become a floating ice shelf that would have calved rapidly until it reached shallower waters where it could ground and restabilise. During this process of rapid deglaciation, ice from the surrounding catchment area would have been drawn down to replace the ice lost at the snout by calving, therefore leading to a thinning and loss of ice on a broader scale.

The rapid retreat of marine ice indicates the importance of ice shelves for contemporary ice sheets, since fringing ice shelves act as natural buffers to warming oceans and atmospheres. However, marine ice is particularly vulnerable to climate change since ice on the shelf bottom is subject to warming waters and the ice on the shelf surface is subject to a warming atmosphere. The ice can therefore be eroded from both sides, making ice loss more probable and more rapid. The paleo-record indicates that the retreat of marine ice can be catastrophic and abrupt. This should serve as a strong warning for the stability of modern ice sheets, and their fringing ice shelves.

5.2 Dynamics of cold-based ice

Cold-based ice has often been thought of as passive and non-erosive ice that moves slowly and produces little landscape modification. This is true, but cold-based ice is also capable of causing extensive disturbance of the bed – folding, thrusting and rafting bedrock and glacial sediments (Benn and Evans, 2010). On south Banks Island there is widespread evidence of this ‘glacitectonism’ by cold-based ice, most notably in the form of large moraine belts running along the south coast. These landforms highlight the dynamic behaviour and erosive power of cold-based ice in a permafrost terrain.

These findings shed light on modern cold-based ice sheets in permafrost terrain (including large parts of the East Antarctic and Greenland ice sheets) which should not be thought of as dormant or stable systems, but rather as active agents of landscape modification that can respond dynamically to climate change.

6 Why is a paleoenvironmental perspective relevant to ‘Our ice dependent world?’

The cryosphere exerts a profound influence on the global climate system. The melting of the cryosphere has direct implications for mankind, since melting ice leads to positive feedbacks that act to exacerbate warming, which in turn enhance the melting of ice and the rate of global sea level rise. In order to understand the role and response of ice to our changing climate, we need to put this change into context. A long-term, paleoenvironmental context provides a framework for natural, cyclical climate change. This framework serves to highlight anthropogenic or anomalous change, and probable future change. The application of past analogues to modern environments is an exceptional tool for providing an insight into how the current cryosphere may respond as global warming progresses, since the processes that occurred during past episodes of warming still operate today. If we have an understanding of the likely sensitivities, triggers, and dynamics of the cryosphere to warming (established by studying the paleo-record) then we can more effectively mitigate, plan, and govern for the future.

7 Conclusion

For the past half-century, reconstructions of North American Ice Sheets during the Late Wisconsinan have shown ice-free terrain in the western Canadian Arctic (Prest, 1957, 1969; Dyke and Prest, 1987; Dyke *et al.*, 2002). The seminal Quaternary glacial model of Vincent (1982, 1983) until recently stood as the most compelling evidence in support of an unglaciated landscape. This model ascribes glacial deposits on Banks Island to multiple, increasingly less extensive Quaternary glaciations, culminating in largely ice-free terrain during the Late Wisconsinan (Vincent, 1982, 1983).

However, recent mapping and dating of widespread glacial landforms and sediments on Banks Island by Dr. England and his research group at the University of Alberta contradict this previous ice-free model and support the amalgamation of Vincent's multiple glaciations into a single Late Wisconsinan glaciation (England *et al.*, 2009). An extensive Late Wisconsinan Laurentide Ice Sheet in the western Canadian Arctic is compatible with evidence for Laurentide ice entering the Richardson Mountains (Yukon) to the south (Duk-Rodkin and Hughes, 1991; Bateman and Murton, 2006) and with the Innuitian Ice Sheet occupying the Queen Elizabeth Islands to the north (England, 1999; England *et al*., 2006). More extensive ice in the western Canadian Arctic has important scientific, environmental, social, and economic implications.

The reconstruction of past ice sheets provides important insights into the behaviour and dynamics of ice, most notably during periods of warming. Increasing our knowledge of how ice sheets behaved in the past is directly applicable to contemporary ice sheets, since the same processes operate today.

Banks Island preserves a rich and detailed glacial history that serves to highlight the dynamic and complex behaviour of ice. From this history, relevant analogues can be gleaned – such as the instability of ice shelves and the active behaviour of cold-based ice in permafrost terrain. This paleoenvironmental record is a valuable tool for the effective monitoring, prediction, and mitigation of global ice melt today.

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9 References

Bateman, M.D., Murton, J.B. 2006. The chronostratigraphy of Late Pleistocene glacial and periglacial aoelian activity in the Tuktoyaktuk coastlands, NWT, Canada. Quaternary Science Reviews, 25: 2552-2568.

Barendregt, R.W., and Vincent, J-S. 1990. Late Cenozoic paleomagnetic record of Duck Hawk Bluffs, Banks Island, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences, 27: 124–130.

Benn, D.I., and Evans D.J.A. 2010. *Glaciers and Glaciation*. London: Hodder Education.

Bromwich, D.H., Toracinta, E.R., Wei, H., Oglesby, R.J., Fastook, J.L., Hughes, T.J., 2004. Polar MM5 simulations of the winter climate of the Laurentide Ice Sheet at the Last Glacial Maximum. Journal of climatology, 17: 9-31.

Darby, D.A., Polyak, L., Bischof, J., Ortiz, J.D., Darby, D.A., Channell, J.E.T., Xuan, C., Kaufman, D.S., Løvlie, R., Schneider, D.A., Eberl, D.D., Adler, R.E., Council, E.A. 2006. Past glacial and interglacial conditions in the Arctic Ocean and marginal seas – a review. Progress In Oceanography, 71: 129-144.

Darby, D.A., Bischof, J.F., Spielhagen, R.F., Marshall, S.A., Herman, S.W., 2002. Arctic ice export events and their potential impact on global climate during the Late Pleistocene. Paleoceanography, 17: 15.

Duk-Rodkin, A. and Hughes, O. L. 1991. Age relationships of Laurentide and montane glaciations, Mackenzie Mountains, Northwest Territories. Géographie physique et Quaternaire, 45: 79-90.

Dyke, A. S. Andrews, J. T. A., Clark, P. U., England, J. H., Miller, G. H., Shaw, J., & Veillette, J. J. 2002. The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. Quaternary Science Reviews, 21: 9-31.

Engels, J.L., Edwards, M.H., Polyak, L., Johnson, P.D., 2007. Seafloor evidence for ice shelf flow across the Alaska-Beaufort margin of the Arctic Ocean. Earth surface processes and landforms, 10: 1002.

England, J., 1999. Coalescent Greenland and Innuitian Ice during the last glacial maximum: revising the Quaternary of the Canadian high arctic. Quaternary Science Reviews, 18: 421-456.

England, J., Atkinson, N., Bednarski, J., Dyke, A.S., Hodgson, D.A., Cofaigh, C.O., 2006. The Innuitian Ice Sheet: Configuration, dynamics, and chronology. Quaternary Science Reviews, 25: 689-703.

England, J.H., Furze, M.F.A., Doupe, J.P. 2009. Revision of the NW Laurentide Ice Sheet: Implications for paleoclimate, the northeast extremity of Beringia, and Arctic Ocean Sedimentation. Quaternary Science Reviews, 28: 1573-1596.

Harrington, C.R., 2005. The eastern limit of Beringia: mammoth remains from
Banks and Melville Islands, Northwest Territories. Arctic ,58: 361–369.

Hobbs, W.H., 1945. The boundary of the latest glaciation in Arctic Canada. Science, 101: 549-551.

Jakobsson, M., Lovlie, R., Arnold, E.M., Backman, J., Polyak, L., Knutsen, J-O., Musatov, E., 2001. Pleistocene stratigraphy and paleoenvironmental variation from Lomonosov Ridge sediments, central Arctic Ocean. Global and Planetary Change, 31: 1-22.

Jenness, J.L., 1952. Problem of glaciation in western Islands of Arctic Canada. Bulletin of the Geological Society of America, 63: 939-952.

Kaufman, D.F., and Brigham-Grette, J. 1993. Aminostratigraphic correlations and paleotemperature implications, Pliocene-Pleistocene high sea level deposits, northwest Alaska. Quaternary Science Reviews, 12: 21-33.

Kristoffersen, Y., Coakley, B., Jokate, W., Edwards, M., Brekke, H., Gjengdeal, J., 2004. Seabed erosion on the Lomonosov Ridge, central Arctic Ocean: A tale of deep draft icebergs in the Eurasia Basin and the influence of Atlantic water inflow on iceberg motion?, 19: 1-14.

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas and T. Zhang, 2007. Observations: Changes in Snow, Ice and Frozen Ground. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change:* Cambridge University Press, Cambridge, United Kingdom.

Polyak, L., Curry, W.B., Darby, D.A., Bischof, J., Cronin, T.M., 2004. Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge. Paleogeography, Paleoclimatology, Paleoecology, 203: 73-93.

Prest, V.K., 1967. Pleistocene geology and surficial deposits, Chapter 7 of C. H. Stockwell, ed., Geology and economic minerals of Canada, Geological Survey of Canada. 85-14: 38.

Prest, V.K., 1969. Retreat of Wisconsin and Recent ice in North America, Geological Survey of Canada. Map 1257A, 1:5,000,000.

Serreze, M.C., and Barry, R.G., 2011. Processes and impacts of Arctic amplification: a research synthesis. Global and Planetary Change, 77: 85-96.

Stokes, C.R., Clark, C.D., Darby, D.A., Hodgson, D.A., 2005. Late Pleistocene ice export events into the Arctic Ocean from the M’Clure Strait Ice Stream, Canadian Arctic Archipelago. Global and Planetary Change, 49: 139-162.

Stokes, C.R., Clark, C.D., Darby, D.A., Hodgson, D., 2005. Late Pleistocene ice export events into the Arctic Ocean from the M'Clure Strait Ice Stream, Canadian Arctic Archipelago. Global and Planetary Change, 49: 139-162.

Stokes, C.R., and Clark, C.D., Winsborrow, M.C.M., 2006. Subglacial bedform evidence for a major paleo-ice stream and its retreat phases in Amundsen Gulf, Canadian Arctic Archipelago. Journal of Quaternary Science, 21: 399-412.

Stokes, C.R., and Clark, C.D., Storrar, R. 2009. Major changes in ice stream dynamics during deglaciation of the north-western margin of the Laurentide Ice Sheet. Quaternary Science Reviews, 28: 721-738.

Vincent, J-S., 1982. The Quaternary History of Banks Island, N.W.T., Canada. Geographie physique et Quaternaire, 36: 209-232.

Vincent, J-S., 1983. La geologie du Quaternaire et la geomophologie de l'ile Banks. Arctic Canadien, Commission geologique du Canada, 405: 118.