Evaluating Rates and Pattern of Glacial Isostatic Adjustment (GIA) in the Lake Superior Region

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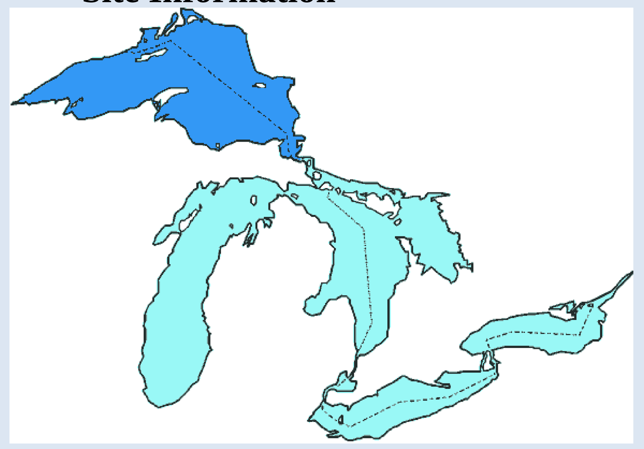
1. Abstract

The motion of the ground beneath and adjacent to Lake Superior continues to be influenced by the long-gone Laurentian Ice Sheet. The rate and pattern of vertical ground movement, glacial isostatic adjustment (GIA), is related to many factors that include variations in ice thickness and duration during the oscillatory retreat of the Laurentian Ice Sheet. Many previous research projects have recorded data of, or associated with, GIA by various methods; however, considering the different time periods examined by different research projects, the accuracy and consistency of these data is unknown. Hence, these data need to be analyzed and compiled to provide one view of GIA near Lake Superior. Here we present data collected from two sources, global positioning system (GPS), lake level gauges. Published rates of GIA from GPS stations surrounding Lake Superior were selected from a dataset covering North America. These data were then plotted and contoured to derive a rate and pattern of GIA based upon GPS data spanning recent decades. Water level gauge data for Lake Superior was updated from 2006 and reanalyzed following methods used in the most recent International Upper Great Lakes Study. This provided a view of GIA based upon water level gauge data that extended many decades before GPS data. After each source was analyzed independently, these two results were then compared between each other. For future work, these results can be compared with a rate and pattern of GIA provided by analyzing ancient shorelines or strandplains of beach ridges that are several millennia old adjacent to Lake Superior.

2. Introduction

- **Site Information**



During the Pleistocene epoch of the Quaternary period the Laurentide Ice Sheet oscillated multiple times across the Great Lakes. The most recent major ice advance is called the Wisconsinan glaciation and reached its maximum extent approximately 20,000 years ago. A minor advance of an ice lobe of the Laurentide Ice Sheet occurred around 10,000 years ago in the Lake Superior basin. Since then, the ground surface near the Lake Superior region has been (and is still) adjusting from ice unloading. This is called GIA.

- **Background**

Data			Scale	Date	Methodology
GPS	Sella et al	*Observation of glacial isostatic adjustment in "stable" North America with GPS*	North America	2007	Only GPS
	Peltier et al.	Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model	North America, Northwestern Europe/Eurasia, and Antarctica	2015	GPS data used in model
Lake Level Gauges	Mainville & Craymer	Present-day tilting of the Great Lakes region based on water level gauges	The Great Lakes	2005	Water level difference plots
	Bruxer & Southam	Review of Apparent Vertical Movement Rates in the Great Lakes Region	The Great Lakes	2006	
Shore-lines	Johnston et al.	A Sault-outlet-referenced mid-to late-Holocene paleohydrograph for Lake Superior constructed from strandplains of beach ridges	Lake Superior	2012	paleohydrograph difference plots

3. Methods

- **GPS Data**

Contour data from Peltier et al. (2015) to create an isobase profile map with contour interval of 0.5mm/year

- **Water Level Gauges Data**

Bruxer and Southam (2006) updated the rates and GIA analyses to 2006, we updated to 2015 using the same methods.

✓ Collect data from the Canadian Hydrographic Service and the U.S. National Ocean Service.

✓ Converting water level data into relative rates of vertical ground movement to Point Iroquois by plotting water level difference plots

7. References

Bruxer, J., & Southam, C. (2008). Review of Apparent Vertical Movement Rates in the Great Lakes Region. *Burlington, ON.*;

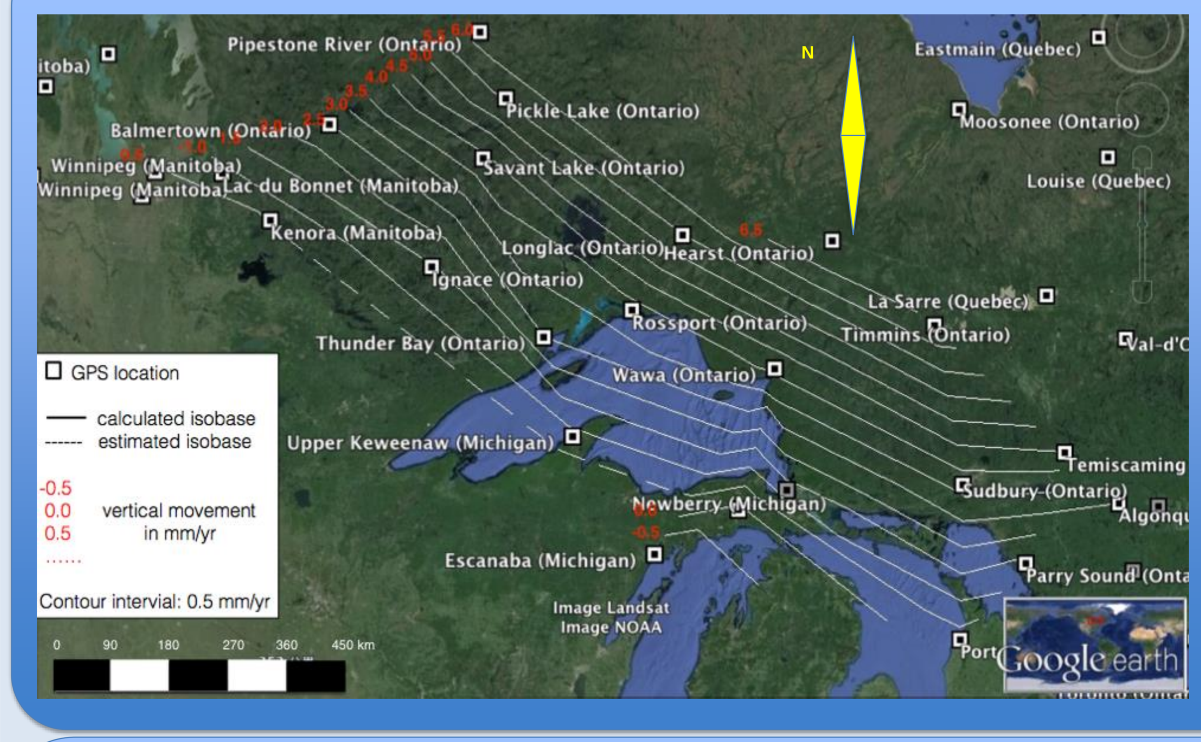
Tushingham, A.M., and Peltier, W.R. (1991). ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. *Journal of Geophysical Research*, v. 96, p. 4497–4523.

Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*, *120*(1), 450-487.

Johnston, J. W., Argyilan, E. P., Thompson, T. A., Baedke, S. J., Lepper, K., Wilcox, D. A., & Forman, S. L. (2012). A Sault-outlet-referenced mid-to late-Holocene paleohydrograph for Lake Superior constructed from strandplains of beach ridges. *Canadian Journal of Earth Sciences*, *49*(11), 1263-1279.

4. Results

- **GPS Data**



✓ Rate:

Range: lowest: ≤-0.9mm/yr; highest: 3.6mm/yr

Difference = 4.5mm/yr

⇒100 year = rise 36cm, drop 9cm = till 45cm

✓ Pattern:

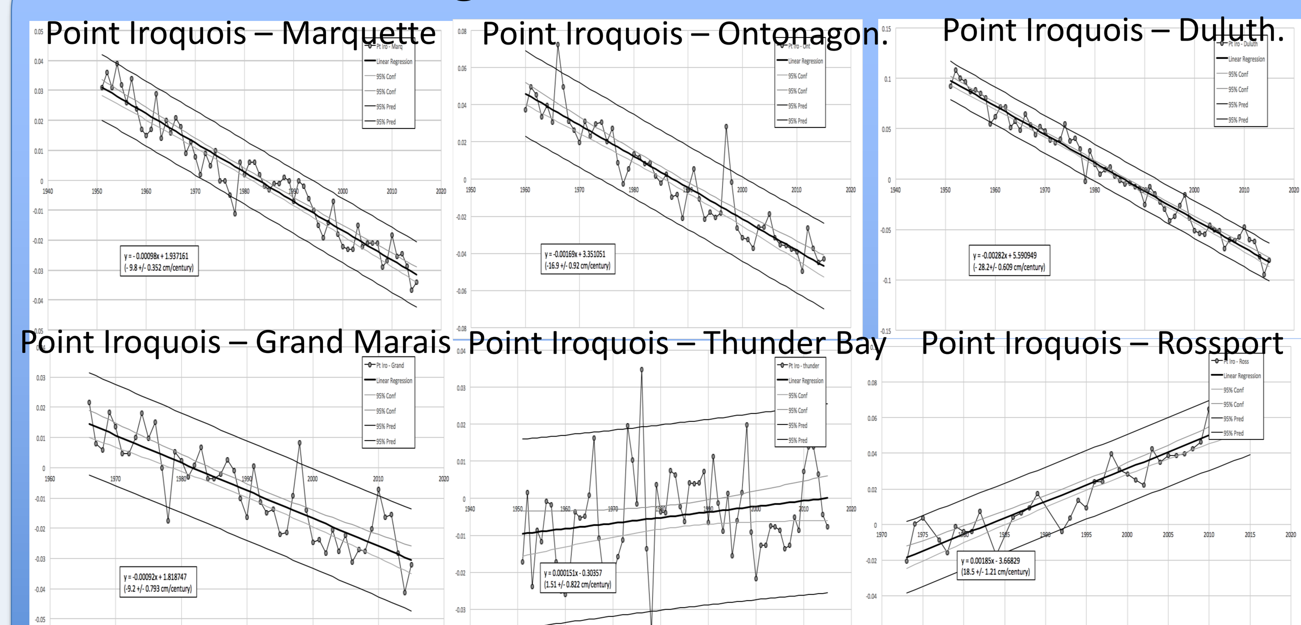
Highest rate: north-east; lowest rate; south-west

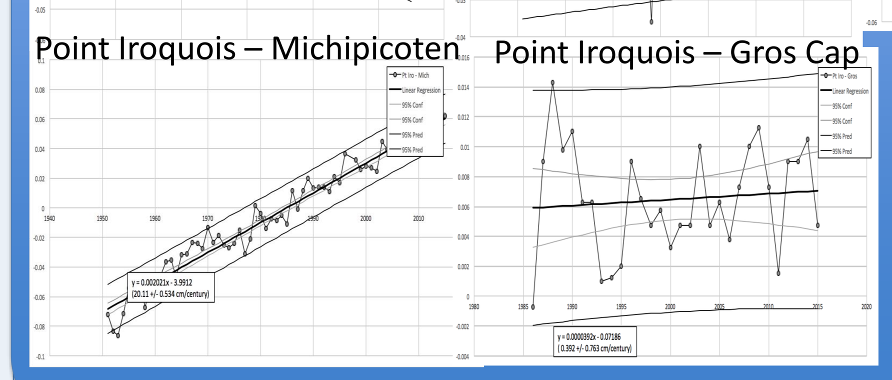
Rate gradient: 4.5mm/yr / 223.65km = 0.02(mm/yr)/km.

The isobase lines: 65.81° SE (i.e. strikes 114.19° N).

⇒100km along the direction that perpendicular to the isobase lines = rate change 2mm/yr.

- **Water Level Gauges Data**

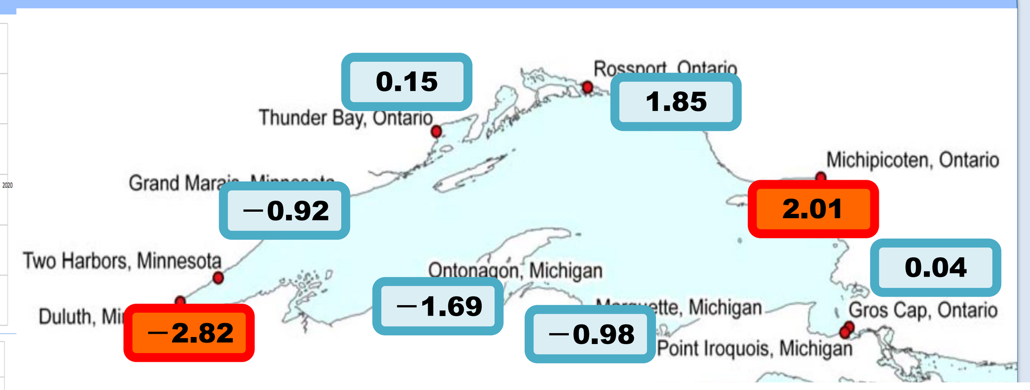




Water level difference plot relative to Point Iroquois, the closest station to outlet

Note: the plots are removed variable data

The relative rate to Point Iroquois = slope



Water level gauge stations with relative rates to Pint Iroquois labeled

Maximum subsidence: southwest end, -2.82mm/yr

Maximum uplift: northeast end, 2.01mm/yr

Rate difference: 4.83mm/yr

Rate gradient: 0.0117(mm/yr)/km (100km-->1.17mm/yr)

6. Conclusion and Recommendation

- **Conclusion**

For GPS data, the rates and pattern are summarized in an isobase profile map. For water level gauges data, the rates are obtained by water level difference plots relative to Point Iroquois, and the pattern is obtained by plotting all the water level stations onto the map of this region. Comparison between the two series of rates and pattern shows relative similarity. The potential reasons are provided in the discussion part. Although there is slightly difference between the two results obtained from the two datasets, the results are statistically similar with each other for the majority of observations. For this reason, both of the two datasets and the two results of GIA are considered to be reasonable and reliable.

- **Recommendation**

→First of all, in terms of shoreline data collected from Johnston et al (2012), other methods need to be explored to evaluate the paleohydrographs for GIA analysis. Also, analysis results by shoreline data should be compared with the results obtained from GPS data and water level gauges data.

→Secondly, considering there are only nine water level gauge stations surrounding Lake Superior, more stations could be installed to obtain more data for GIA analysis. Also, for GPS data, because of no observation in the southwest part of Lake Superior, we can only estimate some isobases during construction of the isobase profile map. Hence, more GPS observation sites are recommended to install in the southwest part of the lake.

→Lastly, future research could aim at constructing a suitable model instead of linear regression to understand rate change spatially for GPS data and temporally for water level differences.

5. Discussion

- **GPS Data**

There are several reasons that may cause error and inaccuracy.

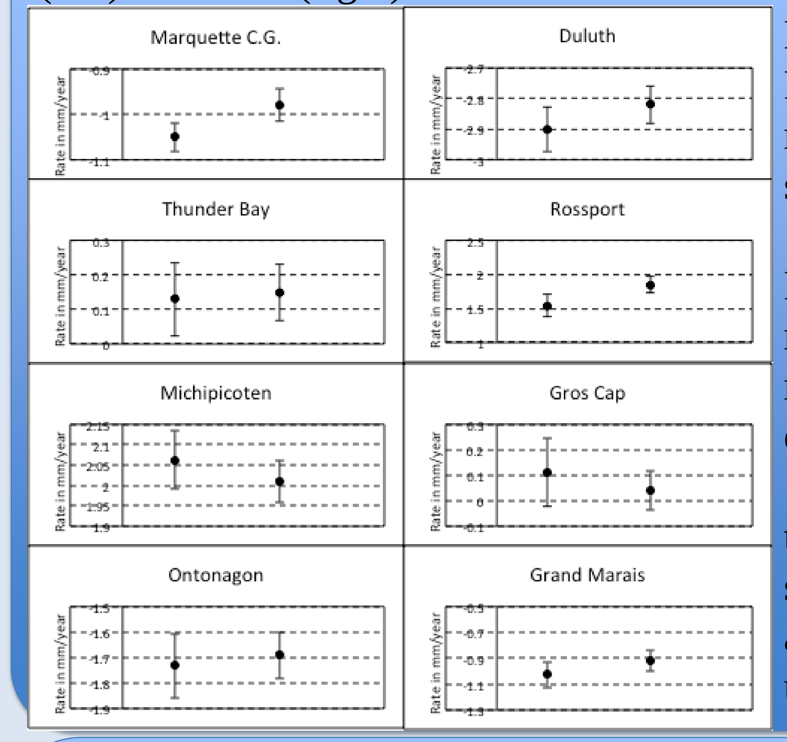
✓ Because the data is limited spatially, the error can be caused by the estimated isobase lines.

✓ The points with 0.5n (n=-1,0,1,2,3,…) mm/yr are determined by considering the rate change is linear.

✓ Since the Laurentian Ice Sheet has been gone for a long time, we consider that during historical time the rate is close to be a constant over time (linear); however, actually, the rate should slightly decrease over time in an exponential function.

- **Water Level Gauges Data**

Comparing rates of GIA between data updated to 2006 (left) and 2015 (right).



→except Marquette and Rossport, the error ranges for the other stations overlap.

→Marquette and Rossport: the two ranges are relatively close to each other.

→the new updating to 2015 is statistically similar as the result updated to 2006.

- **Comparison**

■ Rates

Water level gauges data: relative rates to Point Iroquois (PI)

GPS data: absolute rates to geo-center

✓ Convert GPS rates to relative rates by subtracting rate (PI) from rate (other individual stations)

Stations	Relative rate (mm/year) to Point Iroquois by GPS	Water level differences (mm/year) to Point Iroquois by water level gauges
Marquette C.G.	-0.8	-0.98 +/- 0.0352
Ontonogan	-1.0	-1.69 +/- 0.0920
Duluth	-2.1	-2.82 +/- 0.0609
Grand Marais	-0.7	-0.92 +/- 0.0793
Thunder Bay	1.3 +/- 2.1	0.15 +/- 0.0822
Rossport	2.1 +/- 2.1	1.85 +/- 0.1210
Michipicoten	2.2	2.01 +/- 0.0534
Gros Cap	0.1 +/- 2.8	0.04 +/- 0.0763
Point Iroquois	0	0

■ Pattern

✓ Same: uplift in the northern part, maximum at NE end; subsidence in the southern part, maximum at SW end

✓ Similar rate gradient (mm/yr): GPS 0.02; water level gauges 0.0117

■ Reasons for any differences

✓ Spatially:

GPS no data around SW end; linear regression through distance

water level gauges only 8 stations (except reference station PI)

✓ Temporally:

GPS short period of record (5-20 years); linear regression through time

water level gauges only summer months; short period of record (decades); linear regression through time