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Mid-Holocene Precedent for a Future Rise in Sea-Level Along the Atlantic Coast of North America

D.B. Scott†, P.T. Gayes‡ and E.S. Collins†

†Centre for Marine Geology
Dalhousie University
Halifax, Nova Scotia B3H 3J5, Canada

‡Center for Marine and Wetland Studies
University of South Carolina–Coastal Carolina University
Conway, SC 29526, U.S.A.

ABSTRACT

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Sea level oscillated between 5500 and 3500 years ago at Murrells Inlet, South Carolina (33°33′N, 79°02′W). The oscillation is well constrained by marsh foraminiferal zonations. For the same time interval, data from Nova Scotia indicate an acceleration in sea-level rise and a report from the Gulf of St. Lawrence suggests an oscillation of sea level at the same time. The implications are: (1) there was a eustatic sea-level oscillation of about 2 m in the mid-Holocene on the east coast of North America that is not detectable in present geophysical models of relative sea-level change; (2) if an anthropogenically derived global warming of 4°C takes place, sea level may rise as much as 2 m in 500 yr along the east coast of North America.

It appears that the initial rapid rise is recorded all along the eastern seaboard of North America, but detection of the subsequent fall is dependent on existing glacio-isostatic effects (either subsidence or rebound) that are independent of eustatic sea level.

ADDITIONAL INDEX WORDS: *Mid-Holocene, oscillation, sea level, marsh foraminifera.*

INTRODUCTION

In geology, it is often said that the present is the key to the past, but in the study of global climate/sea-level change, the reverse may also be true. There are many predictions in the literature (*e.g.,* BARTH and TITUS, 1984; HOUGHTON *et al.,* 1990) regarding how sea level may respond to global warming. However, many appear to neglect the most recent global warming that occurred in mid-Holocene (4°C) (HOUGHTON *et al.,* 1990). This event may be an analogue to the predicted "Greenhouse" warming, since a 4°C (in higher latitudes) rise in temperature is projected if present trends continue (HOUGHTON *et al.,* 1990). During the mid-Holocene, sea levels in some parts of the world were indeed higher than present (*e.g.,* DOMINQUEZ *et al.,* 1987; GIRESSE, 1989) which conform with the most comprehensive geophysical model of sea level, ICE-2 (PELTIER, 1988).

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The ICE-3G model (TUSHINGHAM and PELTIER, 1991) provides a better model but does not include the detail reported in 1988. In the North Atlantic basin, no higher-than-present relative sea levels have been reported for the Holocene (except for areas with active isostatic rebound). However, rapid (less than 1000 yr) mid-Holocene sea-level oscillations have been suggested by earlier workers for the southeastern United States (COLQUHOUN and BROOKS, 1986, DE PRATTER and HOWARD, 1981) and for the Gulf of St. Lawrence (DIONNE, 1988). There are many reports of fluctuating sea levels in Scandinavia (PIRAZZOLI, 1991) but they are not limited to the mid-Holocene. Much earlier, FAIRBRIDGE (1961) had suggested a highly fluctuating sea level throughout the Holocene. These reports (except the Scandinavian levels, many of which relate to crustal rebound) had been either ignored or disregarded by many sea-level workers (including the senior author of this paper) because of poorly constrained data sets. Indeed, PELTIER's (1988) models do not predict any important Holocene oscillations in the mid-Holocene for the North Atlantic although this same model does predict the South Atlantic high-stand. Previous relative sea-level records from the east coast of North America supported the model predictions, apparently suggesting that the eustatic sea-level event that occurred in much of the South Atlantic and many locations in the Indian and Pacific Oceans had no detectable impact in the North Atlantic Basin. By inference, the suggested global warming and rise in global sea levels caused by anthropogenically induced global warming might also be unevenly distributed and not have much impact in the North Atlantic. However, even the newer, more high resolution models of former sea levels are probably incapable of predicting a rapid, relatively small scale (~2m) oscillation in sea level.

BACKGROUND OF LONG TERM SEA-LEVEL CHANGE

In areas such as eastern South America, West Africa and Australia where sea-level changes are largely caused by water volume changes rather than land movement, sea-level rise essentially stopped 4000 to 6000 years ago and has actually fallen in many places (*e.g.*, Brazil, DOMINQUEZ *et al.*, 1987). It has been suggested that the subsequent fall of sea level after the mid-Holocene in Australia (and by comparison in S. America) was a result of hydro-isostasy (CHAPPELL *et al.*, 1982) where water loading caused a small emergence along coastlines after the sea-level maximum. Most of the North Atlantic margin is in a tectonically inactive zone but most areas are still experiencing relatively rapid submergence which must be the result of some factor other than eustatic sea-level rise.

Many models (*e.g.*, PELTIER, 1988; TUSHINGHAM and PELTIER, 1991) suggest that isostatic adjustment of the Earth's surface following deglaciation plays the major role in relative sea-level change, especially in the North Atlantic, with a smaller contribution from water volume change. These models and many sea-level records from the east coast of North America suggest that this isostatic adjustment affected most, if not all, of the eastern North American coastline over the last several thousand years even though the ice margin ended in New York. PELTIER (1988) suggests that all the tide gauge data from the N.E. coast of the U.S. can be explained by isostatic adjustment which conforms with most long term sea-level records from the eastern seaboard, however DOUGLAS (1991), using the ICE-3G model (TUSHINGHAM and PELTIER, 1991) suggests a 1.8 mm/yr rise globally which is presumably water level rise. SCOTT *et al.* (1987a) calibrated QUINLAN and BEAUMONT's (1981) model (a small scale derivation of one of Peltier's early models) for a former ice margin in Maritime Canada but calibration to the south has been lacking. However a direct comparison between an area just at the former ice margin (Nova Scotia) and South Carolina (several hundreds of kilometers south of an ice margin) shows a large differential, about 30 cm/100 yr of submergence in the last 2500 yr in Nova Scotia (SCOTT *et al.*, 1987a) vs. less than 10 cm/100 yr in South Carolina (Murrells Inlet, GAYES *et al.*, 1992). Curves between these areas show varying rates of relative sea-level rise but rates tend to decrease north to south falling between the extremes of Nova Scotia and South Carolina (*e.g.*, KRAFT, 1971). If, as DOUGLAS (1991) suggests, the global average is 1.8 mm/yr. (= 18 cm/100 yrs), it has started relatively recently in places like South Carolina where we have dates on salt marsh peat that indicate rates

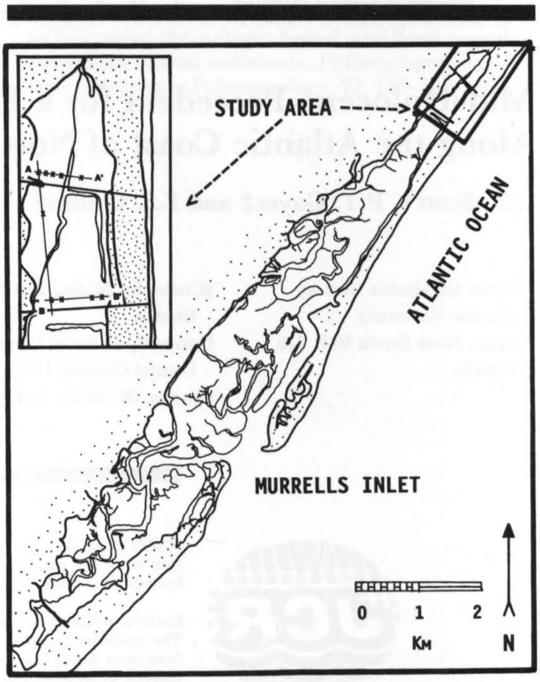

Figure 1. Location map of South Carolina curve—Murrells Inlet. Locations for the Nova Scotian and Gulf of St. Lawrence sites can be found in SCOTT *et al.* (1987b) or DIONNE (1988). Coordinates for Murrells Inlet are 33°33′N, 79°02′W.

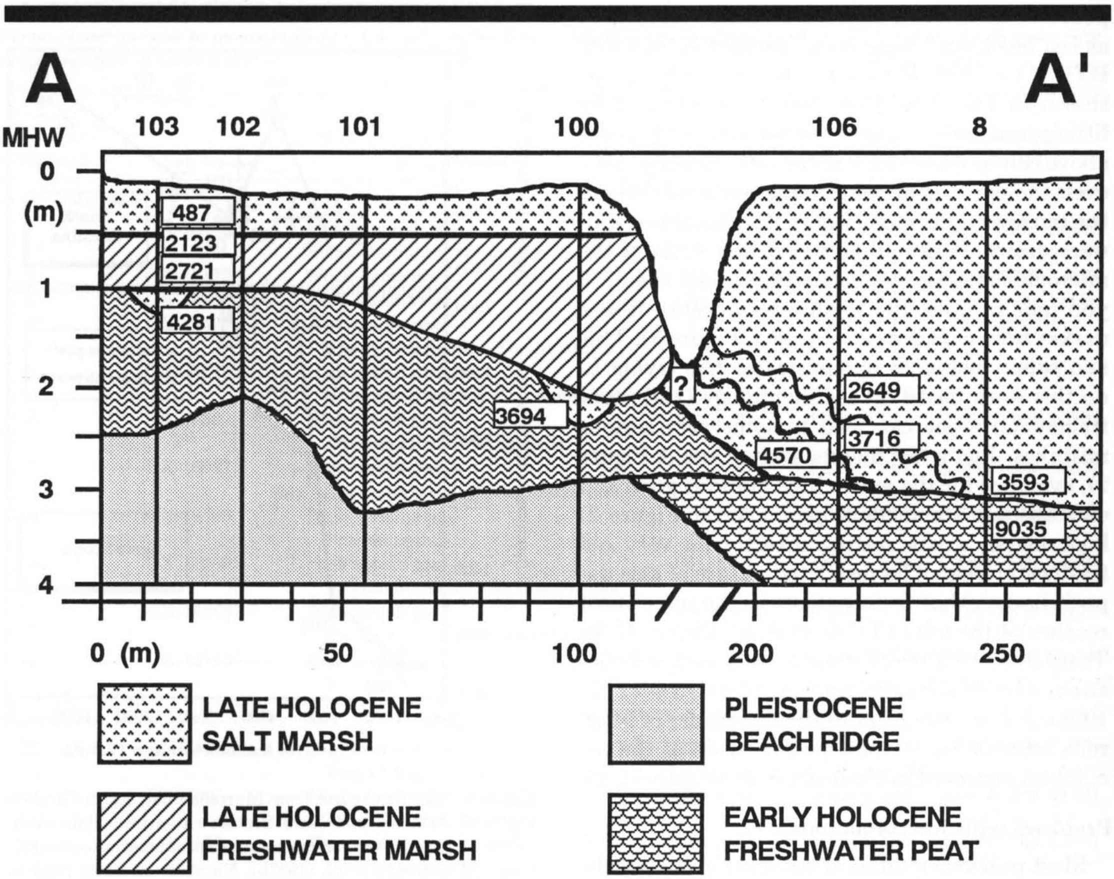

Figure 2. Lithostratigraphy of the most critical transect of this study from Murrells Inlet, S.C. Line A to A[1] goes seaward with A being at the tree line. Numbers along the top refer to vibracore numbers and numbers in open boxes are sidereal ages. Only those dates used in Figure 3 are contained in Table 1. Others can be found in GAYES *et al.* (1992).

of no more than 10 cm/100 yrs over the last 500 years.

NEW EVIDENCE OF A RAPID MID-HOLOCENE OSCILLATION

Interpretation of Results

GAYES *et al.* (1992) have reported a rapid mid-Holocene sea-level oscillation along the South Carolina coast where relative sea level oscillated from −3 m at 4570–5200 yBP to 1 m below its present position by 4280 ybp and then fell to −3 m by 3600 ybp before rising again to its present position. Since the publication of GAYES *et al.* (1992), more micropaleontologic work has been done and extra intermediate sea levels have been located and C^{14} dated. This modifies sections shown in the earlier paper and actually strengthens the existence of the oscillation with new data (Figures 1–3). The complexity of the critical interval that contains the mid-Holocene high illustrates why this interval may have been overlooked previously (Figure 2). There is thin salt marsh, followed by a thin freshwater peat with salt marsh on top (Core 103, Figure 2). This sequence is repeated in core 100 but the thin salt marsh underlying the freshwater peat is deeper in the core and records the last of the regression before the lowstand at −3 m. Even where this interval is preserved there are large gaps, such as in core 106 (Figure 2) where a thin pre-high stand high marsh is preserved below younger high marsh that formed as sea level dropped below this point after the high stand in Core 103. Just above the 3716 ybp peat in Core 106 is a high marsh peat that formed as sea level was rising to its present level (2649 BYP, Core 106, Figure 2). The unconformities shown in Fig. 2 for Core 106 are confirmed by lithological breaks where burrows from the layer above can be observed into the underlying peat—even though it is all salt marsh material. Where the burrows occurred is where the unconformities were drawn. It should be noted that without the micropaleontology we incorrectly called the 3716 ybp unit in Core 106 freshwater because it was darker brown (GAYES *et al.*, 1992, Figure 3). This and other instances demonstrate that trying to do this work based on sedimentology (and plant fragments) alone can lead to some very serious mistakes. Just a few meters away (Core 8, Figure 2), evidence for the entire high stand is gone and only the low stand (3593 ybp, Core 8, Figure 2) high marsh exists resting directly on very old freshwater peat. The restricted nature of this deposit is such that it only exists in the uppermost reaches of the inlet (Transect A-A[1], Figure 1). In Transect B-B[1] already the sequence is largely destroyed by tidal creek migration (see GAYES *et al.*, 1992). Almost 100 cores in the remainder of Murrells Inlet failed to show preservation of the oscillation observed in Transect A-A[1] (Figures 1, 2).

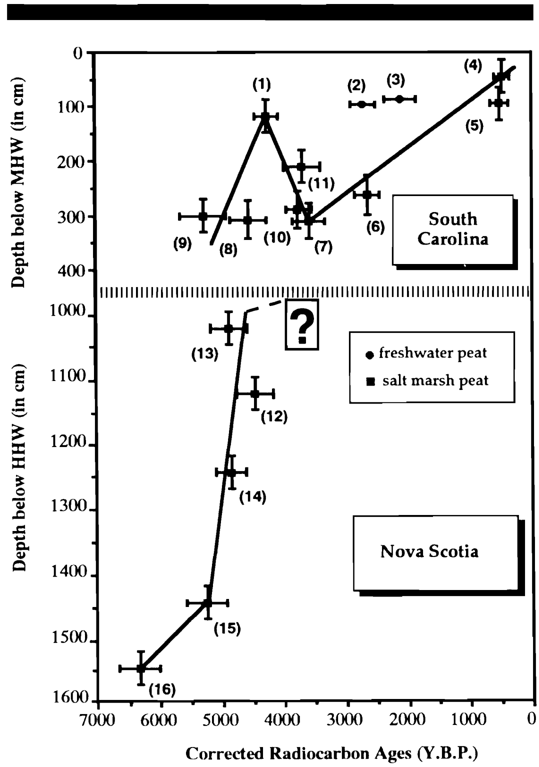

Figure 3. Sea-level curve from Murrells Inlet, South Carolina (33°33′N, 79°02′W) and Nova Scotian curve from Baie Verte (46°00′N, 63°40′W), taken from a series of submarine cores documented in SCOTT *et al.* (1987b). Numbers on dates refer to Table 1. All C[14] ages have been converted to sidereal ages according to STUIVER and REIMER (1986, 1987).

Problems with Interpretations

Most previous studies of sea level in the southeastern United States have not used techniques with the spatial precision (± 30 cm in South Carolina marsh foraminiferal zones) now available with marsh foraminiferal zonations (SCOTT and MEDIOLI, 1978, 1980; SCOTT *et al.*, 1991; PATTERSON, 1990; JENNINGS and NELSON, 1992). The foraminiferal results here were not as conclusive as those we have obtained from places farther north (*e.g.*, SCOTT *et al.*, 1987a,b) because the foraminiferal numbers in the core sequences were often low. GOLDSTEIN and FREY (1986) also saw low subsurface numbers in Georgia, even lower than we saw, and it appears some of the agglutinated foraminifera may not be preserved in the subsurface of the marshes in the southeastern United States—possibly due to the high temperatures and aeration of the subsurface by fiddler crab holes. COLLINS, in still unpublished Ph.D. material, has shown that foraminiferal zones in South Carolina are as accurate as other places. He is also addressing the preservation problem, but it does not appear as severe as reported by GOLDSTEIN and FREY (1986) in Georgia. Despite this problem, we are still confident of the sea-level points to ± 30cm. Another problem common to all studies in marsh deposits is autocompaction of the peat. We feel that our most critical dates—*i.e.*, the two low stands (4570—Core 106, 3593—Core 8) and the high stand (4281—Core 103) are resting on non-compactible material. The old freshwater peat was extremely hard and weathered before the marine material was deposited on it and the sandy freshwater material underlying the high stand in core 103 is also not compactible. However, all the other dates that were within peat sequences could have been compacted and hence actually formed at a level higher than they were found in the core (*e.g.*, dates in Core 103,106). However, this would not change the position of the highstand, but it might change the slope of the curves. All data points are listed in Table 1 with C[14] years, sidereal years (STUIVER

Table 1. *Carbon [14] dates and conversion to sidereal dates (*Stuiver *and* Reimer*, 1986, 1987) for sea-level points discussed in this paper. Numbers refer to points in Figure 3. yr BP = years before present. Foraminiferal zones are largely high marsh zones—for documentation on these zonations, see* Scott *and* Medioli *(1980) or* Scott *et al. (1991); MHW = mean high water.*

#'s Corresponding to Figure 3	Lab #	Material Dated and Foram Zone (if applicable)	Sample Depth Below Present MHW (cm)	C^{14} Age (yr BP)	Sidereal Age (yr BP)
South Carolina					
1.	GX-16478	Middle marsh peat—*Ammostauta inepta*	119 ± 30	3,850 ± 145	4,281 (4,449–4,089)
2.	GX-16477	Wood—freshwater	98	2,510 ± 140	2,721 (2,769–2,369)
3.	GX-16476	Peat—freshwater	88	2,140 ± 230	2,123 (2,369–1,860)
4.	GX-16475	High marsh peat—*Haplophragmoides-Trochammina*	45 ± 30	405 ± 145	487 (550–310)
5.	GX-16479	High marsh peat—*Haplophragmoides-Trochammina*	98 ± 30	475 ± 180	522 (660–320)
6.	GX-16567	High marsh peat—*Trochammina-Arenoparella*	263 ± 30	2,475 ± 135	2,649 (2,759–2,359)
7.	GX-15987	High marsh peat—*Haplophragmoides-Arenoparella*	312 ± 30	3,340 ± 240	3,593 (3,889–3,359)
8.	GX-16569	High marsh peat—*Trochammina*	310 ± 30	4,090 ± 235	4,570 (4,879–4,289)
9.	GX-15989	High marsh peat—*Trochammina-Haplophragmoides*	301 ± 30	4,560 ± 270	5,239 (5,599–4,859)
10.	GX-16568	High marsh peat—*Trochammina-Arenoparella*	289 ± 30	3,460 ± 155	3,716 (3,929–3,559)
11.	GX-18812	High marsh peat—*Trochammina arenoparella*	220 ± 30	3,435 ± 105	3,694 (3,839–3,579)
Nova Scotia					
12.	GX-7536	High marsh peat—*Trochammina*	1,120 ± 10	4,010 ± 190	4,486 (4,829–4,239)
13.	GX-6803	High marsh peat—*Trochammina*	1,030 ± 10	4,360 ± 190	4,931 (5,284–4,653)
14.	GX-7537	High marsh peat—*Trochammina*	1,240 ± 10	4,320 ± 180	4,868 (5,256–4,616)
15.	GX-6802	High marsh peat—*Trochammina*	1,440 ± 10	4,565 ± 170	5,295 (5,573–4,869)
16.	GX-7539	High marsh peat—*Trochammina*	1,550 ± 10	5,460 ± 165	6,292 (6,419–5,996)
St. Lawrence Estuary					
17.	UL-53 (from Dionne, 1988)	Ferns, Freshwater	Above MHW now	4,370 ± 70	4,931 (5,214–4,859)

and Reimer, 1986, 1987), lab numbers, marsh zones, depth below MHW, and associated foraminifera.

PREVIOUS REPORTS OF A MID-HOLOCENE SEA-LEVEL EVENT FROM THE WESTERN NORTH ATLANTIC

The only other report of an event at this time in the North Atlantic zone north of South Carolina is an occurrence observed by DIONNE (1988, Table 1, Date no. 17) from the North Shore of the St. Lawrence River estuary where he observes an oscillation in a deposit that is now raised above present sea level by isostatic rebound.

However, previously reported data from the Nova Scotian coast (Scott *et al.*, 1987b, Figure 3, Table 1) shows a sharp acceleration of a sea-level rise at the same interval and new data from the Atlantic coast of Nova Scotia also shows the acceleration at the same time, ending at the time (as close as we can tell from C^{14} dating) of the highstand in South Carolina (Brown, 1993). The vertical integrity of both sets of Nova Scotian points is high because each point was determined using the most accurate marsh foraminiferal zonations.

All sea-level curves discussed here (St. Lawrence, Murrells Inlet, Nova Scotia) indicate an acceleration of the rate of sea-level rise at around 4500–5000 yBP. In South Carolina, there is no evidence that sea level was rising at twice its present rate just prior to 5000 yBP (COLQUHOUN and BROOKS, 1986); in the St. Lawrence report, there must be an acceleration of sea-level rise to override the isostatic rebound; and in the Nova Scotian case, we can actually see the acceleration after 5200 yBP from the rate between 6000 and 5200 yBP (Figure 3). Only in South Carolina can we document a fall of eustatic sea level; in Quebec the fall from isostatic rebound masks any eustatic fall while in Nova Scotia background isostatic subsidence appears to mute any subsequent fall.

DIFFICULTIES IN DETECTION OF THIS OSCILLATION

For detection of the mid-Holocene oscillation, eustatic sea-level change (both rise and fall) must be sufficiently rapid to overprint the background relative sea-level rise resulting from subsidence caused by isostatic adjustment. In areas of substantial isostatic subsidence such as Nova Scotia, it appears that background isostatic subsidence may mask the subsequent fall we see in South Carolina; the oscillation also does not appear in a dense data set from Virginia (VAN DE PLASSCHE, 1990) possibly because this record contains material too young to detect this oscillation. This excursion is not observed by FAIRBANKS (1989) in Barbados, but this may be the result of incomplete data in the last 6000 years of the Barbados curve. There are many other records of relative sea level reported for the eastern seaboard of the United States (*e.g.*, KRAFT, 1971) but none outside of those mentioned above report the mid-Holocene oscillation. This is partly because the record in coastal sediments of this age is more fragmented and the indicators used in previous studies do not provide the confidence levels that we can obtain with marsh foraminiferal zonations. One thing seems apparent, however, the mid-Holocene eustatic sea-level high stand did not exceed present sea level in the North Atlantic above the narrowest part of the Atlantic between Africa and South America, implying that subsequent subsidence of varying magnitudes has submerged the eustatic high stand markers below present sea level in the North Atlantic (except in isostatically emergent areas). As PELTIER's (1988) model would suggest, subsidence resulting from glacio-isostatic adjustment is restricted to the North Atlantic.

POSSIBLE CAUSATIVE FACTORS

Many climatic records suggest a warming trend in the mid-Holocene followed by a cooling to the present (see HOUGHTON *et al.*, 1990) that might account for both the rapid rise and fall in sea level (as ice accumulated again after the mid-Holocene). Others suggest ice surging in the Antarctic caused by a steadily rising sea level may cause rapid rises in eustatic sea level (ANDERSON and THOMAS, 1991). DOMACK *et al.* (1991) suggest increased glacial advances in Antarctica during the mid-Holocene warming which may have enhanced the rapid rise in sea level between 5000 and 4000 ybp but fail to explain the subsequent rapid fall that occurred in the mid-Holocene as a result of climatic cooling and probably ice accumulation. It was suggested that the subsequent fall of sea level in Australia might have been the result of hydro-isostatic adjustment, not a eustatic fall in sea level (CHAPPELL *et al.*, 1982). However, the time frame appears to be over 5000 yr in Australia which clearly does not explain the rapid time frame reported for the oscillation we see in South Carolina. Hence, we would suggest that the mid-Holocene sea-level oscillation (including the fall of sea level in South Carolina) is a climatic effect rather than a result of ice surging in the Antarctic or hydro-isostasy. If we take this one step further, we can actually correlate the mid-Holocene temperature rise (about +4°C globally, HOUGHTON *et al.*, 1990) with various reported values of mid-Holocene eustatic sea level rise vary from 2 m to a high of 5 m (in South America). Some climate models suggest a much lower water volume increase and subsequent rise in sea level (including both thermal expansion and ice melt, 8–12 cm) with an equivalent amount of global warming (about 4°C, KUHN, 1989) which based on data here appears excessively low.

IMPLICATIONS FOR THE FUTURE

Although the former mid-Holocene high stand of sea level is lower than present day in the North Atlantic, it does indicate that rapid climatic fluctuations can cause a sharp variation in the rate of sea-level change in a short term event. Also, we can see variance of response to this change from South America where the amount of sea-level rise was over 5 m to only 2 m in South Carolina. It was perhaps less in the northeast United States and Canada with no detectable fall in sea level (at this point at least) north of South Carolina. The variation in response might be twofold: unequal distribution of meltwater that maintains an equipotential sea surface (TUSHINGHAM and PELTIER, 1991) and/or isostatic adjustment which appears to mute the subsequent fall to just a decrease in the rate of RSL rise as you approach the former ice center. In Quebec, only the acceleration that overtakes the rebound can be observed, and it is impossible to measure the rate of water volume decrease over the emergence caused by isostatic rebound.

If there is a "greenhouse" induced global sea-level rise, it presumably will not rise to a maximum and then fall (as in the mid-Holocene event) unless the greenhouse process is reversed. However, the mid-Holocene fluctuation does show that a climatically induced sea-level trend can be reversed quickly, even with natural processes. For records covering the last 2000 years along the eastern seaboard of North America, there is no evidence of an accelerated sea-level rise in the last 100 years; hence, no suggestion that the "greenhouse" effect is causing a rise in sea level yet (PELTIER, 1988). This could be a result of non-detection (as tide gauges would suggest, DOUGLAS, 1991) or a delayed response to global warming, as was the case for the mid-Holocene event. Most of the mid-Holocene warming appears to have taken place prior to 6000 yBP (HOUGHTON *et al.*, 1990) while most of the higher sea levels occurred at least 1000 years later. However, one possible explanation for the delay overall is that ice melt was initiated at the climatic maximum and continued for some time after the maximum temperatures, causing the lag in sea-level response. If the same climatic phenomenon occurs again, a global warming occurring in the near future (*i.e.*, over the next 100 years) might register a sea-level response that lags behind the global warming trend and reflect a few meters of eustatic sea level rise, not a few centimeters as some climate models predict (*e.g.*, KUHN, 1989).

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