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Late Holocene sea-level changes and isostatic crustal movements in Atlantic Canada

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Abstract

It has long been recognised that sea levels along the shores of Atlantic Canada have been rising rapidly during the Holocene in response to isostatic crustal movements. New sea-level data for the Bay of Fundy coast of southern New Brunswick (Little Dipper Harbour) and the Atlantic coast of Nova Scotia (Chezzetcook Inlet) show that late Holocene average rates of sea-level rise in these areas have been 1.0 and 2.5 m per 1000 yr, respectively. Numerical model calculations suggest that the high rates of sea-level rise are due to crustal subsidence produced by the combined effects of Laurentide ice loading (forebulge collapse) and ocean loading of the Scotian shelf. Although ice loading is the dominant contributor to the regional sea-level pattern, ocean loading is also important, contributing up to ~40% of the total crustal subsidence in some areas. Tide gauges record rates of sea-level rise during the 20[th] century that are 0.7–1.9 mm/yr higher than late Holocene trends, with the highest residuals occurring in the Bay of Fundy.

1. Introduction

The spatial variability of crustal motion along the Atlantic coast of North America makes this area an interesting testing ground to assess geophysical models of glacial isostatic adjustment (GIA) and thereby increase our understanding of the Earth's response to changing loads. Several studies have refined the Holocene relative sea-level history in the Gulf of Maine and Bay of Fundy region (Kelley et al., 1992; Gehrels and Belknap, 1993; Barnhardt et al., 1995; Gehrels et al., 1995,1996; Donnelly, 1998; Stea et al., 1998; Shaw et al., 2002). They have highlighted some challenging discrepancies with geophysical predictions (Plag et al., 1998). For example, GIA fails to predict accurately the highstand of sea level in Maine of 128.6 m above present sea level (Thompson et al., 1989) and the rapid fall and rise of sea level around an early Holocene lowstand in the northern Gulf of Maine of 55 m below present sea level (Barnhardt et al., 1995). However, GIA models are useful to further our understanding of broad patterns of postglacial isostatic behaviour along the Atlantic coast of North America by offering insights into processes of forebulge collapse and ocean loading following deglaciation (e.g., Clark et al., 1978). These processes continue to be important contributors to vertical crustal movements along coastlines in the region and should therefore be considered when predictions of future sea-level rise are made.

Patterns of relative sea-level change during the middle and late Holocene in the Gulf of Maine/Bay of Fundy region carry a significant component of isostatic crustal motion which is spatially variable. Published studies indicate that, during the past 4000 years, relative sea level in Machiasport, eastern Maine, has risen only 4 m, while sea level in Chezzetcook, Nova Scotia, has risen by as much as 12 m (Fig. 1; Gehrels et al., 1995,1996; Scott et al., 1995; Donnelly, 1998). Sea-level work in Atlantic Canada has been ongoing since the early 1970s (Grant, 1970) and has resulted in a considerable data base of Holocene sea-level index points (e.g., Scott and Greenberg, 1983). However, the southern coast of New Brunswick has hitherto not been investigated for presumed lack of suitable salt-marsh peat sequences,

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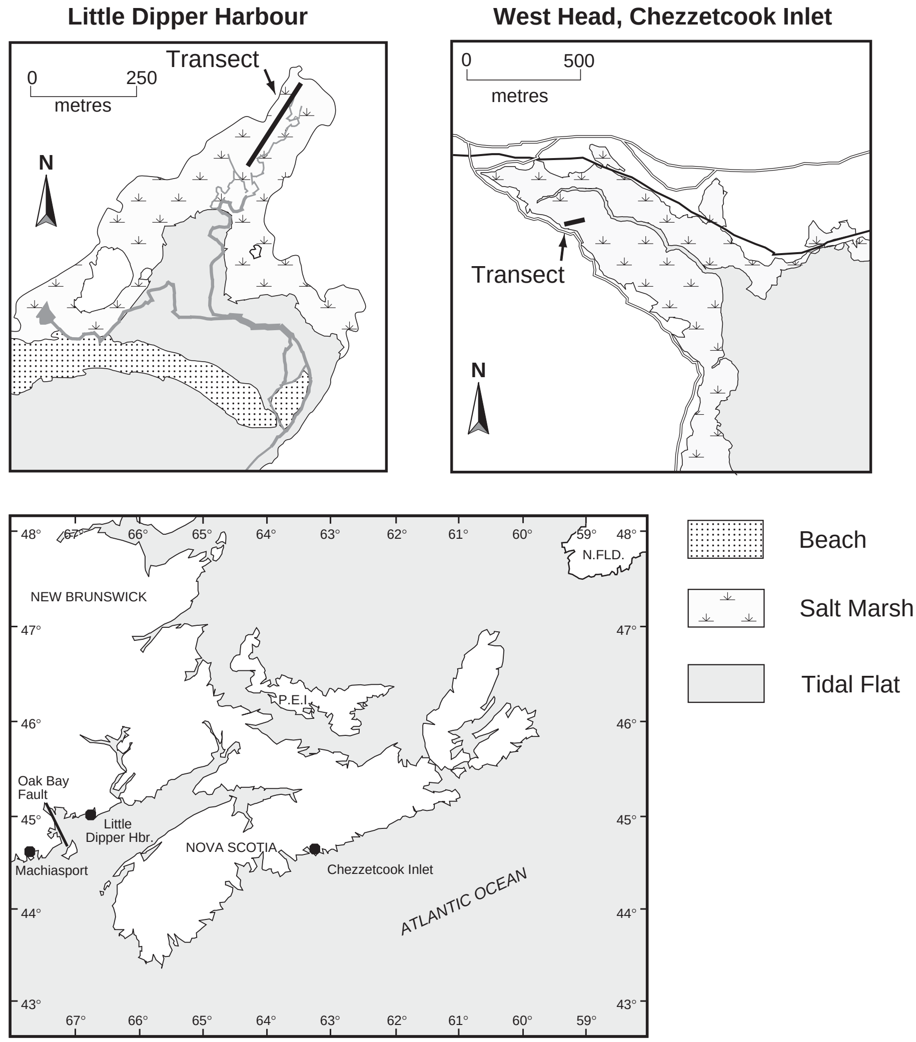

Fig. 1. Location map of study sites and coring transects. Also shown are the position of the Oak Bay Fault, on the border of Maine and New Brunswick, and Machiasport, the site of a nearby sea-level study in eastern Maine (Gehrels and Belknap, 1993; Gehrels, 1994; Gehrels et al., 1996; Gehrels, 1999).

while very few late Holocene sea-level index points have been collected from the Atlantic coast of Nova Scotia (Scott et al., 1995).

Here we focus on an interesting feature of the middle-to-late Holocene sea-level history of the region, i.e. the rapid rates of sea-level rise along the coasts of Atlantic Canada. There have been suggestions made in the literature attributing anomalous subsidence in Atlantic Canada to both the hydro-isostatic and the glacio-isostatic components of the GIA process causing deformation of the Scotian shelf (Grant, 1970). Also, tectonic movements along Triassic–Jurassic rift structures may be of importance (Belknap et al., 1989) whereas in the Bay of Fundy tidal amplification has played a significant role (Scott and Greenberg, 1983; Gehrels et al., 1995). In this paper we offer an explanation for rapid rates of late Holocene sea-level rise along the shores of Atlantic Canada based on predictions of a GIA model. The model explains the pattern of observed sea-level rise in terms of enhanced crustal subsidence due to the combined effects of ice and ocean loading.

The aims of this paper are to: (1) produce a new late Holocene sea-level record for the southern New Brunswick coast at Little Dipper Harbour salt marsh, New Brunswick (66°22′00″N, 45°07′30″W); (2) add late Holocene data points to the sea-level record of Atlantic Nova Scotia at the West Head of Chezzetcook Inlet (44°44′25″N, 63°15′11″W); and (3) analyse patterns of late Holocene isostatic crustal behaviour in the region.

2. Methodology

2.1. Sample collection

Cores from Little Dipper Harbour salt marsh were collected with a vibracorer in August 1998. Additional hand (Eijkelkamp) cores were collected in July 2000. The heights of the cores were surveyed to Canadian Geodetic Datum and linked to local tidal datums provided by the Canadian Hydrographic Survey. Chezzetcook cores were collected with an Eijkelkamp corer in July 2000. Core sites were surveyed and their elevations were calculated by also surveying a nearby foraminiferal transect for which sample heights were published by Scott and Medioli (1980). They had surveyed their transect and tied it into a nearby geodetic benchmark, but this benchmark could not be re-located during the present study. Plant material for AMS ^{14}C dating was collected from near the base of the cores to minimise compaction problems (Törnquist et al., 1998; Gehrels, 1999). A duplicate peat sample was collected at the same stratigraphic level and analysed for foraminifera to establish the indicative meaning of the basal peat. Sample preparation techniques for foraminiferal analyses followed Gehrels (2002). The plant fragments used for dating were carefully washed with distilled water, dried overnight at $\pm 80^{\circ}C$, weighed, placed in a vial, and refrigerated upon return to England. Sample preparation for AMS ^{14}C dating took place at the NERC Radiocarbon Laboratory in East Kilbride, Scotland, while samples were dated at the NSF Facility at the University of Arizona. Ages in this paper refer to calendar years, unless specifically stated otherwise.

2.2. GIA model

The GIA model consists of three key components: an ice loading model, an Earth model, and an algorithm to compute the sea-level change (and thus ocean load component). The ice component of the surface loading is based on the global ICE-3G deglaciation model (Tushingham and Peltier, 1991) with a glaciation phase added by reversing the unloading history and extending the time period between successive loading increments to 7000 y. The Earth response is computed using a spherically symmetric, Maxwell visco-elastic Earth model that is self-gravitating and compressible (e.g., Wu and Peltier, 1982). The elastic structure of the model is based on the seismic model PREM (Dziewonski and Anderson, 1981) and the viscous structure is chosen to be the same as that which the ICE-3G deglaciation model is based upon: a 120 km lithosphere (the viscosity is set to very high values in this region so that the material responds in an elastic fashion on typical GIA timescales), an upper mantle viscosity of 10^{21} Pa s and a lower mantle viscosity of 2×10^{21} Pa s. The upper mantle is the region bounded by the base of the lithosphere and the seismic discontinuity at 670 km depth, and the lower mantle is the region from this depth to the core-mantle boundary. Sea-level predictions were computed in a gravitationally self-consistent manner by solving a revised sea-level equation that takes into account such effects as migrating shorelines, the retreat of marine-based ice sheets and GIA-perturbations in Earth rotation (e.g., Milne, 2002).

Only one Earth–ice model pair is considered in this analysis since our main aim is to make a broad comparison between the observed spatial sea-level trend and that predicted by a realistic GIA model. We will perform a more complete modelling analysis in a future study that considers a number of alternative ice and Earth model combinations in order to determine a GIA model that best fits the regional sea-level data set.

3. Study sites

The Little Dipper Harbour salt marsh in Chance Harbour, New Brunswick, is part of a small back-barrier lagoon-marsh system (Fig. 1) on the macrotidal Bay of Fundy coast. The mean spring tidal range is 6.61 m while the highest astronomical tide (HAT) is 3.98 m above mean sea level (MSL; Canadian Hydrographic Service, pers. comm., 1998; Hydrographer of the Navy, 2000). All cores were collected from the high salt marsh, dominated by the grass *Spartina patens*.

Chezzetcook Inlet, located 45 km ENE of Halifax (Fig. 1), contains the only extensive salt-marsh area on the Atlantic coast of Nova Scotia. This coast is micro- to mesotidal; the mean spring tidal range is 2.14 m at the mouth of the inlet and 1.86 m at the "West Head" of Chezzetcook Inlet near where the cores were collected (Scott and Medioli, 1980). Here, HAT is only 0.73 m above MSL (Scott and Medioli, 1980). The salt marsh at the "West Head" is mature and predominantly vegetated by *Spartina patens*. *Juncus gerardii* and some sedges occupy the landward edges of the marsh.

4. Results

4.1. Salt-marsh stratigraphy

The stratigraphy of Little Dipper marsh consists of high salt-marsh peat. The peat contains the fossilised remains of *Spartina patens* and overlies pre-Holocene sands and silts (Fig. 2a). Within the salt-marsh peat there are no signs of erosion by meandering tidal creeks and the sequence is considered to be relatively undisturbed. Samples collected from the base of the peat along the slope of the pre-Holocene substrate are not affected by compaction due to the uncompactable nature of the substrate. Their ages should represent the time of the earliest onset of the Holocene transgression. This is confirmed by the foraminiferal content of the basal peat (Table 1). All basal samples contain a foraminiferal assemblage of *Jadammina macrescens* and *Balticammina pseudomacrescens* and concentrations of

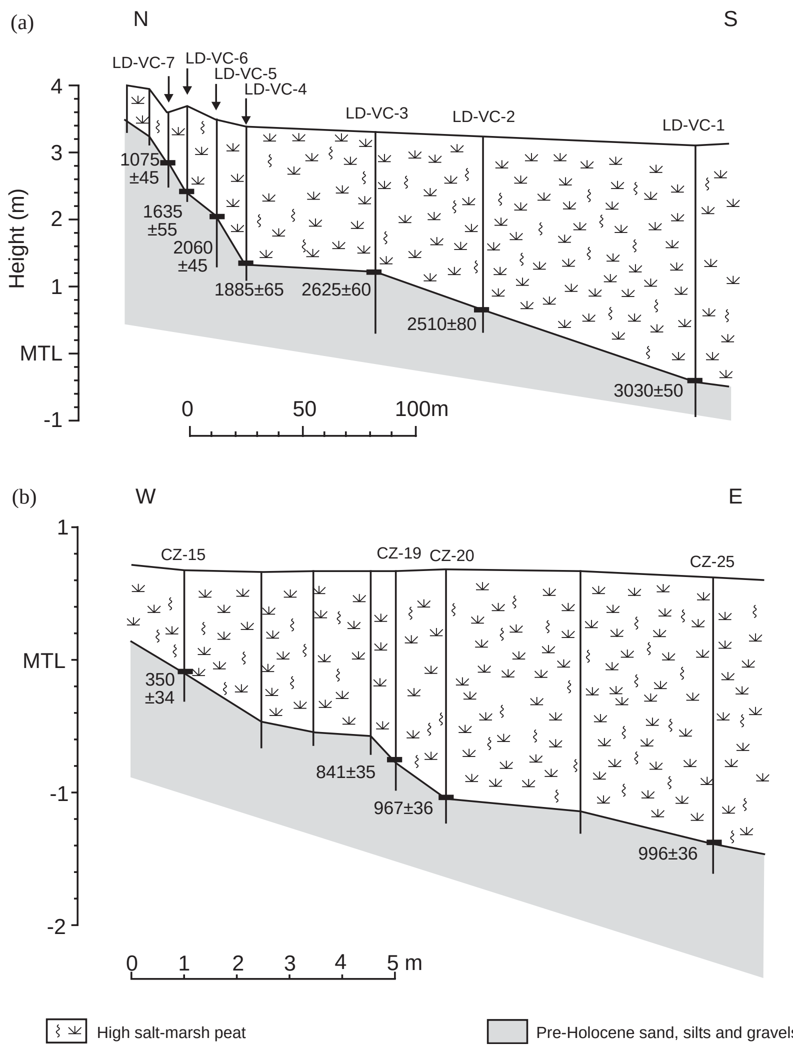

Fig. 2. (a) Stratigraphy of Little Dipper Harbour marsh based on vibracores, and radiocarbon ages on basal peat. (b) Stratigraphy of West Head of Chezzetcook Inlet based on Eijkelkamp cores and radiocarbon ages on basal peat. MTL—mean tide level.

foraminifera are low. In modern settings, these foraminifera are found only in low numbers near the landward edge of salt marshes (Gehrels and Van de Plassche, 1999), close to the highest tidal limit and we therefore assign an indicative meaning of HAT to all basal samples.

In the longest core from the Little Dipper Harbour marsh we also encountered an organic deposit embedded within the glaciomarine sediments. This peat contains dinoflagellates and can therefore be considered to represent a meaningful sea-level index point, dating the time when sea level stood briefly near present sea level while falling to its postglacial lowstand. The age of this index point does not fall within the late Holocene and so will not be discussed further in this paper.

The stratigraphy along our coring transect in Chezzetcook Inlet also consists of an undisturbed section of high salt-marsh peat (Fig. 2b). Samples were collected at various heights from the base of the Holocene section and radiocarbon-dated. The samples contained low concentrations of foraminifera and testate amoebae, indicative of HAT (Table 1).

4.2. Relative sea-level change

The tidal range in the Bay of Fundy is the largest in the world and has increased during the Holocene (Scott and Greenberg, 1983). A modelling study was conducted by Gehrels et al. (1995) to quantify the M_2 tidal amplification for the Gulf of Maine and the Bay of Fundy. Data for the southern New Brunswick coast at Little Dipper Harbour are shown in Fig. 3. With these data it is possible to correct the sea-level history based on salt-marsh indicators for tidal changes and to obtain the 'true' mean tide-level change. The tidal range on the Atlantic coast of Nova Scotia has not changed significantly during the Holocene (Gehrels et al., 1995)

Table 1
Samples dated by AMS ^{14}C

Index number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Publication code	AA-33350	AA-33351	AA-33352	AA-33353	AA-33354	AA-33355	AA-33356	AA-53489	AA-53488	AA-33833	AA-47216	AA-47217	AA-47218	AA-47219	AA-47220
^{14}C age (yrs BP $\pm 1\sigma$)	3030 ± 50	2510 ± 80	2625 ± 60	1885 ± 65	2060 ± 45	1635 ± 55	1075 ± 45	998 ± 49	138 ± 35	10960 ± 70	350 ± 34	modern	841 ± 35	967 ± 36	996 ± 36
Calendar 2σ age range (yrs BP)	3360–3077	2774–2350	2849–2544	1987–1693	2147–1899	1692–1408	1062–926	1048–788	280–0	13155–12665	503–308	n/a	882–674	951–789	967–794
$\delta^{13}C$‰	−28.1	−28[a]	−28.0	−27[a]	−26.1	−26.5[a]	−26.7	−25.8[a]	−25.9	−29.1	−29.9	−27.1	−27.3	−29.5	−29.1
Core	LD-VC-1	LD-VC-2	LD-VC-3	LD-VC-4	LD-VC-5	LD-VC-6	LD-VC-7	LD-3	LD-2	LD-VC-1	CZ-15	CZ-16.5	CZ-19	CZ-20	CZ-25
Sample depth in core (m)	3.34	2.66	1.96	1.85	1.33	0.88	0.57	0.52	0.38	3.75	0.81	1.15	1.41	1.61	1.97
Sample MTL elevation (m)	−0.41	0.43	1.24	1.39	2.08	2.48	2.87	2.80	3.12	−0.82	−0.13	−0.48	−0.72	−0.92	−1.32
Material	detrital plant fragments	detrital plant fragments	detrital plant fragments	detrital plant fragments	detrital plant fragments	*Juncus* spp.	detrital plant fragments	detrital plant fragments	*Solidago* fragment	detrital plant fragments	*Juncus* spp.	*Juncus* spp.	*Juncus* spp.	*Juncus* spp.	unid. woody material
Weight (mg)	20.0	11.0	12.0	11.0	19.0	18.0	31.0	15.5	69.0	24.5	12.5	12	10.5	32.5	11
Balticammina pseudomacrescens	1	26	4	0	6	17	0	0	0	0	15	n/a	38	1	1
Jadammina macrescens	40	29	37	20	28	22	7	3	16	0	8	n/a	9	0	0
Tiphotrocha comprimata	0	0	0	0	0	0	0	0	0	0	0	n/a	5	0	0
Testate amoebae	0	0	0	0	0	0	0	0	0	0	5	n/a	13	0	11
Volume counted (ml)	3.5	2.0	3.0	5.0	6.0	5.0	6.0	4.0	1.0	0.5	1.0	n/a	0.75	1.0	2.0
Indicative meaning	HAT	HAT	HAT	HAT	HAT	HAT	HAT	HAT	HAT	n/a	HAT	n/a	HAT	HAT	HAT

LD cores are from Little Dipper Harbour salt marsh, New Brunswick. CZ cores are from the West Head of Chezzetcook Inlet, Nova Scotia. HAT—highest astronomical tide. n/a—data not available.

[a] Estimated $\delta^{13}C$ value—insufficient material for an independent $\delta^{13}C$ measurement.

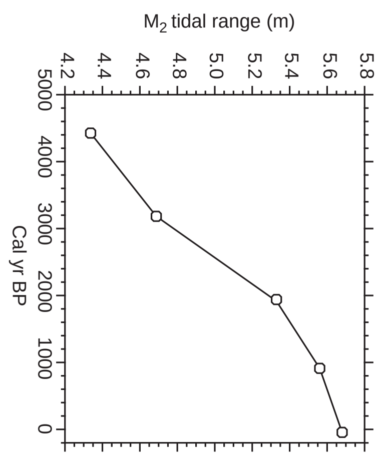

Fig. 3. Modelled late Holocene M_2 tidal range change at Little Dipper Harbour. Data from Gehrels et al. (1995).

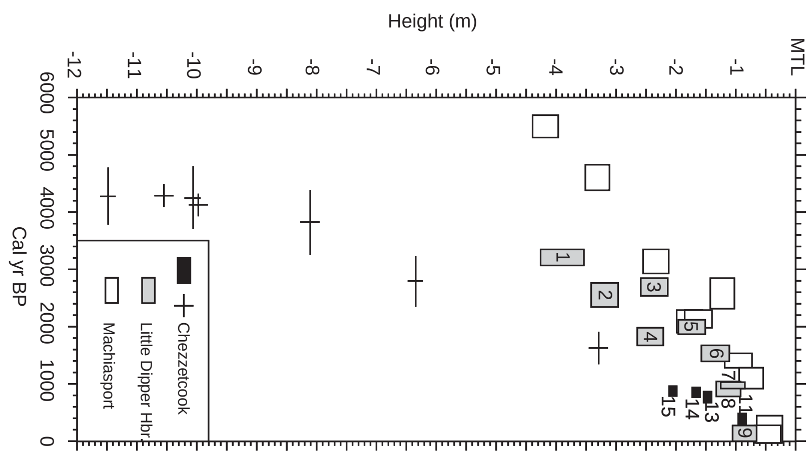

Fig. 4. New sea-level index points for Little Dipper Harbour, New Brunswick (grey boxes) and Chezzetcook Inlet, Nova Scotia (black boxes). Eastern Maine data (white boxes) from Machiasport (Gehrels and Belknap, 1993; Gehrels, 1994; Gehrels et al., 1996; Gehrels, 1999) are shown for comparison. Crosses are Chezzetcook data published by Scott et al. (1995). Index numbers correspond with Table 1.

and no tidal correction has been applied to the Chezzetcook data.

New sea-level data are shown in Fig. 4. The vertical uncertainty is estimated at ± 0.2 m (Gehrels et al., 1996). The dates form internally consistent sets of sea-level index points, with the exception of two dates from Little Dipper Harbour (index numbers 3 and 4), that plot around the same depth but differ in age by almost

900 yr, and one sample from Chezzetcook (12), that returned a modern age (Table 1). The data for Little Dipper Harbour and Chezzetcook are compared with data for eastern Maine (Gehrels and Belknap, 1993; Gehrels, 1994; Gehrels et al., 1996; Gehrels, 1999) and with published data for Chezzetcook (Scott et al., 1995). The three sites show clearly distinguishable sea-level trends. A linear fit (excluding the origin) yields a mean rate of sea-level rise in eastern Maine of 0.7 m per 1000 years ($r^2 = 0.94$). In southern New Brunswick this rate has been 1.0 m per 1000 years ($r^2 = 0.83$). However, the fastest rate of late Holocene rise has occurred along the Atlantic coast of Nova Scotia. Over the past 5000 yr sea level has risen on average by about 2.5 m every 1000 years ($r^2 = 0.98$). In the past 1000–2000 years, relative sea-level rise has decelerated somewhat. For example, the rise at Chezzetcook during the past 1000 years has been ~2.0 m, of which 0.3 m has occurred in the past century.

5. Discussion

In order to understand the underlying causes of sea-level change in Atlantic Canada we compare the pattern of late Holocene rise with sea-level data obtained from adjacent New England and Québec spanning the past 3000 years (Fig. 5). Sea-level positions were determined from interpolated mean heights and ages of published data (Table 2). Corrections from Gehrels et al. (1995) were applied to account for the increase in tidal range in the Bay of Fundy and Gulf of Maine throughout the Holocene. Because spatial resolution is relatively poor, caution is required when interpreting these plots. Since 3000 BP sea level has risen by over 7 m in Nova Scotia, by about 45 m in Cape Cod and by about 1.5–2.5 m along the coast of Maine (Fig. 5c). In contrast, sea-level fall has occurred along the shores of the Saint Lawrence River. This pattern of a northwest–southeast gradient of relative sea-level rise is consistent throughout the late Holocene (Figs. 5a and b) and is also apparent in the tide-gauge records for the region (Fig. 6).

Fig. 7a shows the ongoing rate of sea-level change predicted by the GIA model described above. For ease of comparison between predicted and observed rates we have superimposed the contours predicted for the eight tide-gauge stations using the same contouring routine that was used to generate contours in Figs. 5 and 6. This superimposition shows the effects of limited spatial sampling. The predicted pattern is similar to that observed throughout the late Holocene, although there are significant discrepancies. The general northwest–southeast trend of a sea-level fall transforming into a sea-level rise is captured well in the model predictions. However, the location of the zero contour is predicted by the model to be too far to the northwest (compare the results in Fig. 7a to those in Figs. 5a–c). Part of this discrepancy could, of course, be due to the lack of spatial resolution in the data plots. Comparison of predicted and observed present-day sea-level rates (Figs. 7a and 6) shows general agreement in magnitude and geographic pattern, although the tide-gauge data have recorded a higher rate of relative sea-level rise in Nova Scotia. This is not surprising given that ICE-3G does not include present-day ice melting. In the model, ice melt ceases around 4000 BP and rates of observed present-day sea-level rise would therefore be expected to be greater by about 1 mm/yr (e.g., Shennan and Horton, 2002; see also discussion below). Observed rates of sea-level rise are, in fact, only up to 0.5 mm/yr faster than

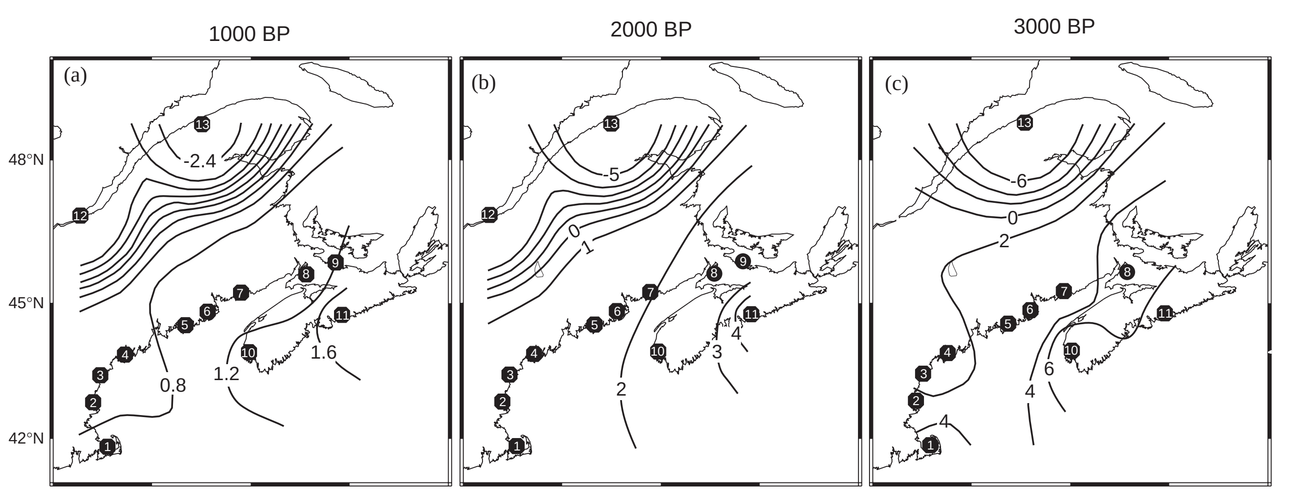

Fig. 5. Relative sea-level rise (m) during the late Holocene in northeastern North America. (1) Barnstable, Massachusetts. (2) Plum Island, Massachusetts. (3) Wells, Maine. (4) Phippsburg, Maine. (5) Gouldsboro, Maine. (6) Machiasport, Maine. (7) Little Dipper Harbour, New Brunswick. (8) Upper Bay of Fundy. (9) Wallace Basin. (10) Yarmouth, Nova Scotia. (11) Chezzetcook Inlet, Nova Scotia. (12) Québec City. (13) Matane, Québec. See Table 2 for data and references.

Table 2
Relative sea-level (RSL) positions used to produce contour plots of Fig. 5

Location	Latitude N	Longitude W	RSL 1000 BP	RSL 2000 BP	RSL 3000 BP	Reference(s)
1. Barnstable	41.7167	70.3333	−1.02	−2.00	−4.65	Redfield (1967)
2. Plum Island	42.7167	70.7833	−0.57	−1.12	−2.22	McIntire and Morgan (1964)
3. Wells	43.3167	70.5667	−0.66	−1.12	−1.49	Kelley et al. (1995), Gehrels et al. (1996)
4. Phippsburg	43.7500	69.8333	−0.59	−1.28	−1.87	Gehrels et al. (1996)
5. Gouldsboro	44.4167	68.0333	−1.00	−1.30	−2.30	Gehrels et al. (1996)
6. Machiasport	44.6833	67.4000	−0.75	−1.70	−2.30	Gehrels and Belknap (1993), Gehrels (1994), Gehrels et al. (1996), Gehrels (1999)
7. Little Dipper Harbour	45.1333	66.3667	−1.00	−2.00	−3.20	This study
8. Upper Bay of Fundy	45.5833	64.4500	−0.98	−1.96	−4.22	Scott and Greenberg (1983), Smith et al. (1984), Scott et al. (1987a), Belknap et al. (1989), Shaw and Ceman (1999)
9. Wallace Basin	45.8333	63.5500	−1.20	−2.50	no data	Scott et al. (1987b,1995)
10. Yarmouth	43.8500	66.1167	−1.35	−2.71	−7.14	Scott and Greenberg (1983)
11. Chezzetcook	44.7403	63.2531	−2.00	−4.40	−7.20	This study; Scott et al. (1995)
12. Quëbec City	46.8333	71.1667	+2.00	+4.00	no data	Dionne (1997)
13. Matane	48.8500	67.5333	+2.50	+5.60	+7.50	Dionne and Coll (1995)

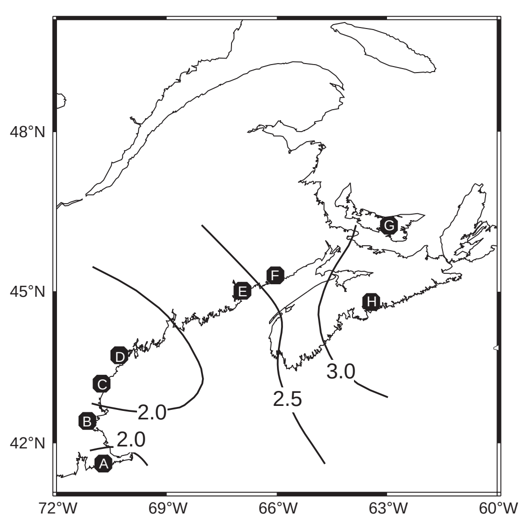

Fig. 6. Rate of sea-level rise (mm/yr) since the 1930s as indicated by tide gauges. (A) Woods Hole (2.6 mm/yr; 1933–2001). (B) Boston (2.3 mm/yr; 1930–2001). (C) Seavey Island (1.6 mm/yr; 1930–1985). (D) Portland (1.9 mm/yr; 1930–2001). (E) Eastport (2.2 mm/yr; 1930–2001). (F) Saint John (2.9 mm/yr; 1930–1999). (G) Charlottetown (3.0 mm/yr; 1938–2001). (H) Halifax (3.2 mm/yr; 1930–2000). Data from the Permanent Service for Mean Sea Level (http://www.nbi.ac.uk/psmsl/). Trends from northern areas are negative but statistically not significant.

those predicted by GIA. The tide gauge at Eastport is the only station where predicted sea-level rise is faster than the observed rate.

The solid Earth deformation caused by the ice and ocean loading accounts for most of the spatial variation shown in Fig. 7a. The sea-level prediction in Fig. 7a also includes a signficant geoid signal which will contribute an effectively uniform sea-level fall on the order of 1 mm/yr across the study area. In order to better understand the origin of the isostatic signal we show the contributions to the present-day vertical deformation induced by the ice load (Fig. 7b) and ocean load (Fig. 7c) components of the GIA model. By comparing these two sets of predictions it is evident that the ice loading dominates the spatial variation shown in Fig. 7a. This is especially the case in eastern New Brunswick where the ice-induced subsidence reaches a maximum of 3–4 mm/yr and the ocean-induced subsidence is relatively small at ~0.25 mm/yr. The ocean loading produces a maximum gradient perpendicular to the coast with maximum subsidence rates of up to ~1 mm/yr in Cape Cod and the east coast of Nova Scotia. The ice-load induced subsidence at Cape Cod is just over 2 mm/yr and so the ocean loading contributes ~40% of the total signal at this location. Thus, the ocean-induced component of the vertical deformation field can be a relatively important contributor to spatial variations in sea-level change within this region.

Previous workers have speculated about possible neotectonic activity in eastern Maine and western New Brunswick, in particular relating to movement along the Oak Bay Fault (Fig. 1) which runs along the southern Maine–New Brunswick border (Kelley et al., 1989; Fader, 1991; Chmura et al., 2001). Our results indicate that the observed patterns of sea-level change in the region can be explained to first-order by GIA alone, a conclusion also reached by Gehrels and Belknap (1993).

Late Holocene rates of relative sea-level rise in the region are high, but during the past century the rate has increased even more. Tide-gauge observations show increases in rates of sea-level rise between 0.7 and 1.9 mm/yr compared to late Holocene rates. The increase is, at least in part, due to global eustatic sea-level rise during the 20th century (Gornitz, 1995; Church et al., 2001). By comparison, Carrera and Vaníček (1988) found an average additional rate of sea-level rise of about 1 mm/yr for Yarmouth, Halifax and Charlottetown, in agreement with findings by Shennan and Horton (2002) along the coastline of Great Britain. We note an increase in this residual from the southwest to the northeast of the region (compare Figs. 5a and 6). This could indicate that the increase in tidal range in the Gulf of Maine during the late Holocene has been overestimated by palaeotidal models (Scott and Greenberg, 1983; Gehrels et al., 1995). If tidal range had remained unchanged in the past 3000 years, 0.1–0.3 mm/yr of the discrepancy could be accounted for, but it requires a tidal range reduction of 50–60% to reconcile fully Holocene sea-level trends with those observed during the past century. A reduction of tidal range is inconsistent with model data (Scott and Greenberg, 1983; Gehrels et al., 1995) and geological observations (Amos, 1978; Amos and Zaitlin, 1984; Bleakney and Janes, 1983), while the tide-gauge record of Saint John appears to show an increase in tidal range during the past century (Godin, 1992). Moreover, the southwest–northeast trend of increased residuals continues beyond the Bay of Fundy; the residual for Charlottetown is also quite large when compared with sea-level index points for Wallace Basin, although the late Holocene sea-level record from Wallace Basin is poorly constrained, with only one index point in the past 3000 years. Using additional radiocarbon data from Prince Edward Island

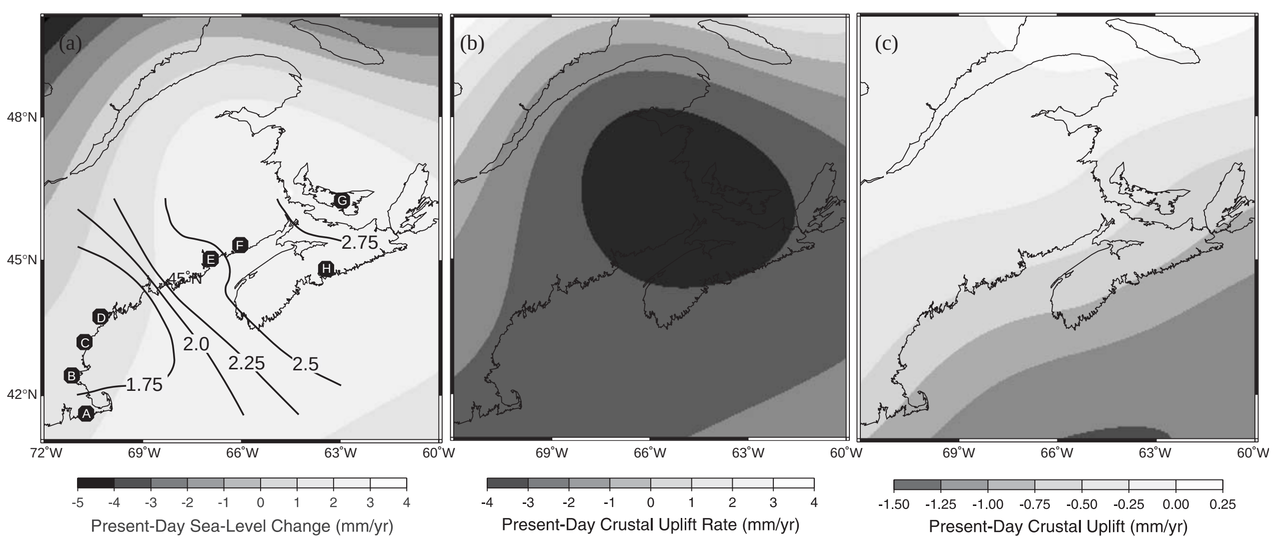

Fig. 7. (a) Numerical prediction of the present-day rate of sea-level change in northeastern North America (grey shading). Superimposed are contours for the eight tide-gauge stations (A–H) produced by the same contouring routine as used for Figs. 5 and 6. (b) Predicted vertical crustal motion due to ice loading. (c) Predicted vertical crustal motion due to ocean loading.

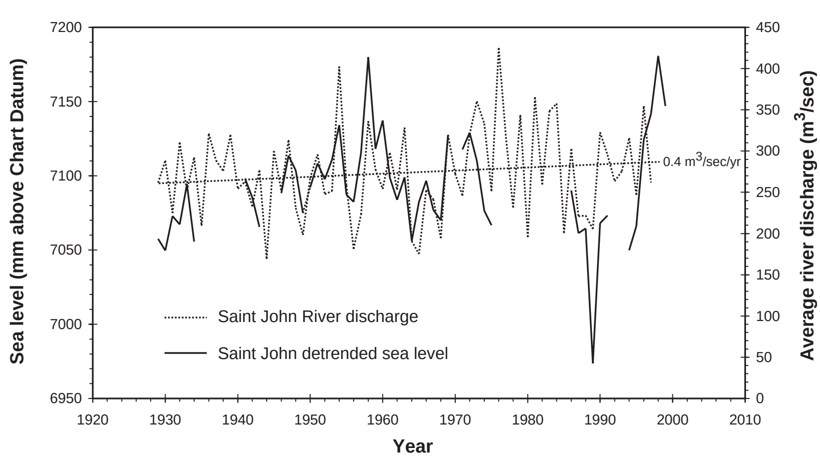

Fig. 8. Comparison between Saint John River discharge measured at Fort Kent and sea-level changes in Saint John Harbour. The correlation is significant ($p = 0.005$). The discharge shows a positive trend during the past 70 yr, albeit statistically not significant ($p = 0.27$).

(Scott et al., 1981), Carrera and Vaníček (1988) found excess rates of 1.3–1.7 mm/yr for the tide gauge at Charlottetown.

Some of the discrepancy between late Holocene trends and tide-gauge rates may be due to decadal variability in the tide-gauge records. Meade and Emery (1971) found that 7% of sea-level change in the entire Gulf of Maine could be accounted for by river runoff. In a similar analysis we compared the 1927–1997 annual discharge record upstream at Fort Kent (available from the Gulf of Maine Watershed Information and Characterization System at http://www.gm-wics.sr.unh.edu/) with average sea levels at Saint John and found in a multiple regression analysis (of sea level on year and river runoff) that the secular trend of sea-level rise explains 75% of the variation of sea level at Saint John while the discharge record accounts for 15%. River discharge and sea level are significantly correlated (Fig. 8).

Other local factors that contribute to variability in tide-gauge records include changes in tidal regime and sediment loading. Godin (1992) estimated that the tidal range in the harbour of Saint John has been increasing at a rate of 1.0 mm/yr during the past century. Although this increase would not necessarily have affected the mean tide level, the Bay of Fundy is highly sensitive to changes in its resonant period and its tidal regime is rapidly evolving under the influence of rising sea levels (Godin, 1992). Sediment loading is an untested factor (Kearney and Stevenson, 1991), but it is probable that during the past few centuries sedimentation rates have increased following widespread settlement and high land-surface erosion rates in the region.

6. Conclusions

Regional late Holocene sea-level data obtained from coastal locations in northeastern North America show a northeast–southwest gradient of crustal motion, reflecting the former distribution of Laurentide ice. Calculations based on a model of GIA predict rates of ice-load induced crustal subsidence of 3–4 mm/yr, centred on the Canadian provinces of New Brunswick and Nova Scotia. Additional crustal subsidence due to ocean loading of around 0.75–1.0 mm/yr is predicted for the Atlantic coast of Nova Scotia. Here, the highest rates of late Holocene sea-level rise in the region occur (an average of 2.5 m per 1000 years), as documented by new and published sea-level data from Chezzetcook Inlet. A new sea-level history produced for the southern New Brunswick coast at Little Dipper Harbour shows that late Holocene sea-level rise at this location has been about 1.0 m per 1000 yr. The regional pattern of sea-level change predicted by the GIA model is consistent with late Holocene data and with tide-gauge records. The latter show a recent acceleration of sea-level rise across the region relative to late Holocene trends. This rapid rise of sea level in the 20th century can at least partly be ascribed to a eustatic rise due to global warming, but a systematic increase in the residual from southwest to northeast across the region requires further investigation.

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We pay tribute to Douglas Grant who recently passed away and whose work on sea-level changes in Atlantic Canada has been instrumental in unravelling its complexities. A colleague fittingly described Doug as "a brilliant earth scientist who forgot more about the Quaternary geology of Atlantic Canada than most of us will ever know".

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