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# Post-Glacial Isostatic Adjustment and Global Warming in Subarctic Canada: Implications for Islands of the James Bay Region

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ABSTRACT. When Rupert's Land and the North-Western Territory became a part of Canada as the Northwest Territories in 1870, the islands of James Bay were included within the new territorial boundaries. These same islands became a part of Nunavut in 1999, when the new territory was created from the eastern region of the Northwest Territories. Although the James Bay islands remain part of Nunavut, the western James Bay Cree assert that the western James Bay islands, including Akimiski Island, were part of the Cree traditional territory and that these islands have never been surrendered through treaty. This land-claim issue is further complicated by the fact that glacial isostatic adjustment (GIA) is occurring in the James Bay region and that the islands of James Bay may one day become part of mainland Ontario or Quebec. We used numerical models of the GIA process to predict how shorelines in James Bay will migrate over the next 1000 years as a result of post-glacial sea-level changes. These predictions, which were augmented by an additional contribution associated with sea-level rise due to global warming, were used to determine whether the islands in James Bay will ever become part of the mainland. The predictions for the islands are sensitive to the two primary inputs into the GIA predictions, namely the models for the geometry of the ancient Laurentide ice sheet and the viscoelastic structure adopted for the solid earth, as well as to the amplitude of the projected global warming signal. Nevertheless, it was found that many of the smaller and larger islands of James Bay will likely join the mainland of either Ontario or Quebec. For example, using a global warming scenario of 1.8 mm sea-level rise per year, a plausible range of GIA models suggests that the Strutton Islands and Cape Hope Islands will join mainland Quebec in ~400 years or more, while Akimiski Island will take at least ~700 years to join mainland Ontario. Using the same GIA models, but incorporating the upper boundary of global warming scenarios of 5.9 mm sea-level rise per year, the Strutton Islands and Cape Hope Islands are predicted to join mainland Quebec in ~600 years or more, and Akimiski Island is predicted not to join mainland Ontario. Since Akimiski Island is already being prospected for diamonds and the future ownership of emergent land remains an issue, these findings have great economic importance.

Key words: sea-level change, subarctic Canada, post-glacial isostatic adjustment, global warming, islands of James Bay

RÉSUMÉ. Quand la Terre de Rupert et le Territoire du Nord-Ouest ont joint les rangs du Canada sous le nom de Territoires du Nord-Ouest en 1870, les îles de la baie James ont été intégrées aux nouvelles frontières territoriales. Ces mêmes îles font maintenant partie du Nunavut depuis 1999, lorsque le nouveau territoire a été créé à partir de la région est des Territoires du Nord-Ouest. Bien que les îles de la baie James fassent toujours partie du Nunavut, les Cris de l'ouest de la baie James soutiennent que les îles du côté ouest de la baie James, dont l'île Akimiski, faisaient partie du territoire traditionnel cri et que ces îles n'ont jamais été cédées par l'intermédiaire d'un traité. Cette revendication territoriale est davantage compliquée par le fait qu'un ajustement isostatique glaciaire est en train de se produire dans la région de la baie James au point où un de ces jours, les îles de la baie James pourraient faire partie de la partie continentale de l'Ontario ou du Québec. Nous avons employé des modèles numériques du processus d'ajustement isostatique pour prédire de quelle manière les littoraux de la baie James migreront au cours des 1000 prochaines années en raison des changements postglaciaires caractérisant le niveau de la mer. Ces prévisions, qui ont été enrichies de données supplémentaires se rapportant à l'élévation du niveau de la mer attribuable au réchauffement climatique, ont été utilisées pour déterminer si les îles de la baie James feront un jour partie du continent. Les prévisions relatives aux îles sont sensibles à deux intrants principaux en matière de prévisions d'ajustement isostatique, notamment les modèles de géométrie de la nappe glaciaire du Laurentien ancien ainsi que la structure viscoélastique adoptée pour la croûte terrestre, de même qu'à l'amplitude du signal projeté relativement au réchauffement climatique. Néanmoins, nous avons déterminé que grand nombre des îles plus petites et plus grosses de la baie James se rattacheront vraisemblablement à la partie continentale de l'Ontario ou du Québec. Par exemple, en s'appuyant sur un scénario de réchauffement climatique donnant lieu à une élévation du niveau de la mer de 1,8 mm par année, une étendue plausible pour les modèles d'ajustement isostatique laisse entendre que les îles Strutton et les îles du cap Hope rejoindront la partie continentale du Québec dans environ 400 ans ou plus, tandis que l'île Akimiski mettra environ 700 ans à s'intégrer à la partie continentale de l'Ontario. À l'aide des mêmes modèles d'ajustement isostatique, mais en tenant compte de la borne supérieure des scénarios

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de réchauffement climatique qui correspond à une élévation du niveau de la mer de 5,9 mm par année, les îles Strutton et les îles du cap Hope devraient rejoindre la partie continentale du Québec dans environ 600 ans ou plus, tandis que l'île Akimiski ne rejoindrait pas la partie continentale de l'Ontario. Puisque l'île Akimiski fait déjà l'objet de l'exploration de diamants et que l'appartenance future des terres émergentes constitue toujours un enjeu, ces observations revêtement une grande importance du point de vue économique.

Mots clés : changement du niveau de la mer, Canada subarctique, ajustement isostatique postglaciaire, réchauffement climatique, îles de la baie James

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## INTRODUCTION

In 1867, when the Dominion of Canada was formed, it included the provinces of Ontario, Quebec, New Brunswick, and Nova Scotia; however, the central provinces, Quebec and Ontario, were only a fraction of their present size (Fig. 1). The country we now know as Canada would be formed through acquisitions. Most of the landmass that has become the prairie and western provinces (except British Columbia), the Yukon and the Northwest Territories, Nunavut and Labrador, and the northern portions of the provinces of Quebec and Ontario was embodied in Rupert's Land and the North-Western Territory (Figs. 1 and 2). In 1870, the Dominion of Canada acquired Rupert's Land and the North-Western Territory through an Imperial (British) Order-in-Council whereby Indian claims to lands required the attention of the Canadian government (Rupert's Land and North-Western Territory – Enactment No. 3, 1870). Schedule A of the Order-in-Council elaborated further on this point that the claims of the Indian tribes to compensation for lands were to be resolved equitably, using principles that had been used by the British Crown in previous dealings with Indians (Cauchon and Cockburn, 1867). Since the British Crown believed that Indians held rights to land in North America, Indian lands could be acquired only through consent, that is, ceded or purchased (Royal Proclamation, 1763; Henry, 2006). Thus, the period from 1870 to 1999 was characterized as one of nation building: the partitioning of the Northwest Territories (formerly Rupert's Land and the North-Western Territory) into new provinces and territories, as well as the extension of boundaries of existing provinces, and other land additions or acquisitions (Fig. 3; INAC, 2007). Numerous treaties between the Canadian government and various Indian groups were signed during these three decades (INAC, 2007).

When Rupert's Land and the North-Western Territory were acquired and amalgamated to form the Northwest Territories within the Dominion of Canada, the islands of Ungava Bay, Hudson Bay, and James Bay were included within the new territorial boundaries (Fig. 2). The inclusion of these islands in the Northwest Territories appears to have been not so much a conscious decision on the part of the Dominion of Canada to keep these islands as part of the Northwest Territories, but rather a result of partitioning only the mainland portion of the Northwest Territories to extend the boundaries of Quebec and Ontario. In other words, the islands of Hudson Bay, James Bay, and Ungava Bay were left as part of the Northwest Territories after the mainland was partitioned. When the western James Bay islands were part of the Northwest Territories, ownership of the islands was inconsequential, as the Cree freely used the islands for their traditional pursuits (e.g., Jonkel et al., 1976) as they had done since the time of the fur trade (see Lytwyn, 2002, for a review of the Hudson's Bay Company's fur trade records). However, this situation was to change when the Inuit-dominated territory of Nunavut was created through the partitioning of the Northwest Territories into eastern and western portions (Fig. 3).

On 1 April 1999, Akimiski Island (Fig. 4) and other islands of the western James Bay region became part of the newly created Nunavut Territory, even though there was no mention of these specific islands in the Nunavut Land Claims Agreement Act (1993): that is, the Inuit did not assert aboriginal title to these islands. However, a clause in the Nunavut Act S.C. 1993 (c. 28, Part 1, 3[b]) stated that the new territory of Nunavut would include "the islands in Hudson Bay, James Bay and Ungava Bay that are not within Manitoba, Ontario or Quebec." In other words, the inclusion of the said islands in Nunavut appears to be based not on aboriginal title, but on geographical location. The western James Bay Cree (i.e., Moose Cree First Nation, Fort Albany First Nation, Kashechewan First Nation and Attawapiskat First Nation) assert that the western James Bay islands have always been part of their traditional territory and have never been surrendered through treaty or other lawful means (Standing Senate Committee on Legal and Constitutional Affairs, 1999). Indeed, Grand Chief Charles Fox has emphasized that the Attawapiskat First Nation claims unfettered title to Akimiski Island of the western James Bay region (Standing Senate Committee on Legal and Constitutional Affairs, 1999). In addition, Senator Lorna Milne has stated that "many of the complaints [boundary and aboriginal title issues] were originally with the Nunavut Act itself. That is when they should properly have been addressed. Unfortunately, they were not addressed at that time. You [First Nations representatives] are quite right: the [Canadian] government did not do its job" (Standing Senate Committee on Legal and Constitutional Affairs, 1999:33).

The western James Bay island issue is further exacerbated by the fact that post-glacial isostatic adjustment is occurring in the James Bay region, and thus shorelines in the area are continuously evolving. Indeed, a former island of

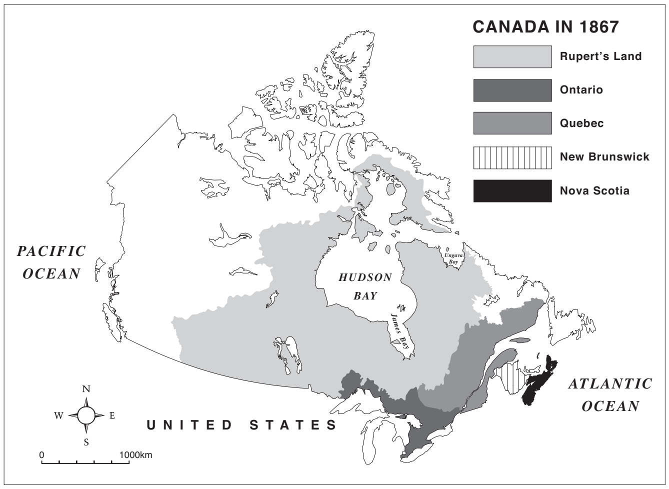


FIG. 1. Canada at Confederation (1867). This map is based on hc1867trty_e (INAC, 2007).

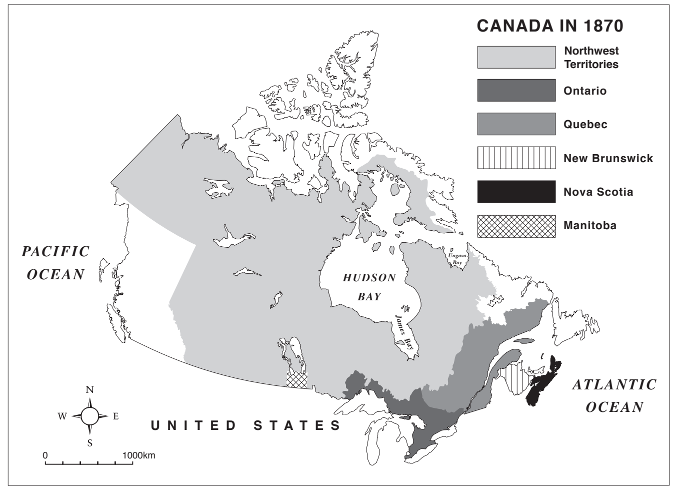


FIG. 2. Canada in 1870 illustrating an island in James Bay located within the boundaries of the Northwest Territories (formerly Rupert's Land and the North-Western Territory). This map is based on hc1870trty_e (INAC, 2007).

the western James Bay region has been shown to be embedded approximately 25 km inland (Webber et al., 1970). As the islands of James Bay were included in the boundaries of Nunavut only by virtue of being islands in a stipulated bay and "not within Manitoba, Ontario or Quebec" (Nunavut Act, 1993), what will happen in the future when and if they are no longer islands? There is also the issue of land ownership of newly emergent land, which is not covered in Treaty No. 9 (Treaty No. 9, 1905). These are novel areas of policy that will have to be explored quite soon, as mining companies have already started mineral exploration of Akimiski Island (Nunavut Mineral Resources Section, 2001). For example, in 2001, a mining company obtained prospecting permits over the western portion of Akimiski Island (Nunavut Mineral Resources Section, 2001); diamondiferous kimberlites have been found just west of the island on the mainland, leading to the development of the Victor Diamond Mine (AMEC, 2004).

A different situation exists in regard to the east coast of James Bay and Hudson Bay. Canada agreed (in 1974) to negotiate with the Quebec Cree and Nunavik Inuit of Quebec with respect to the islands in eastern James Bay and Hudson Bay, as no treaties had been signed with either aboriginal group (Comprehensive Claims Branch, 2007). Since the Crees and the Nunavik Inuit of Quebec did not relinquish aboriginal rights to marine areas and islands adjacent to Quebec in James Bay, Hudson Bay, Hudson Strait, and Ungava Bay through the James Bay and Northern Quebec Agreement of 1975, an agreement relating to overlapping Cree and Inuit offshore areas was reached in 2003 (Grand Council of the Crees and Makivik Corporation, 2003; Comprehensive Claims Branch, 2007). The "Cree Zone" is located roughly in the northernmost offshore area along the east coast of James Bay; the "Joint Inuit/Cree Zone" rests entirely in the southernmost offshore area along the east coast of Hudson Bay; and the "Inuit Zone" lies directly north of the joint zone (Grand Council of the Crees and Makivik Corporation, 2003). The offshore agreement makes no mention of the islands in the southeastern region of James Bay and has no provision for sea-level changes (Grand Council of the Crees and Makivik Corporation, 2003). The effect of sea-level change in this region of James Bay will also become a provincial matter if islands such as the Cape Hope, Strutton, and Charles islands become attached to mainland Quebec.

Over the last several million years, the earth has been subject to a series of so-called ice-age cycles, each with a period of about 100 000 years (or 100 ka). These recent cycles have been characterized by a relatively slow glaciation phase lasting ~90 ka, followed by a much more rapid deglaciation event. The final deglaciation phase of the current ice age began about 20 ka BP (at the so-called last glacial maximum, or LGM) and ended ~8 ka BP. In this context, the last 8 ka, and any earlier period between the end of a deglaciation phase and the start of the next glaciation, is termed an interglacial. At the LGM, major continental ice sheets covered Canada and the northeastern United States (the ancient Laurentide ice sheet), Arctic Canada, Scotland, Fennoscandia, eastern and western Siberia. In addition, ice cover over Greenland and the Antarctic was more extensive than at present.

The prediction of sea-level changes associated with the ice-age cycles is a relatively complex undertaking. Indeed, contributions arise not only from changes in the volume of continental (and grounded marine-based) ice, which account for ~120 – 140 m of sea-level change through the glacial cycle, but also from deformational, gravitational, and rotational effects driven by the changing ice plus water load (e.g., Farrell and Clark, 1976). Since the earth responds viscoelastically to this load, sea-level changes have continued throughout the interglacial period and, indeed, persist today. In the Hudson Bay/James Bay region, the sea-level change is currently dominated by so-called post-glacial rebound. That is, the unloading associated with the melting of the Laurentide ice sheet, which reached a thickness

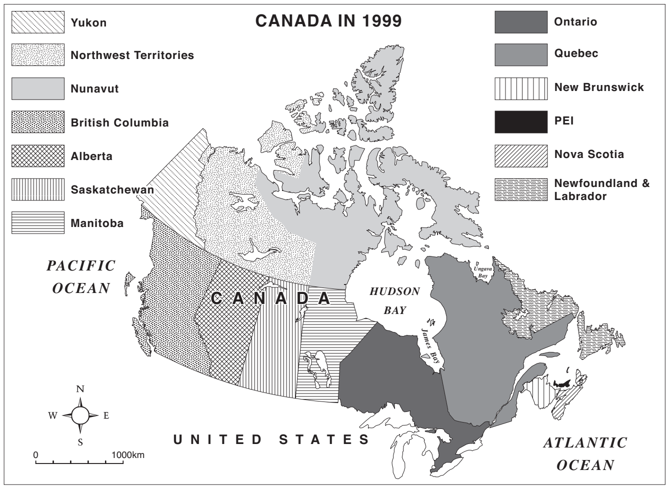


FIG. 3. Canada in 1999. This map is based on hc1999trty_e (INAC, 2007).

of more than 3 km over James Bay, initiated a rebound of the crust that is locally evident as a sea-level fall (or land emergence).

This drop in sea level within Hudson Bay and James Bay will lead to an offlap of water and an outward migration of shorelines. Thus, it is possible that, as the process continues into the future, it will lead to the formation of land bridges connecting the present islands to the mainland. We used numerical models of ongoing, ice age–induced sea-level changes to estimate the plausible range of timing for land bridges to occur in the James Bay region. One complication for such predictions is that the earth is currently subject to global scale sea-level changes associated with global warming, and the signature of these changes will act to at least partially cancel the sea-level fall driven by ongoing post-glacial rebound. Projections of global sea-level rise due to modern climate change are uncertain, and thus we will consider various scenarios for this contribution. These will include, for example, a lower bound scenario in which the globally averaged sea-level rise for the 20th century (~2 mm per year) due to global warming is assumed to continue into the future.

## METHODS

### *Present-day Rate of Sea-level Change in the James Bay Region*

To avoid contamination from global change signals, glacial isostatic adjustment (GIA) models should be compared to the geological record of sea-level fall. The late Holocene record of sea-level change in James Bay and Richmond Gulf, in southeastern Hudson Bay, is discussed in detail by Mitrovica et al. (2000). For example, their analysis of the post-glacial decay time at Richmond Gulf indicates that GIA contributes 9 – 13 mm/yr to the present-day trend at this site. Inconsistencies exist in the geological measurements of relative sea-level change at James Bay, and for this reason the GIA contribution to the present-day sea-level trend in this area is more uncertain; however, a present-day GIA signal of 6 – 9 mm/yr is suggested, depending on the data selection. Certain data selections allow a smaller GIA signal at James Bay, but these also imply a post-glacial decay time that is significantly inconsistent with measurements at Richmond Gulf. Taken together, these analyses suggest a present-day sea-level fall due to GIA in James Bay that is close to 1 cm/yr, with a lower bound of about 6 mm/yr.

We note that this range is consistent with present-day vertical crustal motion inferred from surveying using the Global Positioning System (GPS; e.g., Sella et al., 2007). Unlike measurements of modern sea-level trends, the measurement of vertical crustal motions is relatively less subject to contamination due to global change signals. In this regard, a recent analysis by Sella et al. (2007) estimated an uplift rate of 8 – 10 mm/yr in James Bay. Ignoring changes in the geoid, which will be small, this range suggests that GIA is contributing about an 8 – 10 mm/yr fall to the present-day sea-level signal in the region.

### *Sea-Level Change – Glacial Isostatic Adjustment (GIA)*

Predicting changes in sea level arising from the ice-age cycles of the late Pleistocene is a long-standing problem in geophysical research (Farrell and Clark, 1976). Recent advances in the theoretical treatment of this problem have included the accurate treatment of shoreline migration associated with local changes in sea level and variations in (grounded) marine-based ice (Johnston, 1993; Kendall et al., 2005). In the calculations presented here, we adopt the extended theory described by Kendall et al. (2005). These calculations require two inputs. The first is a history of the space and time geometry of the ice cover. For this purpose, we adopt the ICE-5G global ice model (Peltier, 2004) that encompasses the last full glacial cycle (i.e., it extends back to the last interglacial at ~120 ka BP). The second input is a model for the viscoelastic structure of the earth. With few exceptions, predictions of sea-level change due to the ice age—or more formally, glacial isostatic adjustment—have assumed an earth model that varies with depth alone; that is, lateral variations in earth structure have been ignored. Following this assumption, a prescription of the earth model requires depth-dependent parameters governing the elastic and density structure of the earth and the viscosity of the earth’s interior. The elastic and density model is taken from the so-called Preliminary Reference Earth Model (PREM) derived from seismic constraints (Dziewonski and Anderson, 1981). In contrast, the depth profile of earth viscosity is more uncertain, and it will, at least in part, serve as a free parameter of our modeling.

Specifically, following the traditional approach within the GIA literature, we used three discrete layers to model the viscosity of the earth’s interior above the core-mantle-boundary (at ~2900 km depth). The shallowest and uppermost of these layers is a zone of very high (effectively infinite) viscosity, which physically results in an effectively


FIG. 4. A map showing some of the islands of James Bay. The Ontario–Quebec border marks the dividing line between the western and eastern islands of James Bay.

elastic region known as the lithosphere. In our calculations, the lithosphere is ~120 km thick (for readers unfamiliar with this terminology, we note that the term "plate" in plate tectonics refers to a piece of the lithosphere). The second region extends from the base of the lithosphere to a depth of ~670 km, which marks a well-defined change in seismic properties. This region is termed the sub-lithospheric upper mantle, and we adopt a viscosity of $5 \times 10^{20}$ pascal-seconds (Pa s) for the viscosity in this region. Since the Laurentide ice sheet that covered Canada was several thousands of kilometers across, the sea-level predictions we present below are relatively insensitive to the adopted thickness of the lithosphere. Moreover, the predictions are less sensitive to the choice for the upper-mantle viscosity than to the adopted viscosity of the so-called lower mantle, which extends from ~670 km depth to the core-mantle boundary. As a consequence, we will consider a suite of predictions in which the lower-mantle viscosity is varied over some plausible range.

We narrow the range of lower-mantle viscosity in two ways. First, as discussed above, the GIA model of sea-level change must yield a present-day rate of sea-level change in the James Bay region that matches estimates of this contribution derived from geological records of late Holocene sea-level fall (Mitrovica et al., 2000) and geodetic estimates of present-day crustal uplift (Sella et al., 2007). These two data sets suggest a lower bound on the GIA contribution to the sea-level fall of 0.6 cm/yr. An earth model with a lower-mantle viscosity of $1 \times 10^{21}$ Pa s yields a present-day rate of sea-level fall (0.61 cm/yr) that matches this lower bound. Models with lower-mantle viscosity of 2, 3, 5, 8, and $10 \times 10^{21}$ Pa s predict a present-day sea-level fall of 1.1 cm/yr, 1.3 cm/yr, 1.6 cm/yr, 1.7 cm/yr, and 1.7 cm/yr, respectively. We can refine this range further by invoking geological constraints on the uplift history of the region over the last ~6000 years. These constraints, parameterized into the so-called decay time of uplift (Mitrovica and Forte, 1997, 2004; Peltier, 1998), suggest that a lower-mantle viscosity of more than $5 \times 10^{21}$ Pa s is unlikely, at least for the mantle region below Hudson Bay. (However, for a contrary view, see Wolf et al., 2006.) Therefore, in the predictions presented below, we limit our attention to results for four values of lower-mantle viscosity: $1 \times 10^{21}$ Pa s, $2 \times 10^{21}$ Pa s, $3 \times 10^{21}$ Pa s, and $5 \times 10^{21}$ Pa s. The ICE-5G ice history is most appropriately paired with a specific viscosity model VM2 (Peltier, 2004). We note that the VM2 model has a mean lower-mantle value that falls near the mid range of the lower-mantle viscosities we adopt in this study. We also computed predictions using the ICE-3G ice history (Tushingham and Peltier, 1991), but these additional results did not alter the range of times over which land bridges were predicted to form within James Bay.

The output of the sea-level code is the geographically variable change in relative sea level (i.e., the change in the height of the sea-surface equipotential relative to the solid surface of the earth) over the next 1000 years on a global grid. Since this change is approximately linear over the 1000-year time period, we divided the computed change by 100 to determine the sea-level change over 10-year time increments.

*Sea-Level Change – Global Warming*

As discussed above, sea-level change associated with global warming, including the melting of present-day ice sheets and glaciers and thermal expansion of ocean water, should be superimposed on the numerical GIA predictions. The rate of sea-level rise into the next century is uncertain (IPCC, 2007), and moreover, this rate will be geographically variable (Mitrovica et al., 2001). Accordingly, we assume a constant rate over the small geographic area we are interested in (James Bay; Fig. 4) and use the IPCC (2007) report to define bounds on the projected sea-level change. In this report, projections for global sea-level change over the next century range from 18 cm to 59 cm. Thus, for the global warming (GW) signal, we adopted a lower bound of 1.8 mm/yr rise (18 cm per 100 years; GW = 1.8) and an upper bound of 5.9 mm/yr rise (GW = 5.9). We note that some recent analyses (e.g., Rahmstorf et al., 2007)

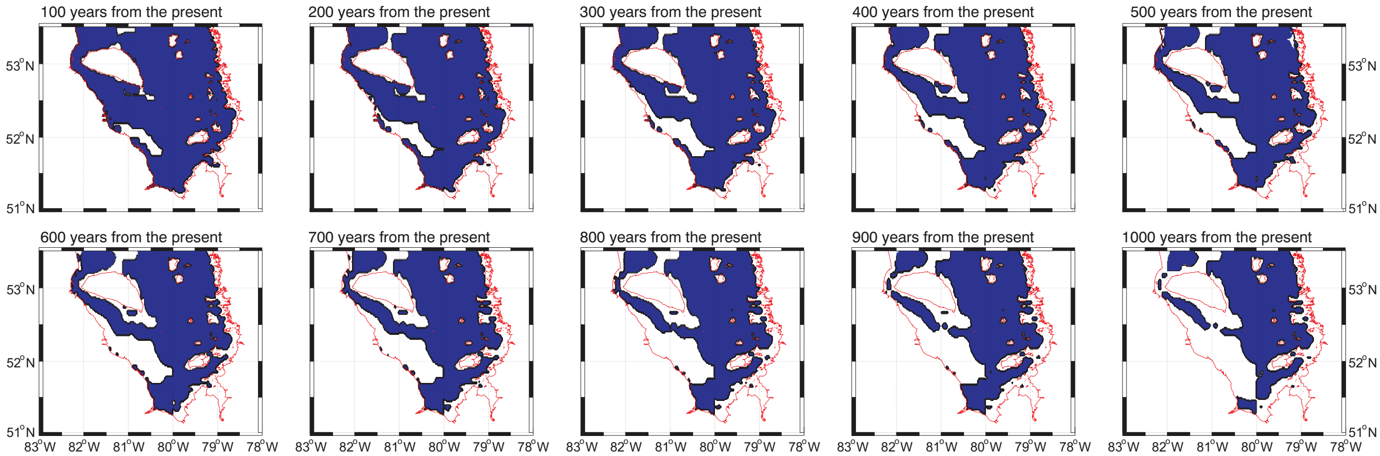


FIG. 5. The predicted evolution of the shoreline in the James Bay region over the next 1000 years, in 100-year time increments. The prediction is based on changes in sea level computed using a glacial isostatic adjustment (GIA) model with a lower-mantle viscosity of $3 \times 10^{21}$ Pa s (details in text) and the global warming scenario GW = 1.8 mm/yr. Within each frame, the red line denotes the present shoreline, the blue regions are areas with negative topography (i.e., water), and the white regions denote positive topography (i.e., land). Thus, the shoreline in any frame is given by the boundary between blue and white.

indicate that the IPCC report may have underestimated projected sea-level rates, and thus the upper bound may prove to be most accurate.

*Shoreline Migration*

The shores of the western James Bay coast are relatively flat (0.5 m/km; Martini, 1981a; Martini and Morrison, 1987). Predicting the migration of these shorelines requires several steps. First, the GIA prediction for a specific lower-mantle viscosity is combined with an assumed global warming scenario (GW = 1.8 or 5.9) to obtain a total predicted rate of sea-level change. A global grid of the total sea-level change at 10-year time increments up to 1000 years into the future is computed by simply multiplying the total (GIA plus GW) sea-level rate by 10, 20, …, 1000 years. Relative sea-level change is the negative of the topography change (i.e., if topography falls, relative sea level rises), and thus the predicted sea-level changes can be combined with a high-resolution data set of present-day topography to track changes in topography over the next 1000 years. Since shorelines are defined as the locations of zero topography (i.e., where the sea surface and ocean bottom have the same height), the position of shorelines over the next 1000 years (in 10-year increments) can also be tracked.

We note that present-day topography datasets for the Hudson Bay and James Bay regions were downloaded from the General Bathymetric Chart of the Oceans (GEBCO) one-minute grid (IOC et al., 2003). Present-day shorelines (used to compare with our predictions of future shoreline location) were specified using the World Vector Shoreline (WVS) data file. This digital data file has a scale of 3 × 3 arc seconds (a data point about every 30 m) and can be downloaded from a coastline extractor website (Signell, 2005) hosted by the National Oceanic and the Atmospheric Administration (NOAA) and the National Geophysical Data Center (NGDC).

## RESULTS

Figure 5 shows snapshots of shoreline migration over the next 1000 years in the James Bay region predicted on the basis of a specific combination of ice-age model and global warming scenario. In particular, the predictions adopt a GIA model in which the lower-mantle viscosity is set to $3 \times 10^{21}$ Pa s and a global warming scenario in which sea-level rises at a rate of GW = 1.8 mm/yr. As one moves forward in time, there is a gradual fall in net sea level and an emergence of the islands within the James Bay region. As a consequence of this trend, both Strutton and Cape Hope islands are predicted to join the mainland 400–500 years from now. Moreover, land bridges develop between Charlton Island and the mainland in 700–800 years, and Akimiski Island and the mainland in 800–900 years. These connections arise from outward shoreline migration (i.e., regression of water) from both the islands and the adjacent mainland.

Table 1 lists more precisely the timing of land-bridge development for these four islands for this specific combination of GIA and global warming effects. For completeness, the table lists land-bridge timing for the two global warming scenarios discussed above (1.8 mm/yr and 5.9 mm/yr) and, for each of these scenarios, three of the four different values of lower-mantle viscosity adopted in the ice age calculation. (The results for a lower-mantle viscosity of $1 \times 10^{21}$ Pa s are not shown because, in this case, land bridges do not form for either global warming scenario over the 1000-year time window being considered in Table 1.) As a companion to this table, Figure 6 shows the predicted shoreline for each of these six scenarios at both 500 years and 1000 years in the future.

Notice that, for a given global warming scenario, the time required for the development of the land bridge grows as the lower-mantle viscosity is decreased within the limits we have considered. This trend has a simple physical explanation. The James Bay–Hudson Bay region of Canada became ice-free about 8000 years ago, and uplift

TABLE 1. Predicted elapsed time (in years) from the present to the time when the larger James Bay islands will connect to the mainland. Predictions are based on two different global warming scenarios (GW = 1.8 mm/yr and 5.9 mm/yr of sea-level rise) and three different values for the lower-mantle viscosity adopted in the ice-age sea-level calculations (LM × $10^{21}$ Pa s). A blank indicates that the island will not join the mainland within the 1000-year period of the calculation.

| Sea-Level Models | Akimiski | Cape Hope | Strutton | Charlton |
|---|---|---|---|---|
| GW = 1.8 mm/year | | | | |
| LM = 5 | 670 | 380 | 380 | 610 |
| LM = 3 | 850 | 470 | 460 | 750 |
| LM = 2 | | 630 | 610 | |
| GW = 5.9 mm/year | | | | |
| LM = 5 | | 560 | 560 | 920 |
| LM = 3 | | 790 | 780 | |
| LM = 2 | | | | |

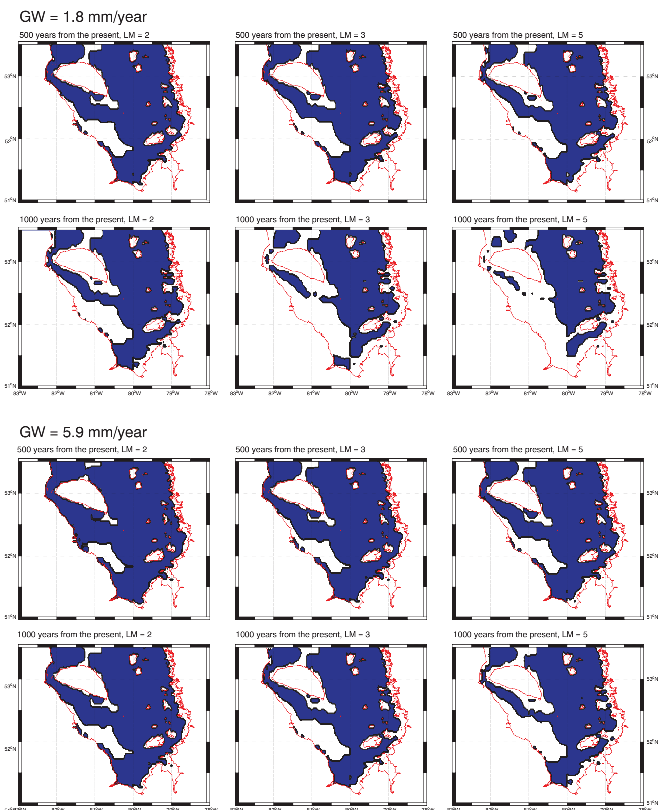


FIG. 6. The predicted shoreline in the James Bay region at (top) 500 years and (bottom) 1000 years in the future for six different combinations of ice age and global warming–induced sea-level changes. The glacial isostatic adjustment (GIA) models are distinguished on the basis of the adopted lower-mantle viscosity (2 × $10^{21}$ Pa s, 3 × $10^{21}$ Pa s, and 5 × $10^{21}$ Pa s) and the global warming scenarios are either GW = 1.8 mm/yr or GW = 5/9 mm/yr (see text for details). Colour representation as in Figure 5.

of the region (i.e., post-glacial rebound) has continued at a gradually slowing pace since that time. Models with progressively weaker lower-mantle regions (i.e., progressively lower viscosities within the lower mantle) will have shorter decay times, and will thus have reached a state closer to their final equilibrium state by the present day. That is, as the lower-mantle viscosity is decreased, the predicted rate of present-day sea-level fall (or post-glacial rebound) due to GIA will decrease. Accordingly, the future rate of emergence is lower, and the time required for land-bridge development is longer, as the viscosity is reduced.

As an example, from Table 1 (GW = 1.8 mm/yr case), Strutton Island is predicted to join the mainland in 380 years, 460 years and 610 years, for lower-mantle viscosities of 5 × $10^{21}$ Pa s, 3 × $10^{21}$ Pa s, and 2 × $10^{21}$ Pa s, respectively. Furthermore, while Akimiski Island is predicted to join the mainland in 670 years when a lower-mantle viscosity of 5 × $10^{21}$ Pa s is adopted, the land bridge does not develop in the next 1000 years if the viscosity used in the calculations is reduced to 2 × $10^{21}$ Pa s.

Not surprisingly, the timing for land-bridge development is also increased as the sea-level rise associated with global warming is increased. As an example, for the GW = 5.9 mm/yr scenario, none of the four James Bay islands are predicted to join the mainland over the next 1000 years for a lower-mantle viscosity of 2 × $10^{21}$ Pa s, while all but Akimiski will join during this time window if the viscosity is increased to 5 × $10^{21}$ Pa s. Of course, there can still be significant emergence of the islands over this time period even if this trend does not lead to a land bridge (Fig. 6).

In any event, the results in Figures 5 and 6 and Table 1 indicate that in most cases a land bridge will develop over the next 1000 years for the four listed islands; however, the exact timing of this development is dependent on future levels of sea-level rise due to global warming and the current rate of ice age–induced post-glacial land emergence (which is, in turn, a function of the lower-mantle viscosity of the earth model).

## DISCUSSION

Gough (1998) estimated future sea-level changes in Hudson Bay assuming an ongoing rate of post-glacial rebound of 0.8 cm/yr, a range of ongoing ice-melt rates, and two models of ocean thermal expansion (derived using a one-dimensional calculation and a three-dimensional ocean general circulation model). He concluded that climate warming has the potential to mitigate the effects of post-glacial rebound. Gough (1998) did not investigate the potential range of ice-age signal, nor was he concerned with shoreline migration and the potential development of land bridges.

We have also noted that sea-level rise due to global warming acts in opposition to the fall in sea level (land emergence) associated with ongoing post-glacial rebound in response to the last ice age. However, the results shown in Table 1 indicate that many islands within James Bay will join the mainland in the next 1000 years unless the global warming signature increases significantly from estimates for the 20th century, which are close to 2 mm/yr (e.g., Mitrovica et al., 2001). In this regard, the GW = 5.9 mm/yr is about three times the 20th-century rate (although we note that this value is a projection only to the end of the next century, not the next millennium). For this scenario, we note from Figure 6 that land emergence, particularly in the short term, will be significant. The potential changes in shoreline geometry associated with this sea-level change should be recognized in negotiations of land claims for the region.

Our suite of GIA models yields sea-level rates in the range from -6 to -16 mm/yr, and we adopt global warming signals of close to 2 and 6 mm/yr. This range of models encompasses a net sea-level change between -14 and 0 mm/yr. While our calculations involve a number of simplifying assumptions (constant global warming rates; a linear, 1-D and 3-layer viscosity profile), it is unlikely that these simplifications have limited an already broad range of sea-level scenarios. Consider, for example, the possible inclusion of lateral variations in mantle viscosity. State-of-the-art GIA predictions that permit 3-D variations in viscosity suggest that the effect on sea-level predictions will be on the order of a few mm/yr (e.g., Paulson et al., 2005; Wu et al., 2005; Kendall et al., 2006).

As we have shown, past and future shoreline locations can be predicted with knowledge of present-day topography and projections of future sea-level changes associated with both global warming and ongoing GIA. The accuracy of these predictions will improve as the projections are refined, and future analyses might also bring to bear observational constraints derived from geodetic measures of sea-level change (land or satellite or both; e.g., Tushingham, 1992; Gough and Robinson, 2000). In this regard, there is also a pressing need to establish a high-quality, high-resolution topography data set for the region. (Specifically, the GEBCO topography data set and others we considered were characterized by topographic discontinuities within James Bay that appear to be a result of combining independent data sets.) It should also be noted that GIA is not the only process affecting land-bridge formation in the western James Bay region; sedimentary processes are also important (Martini and Glooschenko, 1984; Poehlman, 1996). As GIA occurs in the western James Bay region, islands are being enlarged by the addition of islets and shoals, which eventually become silted and develop into marshes (Martini and Glooschenko, 1984). In addition, Martini and colleagues (Martini, 1981b; King and Martini, 1984; Martini and Morrison, 1987) have shown for the western James Bay coastal zone that river-borne sediments (silts to boulders) are dispersed by waves, tides, long-shore currents, and ice rafting; only a small portion of these sediments is deposited at the mouths of rivers. In contrast to the sedimentary processes, the freezing of ice blocks to the ground on the coast and the lifting of the ice during spring tides remove vegetation and sediments. An indirect effect of sea ice is the creation of ice-walled channels and bays that canalize tidal currents and erode parts of the sand flats (Martini, 1981b). Thus, geomorphological phenomena introduce some uncertainties with respect to the timing of land-bridge formation. Nevertheless, despite these uncertainties, the implications of our results for land-claim negotiations (including past settlements and future efforts), and more generally, for both the economic and non-economic (e.g., ecological, social, and cultural) welfare of aboriginal communities are substantial.

The migration of shorelines in the James Bay region raises numerous pressing issues for land-claim negotiations. For example, if the western James Bay islands become part of mainland Ontario, the issue of Cree ownership of the islands as opposed to Nunavut's claim would no longer be just a federal matter, but also a provincial concern because of Ontario's potential jurisdictional claim. As the James Bay lowlands region is rich in diamonds (AMEC, 2004) and metals (Koven, 2007; Larmour, 2007), the economic worth to the competing groups is significant, especially taking into account that the value of the land to the First Nation Cree also includes social and cultural factors.

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