Secular changes of the M_2 tide in the Gulf of Maine

R. D. Ray

NASA Goddard Space Flight Center, Code 697, Greenbelt, Maryland, USA

Abstract

Analyses of long time series of hourly tide-gauge data at four stations in the Gulf of Maine reveal that the amplitude of the M_2 tide underwent a nearly linear secular increase throughout most of the twentieth century. In the early 1980s, however, the amplitude of M_2 abruptly dropped. Sea level changes alone appear inadequate to explain either the long-term trend or the recent trend discontinuity. Tidal models that account for Holocene sea level rise do predict an amplification of M_2, but much smaller than the currently observed trends. Nor do recent annual mean sea levels correlate with the recent trend discontinuity. Some unknown fraction of the open Atlantic may be similarly affected, since the M_2 discontinuity, but not the long-term secular increase in the tide, is evident also at Halifax.

Key words: Tides, Gulf of Maine, Tidal changes

Long ago Doodson (1924) called attention to some curious features of the semidiurnal tide as measured at St. John, New Brunswick, on the western shore of the Bay of Fundy. He surmised a secular change in M_2, but his time series turned out too short (22 years) to determine definitively even the sign of this change. The problem was revisited by Godin (1992; 1995), who supplemented Doodson's earlier data with new measurements over the timespan 1932–1980. Godin convincingly showed that the amplitude of M_2 is increasing rapidly; he estimated 12.6 cm century^{-1}. This is one of the largest known rates of secular tidal change for a site that is relatively well exposed to the open sea (compare, for example, other studies by Cartwright, 1972; Woodworth et al., 1991; Amin, 1993; Flick et al., 2003). Godin's rate at St. John is significantly larger than model-based estimates of Holocene tidal trends in the region, which generally average less than a few cm/cy over the past few thousand years (e.g., Scott and Greenberg, 1983; Gehrels et al., 1995; Egbert et al., 2004).

The purpose of this short note is twofold: to report (1) that the large positive trend in the M_2 amplitude at St. John, evident since 1890, abruptedly stopped in the early 1980s and (2) that similar changes are found throughout the entire Gulf of Maine.

Digitial hourly data from the St. John tide gauge are now available since 1896. The time series is substantially complete since 1905, except for a few multi-year gaps in the 1920s and 1930s. These data have been here partitioned into yearly segments and each segment subjected to independent tidal analysis by least squares. Figure 1 shows the yearly estimates of the amplitude of M_2 based on the hourly St. John data. These estimates were computed without the usual 'nodal correction' adjustments that allow for the 18.6-year precession of the lunar orbit plane. The standard nodal adjustment is 3.7% (Doodson and Warburg, 1941), but this is known to be inapplicable to the Bay of Fundy owing to effects of friction and resonance (Ku et al., 1985). Hence, the dominant signal seen in Figure 1 is the 18.6-y oscillation in the M_2 amplitude. Allowing for that, however, one notices a clear trend of increasing amplitudes throughout the series until the early 1980s, after which the amplitudes drop and become comparable to the period around 1940. This is perhaps more easily seen in Figure 2 by comparing against a reference curve consisting of a linear trend plus a sinusoid of period 18.6 y (plus a second harmonic which approximately captures an additional small modulation from third-degree tides within the constituent; see Cartwright and Edden, 1973). The curve is fitted by least squares to the 1900–1980 data, and it clearly delineates the offset beginning around 1982.

Tidal analysis of a full 19 years of data can adequately resolve the central M_2 line without the complications of modulating side-lines. Five such analyses are summarized in Table 1, and they confirm the increasing M_2 amplitudes up until the most recent timespan.

Table 1 also suggests the phase of M_2 is slowly changing, but with no evident secular trend unless we discount the earliest period. Examination of yearly estimates (not shown) suggests no obvious disjoint in phase near 1982.

Other semidiurnal constituents display temporal effects as well, although generally of complex nature and less easily extracted from background noise. The S_2 amplitude appears to have been fairly constant, within the uncertainties of the estimates, until around 1950, after which it has decayed relatively rapidly, with trend approximately -5 cm/cy. This decline in S_2 was noted also by Godin (1995). The phase appears to be advancing. N_2, which at St. John is larger than S_2, exhibits no significant trend to within current noise levels.

The changes at St. John could conceivably be caused by instrumentation changes or difficulties with the tide gauge, or they could be the result of localized changes in the harbor or its immediate vicinity. For example, it is known that the gauge was affected by siltation during the 1980s (D. Greenberg, pers. comm., 2005). Moreover, sea level at St. John is known to be correlated with river discharge (e.g., Gehrels et al. 2004). For such reasons it is essential to compare the St. John M_2 results with other tide gauges in the region.

Data from four additional stations (see map in Figure 3) have been processed in similar fashion, and the resulting M_2 amplitudes are shown in Figure 4. It is plainly evident that the St. John variations—increasing M_2 amplitudes with a discontinuity in the early 1980s—are occurring in the entire Gulf of Maine region. Most surprisingly, the station at Halifax, which is directly open to the Atlantic Ocean and must be far less sensitive to local changes in the Gulf of Maine, exhibits the 1982 discontinuity clearly, but with hardly any long-term trend. Table 2 lists some relevant statistics for all five sites. Note that the Halifax nodal modulation is very close to the 3.7% equilibrium value, underlining its relative independence to effects in the Gulf.

That Halifax exhibits the same curious offset in the early 1980s suggests a mechanism affecting a much wider region of the Atlantic Ocean. Several other stations along the eastern United States seaboard have been examined, but no similar features have been found. Newport, Rhode Island, does show a small secular decrease in M_2 amplitude (which is predicted, at least qualitatively, by the series of Holocene global models described by Egbert et al., 2004), but Newport shows no particular jumps in the early 1980s. Nor are such effects seen at Bermuda, the closest available station from the deeper open Atlantic. To the north, the tide gauge at Charlottetown, Prince Edward Island, in the Gulf of St. Lawrence, has one of the longest time series of hourly data readily available; unfortunately, the M_2 estimates at Charlottetown before about 1965 appear anomalous, and the post-1965 timespan is too short to allow definitive statements about trends.

What are the causes of the temporal changes in the Gulf of Maine tide? The M_2 tide is highly resonant in this region (e.g., Garrett, 1972), so it is expected to be sensitive to relatively small changes in water depth, in basin configuration, or in the Atlantic tide at the mouth of the gulf. Certainly, the general rise in sea level throughout most of the Holocene has caused increasing M_2 amplitudes in the Gulf, although as noted above, published tide model predictions based on long-term (1 to 5 thousand years) sea-level histories are not in good quantitative agreement with the observed twentieth-century trends of Table 2 (excluding Halifax). Moreover, the currently observed trends are very large and could not possibly be maintained over, say, several thousand years, lest we should now be seeing 5-meter tides throughout the Gulf. This suggests more recent causes. In fact, Gehrels et al. (2002) report evidence for a rapid sea-level rise in the Gulf since 1800, and Gehrels et al. (2005) show a doubling of the rate of sea level rise at Chezzetcook (near Halifax) since about 1900. But according to tidal models (e.g., Scott and Greenberg, 1983; Gehrels et al., 1995) this should induce an M_2 amplification of no more than about 1%, which is smaller than the largest trends of Table 2.

For the more recent times, mean sea-level curves for each of our five stations (Figure 5) suggest nothing especially unusual around 1982, although St. John (alone) is currently experiencing a rapid rise that began around 1995.

In summary, it appears likely that twentieth-century tidal trends, as well as the curious effect in the early 1980s, are caused by mechanisms related to or enhanced by the resonance nature of the Gulf of Maine, but they are not at this point well understood. It is nonetheless clear that these temporal variations are robust features of the tide and that they are occurring throughout the entire Gulf of Maine, apparently extending some ways into the Atlantic itself.

Acknowledgements

For the sea level data used here I am indebted to the Marine Environmental Data Services of the Canadian Department of Fisheries and Oceans, the University of Hawaii Sea Level Center, the British Oceanographic Data Centre, and the Permanent Service for Mean Sea Level; the latter two centers are located at the Proudman Oceanographic Laboratory, Liverpool. I thank Philip Woodworth, Roland Gehrels, and David Greenberg for useful comments and suggestions.

References

[1] Amin, A., 1993. Changing mean sea level and tidal constants on the west coast of Australia. *Australian Journal of Marine and Freshwater Research*, 44, 911–925.

[2] Cartwright, D. E., Edden, A. C., 1973. Corrected tables of tidal harmonics. *Geophysical Journal of the Royal Astronomical Society*, 33, 253–264.

[3] Doodson, A. T., 1924. Perturbations of harmonic tidal constants. *Proceedings of the Royal Society, London*, A106, 513–526.

[4] Doodson, A. T., Warburg, H. D., 1941. *Admiralty Manual of Tides,* HMSO, London.

[5] Egbert, G. D., Ray, R. D., Bills, B. G., 2004. Numerical modeling of the

global semidiurnal tide in teh present day and in the Last Glacial Maximum. *Journal of Geophysical Research*, 109, C03003.

[6] Flick, R. E., Murray, J. F., Ewing, L. C., 2003. Trends in United States tidal datum statistics and tide range. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 129, 155–164.

[7] Garrett, C., 1972. Tidal resonance in the Bay of Fundy and Gulf of Maine. *Nature*, 238, 441–443.

[8] Gehrels, W. R., Belknap, D. F., Pearce, B. R., Gong, B., 1995. Modeling the contribution of M_2 tidal amplification to the Holocene rise of mean high water in the Gulf of Maine and the Bay of Fundy. *Marine Geology*, 124, 71–85.

[9] Gehrels, W. R., Belknap, D. F., Black, S., and Newnham, R. M., 2002. Rapid sea-level rise in the Gulf of Maine, USA, since AD1800. *The Holocene*, 12, 383–389.

[10] Gehrels, W. R., Milne, G. A., Kirby, J. R., Patterson, R. T., and Belknap, D. F., 2004. Late Holocene sea-level change and isostatic crustal movements in Atlantic Canada. *Quaternary International*, 120, 79–89.

[11] Gehrels, W. R., Kirby, J. R., Prokoph, A., Newnham, R. M., Achterberg, E. P., Evans, H., Black, S., Scott, D. B., 2005. Onset of recent rapid sea-level rise in the western Atlantic Ocean. *Quaternary Science Reviews*, 24, 2083–2100.

[12] Godin, G., 1992. Possibility of rapid changes in the tide of the Bay of Fundy, based on a scrutiny of the records from Saint John. *Continental Shelf Research*, 12, 327–338.

[13] Godin, G., 1995. Rapid evolution of the tide in the Bay of Fundy. *Continental Shelf Research*, 15, 369–372.

[14] Ku, L.-F., Greenberg, D. A., Garrett, C. J. R., Dobson, F. W., 1985.

Nodal modulation of the lunar semidiurnal tide in the Bay of Fundy and Gulf of Maine. *Science*, 230, 69–71.

[15] Scott, D. B., Greenberg, D. A., 1983. Relative sea-level rise and tidal development in the Fundy tidal system. *Canadian Journal of Earth Science*, 20, 1554–1564.

[16] Woodworth, P. L., Shaw, S. M., Blackman, D. L., 1991. Secular trends in mean tidal range around the British Isles and along the adjacent European coastline. *Geophysical Journal International*, 104, 593–609.

Table 1

Tidal estimates at St. John

	M_2		S_2	
Timespan	Amplitude (cm)	Phase lag	Amplitude (cm)	Phase lag
1905–1923	299.78 ± 0.29	$342.98° \pm 0.06°$	50.27 ± 0.29	$17.02° \pm 0.33°$
1924–1942	300.61 ± 0.56	$341.43° \pm 0.11°$	50.98 ± 0.56	$15.53° \pm 0.63°$
1943–1961	302.13 ± 0.25	$341.60° \pm 0.05°$	49.91 ± 0.25	$16.70° \pm 0.29°$
1962–1980	304.26 ± 0.25	$341.92° \pm 0.05°$	49.35 ± 0.25	$17.31° \pm 0.29°$
1981–2004	301.18 ± 0.25	$343.16° \pm 0.05°$	47.62 ± 0.25	$19.63° \pm 0.30°$

Table 2

Estimated trends (pre-1980) in M_2 amplitude

Timespan	Trend (cm/century)	Nodal modulation*
St. John	8.5	2.3%
Eastport	13.3	2.3%
Portland	7.8	2.7%
Boston	4.3	2.8%
Halifax	0.0	3.6%

*Equilibrium modulation is 3.73%.

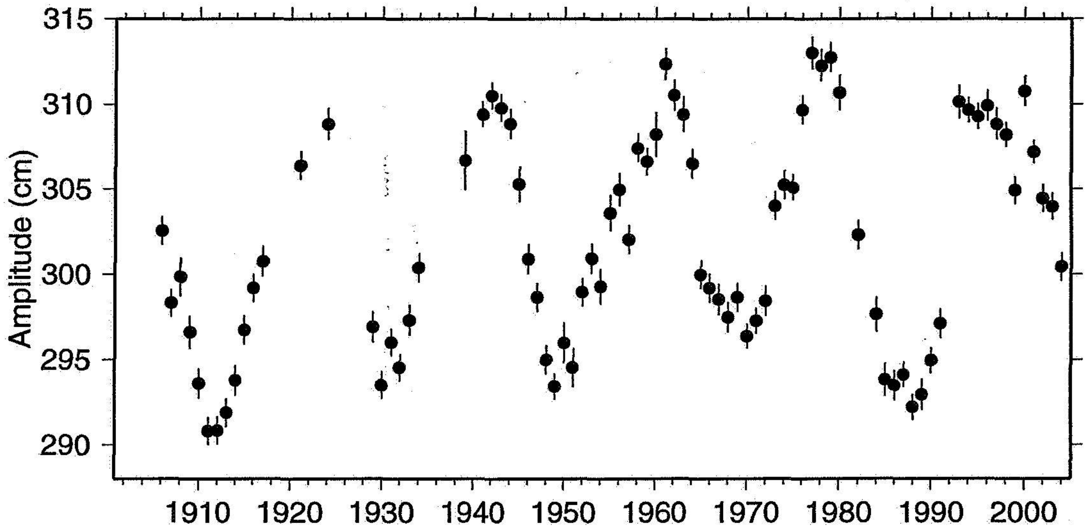

Fig. 1. Yearly estimates of the amplitude of the M_2 tide at St. John. Standard errors are deduced from the spectrum of residuals in the vicinity of the semidiurnal band.

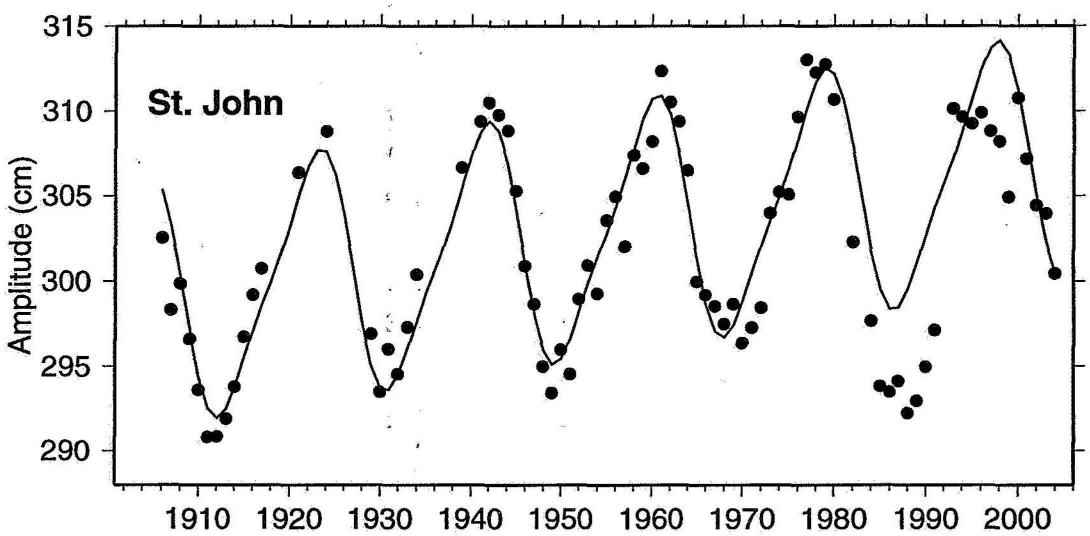

Fig. 2. Yearly estimates of the amplitude of M_2, as in Figure 1, with (solid curve) least-squares fit to the pre-1980 data. Fitted curve consists of of a bias, trend, and 2 sinusoids of period 18.6 years and 9.3 years.

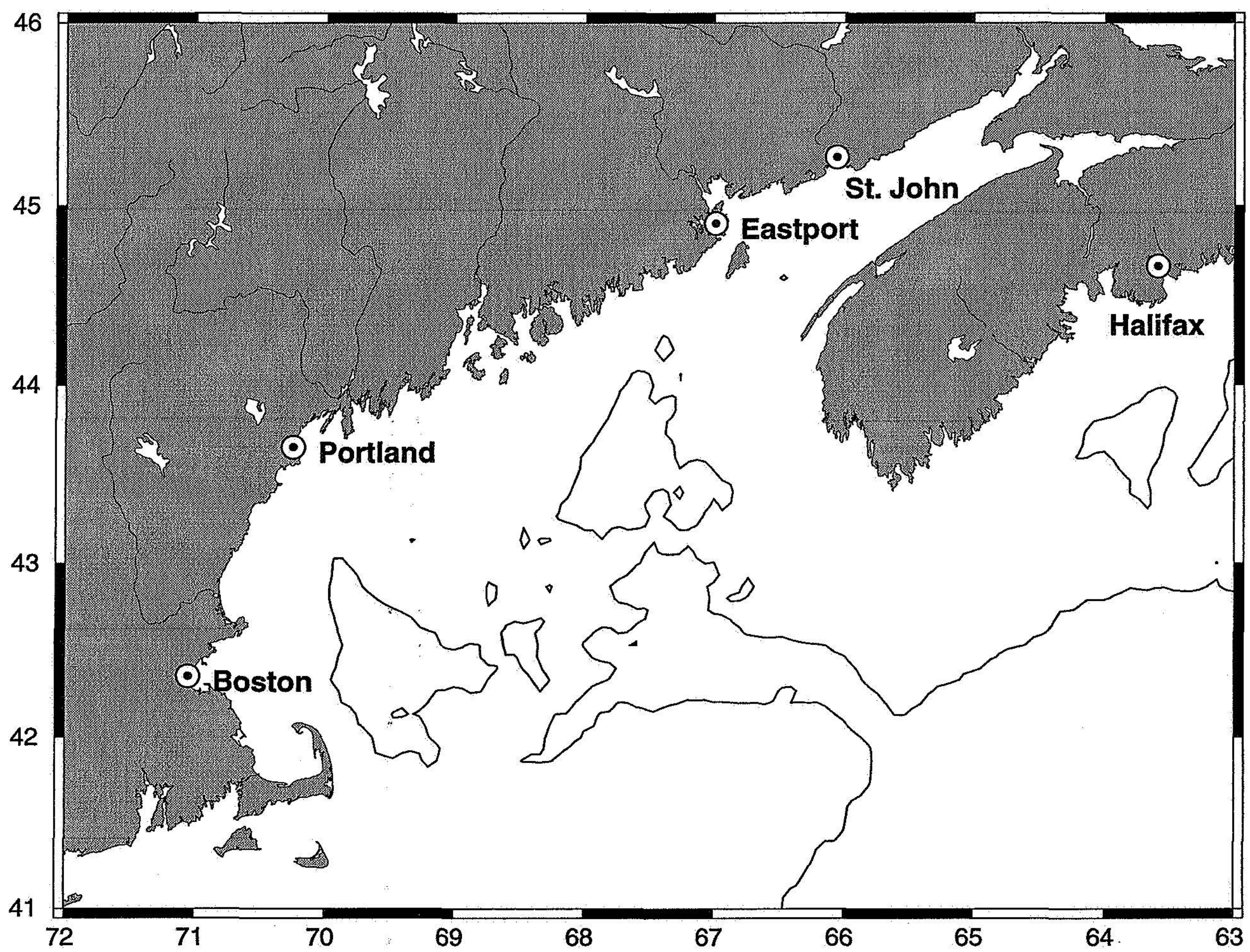

Fig. 3. Locations of tide gauges. Contour line is the 200-meter isobath.

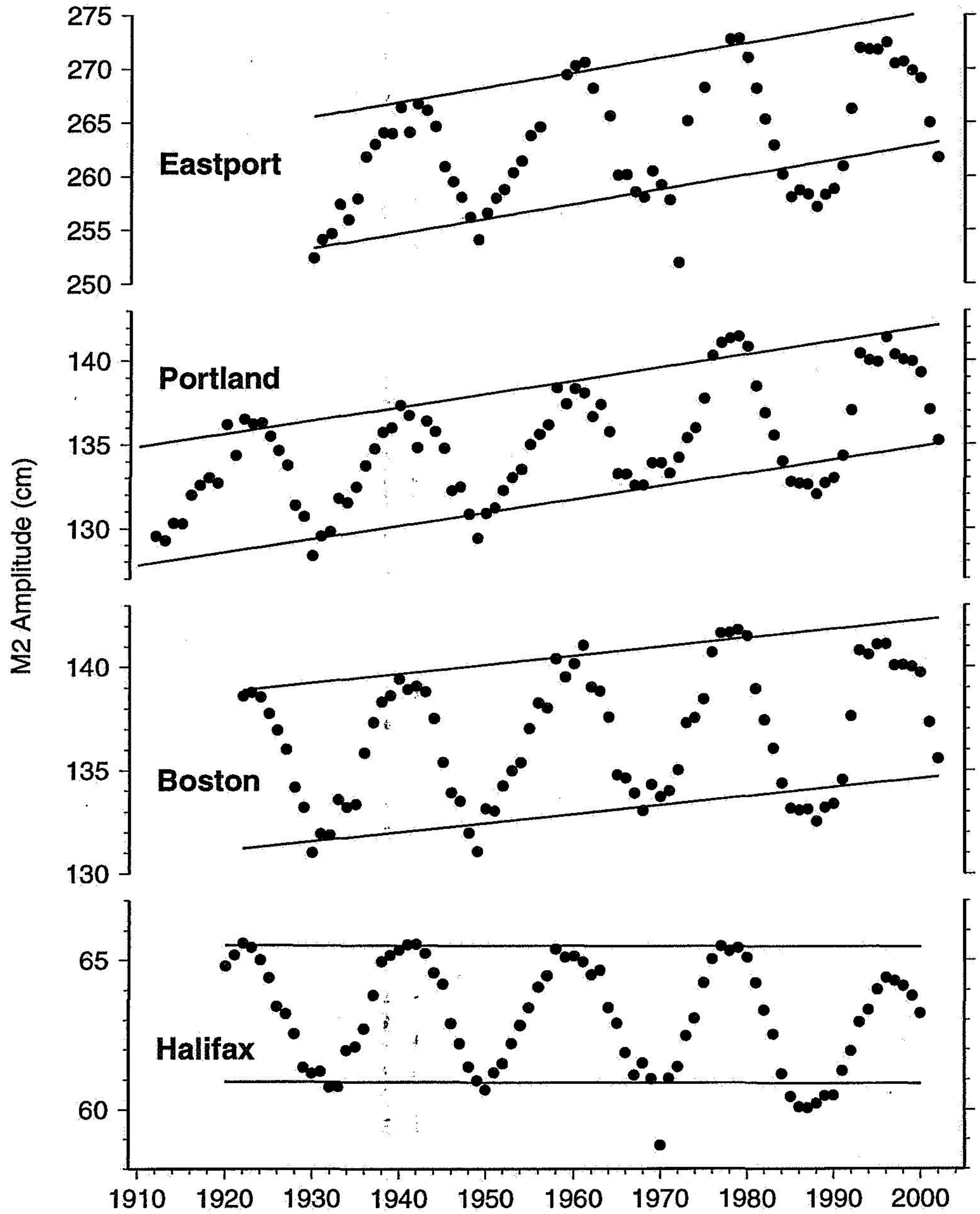

Fig. 4. Yearly estimates of the amplitude of the M_2 tide at four tide-gauge stations. Straight lines delineate upper and lower extrema of a pre-1980 least-squares fit to each dataset, with functional form of a bias plus trend plus 18.6-y sinusoid.

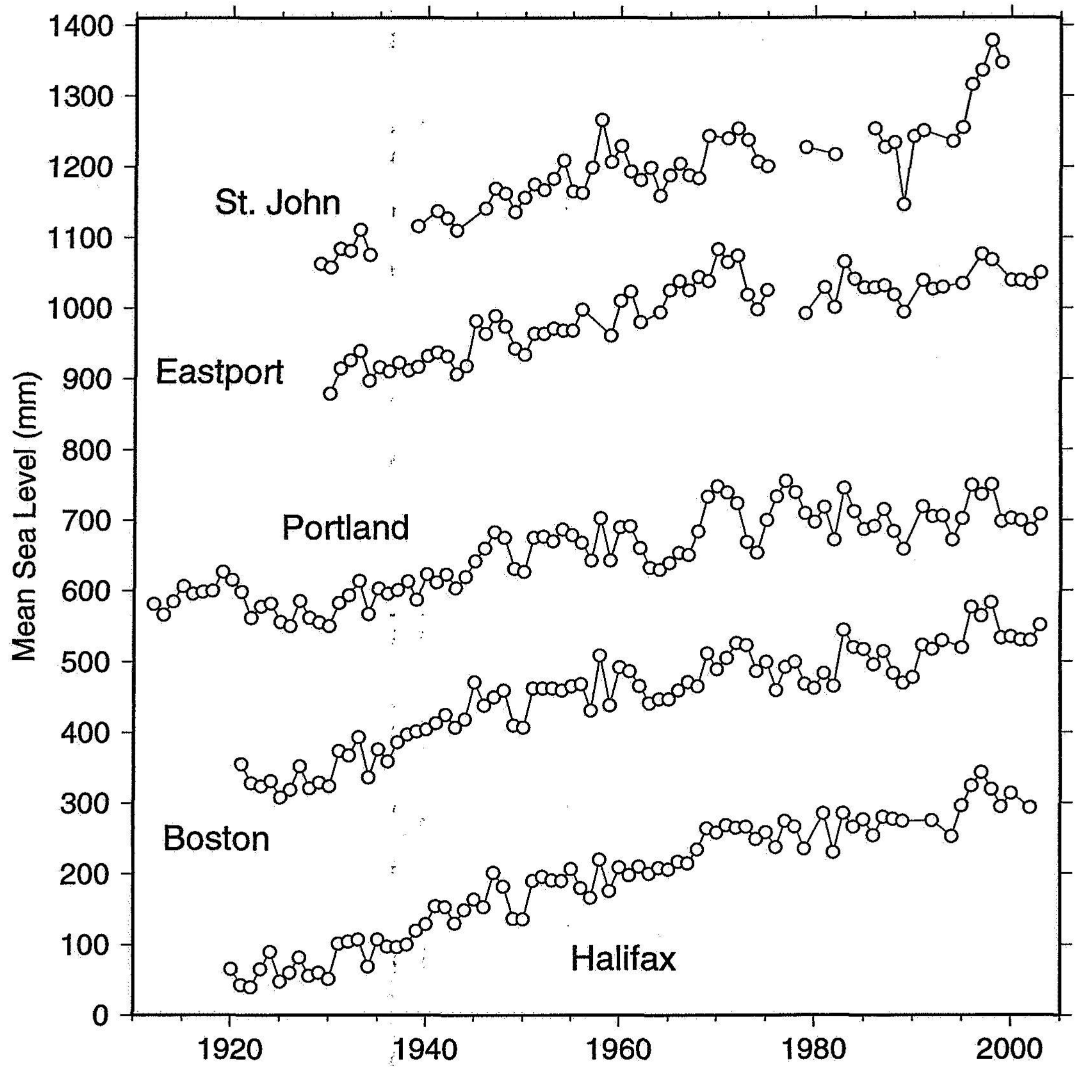

Fig. 5. Relative sea levels (annual means) at 5 tide-gauge stations. Least-squares estimates of trends are: 2.9 $\mathrm{mm\,y^{-1}}$ (St. John); 2.1 $\mathrm{mm\,y^{-1}}$ (Eastport); 1.8 $\mathrm{mm\,y^{-1}}$ (Portland); 2.6 $\mathrm{mm\,y^{-1}}$ (Boston); 3.4 $\mathrm{mm\,y^{-1}}$ (Halifax). Data provided by the Permanent Service for Mean Sea Level.