# Compilation of a Map of Recent Vertical Crustal Movements in Eastern Canada Using Geographic Information System

Azadeh Koohzare[1]; Petr Vaníček[2]; and Marcelo Santos[3]

**Abstract:** In this paper, we use geographic information system as a useful tool in compiling vertical crustal movement (VCM) over Eastern Canada. For modeling linear VCM, we employ tide gauge records and precise releveled segments, which reflect the glacial isostatic submergence of the coasts, as well as other global, regional, and local effects. The area of study is divided into two zones: Maritimes and South St. Lawrence zones. Piecewise polynomial surfaces of different orders are calculated by the method of least squares for each region to obtain representations of the recent vertical movements. This work provides the framework for multidisciplinary studies of geodynamics in the region, allowing different selection of zones for vertical crustal movements and simplifying the incorporation of more data in future investigations. We use ArcGIS to visualize the theoretical approaches, and to integrate and analyze different spatially distributed data. This powerful tool helps us to produce a more physically meaningful VCM map for the region. The map reflects the most significant geophysical phenomenon in the region, postglacial rebound, and it is in good agreement with the 2004 glacial isostatic adjustment model of Peltier [ICE-5G(VM2)].

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**CE Database subject headings:** Geographic information systems; Tidal water; Tides; Leveling; Dynamic models; Approximation methods; Mapping; Canada.

## Introduction

The work on the map of recent vertical crustal movements (VCM) for Canada got underway at the beginning of 1974 (Vaníček and Christodulids 1974) where the velocity surface was sought in terms of a two-dimensional algebraic polynomial in a unified map. Since then, considerably more data were gathered and this, together with additional insights into the nature of the data, led to new versions of the map of VCM. The problem of those works was that the order of the velocity surface would have to be too high to represent the needed details and this normally causes wild oscillations. A practical approach was suggested by Vaníček and Nagy (1981) in which the region was divided into overlapping zones of approximately the same size and the velocity surface was sought piecewise. The shapes of the zones were dictated by data distribution. The recompilation of the map of VCM was carried on by Carrera et al. (1991) in which more data were considered in addition to new insights into the nature of the data. Those studies had some limitations: First of all, the recorded data, analysis, and the subsequent reports cannot be updated. In addition, as the analysis results have been typically summarized in a report or tabular format, it is cumbersome to quickly identify geographic areas most likely to experience significant local impacts. Second, the shape of the zone should be controlled not only by distribution of data but also by other factors, most importantly geophysical characteristics of each region. With the introduction of geographic information system (GIS) technology, many of those limitations have been overcome and updating of databases can be performed quickly.

In this study, we show how effectively GIS is utilized in selection of suitable tide gauges for a differencing method to be carried out based on correlation matrices. Different thematic map layers, such as the geological map of Canada and the map of rivers, are converted to ArcGIS coverages (in *.shp format). Moreover, we use spatial analysis in ArcGIS for selecting geodetic data in Eastern Canada. We show how we divide Eastern Canada into the Maritimes zone and the South St. Lawrence River zone, and how a vertical velocity surface is produced. Smooth piecewise algebraic approximation is used to represent the vertical crustal movements in Eastern Canada in which the area is divided into zones based on the data distribution and the geophysical characteristic of each region. A simultaneous solution for the whole area is then obtained. [For details about the theory of smooth piecewise algebraic approximation, please see Koohzare et al. (2006)]. Inspection of these analyses leads to a more physically meaningful VCM for Canada.

The use of GIS in this study is an ongoing work. We are going to extend the work to the west of Canada and incorporate more data. The produced map is going to be compared with other VCM maps such as global positioning system (GPS) produced vertical velocities, as well as the map of gravity changes and the postglacial rebound map.

[1]Ph.D. Candidate, Dept. of Geodesy and Geomatics Engineering, Univ. of New Brunswick, P.O. Box 4400, Fredericton, N.B., Canada E3B 5A3 (corresponding author). E-mail: a.koohzare@unb.ca

[2]Professor Emeritus, Dept. of Geodesy and Geomatics Engineering, Univ. of New Brunswick, P.O. Box 4400, Fredericton, N.B., Canada E3B 5A3. E-mail: vanicek@unb.ca

[3]Associate Professor, Dept. of Geodesy and Geomatics Engineering, Univ. of New Brunswick, P.O. Box 4400, Fredericton, N.B., Canada E3B 5A3. E-mail: msantos@unb.ca

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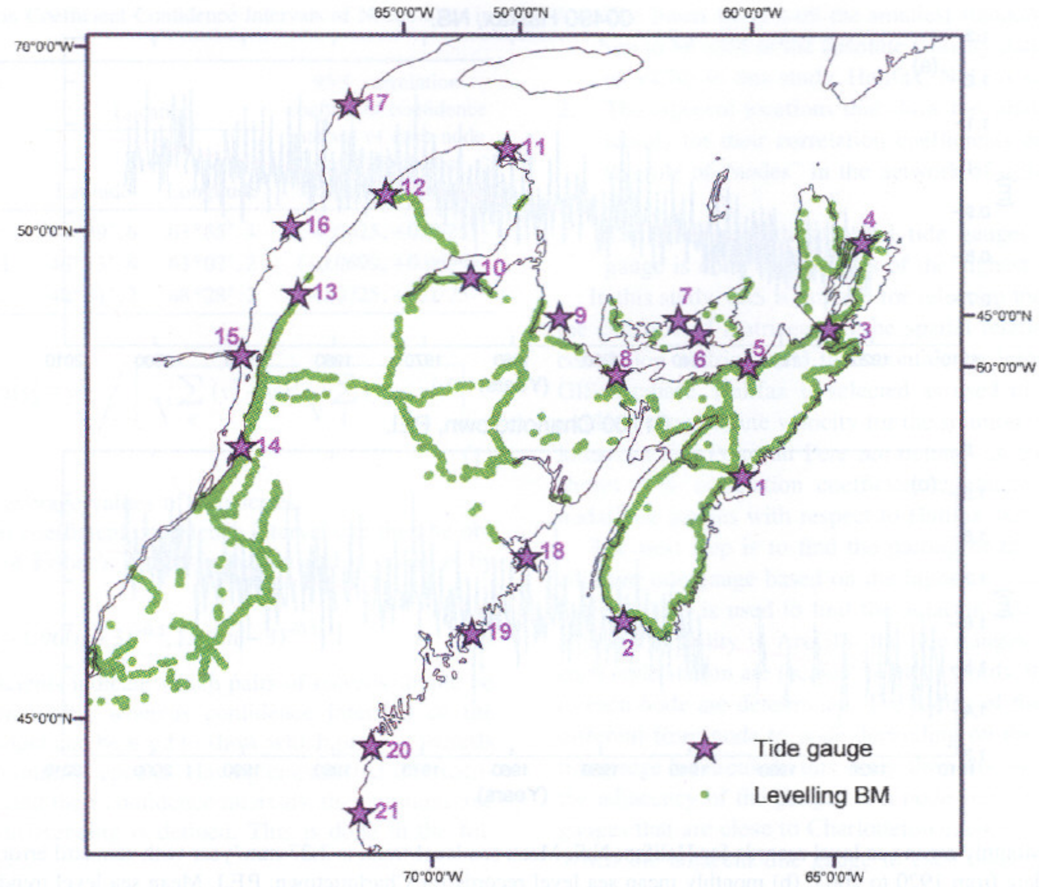


**Fig. 1.** (Color) Data distribution used in computations. Stars indicate location of tide gauges from which data are employed in analysis of secular sea level change. Releveled segments are shown by their leveling BMs.

## Sea Level Analysis in Eastern Coast of Canada

The analysis of the tide gauge records is based on monthly mean sea level data from 17 tide gauge stations on the eastern coast of Canada and four tide gauges on the United States coast (Fig. 1). Typically, monthly averages of sea level oscillate within the range of about 0.5 m throughout the years of observations (Vaníček and Carrera 1993). Since the linear trend we are interested in is a fraction of 1 cm/year, it is important to have records as long as possible. In the studies of vertical crustal motions, tide gauge records with longer time spans are more reliable. Sea level records with a duration of a few tens of years may not be taken as representative of the secular trends sought, if they are studied individually. However, when they are treated in a differenced mode, the secular variations can be accurately estimated. Therefore, the subset of sites is selected to include all stations for which continuous records of at least 10 years duration are available. The importance of applying this selection criterion is a consequence of the strength of the interannual variability, which must be averaged over if the secular variations are to be accurately estimated. Figs. 2(a and b) show the monthly mean sea level records of stations Halifax and Charlottetown which contain the longest records along the Atlantic coast and give the best standard deviations for the linear trend.

It is suspected that some local and regional effects such as plate tectonics, seasonal/interannual oceanographic effects, river discharge, and sedimental subsidence contaminate the records of tide gauges. All of these impacts have the potential to obscure or even hide the long-term eustatic and isostatic relative sea level changes, which are defined as the position and height of sea relative to the land. Therefore, the effects should be eliminated from the records of each individual tide gauge. Another alternative is that the contaminated records by the above impacts are rejected for the trend analysis. In this study, the second approach was considered. As an example, the records of Port aux Basques station in Newfoundland are depicted in Fig. 3. The records show an error throughout the years of 1935–1959 probably due to datum changes. For this reason, data from this period were rejected from the analysis.

There is another well documented feature of tide gauge records: their striking similarity when they are obtained at two close-by locations (Vaníček and Carrera 1993). This spatial coherence is caused by common atmospheric and oceanic noise. Clearly, a large portion of these variations disappears when the records are differenced. This behavior offers an alternative way of treating sea level trends in close-by tide gauges: a mean sea level trend of only one tide gauge is used as a point velocity at the absolute velocity for the map of VCM and the rest of the tide gauge records are differenced to obtain velocity differences. We compute the Pearson linear correlation coefficient for any pair of series to find the optimum network of tide gauges for differencing. Denoting the corresponding parts or the common epoch of the two series as $\mathbf{y}^i=(y_1^i,y_2^i,\dots,y_n^i)$ and $\mathbf{y}^j=(y_1^j,y_2^j,\dots,y_n^j)$, and $n$ the number of elements of each series, the correlation coefficients are given by Vaníček and Carrera (1993) as

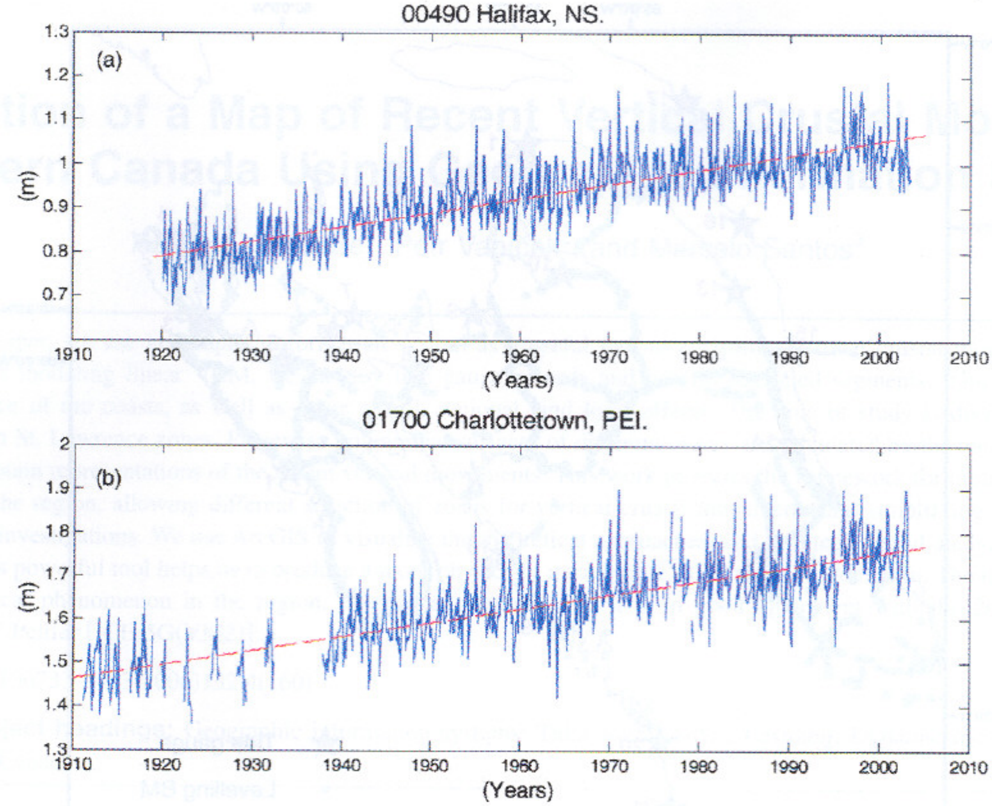


**Fig. 2.** (Color) (a) Monthly mean sea level records for Halifax, N.S. Mean sea level trend is 3.27 mm/year with standard error of 0.05 mm/year based on sea level data from 1920 to 2003; (b) monthly mean sea level records for Charlottetown, P.E.I. Mean sea level trend is 3.21 mm/year with standard error of 0.08 mm/year based on sea level data from 1911 to 2003.

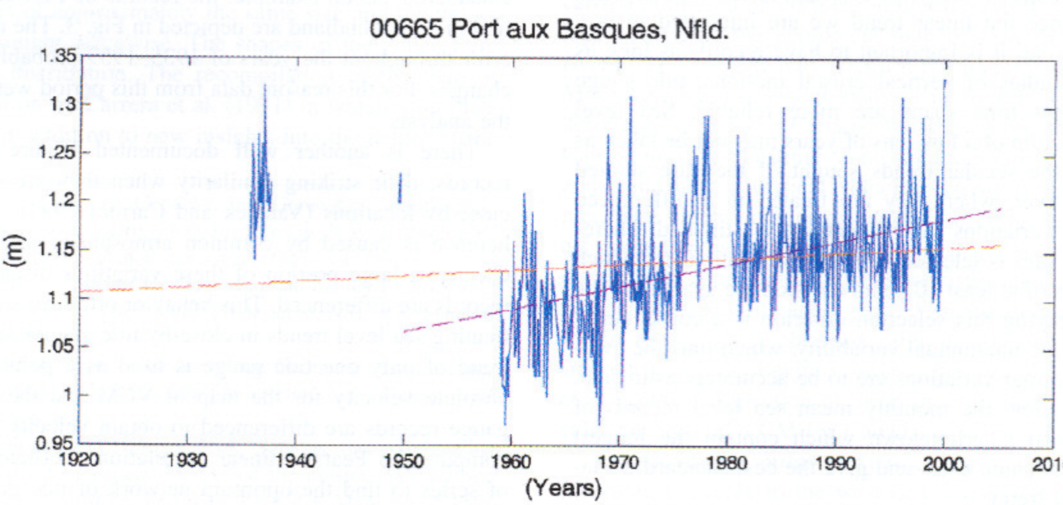


**Fig. 3.** (Color) Monthly mean sea level records for Port aux Basques, Que. Monthly mean sea level trend is 0.61 mm/year based on sea level data from 1935 to 2003. Records from 1935 to 1959 show an error, and are thus rejected in analysis. Monthly mean sea level trend is 2.34 mm/year based on new set of data (1985–2003).

**Table 1.** Correlation Coefficient Confidence Intervals of Nodes Sites in Eastern Canada

| Tide gauge | Location | | 95% correlation coefficient confidence interval of each node site with respect to Halifax record |
|---|---|---|---|
| | Latitude | Longitude | |
| Halifax, N.S. | 44°39′.6 | 63°35′.4 | ⟨−0.0625, +0.0625⟩ |
| Charlottetown, P.E.I. | 46°13′.8 | 63°07′.2 | ⟨−0.0699, +0.0699⟩ |
| Point au Pere, Que. | 48°31′.2 | 68°28′.2 | ⟨−0.0725, +0.0725⟩ |

$$r_{ij} = \sum_k (y_k^i - y^i)(y_k^j - y^j) \Bigg/ \left[ \sqrt{\sum_k (y_k^i - y^i)^2} \sqrt{\sum_k (y_k^j - y^j)^2} \right] \tag{1}$$

where $y^i$ and $y^j$ = average values of two series.

The correlation coefficient confidence interval can then be obtained by means of Fisher's $Z$ transformation and is given as by David (1949) as

$$\langle -1.96(n-3)^{-0.5}, 1.96(n-3)^{-0.5} \rangle \tag{2}$$

Correlation coefficients indicate which pairs of records should be differenced preferentially, whereas confidence intervals of the correlation coefficient can be used to show which pairs of records have the longest common epochs. Having constructed the matrices of correlation and their confidence intervals, the optimum tree diagram for the differencing is defined. This is done in the following three steps:

1. The linear trend with the smallest standard deviation is chosen to be used as the absolute velocity datum for the solution of VCM. In this study, Halifax, N.S., is selected;
2. The adjacent locations that show the smallest confidence intervals for their correlation coefficients are selected to play the role of "nodes" in the network of differenced velocities; and
3. The pairing of these nodal tide gauges and adjacent tide gauge is done on the basis of the highest correlations.

In this study, GIS is utilized for selecting the tide gauges using the constructed matrices and the spatial relationships. Using the correlation matrices and their confidence intervals added to the GIS database, Halifax is selected as used in the point velocity mode or the absolute velocity for the solution of VCM, and Charlottetown and Point au Pere are defined as node points. Table 1 shows 95% correlation coefficient confidence intervals of the nodal tide gauges with respect to Halifax station.

The next step is to find the pairing of these nodal sites with adjacent tide gauge based on the highest correlations.

First, GIS is used to find the adjacent tide gauges. Using the adjacency facility in ArcGIS, the tide gauges which are close to each node station are located. In other words, the closest $n$ gauges to each node are determined. The radius of the adjacency can be different from node to node depending on the distribution of the tide gauge locations. In this study, the value of 500 km was set for the adjacency of the gauges to a node site. Fig. 4 shows the tide gauges that are close to Charlottetown, considered as a node site. When the adjacent tide gauge to each node site is selected, the

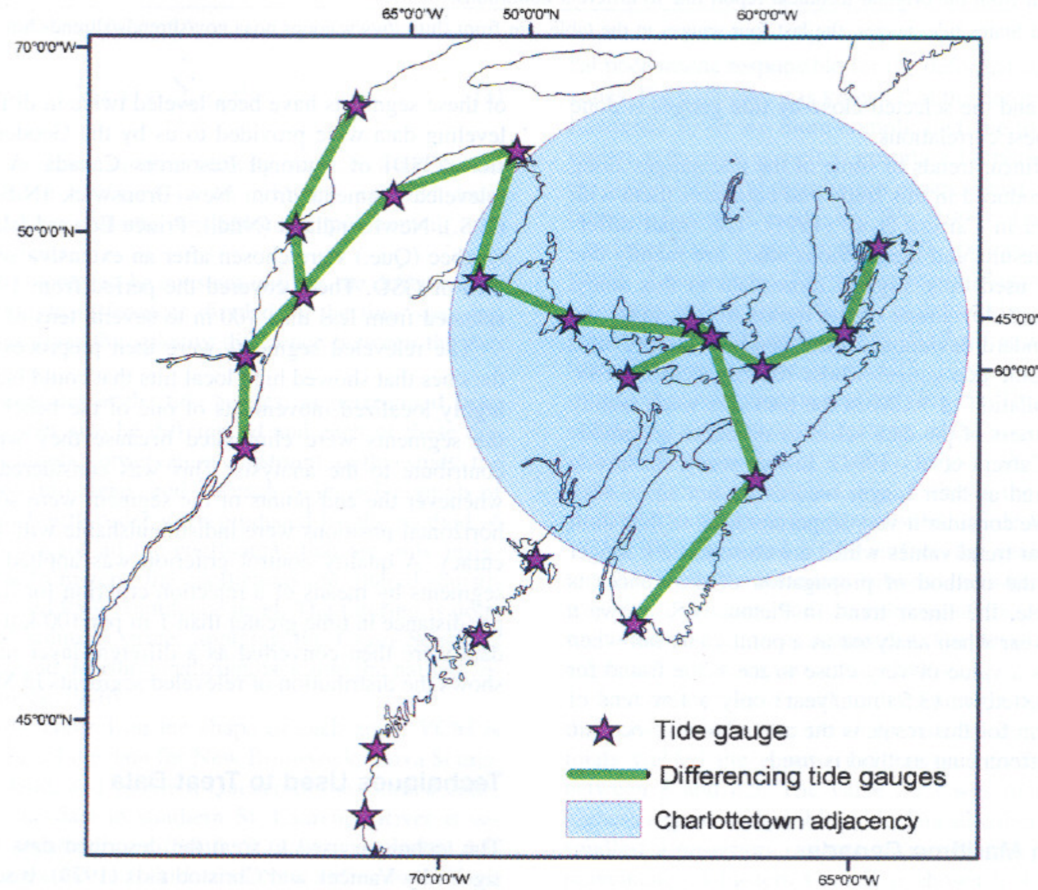


**Fig. 4.** (Color) Optimum tree diagram of tide gauges for differencing. Tide gauges inside circle boundary are adjacent to Charlottetown.

Table 2. Sea Level Linear Trends and Their Standard Deviations of Some of Tide Gauges in Atlantic Canada (in mm/year)

| Code | Tide gauge | Location: Latitude | Location: Longitude | Velocity based on differencing from Carrera et al. (1991)[a] (mm/year) | Data available for this study | Point velocity (mm/year) | Velocity based on differencing in this study (mm/year) |
|---|---|---|---|---|---|---|---|
| 1 | Halifax, N.S. | 44°39′.6 | 63°35′.4 | 3.56±0.08 | 1919–2003 | 3.27±0.05 | 3.27±0.05 |
| 2 | Yarmouth, N.S. | 43°50′.4 | 66°07′.2 | 4.75±0.35 | 1900–2003 | 2.85±0.15 | 4.17±0.18 |
| 3 | Point Tupper, N.S. | 45°06′.0 | 61°22′.2 | 4.31±0.79 | 1971–1992 | 1.67±0.70 | 3.12±0.80 |
| 4 | North Sydney, N.S. | 46°13′.2 | 60°15′.0 | 3.87±0.46 | 1970–2003 | 3.07±0.54 | 3.42±0.37 |
| 5 | Pictou, N.S. | 45°40′.8 | 62°42′.0 | 3.68±0.33 | 1957–1996 | 2.30±0.35 | 3.70±0.21 |
| 6 | Charlottetown, P.E.I. | 46°13′.8 | 63°07′.2 | 3.55±0.11 | 1905–2003 | 3.21±0.08 | 3.30±0.09 |
| 7 | Rustico, P.E.I. | 46°28′.2 | 63°16′.8 | 3.28±0.47 | 1972–1996 | 3.92±0.68 | 3.92±0.68 |
| 8 | Shediac Bay, N.B. | 46°15′.0 | 64°31′.8 | — | 1971–1992 | 1.23±0.16 | 2.50±0.14 |
| 9 | Lower Escuminac, Que. | 47°04′.8 | 64°53′.4 | 2.12±0.48 | 1973–2003 | 1.98±0.66 | 2.10±0.31 |
| 10 | Bellendume, N.B. | 47°54′.0 | 65°51′.0 | — | 1964–2003 | 1.41±0.98 | 1.09±0.12 |
| 11 | Riviere au Renard, Que. | 48°58′.8 | 64°22′.2 | −0.32±0.77 | 1969–2003 | −0.49±0.16 | −0.32±0.15 |
| 12 | St. Anne des Monts, Que. | 49°07′.2 | 66°28′.8 | −0.55±0.60 | 1967–1997 | −0.89±0.44 | −0.40±0.49 |
| 13 | Point au Pere, Que. | 48°31′.2 | 68°28′.2 | −0.10±0.16 | 1900–2003 | −0.31±0.07 | −0.31±0.07 |
| 14 | St. Jean Port Joli, Que. | 47°13′.2 | 70°16′.8 | −0.88±1.65 | 1968–1980 | −5.38±2.18 | −0.88±1.64 |
| 15 | Tadoussac, Que. | 48°08′.4 | 69°42′.6 | −1.21±0.80 | 1966–1995 | −5.08±0.62 | −1.21±0.21 |
| 16 | Baie Comeau, Que. | 49°13′.8 | 68°07′.8 | −0.62±0.47 | 1964–1991 | −5.77±0.72 | −0.62±0.31 |
| 17 | Sept Illes, Que. | 50°10′.8 | 66°22′.2 | 1.87±0.41 | 1972–2003 | 2.01±0.25 | 0.19±0.11 |
| 18 | Eastport, Me.[b] | 44°54′.2 | 66°59′.1 | — | 1929–1999 | 2.21±0.13 | — |
| 19 | Bar Harbour, Me. | 44°23′.5 | 68°12′.3 | — | 1947–1999 | 2.18±0.16 | — |
| 20 | Portland, Me. | 43°43′.8 | 70°12′.4 | — | 1912–1999 | 1.91±0.09 | — |
| 21 | Seavey Island, Me. | 43°05′.0 | 70°44′.0 | — | 1926–1999 | 1.75±0.17 | — |

[a]The signs are different from the original technical report due to different definitions.

[b]The values for United States tide gauges, the last four gauges in the table, are from ⟨http://www.coops.noaa.gov/sltrends/sltrends.html⟩.

pairing of the node and the selected close-by tide gauges is done on the basis of highest correlations.

Table 2 lists the linear trends of some of the tide gauges along the Atlantic coast produced in this study and compares them with the results published in Carrera et al. (1991). The small differences between our results and the previous study are mainly due to the fact that we used only slightly more data in this study. However, the standard deviations of the trends in this study are smaller than the standard deviations of the trends in the previous studies. There are some tide gauges whose records were not considered in the compilation of VCM in the previous work mainly because of the shortness of the data series or probable systematic errors reported in Carrera et al. (1991). In this study, those tide gauges are considered as their longer records do not show such systematic errors. We consider it very important to note that short records display linear trend values which are close to their longer counterparts when the method of propagation of differences is used. As an example, the linear trend in Pictou, N.S. shows a value of 2.30 mm/year when analyzed as a point value but when differenced acquires a value of very close to the value found for the gauge in Charlottetown (3.53 mm/year) only a few tens of km away. The reason for this result is the attenuation of oceanic signals when the differencing method is used.

## Leveling Data in Maritime Canada

Two adjacent permanent benchmarks, whose height difference is established using geodetic leveling, constitute a segment. Many of these segments have been leveled twice in different years. The leveling data were provided to us by the Geodetic Survey Division (GSD) of National Resources Canada. A total of 14,168 releveled segments from New Brunswick (N.B.), Nova Scotia (N.S.), Newfoundland (Nfld.), Prince Edward Island (P.E.I.), and Quebec (Que.) were chosen after an extensive search of the data files of GSD. These covered the period from 1909 to 2003 and spanned from less than 100 m to several tens of kilometers.

The releveled segments were then preprocessed to eliminate the ones that showed high local tilts that could have resulted from highly localized movements of one of the benchmarks. Some of the segments were eliminated because they were too short to contribute to the analysis. This was considered to be the case whenever the end points of the segment were so close that their horizontal positions were indistinguishable with the available accuracy. A quality control criterion was applied to all releveled segments by means of a rejection criterion for height differences per distance in time greater than 1 m per 100 km per century. The data were then converted as a different layer in ArcGIS. Fig. 1 shows the distribution of releveled segments in Maritime Canada.

## Techniques Used to Treat Data

The technique used to treat the described data was the one designed by Vaníček and Christodulids (1974). It seeks the velocity surface in terms of a two-dimensional algebraic polynomial of the form

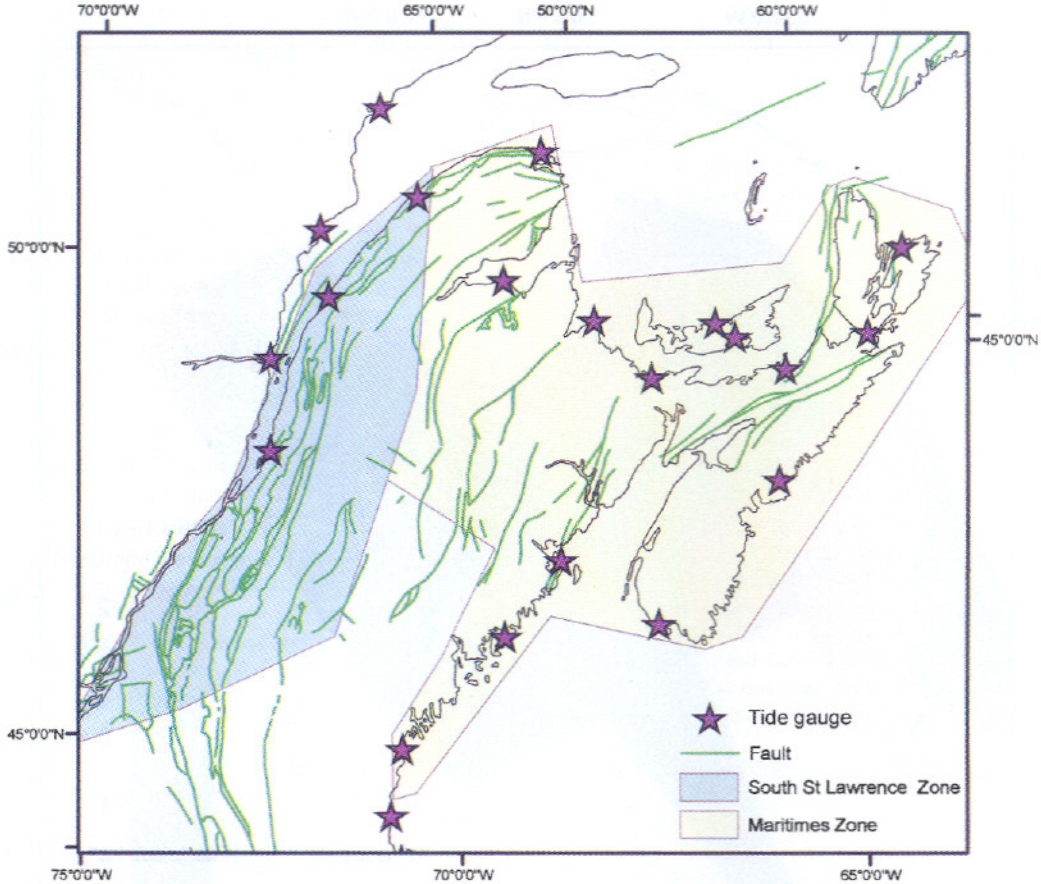


**Fig. 5.** (Color) Polygonal subdivision used to compute partial solutions describing trends of vertical crust movements

$$V(x,y) = \sum_{i,j=0}^{n} c_{ij} x^i y^i \tag{3}$$

where $V$=algebraic least squares velocity surface, fitted to the desired data located at $(x,y)$ in an arbitrary selected local horizontal coordinate system; $n$=degree of polynomial; and $c_{ij}$=sought coefficients.

Assuming the velocity to be constant in time, the difference of the two leveled height differences divided by the time span between the leveling gives the velocity difference between the two end benchmarks.

The crustal velocities at the tide gauges, as determined from sea level records, can also be differenced and each of these differences provides another observation constraint. In this study, the territory is divided into zones, and for each zone, polynomials of second, third, and fourth order were produced by the method of least squares. To discard all the coefficients that are only insignificantly different from zero, the coefficients are filtered statistically on a preselected 95% confidence level. The filtering is done in the orthogonal solution space, applying the Gram–Schmid's orthogonalization, and deorthogonalizing back into the natural solution space (Vaníček 1976).

In order to have control on the shape of each zone, VCM is first produced using all the data for New Brunswick, Nova Scotia, Prince Edward Island, and southern Quebec in one unified zone. In the next step, the data in southern St. Laurence River is selected to form a separate zone (South St. Lawrence zone). Another zone embodies the rest of data in New Brunswick, Nova Scotia, and Prince Edward Island (Maritimes zone). The importance of such selection is the consequence of different geophysical phenomena responsible for the deformation of the crust in two zones. For example, it is known that the deformations in South St. Lawrence River are more complicated due to the tectonic contribution in the area as well as postglacial rebound. For details about the spatio-temporal distribution of stress and changes in fault stability in Eastern Canada, see Wu (1998). The estuary of the St. Lawrence River is an area where 50–100 earthquakes are detected yearly (Lamontagne 2003). The region, known as the Lower St. Lawrence seismic zone (LSZ), is defined by spatial clustering of magnitude $(M) < 5$ earthquakes (Basham et al. 1985). The selection of zones is done in ArcGIS. First, the areas with similar geophysical behavior are marked (Fig. 5). This is done by looking at the map of geophysical features in the area, such as the map of geological faults. Using spatial analysis, the data inside the selected region are analyzed. Fig. 5 shows the polygonal subdivision used to compute the partial solutions describing the trends of VCM. The estimated VCM surface for each zone is then tied together along the boundary between the adjacent zones in such a way that continuity and smoothness of the surface from the simultaneous solution is guaranteed. For details of the mathematical model see Koohzare et al. (2006).

Several tests were made to determine the appropriate degree of the velocity surface to be computed. All degrees of the polynomials yielded the a posteriori variance factor equal to a value between 8 and 8.5. The value $n=3$ was finally selected as the highest degree compatible with data distribution and having the smallest a posteriori variance factor. The map of vertical crustal movements in Eastern Canada is shown in Fig. 6. The standard deviation of the estimated VCM for the area of interest is typically 1.4 mm/year (Koohzare et al. 2006).

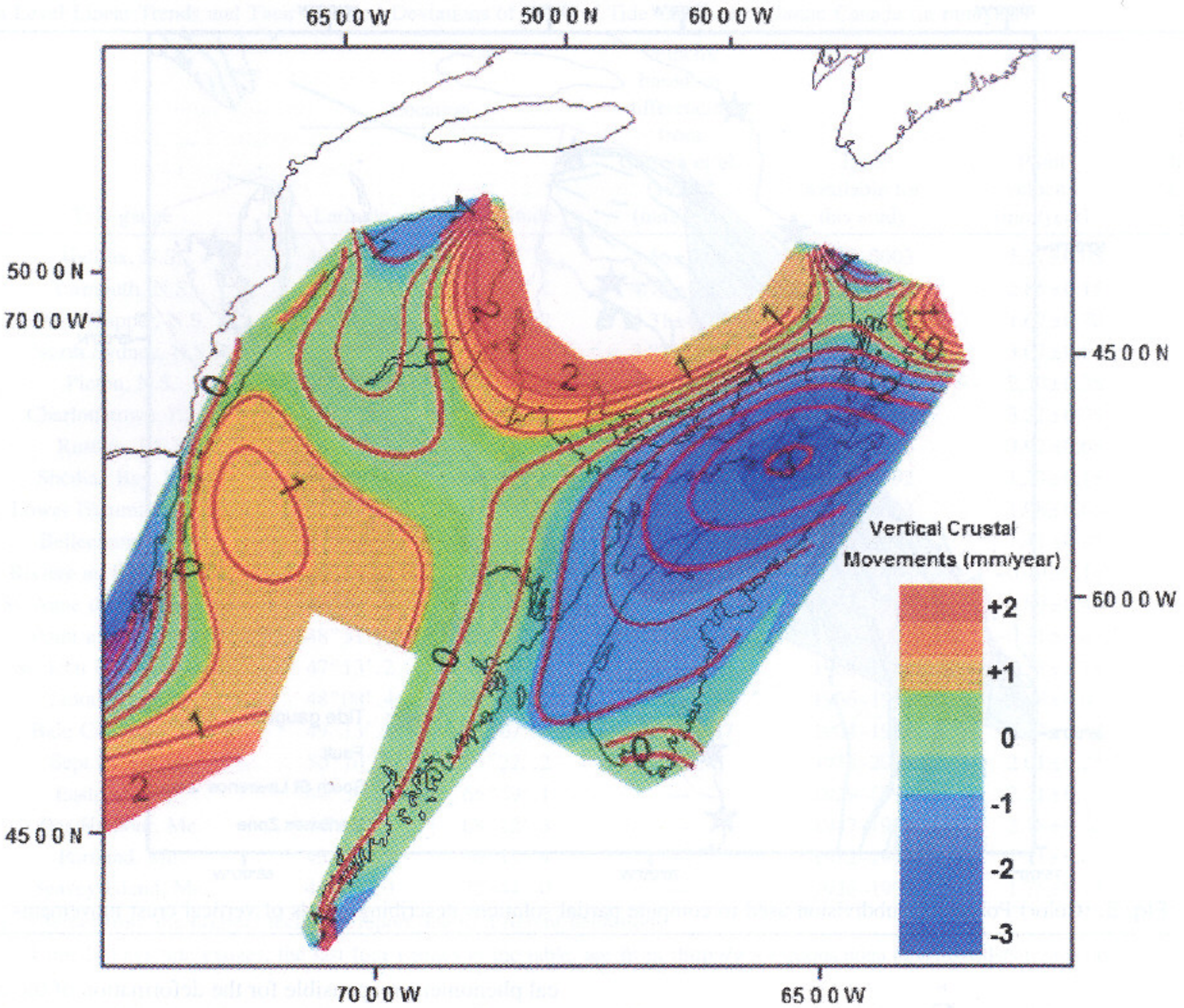


**Fig. 6.** (Color) Pattern of vertical crustal movements in Eastern Canada. Contours are in millimeters/year.

## Discussion

The analysis of relative sea level records demonstrates that the records contain some local contaminants such as river discharge and sediment subsidence as well as regional and global effects of plate tectonics and glacial isostatic adjustment (GIA). Using the differencing method, we reduce the effect of long-term oceanic noises. The results given in Table 1 show an average of change in relative sea level of +3 mm/year obtained from most tide gauges along the Atlantic coast. Subtracting the change from globally averaged sea level contribution of +1.8 mm/year (Douglas 1991), the postglacial related signal of relative sea level records varies between +1 and +2 mm/year for the stations along Atlantic Canada. These values are comparable with the sea level history obtained from the GIA models (Peltier 2001). The apparent sea level rise left after removal of the global eustatic signal may represent a vertical motion of the crust of the same magnitude but opposite sign.

The map of the crustal movements is shown in Fig. 6. The solution is evidently much generalized. The map shown in Fig. 6 depicts clearly the zero line of the postglacial rebound which follows the St. Lawrence River. This is supported by the fact that this zero line has a continuation in the Great Lakes area in the west of St. Lawrence River and in longer comparisons is consistent with GIA models. Another second zero line which passes through New Brunswick Province and follows the tide gauges in Maine is thought to reflect the local changes of the crust and is mostly resulted from the tide gauge trends in Maine with small standard deviations. Present-day radial displacement predictions due to postglacial rebound over North America computed using the VM2 earth model and ICE-5G adopted ice history show a zero line very similar to ours along the St. Lawrence River [see Peltier (2004) for ICE-5G model predictions]. The general Northwest Southeast trend of vertical crustal movements is consistent with the predictions of GIA models.

With respect to the individual features on the map, the subsidence in the Maritimes, predominantly in Nova Scotia and eastern New Brunswick, is due to postglacial rebound. This area lies immediately outward of the region that was covered by the Laurentide ice sheet at the last glacial maximum (LGM) [see Peltier (1996) for maps of surface ice cover from LGM to present]. As the Laurentian ice started to retreat, this so called fore-bulge area began to collapse to compensate for the uplift in the central region of rebounding (Peltier 1996). The map of VCM in this area reflects this phenomenon and is also compatible with the recent map of gravity changes [see Pagiatakis and Salib (2003) for the map of gravity changes].

The vertical crustal movement pattern shown in the south part of the St. Lawrence River reflects the concentration of siesmicity in this area [see Lamontagne (2003) for the map of siesmicity in Lower St. Lawrence seismic zone], which opens new doors into the study of geodynamics of this complex area.

The earlier reported uplift of the northern New Brunswick and the subsidence of the South St. Lawrence River (Carrera et al. 1991) are here more sharply defined.

## Conclusion

An analysis of the tide gauge records demonstrated that the records contain some local contaminants such as river discharge and sediment subsidence as well as regional and global effects of plate tectonics and GIA. When the method of propagation of differences is used, the effect of long-term oceanic noises is reduced. The results showed an average of change in relative mean sea level of +3 mm/year obtained from most tide gauges along the Atlantic coast. Subtracting the change from globally averaged sea level contribution, the postglacial related signal varies between +1 and +2 mm/year for the stations along Atlantic Canada. The map of vertical crustal movements produced in this study is in good agreement with the results of postglacial rebound models [see Peltier (2004) for the map of radial displacements due to postglacial rebound].

GIS was utilized in different stages of the study. GIS is the solution for making such studies a dynamic proposition. Since all data, including precise leveling data and tide gauge trends, has been organized in GIS databases they can be easily updated. Therefore, other sources of information, which may come during the course of our research, can be added for more intensive studies. GIS not only made it easier to select the data visually, but it also offered a powerful tool to control the shape of the zones easily. Consequently, a more geophysically meaningful map of VCM was computed for the region.

## Acknowledgments

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## Notation

*The following symbols are used in this paper:*

$r$ = correlation coefficients;
$V$ = velocity surface; and
$\mathbf{y}$ = corresponding parts of two series of adjacent tide gauges.

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