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Summary

Estimates of the range of sea-level change expected in the next 90 years (2010 to 2100) for five communities in Nunavut (Table S-1) are derived from an assessment of published estimates of projected global sea-level change and an evaluation of vertical land motion. The projections provided here are intended to contribute to discussions on the possible impacts of projected sea-level change and potential mitigation measures that could be implemented at each community. Consideration of other factors affecting coastal stability, such as autumn storms and sea-ice extent, and assessment of shoreline and nearshore land use and infrastructure vulnerability, are also essential parts of the discussion, but are beyond the scope of this report.

Table S-1. Range of probable sea-level change for five pilot communities in Nunavut from 2010 to 2100 (relative to present-day mean sea level)

Community	By the year 2100, sea level will probably not **fall** more than : (cm)	By the year 2100, sea level will probably not **rise** more than: (cm)
Arviat	70	25
Whale Cove	75	20
Kugluktuk	10	50
Cambridge Bay	35	50
Iqaluit	0	70

The global sea-level change scenarios considered in this study provide 15 cm (minimum) to 196 cm (maximum) of sea-level rise at the year 2100 (using 2010 as the start date). The community projections given in Table S-1 are based on our assessment of the likely amount of global sea-level change, spanning from 28 cm to 115 cm by the year 2100 (a range of 87 cm).

Sea-level change from changing glaciers and ice caps is not spatially uniform (Mitrovica et al., 2001) and the community-specific sea-level projections include this “sea-level fingerprinting” effect. Meltwater from the Greenland ice sheet is redistributed in the global oceans in such a way that it contributes to stable or falling sea levels for the five communities, while meltwater from glaciers and ice caps contributes to reduced amounts of sea-level rise compared to the amount that would be expected from uniform meltwater redistribution. The net effect is that the range of projected sea-level change at each community is substantially less than the amount that would have been determined if

melt-water redistribution had been assumed to be uniform.

Some of the community sea-level projections are notable for significant sea-level fall. This is a consequence of land uplift, which is occurring due to glacial isostatic adjustment (GIA). GIA is the delayed response of the Earth to surface unloading caused by deglaciation at the end of the last Ice Age. The rising land ameliorates the effects of global sea-level rise, especially for Arviat and Whale Cove, which are rising the fastest.

The sea-level change projections given in Table S-1 include the effects of uncertainty in vertical land motion and this extends the range of projections significantly, although more than half of the range (uncertainty) in the community sea-level projections is due to the global sea-level projections. An additional unquantified, but potentially large, source of error arises from the assumptions used in assessing the spatially variable meltwater redistribution.

Significant progress in reducing the current large range of sea-level projections could be realized by improving observations of vertical land motion and from carrying out an updated assessment of the spatially variable redistribution of meltwater from Arctic ice caps and the Greenland ice sheet.

1. Introduction

Globally, sea level is projected to rise in the coming decades, but the range of projections varies greatly. There is uncertainty about the expected contribution from warming of the ocean's surface layer, which causes it to expand and raise the surface of the ocean (steric effect) and much greater uncertainty about the meltwater contributions of glaciers and ice caps and the large Greenland and Antarctic ice sheets.

The average rate of sea-level change in the last four decades of the 20th century (1961 to 2003) was 1.8 ± 0.5 mm/yr, but the rate appears to have accelerated in the last decade (1993 to 2003) to 3.1 ± 0.7 mm/yr (Table SPM.1; IPCC, 2007). It is noteworthy, however, that decadal variability in sea-level rise during the 20th century ranged from about -1.0 mm/yr to +3.7 mm/yr (Church and White, 2006); thus it is difficult to be sure how much of the acceleration seen in the 1993-2003 rate is attributable to a change in the trend. Sea-level change is correlated with global temperatures, and because temperatures are projected to rise in the 21st century, the expectation is that global sea level will continue to rise, quite possibly at higher rates than recently observed.

The Nunavut Climate Change Partnership (NCCP) is a collaborative initiative between the Government of Nunavut, Canadian federal government departments (Natural Resources Canada and Indian and Northern Affairs Canada), and the Canadian Institute of Planners (CIP). Five communities in Nunavut (Iqaluit, Arviat, Whale Cove, Kugluktuk and Cambridge Bay – Figure 1) have been chosen by NCCP to be part of the Atuliqtuq project which aimed to produce community climate change adaptation plans. Earlier work considered the communities of Hall Beach and Clyde River. It is planned to provide sea-level projections for those communities in a subsequent report discussing sea-level change across the entire territory. For each community, two volunteer planners from the CIP have worked in close collaboration with government and university scientists and have consulted extensively within the community to develop the climate change adaptation action plans. Climate change issues addressed in the actions plans include the sea-level projections discussed in this report, coastal stability, landscape changes, and changes to water supplies.

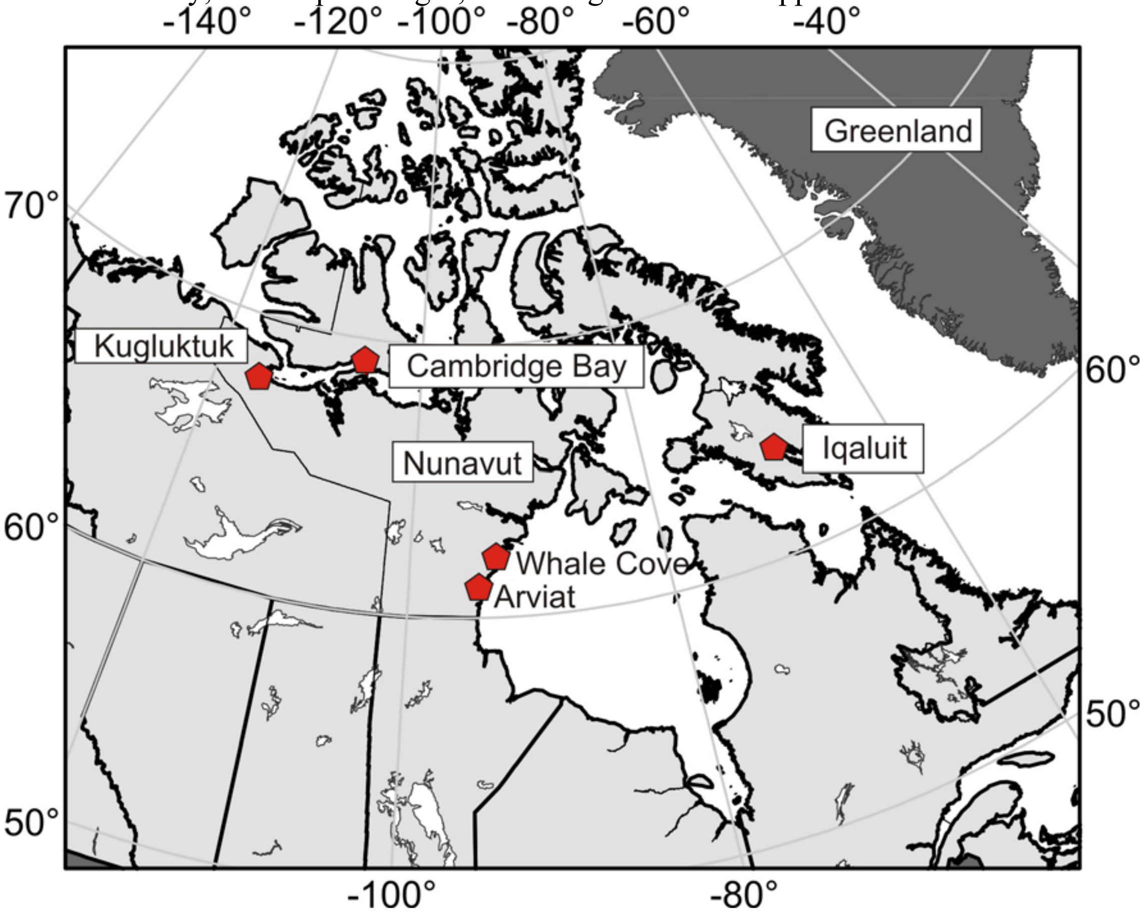

Figure 1. Map indicating the location of the five pilot communities.

In addition to the effects of sea-level change, coastal stability is influenced by the frequency and intensity of extreme events, such as major autumn storms. Indirectly, changes to the extent and duration of sea-ice, such as the time of autumn freeze-up, can also make the coastline more (or less) susceptible to storms. This report does not consider projections of extreme events and changes to sea ice. Instead, the focus here is solely on projections of sea-level change for the five pilot communities, based on the scientific literature and other available information. The assumed time frame is 90 years (2010 to 2100).

2. Contributors to Sea-level Change

A projection of sea-level change at a specific location requires consideration of global sea-level change, the location (attribution) of the sources of global sea-level change, and local vertical land motion. Each of these factors is addressed briefly below.

2.1 Scenarios of Global Sea-Level Change. The Intergovernmental Panel on Climate Change (IPCC), in its most recent Fourth Assessment Report (AR4) (IPCC, 2007), provides projections of global sea-level change for six scenarios. The scenarios correspond to various assumptions about the world economy and the intensity with which conservation measures are adopted. For each scenario, a range of sea-level projections is provided. The scenarios predict as little as 18 cm and as much as 59 cm of sea-level rise (Table 10.7; Meehls et al., 2007) from 1980-1999 to 2090-2099.

At the lower end, the IPCC projections indicate an average rate of sea-level rise similar to that observed for the last half of the 20th century (1.8 ± 0.5 mm/yr). At the higher end, the IPCC projections indicate an average rate of sea-level rise that is nearly double the rate that was observed recently (3.1 ± 0.7 mm/yr).

The IPCC cautions that the projections do not include the "full effects of changes in ice sheet flow, because a basis in published literature is lacking" (IPCC, 2007, p. 14). The report indicates that the upper values of the projections could increase by 10 or 20 cm if the ice-sheet-flow contribution grew proportionally to projected global temperature increase and that even larger contributions are not ruled out. Thus, the IPCC projections are conservative.

Input of new scientific results to the IPCC AR4 ceased around mid-2005. Since that time, a number of studies have appeared that project maximum amounts of sea-level rise that are larger than the upper end of the IPCC projections (e.g., Ramstorf, 2007; Horton et al., 2008; Grinsted et al., 2009). Consequently, although the IPCC projections provide a sound basis for developing local, or community-based, sea-level projections, we also consider scenarios featuring larger amounts of global sea-level rise.

2.2 Sea-Level Fingerprinting. When a glacier or ice sheet loses mass by melting or iceberg calving, the meltwater is not distributed evenly throughout the oceans and does not cause a uniform rise in sea level (Mitrovica et al., 2001). Instead, near the ice sheet, the reduced gravitational pull of the ice sheet causes the surface of the ocean to sink. As well, the reduced surface load causes the Earth to respond elastically and the land rises under the ice sheet and in areas adjacent to the ice sheet. The net response near the ice sheet is that local (relative) sea level falls substantially, even though a melting ice sheet causes global sea-level rise to increase on average. Conversely, at large distances from the ice sheet, the net effect is that sea level rises a little more than the average value.

"Sea level fingerprinting" is important to incorporate into projections of sea-level change, especially for Nunavut. The territory is host to some Arctic ice caps and is relatively close (on a global scale) to the Greenland ice sheet and thus is especially sensitive to spatial variations in the distribution of meltwater and in the Earth's instantaneous (elastic) vertical land motion response to ice sheet and glacier mass change.

2.3 Vertical Land Motion.

At a specific location, sea-level change depends not only on the amount and location of sources of global sea-level rise, but also on the local vertical land motion. For example, if sea level is (hypothetically) projected to rise by 50 cm by the year 2100 at a specific location due to thermal expansion and meltwater input to the oceans, but the land is expected to rise by the same amount, then the net effect would be nil and the projected net sea-level change for the locality would be zero. This net sea-level change is often referred to as the relative sea-level change.

Vertical land motion is significant across much of Canada, and some of the highest rates occur in Nunavut and adjacent parts of Manitoba and Québec. Most of the Canadian land surface was glaciated during the last continental glaciation, which peaked at about 21,000 years ago. The weight of the ice pushed down the surface of the Earth. In contrast to the land subsidence experienced beneath the ice sheet, the land outside the glaciated region rose during glaciation because material deep in the Earth was displaced away from the centre of the ice sheet. The region of where the land was uplifted during glaciation is known as the proglacial forebulge.

With the exception of some glaciers and ice caps remaining in the mountains of western Canada and in the Arctic, the last vestiges of the continental ice sheets disappeared about 7000 to 8000 years ago. In response to deglaciation and the decreased load, the surface of the Earth began to rise beneath the thinning ice sheet, while the peripheral bulge began to sink. Because the interior of the Earth behaves like a very viscous (slow flowing) liquid, the vertical land motion is still occurring today. The Earth's response to glacial loading and unloading is called glacial isostatic adjustment (GIA).

Thus, the pattern of vertical land motion due to GIA comprises a region of present-day uplift where the former ice sheet was thickest and where it persisted the longest, surrounded by a peripheral region where the land is subsiding. Eastern Baffin Island and the western Canadian Arctic, including the Mackenzie Delta, are regions of subsidence. Over most of Nunavut, the land is presently rising.

Computer models of GIA also include the effects of changing amounts of ocean water that occurred in response to ice sheet growth and decay and the effects of the redistribution of ocean water in response to gravitational changes and vertical land motion of the ocean floor. The response of the Earth to changing water loads is called hydro-isostasy and is important for understanding sea-level change.

Within the region of uplift, the rates differ from one location to another because the ice was thicker in some places than in other places, and because ice sheet thinning and deglaciation occurred at different times in different parts of Canada. The magnitude of subsidence is generally no more than 1 or 2 mm/yr, whereas peak uplift can reach 10 mm/yr or greater. The estimates of vertical land motion given in this report are due to GIA.

3. Results.

The specific scenarios of global sea-level rise, effects of sea-level fingerprinting at the five communities, and the estimation of vertical land motion at the five communities are described in the following three sections.

The fourth section synthesizes the results of the previous sections and provides a range of projections for each community. It gives the projections of sea-level change for the five communities and indicates the probable range of sea-level change for each community.

3.1 Scenarios of Global Sea-level Change.

We take the approach of considering a broad range of scenarios of global sea-level rise and attempt to include extreme minimum and maximum scenarios as well as intermediate ones. Sea-level fingerprinting requires that the sources of sea-level change (glaciers and ice caps, Greenland, Antarctica) be identified for each scenario. Depending on the source of the scenario, this sometimes requires that additional assumptions be made. The scenarios are summarized in Table 1. Details of the scenarios and assumptions that were made are given in Appendix A. Here we briefly name and describe the scenarios:

20th Century Sea-level Rise (SLR). This scenario is built on the observed sea-level change of 1.8 mm/yr from 1961 to 2003 (IPCC, 2007) and features 16.2 cm of global sea-level rise in the 90 years from 2010 to 2100.

Late 20th Century Sea-level Rise (SLR). This is a scenario built on observed sea-level change of 3.1 mm/yr from 1993 to 2003 and features 27.9 cm of global sea-level rise.

IPCC Scenarios. The IPCC presents sea-level projections for six scenarios (Meehl et al., 2007, Table 10.7). For each scenario a range of sea-level projections is given corresponding to the 5% and 95% significance levels. We determined sea-level projections using the mid-point of each scenario, as well as at the minimum value of the scenario giving the smallest amount of sea-level rise (B1) and the maximum value of the largest scenario (A1FI). The scenarios give 15.3 cm (minimum of scenario B1) to 50.5 cm (maximum of scenario A1FI) of global sea-level rise. Keep in mind that the time frame of the IPCC report (1980-1999 to 2090-2099) differs from the time frame adopted here and that thus values given in the IPCC report need to be scaled before comparing to values given here.

Post-IPCC scenarios. A number of recent studies suggest that sea-level rise could be larger than the IPCC projections. Rahmstorf (2007) noted that sea levels in the past 150 years have been proportional to global temperatures. Assuming the same relationship holds for the 21st century, he projected sea level to rise by 0.5 to 1.4 m above the 1990 level by 2100 (0.41 m to 1.15 m for a 90-year time span). Grinsted et al. (2009) examined the correlation between temperatures and sea level over the past 2000 years and extrapolated to 2090-2099 using the IPCC scenarios. On average (for the preferred Moberg data set), the sea-level projections ranged from 0.9 m to 1.3 m (0.77 m to 1.12 m for a 90 year time span).

Not all post-IPCC projections are this big. Horton et al. (2008), using the output of coupled global climate models and also correlating temperature to sea-level change, found an average sea-level rise of 0.7 m from 2001-2005 to 2100 (0.65 m for 2010 to 2100). Pfeffer et al. (2008) employed a glaciological approach to project sea-level change, based on probable and extrapolated glacial flow rates and other arguments, and derived two "low" scenarios delivering 0.78 and 0.83 m of sea-level rise to 2100. They suggested that these "provide a 'most likely' starting point for refinements in sea-level forecasts that include ice flow dynamics".

Based on analogies with the previous interglacial period about 125,000 years ago, some authors have suggested the potential for several metres of sea-level rise. Pfeffer et al. (2008) determined that a sea-level rise larger than 2 m by 2100 is physically implausible. Two metres of sea-level rise would require that all variables be immediately accelerated to extremely high limits.

Based on the foregoing summary, we utilize the following post-IPCC scenarios:

Pfeffer Low 1 and Pfeffer Low 2. These scenarios are glaciologically based (Pfeffer et al., 2008) and provide an amount of sea-level rise intermediate between the IPCC scenarios and the larger amounts suggested by other studies. The amount of sea-level rise they deliver is slightly larger than the average amounts suggested by Horton et al. (2008).

Rahmstorf/Grinsted scenario. The peak amount proposed by Rahmstorf (2007) (1.15 m) is similar to the average peak value determined by Grinsted et al. (2009) (1.12 m), and we therefore examine the consequences of 1.15 m of sea-level rise. These studies do not indicate the source(s) of sea-level rise. To address this, we scale a number of other scenarios (Pfeffer et al.'s (2008) three scenarios, 20th Century Sea level Rise, and Late 20th Century Sea Level Rise scenarios) to deliver 1.15 m of sea-level rise and then examine the variability in projected sea-level change brought about because of the differing weighting of meltwater sources.

Pfeffer High 1. This delivers 2 m of sea-level rise (Pfeffer et al., 2008) and is the largest scenario considered in this report.

Subsequent to the analyses described in this report, a new paper by Vermeer and Rahmstorf (2009) has projected sea-level rise ranging from 75 to 190 cm (1990-2100), or 61 to 155 cm over the 90 years remaining to 2100.

Table 1. Scenarios of Global Sea-level Rise Employed in Sea Level Projections

Name of Scenario	Source(s)	Amount of Sea-level Change Delivered from 2010 to 2100 (cm)
20th Century SLR	IPCC, 2007	16
Late 20th Century SLR	IPCC, 2007	28
IPCC – B1 Minimum	Meehl et al., 2007	15
IPCC – B1	Meehl et al., 2007	24
IPCC – B2	Meehl et al., 2007	27
IPCC – A1B	Meehl et al., 2007	30
IPCC – A1T	Meehl et al., 2007	28
IPCC – A2	Meehl et al., 2007	31
IPCC – A1FI	Meehl et al., 2007	36
IPCC – A1FI Maximum	Meehl et al., 2007	51
Pfeffer Low 1	Pfeffer et al., 2008	77
Pfeffer Low 2	Pfeffer et al., 2008	82
Rahmstorf/Grinsted	Rahmstorf (2007); Grinsted et al. (2009)	115
Pfeffer High 1	Pfeffer et al., 2008	196

3.2 Sea-Level Fingerprinting.

As mentioned above, the location of the source of present-day meltwater is important for determining the sea-level change, especially at sites close to the source. Mitrovica et al. (2001) show the change in sea-level for a one millimeter per year sea-level contribution from Antarctica, Greenland, and glaciers and ice caps (Figure 2). For each community, the sea-level response at each community for each meltwater source was read from Figure 2 and is given in Table 2. Meltwater from the Greenland ice sheet is redistributed in the global oceans in such a way that it contributes to stable or falling sea levels for the five communities, while meltwater from glaciers and ice caps contributes to reduced amounts of sea-level rise compared to the amount that would be expected from uniform meltwater redistribution.

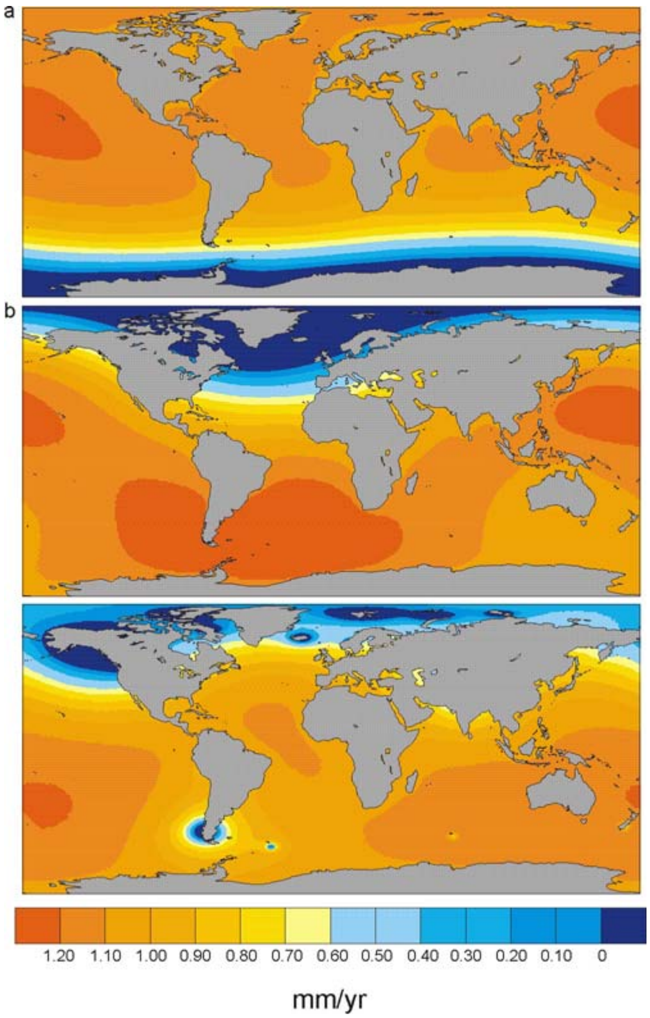

Figure 2. The amount of sea-level rise, in millimetres per year, for an assumed 1 mm/yr contribution to global sea level rise from (a) Antarctica, (b) Greenland, and (c) glaciers and ice caps (figure from Mitrovica et al., 2001).

The figures provide enough information to determine the sea-level response for most communities for most sources. Iqaluit is, however, located relatively close to Greenland and it was felt that extrapolation from the figure was uncertain. G. Milne (pers. comm., 2009) kindly provided the expected sea-level response at Iqaluit to a one millimeter per year sea-level rise sourced from

Greenland. Its response is remarkable for being large and negative, and this has implications for sea-level projections for Iqaluit that will be discussed in detail later.

Table 2. Sea-level rise assuming a 1 mm/yr sea-level contribution from a given source (after Mitrovica et al., 2001)

Community	Greenland	Antarctica	Glaciers and Ice Caps	Thermal Expansion (Steric Effect)
Arviat	-0.3	1.05	0.35	1.0
Whale Cove	-0.4	1.05	0.35	1.0
Kugluktuk	0	1.05	-0.1	1.0
Cambridge Bay	-0.3	1.05	0.05	1.0
Iqaluit	-1.2	1.05	0.4	1.0

3.3 Vertical Land Motion.

Relative sea level has been falling in recent millennia in many areas of Canada because the land is rising in response to the unloading caused by the thinning and retreat of the large ice sheets at the end of the last Ice Age. Frequently, it is possible to radiocarbon-date features such as raised beaches and deltas that are related to past, higher sea levels. In many areas, the amount of information is sufficient to determine a sea-level curve which shows how sea level has changed in the past. The slope of a sea-level curve, at present, shows how quickly sea level is falling and that can be related to the rate at which the land is rising.

The information on past sea levels has also been synthesized as maps showing the elevation of land that was at sea level at a specified time in the past (Dyke, 1996, and unpublished updates incorporating new information). These "isobases" have been determined at 500 year intervals. They interpolate sea-level observations from regions with abundant data to regions that have less data at a given time. For each of the five pilot communities, the isobase values were validated by comparison with available sea-level observations from the vicinity of the community. The validation was successful and present-day rates of sea-level fall were determined and used as estimates of vertical land motion. This procedure is valid because it is thought that global sea level has not changed in the past one thousand to two thousand years (e.g., Fleming et al., 1998), prior to acceleration over the past 200 years (Church and White, 2006).

Another estimate of vertical land motion was obtained from the predictions of a computer model of the GIA process called ICE-5G (Peltier, 2004). ICE-5G is a global model of the glaciation and deglaciation that occurred during the last Ice Age that loads a model of the solid Earth to generate predictions of relative sea-level change. We compared the predictions of the model to the sea-level data from each of the pilot communities, and found good agreement for Kugluktuk, Cambridge Bay, and Iqaluit. ICE-5G predicts too much sea-level fall, however, in the vicinity of Arviat and Whale Cove.

Consequently, the estimates of vertical land motion given in Table 3 are an average of the isobase and ICE-5G rates for Kugluktuk, Cambridge Bay, and Iqaluit, but are derived solely from the isobases for Arviat and Whale Cove. Appendix B provides details on how the vertical land motion was derived.

Table 3. Vertical land motion

Community	Vertical Land Motion (mm/yr)	Uplift in 90 Years (cm)
Arviat	8.1 ± 2	73 ± 18
Whale Cove	8.4 ± 2	76 ± 18
Kugluktuk	2.5 ± 1	23 ± 9
Cambridge Bay	3.7 ± 2	33 ± 18
Iqaluit	0.9 ± 1	8 ± 9

Estimates of vertical land motion derived from empirical isobases, or from model-predicted changes in topography, implicitly include the effect of changes to the Earth's gravitational field caused by glacial isostatic adjustment. This is desirable, because projections of future sea-level change need to take this effect into account. However, the derived rates given in Table 3 are not strictly rates of vertical land motion because they include the gravitational change effect. They will need further adjustment before they can be directly compared to geodetic observations of vertical land motion that can be obtained, for example, from repeated Global Positioning System (GPS) observations.

3.4 Projections of Sea-level Change.

The previous three sections provide the ingredients to generate projections of sea-level change for the five communities. For each scenario, the sea-level contributions from glaciers and ice caps, Greenland, Antarctica, and steric expansion were multiplied by the appropriate sea-level fingerprinting values to obtain the projected sea-level change from global sources at each community. The effect of vertical land motion at each community was then incorporated to obtain the value of projected sea-level change at each location. This was repeated for all the global sea-level change scenarios to obtain a range of sea-level projections for each community. The effect of uncertainties in vertical land motion increases the range of sea-level projections, and this is discussed in section 4.

Figure 3 summarizes the predictions for the IPCC scenarios and the two scenarios of observed twentieth century sea-level change. They show that Arviat and Whale Cove, which are rising the fastest, generally feature more than 50 cm of sea-level fall. Communities that are rising slower still mostly feature sea-level fall, but the amount of fall is smaller.

The range of projected sea level is much greater when post-IPCC scenarios are included (Figure 4). For all of the communities there are scenarios that generate projections of sea-level rise, but the amount of sea-level rise is only 10 or 20 cm for Arviat and Whale Cove, where the land is rising the fastest. For four of the communities, the projected amount of sea-level change tends to be larger for scenarios that deliver greater amounts of water to the oceans.

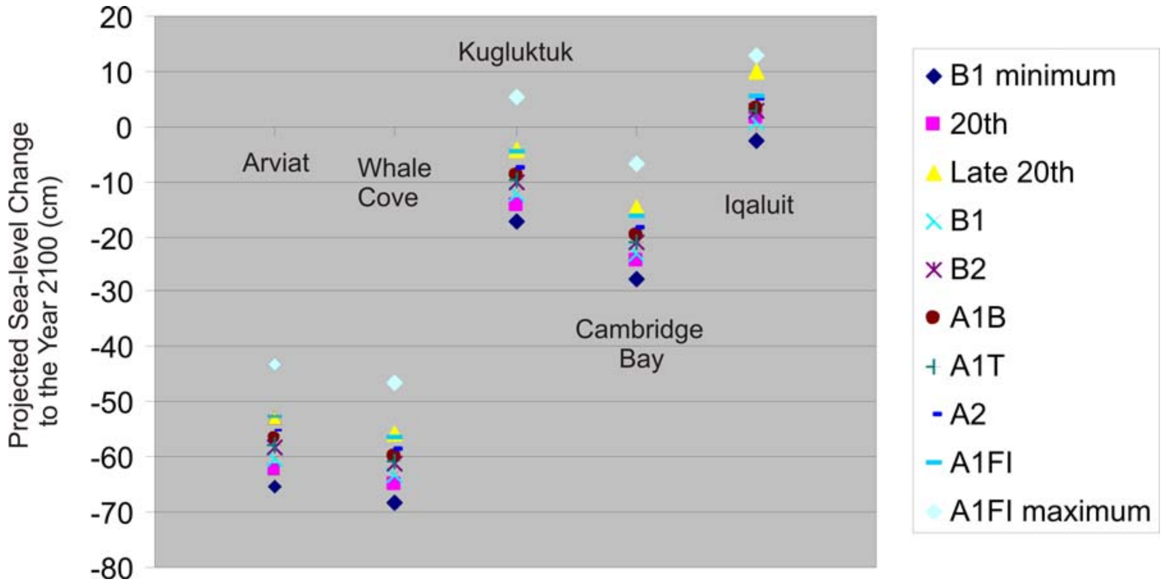

Figure 3. Sea-level projections for the minimum, mid-points, and maximum IPCC projections (Meehl et al., 2007) and for the Twentieth Century and Late 20th Century scenarios.

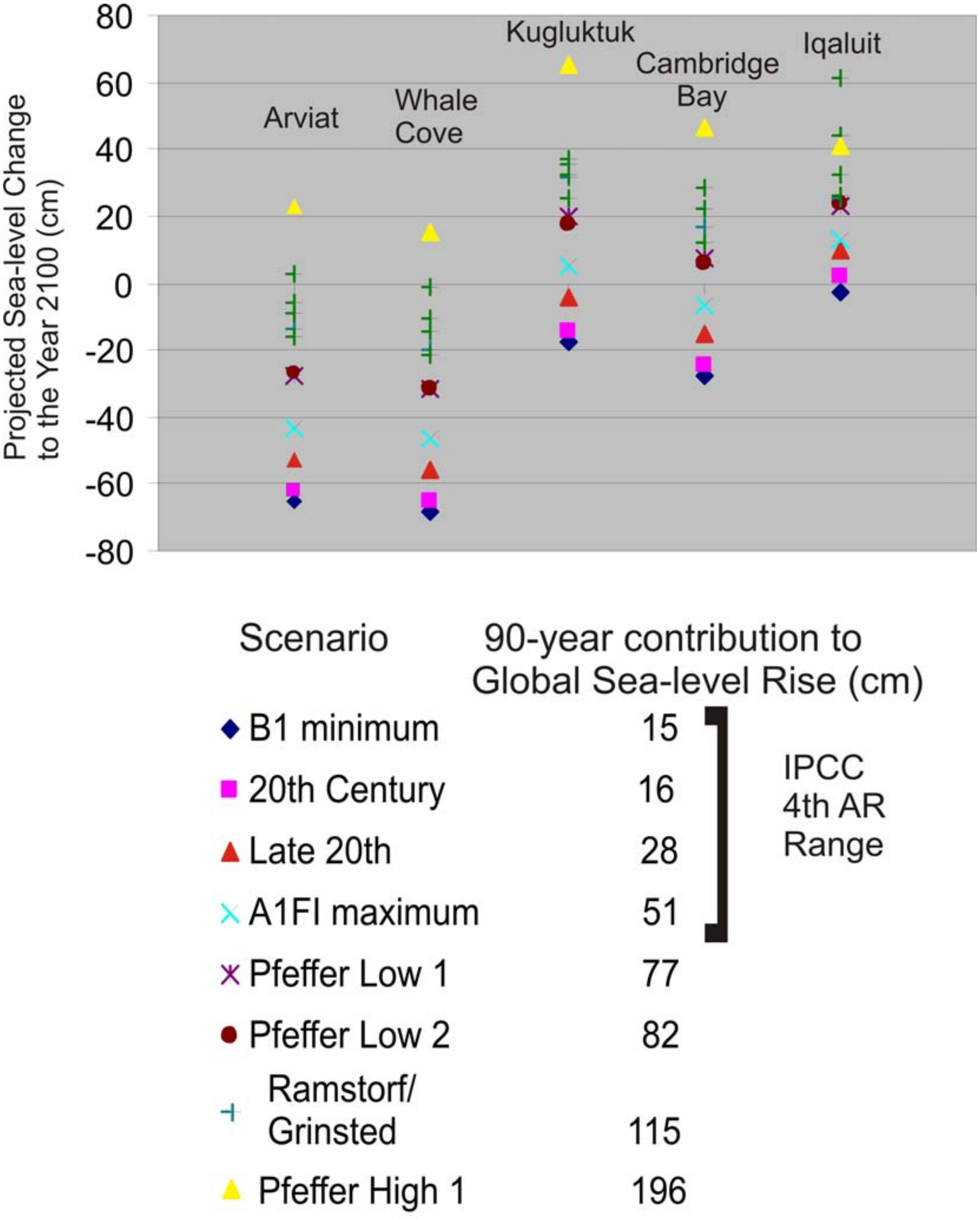

Figure 4. Sea-level projections for the twentieth century scenarios, the extremes of the IPCC scenarios and the post-IPCC scenarios.

The range of sea-level projections shown in Figure 4 is summarized in Table 4. For all communities, the range in projected sea-level change is much smaller than the range of sea-level change delivered to the oceans by the scenarios (35% to 50%). This is a consequence of the sea-level fingerprinting effect (Table 2). For example, suppose that glaciers and ice caps deliver 30 cm more of sea-level rise to the world's oceans in one scenario compared to another scenario. At Whale Cove, the extra contribution to sea-level change from glaciers and ice caps would only be 10.5 cm, because Table 2 indicates that the sea-level fingerprinting effect at Whale Cove due to glaciers and ice caps is 0.35, and 0.35 times 30 cm equals 10.5 cm. The sea-level fingerprinting effect reduces the range of sea-level change experienced at the communities from glaciers and ice caps (all communities) and from Greenland (for four of the five communities). This reduces the range of the total projected sea-level change.

Table 4. Summary of the range of sea-level change scenarios and of community sea-level projections

Sea-level Scenarios	**Range in the Amount of Sea-Level Rise Delivered to Oceans (cm)**
B1 Minimum (15 cm) to Pfeffer High 1 (196 cm)	181
Community	**Range of Projected Sea-level Change (cm)**
Arviat	89
Whale Cove	84
Kugluktuk	82
Cambridge Bay	74
Iqaluit	64

The Rahmstorf/Grinsted scenarios illustrate another source of uncertainty in sea-level projections (Figure 4). All five Rahmstorf/Grinsted scenarios feature the same amount of global sea-level rise (115 cm), but the source of the sea-level rise is apportioned differently among Greenland, Antarctica, and glaciers and ice caps. This leads to variability in the projected sea-level change at each community. For four of the communities, the variability amounts to about 20 cm. For Iqaluit, however, the variability in the Rahmstorf/Grinsted scenarios is about 35 cm. The larger variability is a consequence of the sensitivity of Iqaluit to differing assumptions about the Greenland contribution.

4. Discussion.

The question arises of the range of sea-level projections that are most likely, and which can be considered to be extreme cases. At the low end, sea-level rise increased from 1.8 mm/yr to 3.1 mm/yr from the last 4 decades of the 20th century (1961 to 2003) to the last decade of the 20th century (1993 to 2003). Temperatures are projected to rise in the 21st century, and as sea-level rise is correlated with temperature, it seems appropriate to take the Late 20th Century Scenario as the probable minimum (28 cm of sea-level rise to 2100). We note, however, that natural variability unrelated to temperatures may have been responsible for the increase in sea-level rise observed at the end of the 20th century. Thus, amounts of sea-level rise smaller than the Late 20th Century Scenario (3.1 mm/yr, 28 cm of sea-level rise to the year 2100) are possible.

Table 5. Sea-level scenarios and indication of likelihood

	Minimum Global Sea-Level Change (cm)	Global sea level will probably not be less than (cm)	Global sea level will probably not be more than (cm)	Maximum Global Sea-level Change (cm)
Scenario	B1 Minimum	Late 20th Century	Rahmstorf/ Grinsted	Pfeffer High 1
Amount of Sea-level Rise from 2010 to 2100 (cm)	15	28	115	196

At the upper end, the Pfeffer High 1 scenario (196 cm of sea-level rise from 2010 to 2100) is an extreme case. Its main purpose seems to have been to exclude the possibility of even larger amounts of sea-level rise previously suggested in the literature. The upper end of the Rahmstorf (2007) projection and the average of upper values of the Grinsted et al. (2009) projections (our Rahmstorf/Grinsted scenario, 115 cm of sea-level rise) may provide an upper limit. We note that Grinsted et al. considered all six IPCC scenarios in projecting sea-level change based on observed temperature/sea-level correlations and that some of their scenarios project more than the 115 cm (for a 90-year time frame) of sea-level rise. Thus, amounts of sea-level rise larger than 115 cm, but not exceeding 196 cm, are possible. The range of sea-level projections and our assessment of their likelihood are given in Table 5.

The probable range of sea-level projections for each community is given in Table 6. The values were derived from the probable range of sea-level change summarized in Table 4 and the sea-level projections shown in Figure 4. The ranges are our judgment of the likely sea-level change that each community will experience, based on current knowledge and information. It is probable that these estimates will be revised in the future. Projections for Iqaluit are particularly uncertain owing to the significant, but poorly constrained, influence of the Greenland ice sheet through the sea-level fingerprinting effect.

Table 6. Assessment of probable range of sea-level change for each community at the year 2100 relative to 2010 (relative to present mean sea level)[1]

Community	Minimum Sea-Level Change (cm)	Sea level will probably not be less than (cm)	Sea level will probably not be more than (cm)	Maximum Sea-level Change (cm)
Arviat	-65	-50	5	20
Whale Cove	-70	-55	0	15
Kugluktuk	-20	-5	40	65
Cambridge Bay	-25	-15	30	45
Iqaluit	-5	+10	60	60

[1] Values are rounded to the nearest 5 cm.

4.1 Effect of Uncertainties in the Vertical Crustal Motion.

The sea-level change projections have an additional source of uncertainty that is related to the rate of land uplift. The uncertainties are assessed at ±10 cm for Iqaluit and Kugluktuk and ±20 cm for Arviat, Whale Cove, and Cambridge Bay (Table 3, over 90 years, rounded to nearest 5 cm). The vertical land motion uncertainties increase the range of probable sea-level change for each community (Table 7). The increase is substantial for Arviat, Whale Cove, and Cambridge Bay, where the additional 40 cm nearly doubles the probable range compared to Table 6.

Table 7. Assessment of probable range of sea-level change for each community incorporating uncertainty in vertical land motion

Community	Sea level will probably not be less than (cm)	Sea level will probably not be more than (cm)
Arviat	-70	25
Whale Cove	-75	20
Kugluktuk	-10	50
Cambridge Bay	-35	50
Iqaluit	0	70

5. Suggestions for Future Improvements to the Sea-level Projections.

Our sea-level projections feature substantial uncertainty arising from the range of global sea-level scenarios, uncertainties in sea-level fingerprinting, and uncertainties in vertical land motion. Progress in reducing the uncertainty from all three sources is possible, and could lead to a smaller range of projected sea-level change in the future.

1. Global sea-level projections are likely to be revised, and their range may be reduced, through the concerted, continuing effort of the international scientific community. For example, an improved understanding of ice-sheet dynamics and their projected future behavior may revise future global projections of sea-level change substantially. As well, improved understanding of regional variations in the projected steric (ocean thermal expansion) effect may lead to updated sea-level projections.

2. Regionally, an updated evaluation of the sea-level fingerprinting effect is greatly needed. Mitrovica et al. (2001) made (necessary) assumptions about the distribution of mass change from the three sources – for example, Greenland is assumed to be thinning uniformly. As well, the glaciers and ice caps calculations were carried out using a mass balance compilation that is now outdated (Meier, 1984). An evaluation of the sea-level fingerprinting effect for Arctic ice caps and the Greenland ice sheet, using updated mass balance observations and projections, should be carried out.

3. Locally, field work could be carried out at some communities to improve estimates of vertical land motion. This could include work to improve the record of past sea-level change, thus adding to the information available for both improved sea-level curves and isobases and providing better constraints for models of the glacial isostatic process, such as ICE-5G. As well, installation of new Global Positioning System (GPS) sites and continuing operation of existing sites can provide direct estimates

of vertical crustal motion. (New satellite navigation systems are becoming available and the term Global Navigation Satellite Systems (GNSS) is becoming prevalent.)

It is likely that an updated evaluation of the sea-level fingerprinting effect, combined with better estimates of vertical land motion, could reduce the range of projected sea level, perhaps by half. An updated sea-level fingerprinting analysis could be carried out relatively quickly, but improved estimates of vertical land motion will take more time.

6. Conclusions.

The sea-level projections provide a basis for discussing the possible impacts of sea-level change and the potential adaptation measures that could be implemented at each community. Subsequent dialogue may raise additional questions about the sea-level projections and we will consider revisions to this report as needed.

In contrast to the picture of rising sea levels and coastal inundation that is frequently painted in popular reports, future sea levels may follow a very different trajectory featuring stable or even falling sea level for some communities in Nunavut (Table 7). This is a consequence of two factors.

1– Over much of Nunavut, the land is rising, owing to the delayed response of the Earth to surface unloading caused by deglaciation. Rising land ameliorates the effects of rising global sea levels. Note, however, that some areas, such as eastern Baffin Island and the western Arctic, are subsiding and this is a potential issue as it would exacerbate possible sea-level rise.
2– Owing to their relative proximity to potentially large sources of meltwater (Arctic ice caps and the Greenland ice sheet), sea-level fingerprinting is very important in determining sea-level projections for communities in Nunavut.

Sea-level fingerprinting has the effect of muting or even reversing the sea-level rise produced by regional sources. This is in contrast to regions that are distant from large sources of meltwater, where an amount of sea-level rise close to that delivered to the global oceans would be expected.

The potential issue for some of the communities considered here may be sea-level fall rather than sea-level rise. For communities that are dependant on harbour or docking facilities that presently feature limited depth-under-keel, or communities where traditional beaching sites are in use, the consequences of future sea-level fall bear consideration. For most communities, a larger amount of global sea level rise would help to ameliorate these impacts. On the other hand, all of the communities considered here potentially face a relative sea-level rise, possibly as much as 50 cm by the year 2100 for Kugluktuk and Cambridge Bay and as much as 70 cm for Iqaluit. The implications of a sea-level rise also need to be evaluated for these communities.

Projections of sea-level change provide a lens through which to assess future coastal stability, but the projected sea-level change alone does not determine coastal stability. For example, Hall Beach, which is rising relatively quickly due to glacial isostatic adjustment, is nevertheless experiencing substantial coastline erosion that is affecting structures built closest to the ocean (e.g. Forbes et al., 2008; Manson and Forbes, 2008). Reduced rates of sea-level fall combined with more extensive or persistent open water may exacerbate erosion. There is a need to evaluate projected coastal change in terms of the susceptibility of built structures and in terms of the activities of community members who may depend on access to, or utilization of, the shoreline and near-shore environment.

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8. References

Church, J.A. and White, N.J. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, **33**, L01602, doi:10.1029/2005GL024826.

Dyke, A.S. 1996. *Preliminary paleogeographic maps of glaciated North America*. Geological Survey of Canada, Open File 3296.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K. and Chappell, J. 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters*, **163**, 327-342.

Forbes, D.L., Manson, G.K., Mate, D. and Qammaniq, A. 2008. Cryospheric change and coastal stability: combining traditional knowledge and scientific data for climate change adaptation. *Ice and Climate News*, **11**, 17-18.

Grinsted, A., Moore, J.C. and Jevrejeva, S. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics*, **34**, 461-472.

Horton, R., Herweijer, C., Rosenzweig, C., Liu, J., Gornitz, V. and Ruane, A.C. 2008. Sea-level rise projections for current generation of CGCMs based on the semi-empirical method. *Geophysical Research Letters*, **35**, L02715:10.1029/2007GL032486.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al.* (eds.), Cambridge University Press, Cambridge, U.K.

Lemke, P., and others. 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*, ed. S. Solomon and others, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Manson, G.K. and Forbes, D.L. 2008. Climate-change impacts on an emergent Arctic shoreline, Hall Beach, NU. *Proceedings, Arctic Change 2008*, Québec, QC, 118-119 (on-line at http://www.arctic-change2008.com/pdf/ac-programme.pdf [accessed 2010-10-11])

Meehl, G.A., and others. 2007. Global Climate Projections. 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*, ed. S. Solomon and others, Cambridge University

Press, Cambridge, United Kingdom and New York, NY, USA.

Meier, M.F. (1984). Contribution of small glaciers to global sea level rise. *Science*, **226**, 1418-1421.

Meier, M.F., Dyurgerov, M.B., Rick, U.K., O'Neel, S., Pfeffer, W.T., Anderson, R.S., Anderson, S.P. and Glazovsky, A.F. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, **317**, 1064-1067.

Mitrovica, J.X., Tamisiea, M.E., Davis, J.L. and Milne, G.A. 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, **409**, 1026-1029, 2001.

Peltier, W.R. 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Science*, **32**, 111-149.

Pfeffer, W.T., Harper, J.T. and O'Neel, S. 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, **321**, 1340-1343.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science*, **315**, 368-370.

Vermeer, M. and Rahmstorf, S. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences*, **106**, 21527-21532.

9. Appendix A. Global Sea-Level Change Scenarios

Because sea-level change due to changes in the mass of glaciers, ice caps, and ice sheets is not spatially uniform (Mitrovica et al., 2001), it is necessary to attribute the sources of sea-level change for each scenario among glaciers and ice caps, Greenland, and Antarctica. Mitrovica et al. (2001) utilized Meier's (1984) compilation for glaciers and ice caps, and assumed spatially uniform mass change of Greenland and Antarctica. These assumptions differ from some recent assessments of present-day and future sea-level change, where outlet glaciers and isolated ice caps on the perimeter of Greenland and Antarctica are included in the "ice caps and glaciers" category, rather than the "Greenland" or "Antarctica" categories. For these sources, it is necessary to attribute some of the "ice cap and glacier" contribution back to Antarctica and Greenland in order that the results of Mitrovica et al. (2001) can be used.

The relative contributions from glaciers and ice caps, Antarctica, Greenland, and the steric effect are summarized in Table A1. Here we give a brief description of the development of the scenarios.

Twentieth Century Sea-level Rise and Late 20th Century Sea-level Rise. IPCC (2007) summarizes the sources of sea-level change for the time period 1961 to 2003 and from 1993 to 2003 (Table SPM.1). The glaciers and ice caps contribution includes outlet glaciers of Greenland and Antarctica. In the same IPCC report, Lemke et al. (2007; Table 4.4) give the glaciers and ice caps mass balance for these two time periods with and without glaciers and ice caps around ice sheets. To develop the scenarios, we distributed the sea-level rise from glaciers and ice caps around ice sheets equally between Greenland and Antarctica. For both time ranges, the sum of the individual contributions does not equal the observed total sea-level rise. Consequently, we also scaled the contributions from all sources by a factor so that the sum of the sources equals the observed total sea-level rise reported by IPCC (2007; Table SPM.1)

IPCC Scenarios. Meehl et al. (2007; Table 10.7) give projections of sea-level change for six scenarios. The scenarios correspond to different assumptions about fossil fuel usage in the 21st century. Similar to the case for the 20th century scenarios, the "glaciers and ice caps" contribution includes outlet glaciers from the perimeters of Greenland and Antarctica. Meehl et al. (2007; section 10.6.3.3) suggest that outlet glaciers of Antarctica and Greenland comprise between 10% and 20% of the glaciers and ice caps contribution. Thus, for each scenario, we attributed 7.5% (one half of 15%) of the glaciers and ice caps contribution to Greenland and Antarctica.

We evaluated the mid-points of all six scenarios and the maximum of the largest scenario (A1FI) and the minimum of the smallest scenario (B1). For the mid-point scenarios, the sum of the mid-points of the individual contributions did not equal the mid-point of the total contribution, so the individual contributions were adjusted by a uniform value so that their sum agreed with the total contribution.

For the minimum and maximum cases, the extrema (minimum or maximum) of the individual contributions did not sum to the extremum of the total. Assuming a normal distribution, we determined the mid-point and uncertainty (sigma) for each individual contribution, and then found a unique scale factor S such that the mid-point value ± S times sigma gave the extremum of the sum.

Table A1. Scenario sea-level contribution (cm) by source from 2010 to 2100

Scenario	Thermal Expansion	Glaciers and Ice Caps	Greenland	Antarctica	Total
20th century SLR	6.1	6.3	1.2	2.6	16.2
Late 20th cent SLR	16.0	6.3	2.8	2.8	27.9
B1 minimum	12.2	6.6	2.5	-5.9	15.3
B1 midpoint	14.6	8.5	4.3	-3.4	24.0
B2 midpoint	17.1	8.9	4.8	-3.8	27.0
A1B midpoint	19.3	9.1	5.5	-4.3	29.6
A1T midpoint	18.0	9.2	5.2	-4.2	28.3
A2 midpoint	21.0	9.5	5.6	-4.7	31.2
A1FI midpoint	24.9	9.7	7.6	-5.7	36.4
A1FI maximum	32.0	11.4	10.0	-29.8	50.5
Pfeffer low 1	29.4	17.0	16.1	14.3	76.8
Pfeffer low 2	29.4	23.5	16.1	12.5	81.5
RG[1] – 20th century	43.5	44.6	88.1	18.1	115.0
RG – late 20th cent	40.0	39.7	17.7	17.7	115.0
RG –Pfeffer low 1	30.0	30.5	28.9	25.6	115.0
RG –Pfeffer low 2	30.0	38.3	26.3	20.4	115.0
RG –Pfeffer high 1	30.0	27.4	26.7	30.8	115.0
Pfeffer high 1	29.4	53.9	52.6	60.6	196.3

[1] RG is Rahmstorf/Grinsted

Pfeffer Low 1, Pfeffer Low 2, and Pfeffer High 1 Scenarios. Pfeffer et al. (2008) developed three scenarios of future sea-level change. The sources (Greenland, Antarctica, and glaciers and ice caps) appear to be compatible with Meier's (1984) sources that were used in the sea-level fingerprinting of Mitrovica et al. (2001). Consequently, the only adjustment that was made to their Table 3 was to scale the contributions by a factor of 90/92 = ~0.978 to account for the fact that the study was published in 2008, but that our projections are based on the 2010 to 2100 time frame.

Rahmstorf/Grinsted Scenarios. Here we scaled five other scenarios (Twentieth and Late 20th Century scenarios and Pfeffer's three scenarios) to deliver 115 cm of sea-level rise. The Twentieth Century scenario was scaled directly, and this gives a thermal expansion contribution of 43.5 cm, which is larger than the amount provided by any of the IPCC scenarios (the maximum amount of thermal expansion provided by the A1FI scenario is 41 cm over a 105 year time frame, which gives about a 35 cm contribution over 90 years). A direct scaling of the Late 20th Century scenario generates an even larger amount of thermal expansion, and thus we capped the thermal expansion at 40 cm and scaled the other contributions to obtain a total sum of 115 cm. This yields the scenarios **RG – Twentieth Century** and **RG – Late 20th Century**.

Pfeffer et al.'s (2008) three scenarios were all scaled to provide 115 cm of sea-level rise. The thermal expansion term was held at 30 cm for these scenarios and the other contributors (glaciers and ice caps, Greenland, and Antarctica) were scaled to deliver a total of 115 cm of sea-level rise. This yields the scenarios **RG – Pfeffer Low 1**, **RG – Pfeffer Low 2**, and **RG - Pfeffer High 1.**

10. Appendix B. Derivation of estimates of vertical land motion at the five pilot communities

Background and approach
Rates of relative sea-level change at any specific location can be closely approximated by adding the estimated rate of vertical land motion at that location to a term representing the global rate of sea-level change. Therefore, in order to project 21st century relative sea-level variations for Nunavut communities, we need to know the magnitude and direction of vertical land motion at these locations. To estimate rates of vertical motion at each of the five pilot communities, we have considered two primary sources of information. Empirically derived continental scale isobase maps yield a first estimate of rates of vertical land motion. The Earth's predicted glacial isostatic adjustment (GIA) response to loading and unloading by the ICE-5G model provides a second estimate for present-day rates of vertical land motion. In this appendix, we compare the two sets of estimates, and explain the rationale by which we arrive at a final estimated rate of vertical land motion for each of the five communities.

Isobase approximated rates of vertical land motion
Maps of isobase values are available for North America at 500 year intervals from 500-14,000 radiocarbon years BP (Dyke, 1996, and unpublished updates incorporating new information). The isobase values at any given time represent the elevation of the land surface at that time relative to the present-day value, and are based on observations of past relative sea level. The spatial extent of the isobases therefore depends on the location of past shorelines and the time-varying configuration of the Laurentide ice sheet, and is generally limited to ice-marginal regions.

The isobase contours generally do not intersect exactly with the locations of specific communities. We therefore have to interpolate the isobase contours spatially to estimate vertical motion at most locations. Since the isobases have limited and uneven spatial distribution over the North American continent, the interpolation can be considered reliable only in regions contained by the isobases (fortunately, all five pilot communities fall within the region of the contours).

To estimate rates of vertical land motion from the isobase values, we fit a quadratic curve to the isobase values from the last 2000 years at each of the five pilot communities. The slope of the curve calculated at present-day represents the estimated vertical motion rate. Prior to calculation of the isobase rates, the time intervals from 500-2000 years BP were calibrated to calendar years using a marine-based calibration curve and assuming a marine reservoir correction of 630 years. Uncertainty of each calculated isobase rate was taken to be the uncertainty of the least squares fit to the data points. The present-day vertical land motion rates derived from the isobases are given in Table B1 for each of the five pilot communities.

ICE-5G model-predicted rates of vertical land motion
Numerical models of the GIA process provide a second source of present-day vertical land motion estimates. Topography values for the ICE-5G VM2 v.1.2 model (Peltier 2004) are available online (www.atmosp.physics.utoronto.ca/~peltier/data.php). The topography data are available on a uniform 1° × 1° degree global grid for times from 0-21,000 years BP. The same methodology that was used to estimate present-day rates of vertical land motion from the isobase data was employed to estimate rates from the ICE-5G data set. The topography values were extracted from the ICE-5G grid at the location nearest in latitude and longitude for each of the five communities at times 0-2000 years BP at

500 year intervals. The present-day rate of vertical land motion was estimated to be the value of the slope at time zero of a quadratic curve fit to the topography values for each location. Table 1 gives the model predicted rates of vertical land movement for each of the five communities.

The ICE-5G model is a recent global model of surface topography and ice sheet distribution for the last ~100,000 years (Peltier 2004). The model is in part constrained by observations of relative sea level. Some of the relative sea-level data used to inform the model is the same as the data from which the isobases are constructed; the two sets of present-day vertical motion estimates are therefore not entirely independent of one another. However, the ICE-5G model incorporates additional constraints, such as the rate of change of gravity for central North America, making comparison of the ICE-5G predicted rates to the isobase-derived rates a useful exercise.

Comparing the isobase rates to the ICE-5G rates

Comparing the present-day rates of vertical land motion derived from the isobases to those predicted by ICE-5G at the five communities reveals variation between the two sets of estimates (Table B1). The largest differences are observed at Arviat and Whale Cove (ICE-5G is larger by 5.62 mm/yr and 3.15 mm/yr, respectively). Both the isobase and ICE-5G rates, and the differences between them, are smaller at Cambridge Bay, Iqaluit and Kugluktuk.

The large difference between the isobase and ICE-5G rates observed at Arviat and Whale Cove prompts the question of which source of information should be considered more reliable when determining present-day rates of vertical land movement. To address this question, we have directly evaluated both ICE-5G and the isobases against the existing relative sea-level data at each of the communities. There are no relative sea-level data available for Whale Cove. The two communities nearest Whale Cove for which relative sea-level data exist are Arviat (to the south) and Baker Lake (to the northwest). We therefore use the fit of both the isobase values and the ICE-5G model to the relative sea-level data at Arviat and Baker Lake to infer the reliability of the vertical motion rates at Whale Cove.

We compare ICE-5G to the observed data by extracting the paleotopography of the model at approximately 500 year intervals from 0-21,000 years BP and plotting the values against the relative sea-level observations at each location. At Arviat and Baker Lake, ICE-5G over-predicts relative sea level, and the overall fit to the data is poor at both locations. We therefore infer that the model will also poorly reproduce the data at Whale Cove. At Cambridge Bay, Iqaluit and Kugluktuk, the fit of ICE-5G relative to the data is generally reasonable. Moreover, the fit at these three locations tends to be good particularly at times in the recent past; this tendency is desirable because the behaviour of the model at recent times will more strongly influence the present-day rate of response than earlier times.

To check the isobase values are in agreement with the relative sea-level data, we plot the isobase values from 0-10,000 years BP at 1000 year intervals for the five communities against the relative sea-level observations. There is good agreement between the isobases values and the relative sea-level observations at all locations (Arviat, Baker Lake, Cambridge Bay, Iqaluit, Kugluktuk). Since the isobase contours were empirically derived primarily from the relative sea-level data, this result is anticipated, and provides confidence that the present-day rates of vertical motion determined from the isobase values are in accordance with available data.

At locations where there is significant discrepancy between the isobase-derived rates and the ICE-5G model predicted rates, the observation that the isobase values agree well with the relative sea-level data at all locations lends preference to the isobase-derived rates. This preference assumes the rates inferred from the isobases are, in general, more strongly supported by available site-specific observations than the model-predicted rates.

Final determination of vertical uplift rates at the five pilot communities

The ICE-5G paleotopography fits poorly with the relative sea-level data at Arviat and Baker Lake, and thus, by inference, at Whale Cove as well. Consequently, when determining present-day vertical uplift rates for Arviat and Whale Cove, we neglect the ICE-5G predicted rates and use only the isobase-approximated rates (Table 1). At Cambridge Bay, Iqaluit and Kugluktuk, the ICE-5G model values are in reasonable agreement with the relative sea-level data. Our estimated vertical uplift rates at these three communities are the average of the isobase-derived rate and the ICE-5G predicted rate (Table B1).

The estimated uncertainty on the final rates at each of Cambridge Bay, Iqaluit and Kugluktuk is the larger of the average of the standard deviations between the mean rate and the isobase and ICE-5G rates at the three communities, and the individual standard deviation at each location. The estimated uncertainty at Arviat and Whale Cove is the largest standard deviation of the ICE-5G and isobase derived rates at the other three communities.

The final vertical land motion rates presented here will be applied to different scenarios of global sea-level rise to arrive at a range of projections of relative sea-level change by the year 2100. We assume that the rate of vertical land motion will remain constant over that time interval.

Table B1. A summary of the estimated rates of vertical land motion at Arviat, Cambridge Bay, Iqaluit, Kugluktuk, Whale Cove, and Baker Lake. The final employed rate of vertical land motion is an average of the isobase approximation and the ICE-5G prediction at Cambridge Bay, Iqaluit and Kugluktuk. The final employed rate is solely the isobase approximation at Arviat and Whale Cove. Rates at Baker Lake, discussed in the text, are also shown for reference. The land uplift by 2100 is determined by assuming the final employed rate of vertical land motion is constant from present to 2100; a 90 year interval is assumed.

Community	**Isobase approximation (mm/yr)**	**ICE-5G prediction (mm/yr)**	**Final employed rate (mm/yr)**	**Estimated uncertainty (mm/yr)**	**Uplift by 2100 (cm)**
Arviat	8.1	10.4	8.1	±2	72.9
Whale Cove	8.4	8.9	8.4	±2	75.6
Baker Lake	8.2	9.9	NA	NA	NA
Kugluktuk	2.5	2.5	2.5	±1	22.5
Cambridge Bay	5.1	2.3	3.7	±2	33.3
Iqaluit	0.2	1.5	0.9	±1	8.1