Glacial Isostatic Adjustment Observed using Historical Tide Gauge Records and Precise Re-levelling Data in Eastern Canada

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Introduction

In Canada, the most significant geophysical process that has an evident effect in the shape of the viscoelastic earth is Glacial Isostatic Adjustment (GIA). During the last major glaciation event, immense masses of ice accumulated over regions of North America, causing subsidence of the Earth's crust in the regions, which were ice covered, and uplift in peripheral regions. When this ice has melted during the last 20,000 years, the viscoelastic rebounding of the crust in the ice covered regions started and has been ongoing since.

Intensive researches have being done to formulate the global theory of GIA and improve it either by modifying the Earth rheology parameters [e.g., Peltier, 1998 and Wu, 1999] or by implementing different computational methods. [e.g., Le Meur and Hindmarsh, 2000]. Parallel to these developments, the long period and small steady deformations of the crust due to GIA have being detectable by precise geodetic observations. However, the main problem with observed geodetic variations is that of the time-scale. Geodetic observations can reveal the variations of the shape and the gravity field of the Earth over relatively short time intervals, i.e. several decades, while postglacial rebound has been ongoing on time scale of years. Another problem is that of interpretation: How much of the observed changes is due to GIA process? How can we interpret them in terms of different earth parameters, lithosphere thickness, and the ice sheet history?

Geodetic Observations and Methodologies

In this study, we employ monthly mean sea level records of the tide gauges in eastern Canada to detect the glacial isostatic adjustment. After removing the probable errors in the records, monthly mean sea level linear trends for each individual tide gauge is determined. However, we cannot use them directly to model Vertical Crustal Movements (VCM) because of some regional noises in the records. In order to reduce the common effects, differencing method is used. The method is based on the fact that due to a high degree of coherence between sea level variations at close-by sites, a large portion of these variations disappears when the records are differenced: use only one trend value as a point velocity input and difference the rest to obtain velocity differences. (Vaníček et al. 1993)

The regional correlation matrices and correlation coefficient confidence intervals are constructed to select the optimal pairing of the sites, i.e., a tree diagram for optimal differencing that gives the most precise and accurate velocity differences.

Denoting the corresponding parts of the two series of monthly mean records as:

$\mathbf{y}^i = (y_1^i, y_2^i, ..., y_n^i)$ and $\mathbf{y}^j = (y_1^j, y_2^j, ..., y_n^j)$ n: number of elements of each series

The correlation coefficients are given by Vaníček et al., 1993 as

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

where $\bar{y}^i$ and $\bar{y}^j$ are the 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 (ibid)

$$< -1.96(n-3)^{-0.5}, 1.96(n-3)^{-0.5} > \quad (2)$$

Results

Having constructed the correlation matrices, "Halifax" with the smallest standard deviation in its linear trend is used in the point velocity mode. "Charlettown", "Point au pre", "St Johns", and "Harrington" sites, with the smallest confidence intervals for their correlation coefficients, play a role of nodes, and the pairing of these nodal tide gauge and adjacent tide gauges is done on the base of highest correlation. Figure 1 shows the optimum topology for the tide gauge differencing.

Special attention is also paid to the contribution of other vertical movement effects such as, plate tectonic and sediment subsidence. Eustatic water rise is then removed from the records to obtain the postglacial rebound signal.

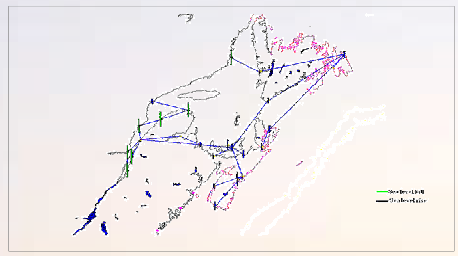

Figure 1: Topology of tide gauge differencing in eastern Canada, along with the profile of sea level changes.

Figure 1 also depicts the profile of sea level changes in eastern Canada. This region lies immediately outside of the Laurentide Ice covered area at the last glacial maximum. As the ice sheet began to decay, the forebulge began to collapse. Therefore, the geodetic data in this region primarily shows the glacial isostatic submergence.

The analyses of tide gauge records illustrated in figure 1 shows a relatively uniform sea level fall along St Lawrence river. Therefore, the zero line of the postglacial rebound must follow the ST Lawrence river. However, more studies should be done to locate the zero line. Present-day radial displacement predictions due to PGR over North America computed using ICE-3 G adopted ice history [Mitrovica et al. 1994] and the analysis of time rate of change of gravity [Pagiatakis, 2003] show a zero line similar to ours along the St. Lawrence River.

Figure 2 shows the tide gauge rates as pluses and the theoretically predicted rates using the ICE-4G (VM2) model (Peltier, 2001) from tide gauges along eastern coast of Canada.

Of utmost interest in these analyses, and a property of these data sets, is the extent to which the ICE-4G model and tide gauge measurements track one another across the 7-degree of latitude spanned by them. It is also clear from the figure that in the region with water rise, there is higher correlation between tide gauge trends and relative sea level (RSL) from ICE-4G (VM2) model, whereas for sites with water fall, (mainly along St. Lawrence), other effects such as plate tectonic may contribute in vertical movements.

Precise relevelled sections in Maritime Provinces have also being used to compute the time variations of the regional tilt.

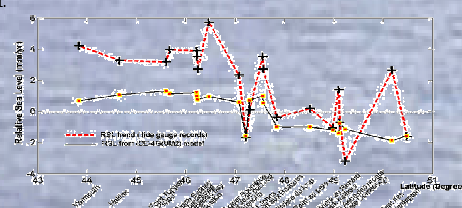

Figure 2: Present day rates of relative sea level change based on tide gauge records (short dashed line) and theoretically predicted rates using the ICE-4G deglaciation history and VM2 structure (solid line).

Conclusions

The analysis conducted for this paper provides some indication into the usefulness of geodetic observations in evaluation of postglacial rebound models and provides us with important insight to model VCM.

Acknowledgments

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