Present-day tilting of the Great Lakes region based on water level gauges

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ABSTRACT

By using monthly mean water levels at 55 sites around the Great Lakes, a regional model of vertical crustal motion was computed for the region. In comparison with previous similar studies over the Great Lakes, 15 additional gauge sites, data from all seasons instead of the 4 summer months, and 8 additional years of data were used. All monthly water levels available between 1860 and 2000, as published by the U.S. National Ocean Survey and the Canadian Hydrographic Service, were used. For each lake basin, the vertical velocities of the gauge sites relative to each other were simultaneously computed, using the least-squares adjustment technique. Our algorithm solves for and removes a monthly bias common to all sites, as well as site-specific biases. It also properly weighs the input water levels, resulting in a realistic estimation of the uncertainties in tilting parameters. The relative velocities obtained for each lake were then combined to obtain relative velocities over the entire Great Lakes region. Finally, the gradient of the relative rates for the regional model was found to agree best with the ICE-3G global isostatic model of Tushingham and Peltier, whereas the ICE-4G gradients were too small around the Great Lakes.

Keywords: Great Lakes, postglacial rebound, water level gauges, least-squares analysis, trend surface analysis, water management.

INTRODUCTION

The Earth's crust north of the Great Lakes in Canada was pressed down by as much as 3 km of ice in some areas during the last glacial era. When the ice began melting some 10,000 yr ago, the crust started rebounding. This phenomenon is called *postglacial rebound* (PGR) and is still ongoing today. While the land north of the Great Lakes is rising, that south of the Great Lakes is subsiding to maintain equilibrium. Hence, residents on the south shores of the Great Lakes have noticed water levels rising slowly over time, while those on the north shores have noticed declining water levels.

Improving our knowledge of PGR over the Great Lakes and central Canada is important for shore industries and inhabitants to help in charting and mapping, management of water, shore constructions, shore erosion, shipping, hydroelectric dams, basins, power generation, flooding (such as along the Red River), environmental changes, groundwater resources (their quantity and pollution), as well as in determining crustal stress in earthquake-prone regions.

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (hereinafter referred to as the Coordinating Committee) has the mandate to "review and update as necessary the apparent vertical crustal and other movement rates between water level gauge sites in the Great Lakes–St. Lawrence River System, and report coordinated findings" (Coordinating Committee, 1995b). Following are these findings, i.e., rates of movement, which are coordinated between the United States and Canada.

An important reason for refining PGR models is to improve the definition of the reference system for heights around the Great Lakes. Whereas the current International Great Lakes Datum (IGLD) of 1985 (Coordinating Committee, 1995a) was established using geodetic spirit leveling, the future reference system is expected to be defined by a geoid model and realized using global positioning system (GPS) techniques (Mainville et al., 1992) combined with a PGR model. This may also be the case for a future vertical reference system covering the whole of Canada. A PGR model helps to predict and manage geographical coordinate changes both vertically and horizontally.

A precise estimation of PGR is achieved here by studying water level records from 55 water level gauges around the Great Lakes in the United States and Canada. Previous studies of PGR in the Great Lakes region from 1898 to 1977 are summarized in a report by the Coordinating Committee (1977).

Recently, in addition to the Coordinating Committee's 1977 report, Tait and Bolduc (1985), Carrera et al. (1991), and Tushingham (1992) used basically the same method, each using additional years of water level data to compute the rates of movement between pairs of gauges. In comparison with these studies over the Great Lakes, 15 additional sites and 8 additional years of data are used here. In addition, whereas only summer months (June to September) were used in previous studies, data from all 12 months are also used here. Finally, an improved mathematical model is applied that provides more realistic accuracy estimates.

Our estimates of the vertical velocities of each of the 55 gauges relative to each other are compared with previous studies and with the global PGR models ICE-3G (Tushingham and Peltier, 1991) and ICE-4G(VM1) and ICE-4G(VM2) (Peltier, 1994, 1995, 2001). A contour map combining our gauge-derived vertical velocities with ICE-3G velocities indicates the current tilting of the land over the Great Lakes. It is hoped that our solution can be used by PGR modelers to calibrate their global models.

DATA

The data used here to determine the vertical movement of the crust at each gauge are monthly mean water levels. The water levels, relative to IGLD 1985, are recorded at 55 gauge sites on the Great Lakes going back to 1860 and are published by the U.S. National Ocean Service and the Canadian Hydrographic Service.

A map of the gauge locations is shown in Figure 1, and the sites are listed in Table 1 together with the years in which water levels were recorded. When a gauge was moved within a harbor, the data from both gauges were merged as if they were the same gauge. Figure 1 also indicates the number of years of recorded data available and used at each gauge site.

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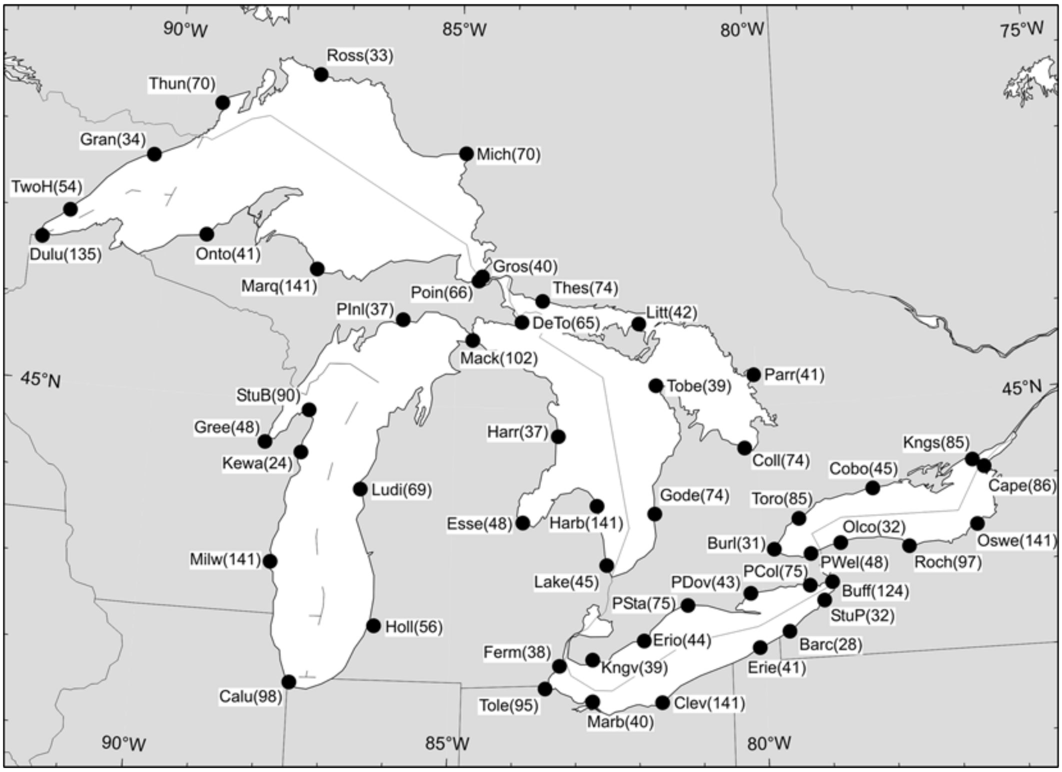


Figure 1. Locations of water level gauging stations. Stations BarP, Fair, and Monr on Lake Erie are not used in our final postglacial rebound (PGR) model. Shown in parentheses is the number of years of recorded water levels at each gauge.

Table DR1[1] indicates the years for which data are not available. See Coordinating Committee (2001, their Fig. 11) for graphs of monthly mean water levels at all 55 gauge sites.

ESTIMATING VERTICAL VELOCITIES

After recording the water level at two lake gauges for many years, the apparent vertical movement of a gauge site relative to the others can be computed. Relative water levels are needed to remove the seasonal water fluctuations common to all sites on each lake (the common bias cancels when differencing between gauges). The relative movement is represented by the linear trend on a plot of the water level differences with respect to time. This is the basic method used by previous studies, which we call Method 1.

An example is provided in Figure 2 for Calumet Harbor, Michigan, relative to Parry Sound, Ontario, using monthly mean water level data from 1960 to 2000. The difference in monthly mean water level is taken as Calumet Harbor minus Parry Sound. The linear trend (solid line) in Figure 2 is 0.32 m per century. Hence, Calumet Harbor is seen to be subsiding 32 cm/century relative to Parry Sound. Such relative movements were computed for all 391 possible pairs of water gauges on all Great Lakes (Fig. 1).

Owing to random errors in the data, the rates obtained on a pair-wise basis as described previously are not consistent among any three stations. For example, Calumet Harbor is subsiding by 10 cm/century relative to Lakeport, and Lakeport is subsiding by 25 cm/century relative to Parry Sound, the sum of which is different than the 32 cm/century rate of Calumet Harbor relative to Parry Sound, just discussed. In previous studies, the Coordinating Committee (1977), Tait and Bolduc (1985), Carrera et al. (1991), Tushingham (1992), and Tackman et al. (1999) published their rates with this inconsistency among stations. Given below is the least-squares adjustment technique of Mikhail (1976), which takes into account this inconsistency to obtain more precise results.

The least-squares adjustment method can be applied to this pair-wise analysis of gauges, here called Method 2. It uses the following observation, equation 1, for each gauge pair, which accounts for the inconsistency between pairs of gauges by using a residual error.

$$\Delta v_{ij}^{\text{obs}} + r_{ij} = v_i - v_j \, . \tag{1}$$

Here, $\Delta v_{ij}^{\text{obs}}$ is the "observed" yearly average relative velocity of point *j* relative to point *i,* computed using Method 1. The other variables are the output of the least-squares adjustment: v_i and v_j are the yearly velocities at gauge site *i* and *j*, respectively; r_{ij} are the residual errors in the observed relative velocities $\Delta v_{ij}^{\text{obs}}$. The $\Delta v_{ij}^{\text{obs}}$ are weighted a priori according to the number of years used to compute them. The a posteriori standard errors obtained from this method were too optimistic and unrealistic, however. The problem lies in the fact that data from some gauges are used in more than one of the estimates of the "observed" velocities. This so-called mathematical correlation between velocities needs to be taken into account, which is not easy to do. Craymer and Beck (1992) devised a method of overcoming this problem for a similar situation encountered in GPS baseline processing. However, this method is correct only when the same amount of data is collected at each site at the same times, which is not the case here.

To get around these problems, we formed a more fundamental observation equation on the basis of the actual observations themselves: the

[1]GSA Data Repository item 2005107, Table DR1: Years when no data are available, i.e., when no monthly water level averages are available per gauge site; Tables DR2–DR5: Comparison of relative vertical velocities and their standard deviation in cm/century between gauges on Lakes Ontario (DR2), Erie (DR3), Michigan-Huron (DR4), and Superior (DR5); Table DR6: Count of outliers (i.e., monthly lake level averages) rejected during this study, per month and per gauge site, for each lake, are available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

TABLE 1. LIST OF 55 WATER LEVEL GAUGE SITES AND THEIR PERIOD OF RECORD USED IN THIS STUDY

Gauge name	Abbr.	ID	Years	Period of record†
Lake Ontario				
Burlington	Burl	13150	31	1970–2000
Cape Vincent	Cape	02000	86	1898–2000, exception
Cobourg	Cobo	13590	45	1956–2000
Kingston	Kngs	13988	85	1916–2000
Olcott	Olco	02076	32	1967–2000, exception
Oswego	Oswe	02030	141	1860–2000
Port Weller	PWel	13030	48	1929–2000, exception
Rochester	Roch	02058	97	1860–2000, exception
Toronto	Toro	13320	85	1916–2000
Lake Erie				
Barcelona	Barc	03032	28	1960–1987
Bar Point	BarP	12005	35	1966–2000
Buffalo Harbor	Buff	03020	124	1860–2000, exception
Cleveland	Clev	03063	141	1860–2000
Erie	Erie	03038	41	1958–2000, exception
Erieau	Erio	12250	44	1957–2000
Fairport Harbor	Fair	03053	26	1975–2000
Fermi Power Plant	Ferm	03090	38	1963–2000
Kingsville	Kngv	12065	39	1962–2000
Marblehead	Marb	03079	40	1959–2000, exception
Monroe	Monr	03087	14	1975–1988
Port Colborne	PCol	12865	75	1926–2000
Port Dover	PDov	12710	43	1958–2000
Port Stanley	PSta	12400	75	1926–2000
Sturgeon Point	StuP	03028	32	1969–2000
Toledo	Tole	03085	95	1877–2000, exception
Lake Huron				
Collingwood	Coll	11500	74	1927–2000
De Tour	DeTo	05098	43	1896–1983, exception
De Tour Village		05099	23	1977–2000
De Tour Village	DeTo3‡		65	1896–2000
Essexville	Esse	05034	26	1953–1978
Essexville		05035	24	1977–2000
Essexville	Esse3‡		48	1953–2000
Goderich	Gode	11860	74	1927–2000
Harbor Beach	Harb	05014	141	1860–2000

continued

TABLE 1. LIST OF 55 WATER LEVEL GAUGE SITES AND THEIR PERIOD OF RECORD USED IN THIS STUDY (*continued*)

Gauge name	Abbr.	ID	Years	Period of record†
Lake Huron				
Lakeport	Lake	05002	45	1955–2000, exception
Little Current	Litt	11195	42	1959–2000
Mackinaw City	Mack	05080	102	1899–2000
Parry Sound	Parr	11375	41	1960–2000
Thessalon	Thes	11070	74	1927–2000
Tobermory	Tobe	11690	39	1962–2000
Lake Michigan				
Calumet Harbor	Calu	07044	98	1903–2000
Green Bay	Gree	07078	29	1953–1981
Green Bay		07079	22	1979–2000
Green Bay	Gree3‡		48	1953–2000
Holland	Holl	07031	56	1894–1997, exception
Kewaunee	Kewa	07068	24	1974–1997
Ludington	Ludi	07023	69	1895–2000, exception
Milwaukee	Milw	07058	110	1860–1969
Milwaukee		07057	31	1970–2000
Milwaukee	Milw3‡		141	1860–2000
Port Inland	PInl	07096	37	1964–2000
Sturgeon Bay C.	StuB	07072	90	1905–2000, exception
Lake Superior				
Duluth	Dulu	09064	135	1860–2000, exception
Grand Marais	Gran	09090	34	1966–2000, exception
Gros Cap	Gros	10920	40	1961–2000
Marquette	Marq	09016	121	1860–1980
Marquette C.G.		09018	21	1980–2000
Marquette C.G.	Marq3‡		141	1860–2000
Michipicoten	Mich	10750	70	1931–2000
Ontonagon	Onto	09044	41	1959–2000, exception
Point Iroquois (Brimley)	Poin	09004	66	1930–2000, exception
Rossport	Ross	10220	33	1967–2000
Thunder Bay	Thun	10050	70	1931–2000
Two Harbors	TwoH	09070	54	1887–1988, exception

†Records are mainly up to December 2000. See Table DR1 (see footnote 1) for periods for which data are not available.
‡Records from two gauges at same location were merged for this study.

independent monthly mean water level measurements. This method, here called Method 3, is similar to that used by Walcott (1972, p. 871) and avoids altogether the inconsistencies encountered in the previous two methods. The observation equation is of the following form for gauges $i = 1,...,n$ and epochs $j = 1,...,m$:

$$w_{ij}^{obs} + r_{ij} = (w_{i0} + a_i) + b_j + v_i\,(t_j - t_0). \quad (2)$$

Here, w_{ij}^{obs} are the observed monthly mean water levels given at each gauge $i = 1,...,n$, and for each epoch t_j, $j = 1,...,m$, w_{i0} is the water level at gauge i at a given reference epoch t_0, a_i is a site dependent bias, b_j is an epoch dependent bias for each monthly mean water level observation and is common to all gauges on a lake, v_i is the velocity at each gauge site, r_{ij} are the residuals (errors in each month's water levels). Because w_{i0} and a_i are both site dependent, they cannot be separately estimated. Hence, the combination of both is computed, i.e., $\alpha_i = (w_{i0} + a_i)$, one for each gauge site. The reference epoch used here was $t_0 = 1985.5$, which corresponds to the reference water level of IGLD 1985.

Finally, we weighted each monthly mean water level equally, which effectively results in sites with more monthly levels receiving greater weight, as would normally be desired. The a posteriori standard errors obtained with this method were found to be more realistic and meaningful than those with the other methods and are presented later. The summary statistics for the adjustment of each lake are provided in Table 2.

LAKEWIDE PGR RESULTS

Because the water level of each lake varies independently, each lake is adjusted individually, following each of the three methods described previously. The adjustment in Method 3 computes the monthly biases, site biases, velocities, and residuals by minimizing the sum of the square of the residuals. If a residual r_{ij} is three times larger than the average residual, the corresponding monthly mean water level is removed and the adjustment repeated. This process is iterated until no more outliers remain. The final adjusted velocities and their standard deviations are listed in Table 3 and presented in Figure 3. Note that the velocities are given relative to a gauge at the lake outlet, because the mathematical model requires that we fix the velocity of one gauge.

Figure 3 illustrates uplift in the northeast and subsidence in the south, indicating a pattern of land tilting upward to the northeast. The flattening of the velocities in the southern parts of Lakes Michigan and Erie may suggest that these parts of the lakes are on or are approaching the subsiding forebulge of the PGR. However, our

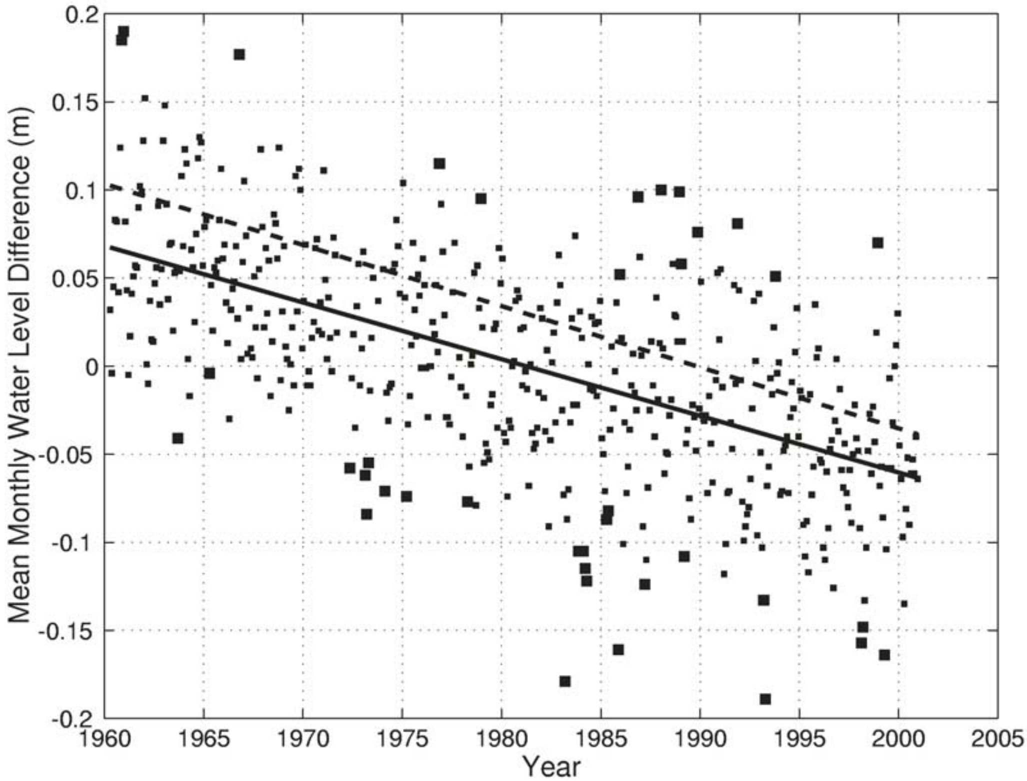


Figure 2. Example of vertical movement of Calumet Harbor, Michigan, relative to Parry Sound, Ontario, as determined from the difference between the monthly mean lake levels recorded at both gauges, from 1960 to 2000. The solid straight line is the linear trend obtained by regression from the data in the plot taken out of context of the other gauges (Method 1). The dashed straight line is the linear trend obtained from a simultaneous least-squares adjustment that takes into account all gauges on the lake (Method 3). The large squares are outliers rejected by the least-squares adjustment process.

results are not significant enough to actually support this claim.

The relative velocities between each pair of gauges can be derived simply, using the estimated velocities in Table 3. They are listed in Tables DR2–DR5 (see footnote 1) in column 7 together with the relative velocities (trends) computed using Method 1 (column 6) and the results of previous studies by the Coordinating Committee (1977), Tait and Bolduc (1985), Carrera et al. (1991), and Tushingham (1992).

Although the standard deviations tabulated in these tables represent the uncertainty with a 68% confidence level, uncertainty estimates for 95% confidence can be obtained by multiplying the standard deviation by 1.96, and for 99% confidence, by 2.58.

The lake-adjusted velocities from Method 3 indicate that Calumet Harbor is subsiding by 35 ± 1.2 cm/century relative to Parry Sound, instead of 32 cm/century as determined by Method 1. In Figure 2, the adjusted velocity (linear trend) from Method 3 is the dashed line, and the velocity from Method 1 is the solid line. See Coordinating Committee (2001, their Fig. 12) for plots of velocity trends for all the gauge pairs.

In addition to the trends, the adjustment computes three other useful values: monthly biases, site biases, and residuals. Each month there is a different bias in the water level of a lake, resulting from such causes as precipitation, evaporation, barometric pressure, wind, snow melt, and water level regularization at dams. The Method 3 adjustment computes one bias b_j per month common to all gauges on the lake. It indicates the average level of the water after removing the trend and the site biases. It is a time-varying basinwide bias, which relates to the lowering or raising of lakewide water. Hydrologists and hydraulic engineers of the Great Lakes study how well this quantity correlates from basin to basin. The mean monthly values obtained by using Method 3 are more precise than those usually used and may help in this analysis.

The site bias is specific to each gauge site. It may be used to improve future datum definitions: i.e., adding the site bias to the height relative to IGLD 1985 would provide a height at each gauge site that would match heights established using GPS and a very accurate geoid height. The biases and their estimated standard deviations are listed in Table 3 and plotted in Figure 4. They are small in magnitude, mostly

TABLE 2. STATISTICS ON THE LEAST-SQUARES ADJUSTMENT FOR EACH LAKE

Lake	Ontario	Erie	Mich.-Huron	Superior
No. of gauge sites	9	16	20	10
No. of velocities and no. of site biases solved for	8	15	19	9
No. of monthly average water levels inputted	7693	10,399	15,542	7979
No. of monthly water level rejected	269	516	331	147
No. of residuals	7424	9883	15211	7832
No. of monthly biases solved for	1627	1680	1683	1668
RMS of residuals (cm)	0.9	2.4	1.7	1.2
σ_0 a priori (mm)	3.1	5.1	4.3	3.7
σ_0 a posteriori (mm)	3.1	5.1	4.3	3.7

below 1 cm, which indicates the stability of the local datum at each gauge and the quality of the water level data.

The residuals represent the random errors in the data (monthly mean water levels) left after removing the monthly biases, the trends (i.e., the vertical movement of the crust at each gauge), and the site biases. The residuals are fairly small in magnitude: below 3, 7, 5, and 4 cm for Lakes Ontario, Erie, Michigan-Huron, and Superior, respectively. This indicates the quality of the data to be very good. Many outliers have been rejected for two of the four lakes. Statistically, up to 5% are allowed when using a 95% confidence interval to detect outliers. There are 3.6% rejections by adjustment for Lake Superior, 4.3% for Lakes Michigan-Huron, 9.9% for Lake Erie, and 7.0% for Lake Ontario. Systematic trends and unexplained outliers in the residuals have not been further investigated and may point to errors in the data that could have an impact on the accurate determination of the movement rates. Specifically, the residuals at Port Weller, Rochester, De Tour, Ludington, and Rossport show undesirable systematic trends. Hence the data at these sites should be investigated in later studies.

Some monthly mean water levels were rejected as outliers by the adjustment process. When a residual, as explained earlier, was larger than three times the root mean square of all the residuals, its water level was automatically rejected. The number of outliers for each gauge and for each month are listed for each lake in Table DR6 (see footnote 1). For more details about the outliers, see Coordinating Committee (2001, their Table 3e–h and Figs. 11, 12, and 14).

Previous studies used only the four summer months (June to September) because winter months were found to be noisy. As seen in Table DR6 (see footnote 1), it is true that most outliers occur during the winter months, but nevertheless, 95% of the data from October to May contributed to our solution.

The small magnitude of the estimated standard deviations and residuals demonstrated for the first time the consistency of all gauges over each lake in measuring the same phenomenon of a tilting of the land resulting from PGR.

In concluding this section, the estimated velocities provide a direct measurement of the relative movement of the Earth's crust. For example, over 100 yr, the land at Calumet Harbor became 10 cm lower than the land at Lakeport, and 35 cm lower than the land at Parry Sound. Again, these velocities are relative to one gauge site on each lake and thus are listed lake-by-lake in Table 3 and Tables DR2–DR5 (see footnote 1). The steps in determining relative

TABLE 3. GAUGE VERTICAL VELOCITY AND SITE BIAS

Gauge	Latitude (°N)	Longitude (°W)	Vertical velocity (cm/century)	Site bias (mm)	Comment
Lake Ontario—Relative to Cape Vincent					
Burlington	43°20′20″	79°46′08″	–20.0 ± 0.7	4 ± 0.7	
Cape Vincent	44°07′48″	76°19′47″	0	0	Outlet
Cobourg	43°57′28″	78°09′54″	–7.7 ± 0.4	6 ± 0.7	
Kingston	44°13′01″	76°31′01″	2.5 ± 0.2	3 ± 0.7	
Olcott	43°20′24″	78°43′48″	–11.3 ± 0.6	5 ± 0.7	
Oswego	43°27′36″	76°30′36″	–4.5 ± 0.2	7 ± 0.7	
Port Weller	43°14′13″	79°13′11″	–14.7 ± 0.3	5 ± 0.7	
Rochester	43°15′35″	77°37′47″	–10.2 ± 0.2	6 ± 0.7	
Toronto	43°38′24″	79°22′51″	–12.1 ± 0.2	12 ± 0.7	
Lake Erie—Relative to Buffalo					
Barcelona	42°19′47″	79°35′59″	–1.3 ± 2.1	–1 ± 3.1	
Bar Point	42°02′59″	83°06′39″	–16.1 ± 1.4	–17 ± 1.8	Rejected
Buffalo Har.	42°53′24″	78°53′24″	0	0	Outlet
Cleveland	41°31′48″	81°38′24″	–9.8 ± 0.3	–8 ± 1.6	
Erie	42°08′59″	80°04′47″	–12.1 ± 1.2	8 ± 1.9	
Erieau	42°15′35″	81°54′54″	–9.6 ± 1.1	–11 ± 1.8	
Fairport Ha.	41°45′35″	81°17′24″	–21.7 ± 2.2	6 ± 2.1	Rejected
Fermi Pow.	41°58′00″	83°15′00″	–9.6 ± 1.3	–16 ± 1.8	
Kingsville	42°01′37″	82°44′05″	–10.3 ± 1.2	–14 ± 1.8	
Marblehead	41°32′59″	82°43′48″	–8.4 ± 1.2	–17 ± 1.9	
Monroe	41°53′59″	83°21′35″	–16.0 ± 5.9	–16 ± 3.2	Rejected
Port Colbor.	42°52′26″	79°15′10″	–5.7 ± 0.5	2 ± 1.8	
Port Dover	42°46′51″	80°12′07″	–1.8 ± 1.1	1 ± 1.8	
Port Stanley	42°39′32″	81°12′46″	–7.4 ± 0.5	1 ± 1.8	
Sturgeon P.	42°40′47″	79°01′48″	2.1 ± 1.6	–2 ± 1.9	
Toledo	41°42′00″	83°28′48″	–8.6 ± 0.4	–9 ± 1.8	
Lakes Huron–Michigan—Relative to Lakeport					
Collingwood	44°30′18″	80°13′01″	16.6 ± 0.7	–5 ± 1.3	
De Tour	46°00′00″	83°54′00″	17.3 ± 0.8	–3 ± 1.3	
Essexville	43°38′59″	83°50′59″	–1.3 ± 0.9	–1 ± 1.4	
Goderich	43°44′45″	81°43′44″	–1.5 ± 0.7	–1 ± 1.3	
Harbor	43°51′00″	82°39′00″	0.1 ± 0.7	6 ± 1.3	
Harrisville	44°40′12″	83°16′48″	8.0 ± 1.1	–3 ± 1.4	
Lakeport	43°08′59″	82°30′00″	0	0	Outlet
Little Current	45°58′51″	81°55′40″	27.0 ± 1.0	–3 ± 1.3	
Mackinaw	45°46′48″	84°43′11″	10.0 ± 0.7	–3 ± 1.3	
Parry Sound	45°20′16″	80°02′09″	24.3 ± 1.0	–8 ± 1.4	
Thessalon	46°15′10″	83°33′07″	20.8 ± 0.7	0 ± 1.3	
Tobermory	45°15′32″	81°39′57″	16.7 ± 1.0	5 ± 1.3	
Calumet	41°42′00″	87°30′00″	–10.4 ± 0.7	7 ± 1.3	
Green Bay	44°30′00″	88°05′59″	–6.2 ± 0.9	0 ± 1.4	
Holland	42°23′59″	86°12′00″	–7.9 ± 0.8	7 ± 1.4	
Kewaunee	44°23′59″	87°30′00″	–8.5 ± 1.8	–1 ± 1.5	
Ludington	44°00′00″	86°30′00″	–12.2 ± 0.8	–1 ± 1.3	
Milwaukee	43°06′00″	87°54′00″	–14.4 ± 0.7	0 ± 1.3	
Port Inland	46°00′00″	85°54′00″	9.4 ± 1.1	–4 ± 1.4	
Sturgeon	44°53′59″	87°24′00″	–3.8 ± 0.7	–2 ± 1.3	
Lake Superior—Relative to Point Iroquois					
Duluth	46°40′12″	92°05′59″	–25.3 ± 0.3	–18 ± 0.9	
Grand Mara.	47°45′00″	90°19′47″	–7.6 ± 0.8	–3 ± 1.0	
Gros Cap	46°31′44″	84°35′05″	1.6 ± 0.7	–8 ± 1.0	
Marquette	46°32′59″	87°23′24″	–12.2 ± 0.3	2 ± 0.9	
Michipicoten	47°57′43″	84°54′03″	23.3 ± 0.3	–4 ± 1.0	
Ontonagon	46°52′11″	89°18′36″	–18.7 ± 0.7	–8 ± 1.0	
Point Iroqu.	46°28′47″	84°38′24″	0	0	Outlet
Rossport	48°50′02″	87°31′11″	27.5 ± 0.8	–6 ± 1.0	
Thunder B.	48°24′32″	89°13′01″	2.4 ± 0.3	–9 ± 1.0	
Two Harb.	47°00′35″	91°40′12″	–21.2 ± 0.5	–2 ± 1.0	

Note: Vertical velocity standard error in cm/century, relative to each lake outlet. Site bias and its standard error in mm, also relative to the outlet.

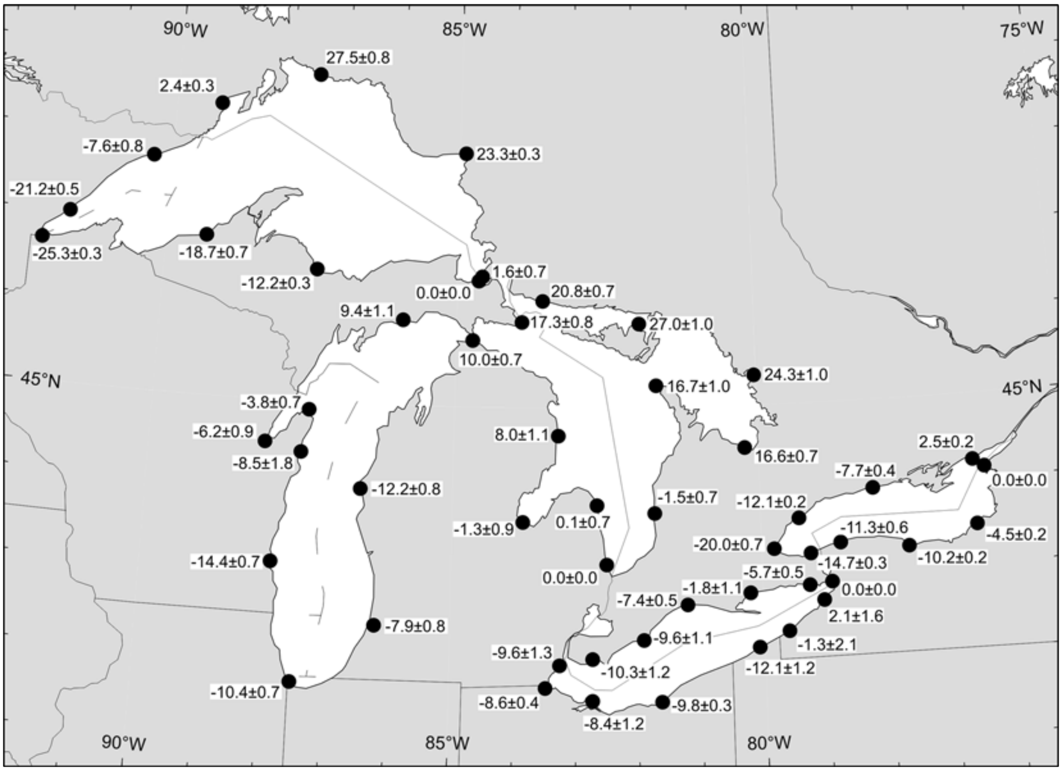


Figure 3. Vertical velocity and standard error relative to each outlet: Cape Vincent for Lake Ontario, Buffalo for Lake Erie, Lakeport for Lakes Michigan-Huron, Point Iroquois for Lake Superior, in centimeters per century.

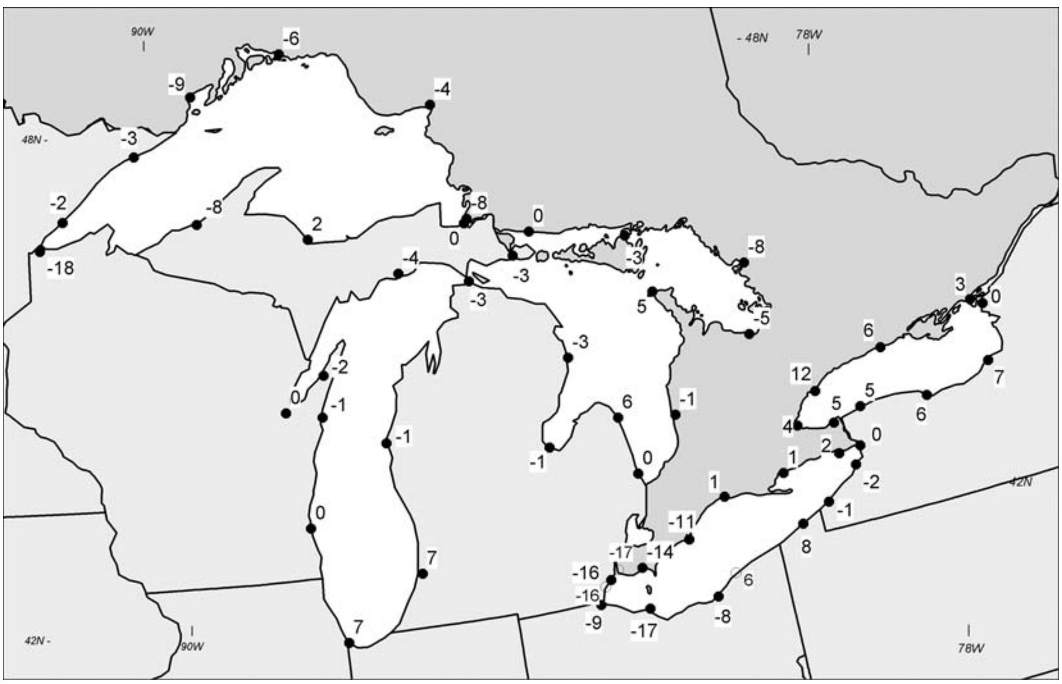


Figure 4. Site biases (in millimeters) relative to reference gauge near each lake outlet.

velocities between locations on any two lakes are given in the following section.

REGIONWIDE PGR RESULTS

The vertical movement of the crust over the whole Great Lakes region is derived by tying the previous lakewide results together. Note that the computed lakewide velocities in Table 3 are relative to the outlet of each lake and are referred to as relative velocities here. These relative velocities are first mapped using contours as seen in Figure 5. An extrapolation of the contours for Lakes Superior and Huron allows us to assign with some confidence the same velocity at Gros Cap and Thessalon (see Gros and Thes in Figs. 1 and 5). Similarly, Buffalo on Lake Erie is assigned the same velocity as Port Weller on Lake Ontario (see Buff and PWel in Figs. 1 and 5). Here, various scenarios were tried by adding or subtracting 1, 2, 3, 4, 5, 6, and 9 cm/century at Toronto relative to Collingwood (and similarly at Buffalo relative to Port Weller) and watching the smoothness of the contours, especially those joining Lakes Michigan-Huron to Lake Erie. Finally, Toronto on Lake Ontario was assigned 6 cm/century less than the velocity at Collingwood on Lake Huron (not 3 cm/century, as the dotted line in Fig. 5 tends to indicate; see Toro and Coll in Figs. 1 and 5). In this way the relative velocities over the four lakes are now connected.

Relative vertical movement over the region can also be obtained by using global PGR models such as ICE-3G, ICE-4G(VM1), and ICE-4G(VM2). The development of the ICE-3G and ICE-4G models did not make use of lake level gauges (Peltier, June 1999, personal commun.). Our gauge-derived relative velocities therefore provide an independent check on these models. The ICE-4G models were tested (see next section), but the gradients of the contours (relative velocities) were too small in comparison with the gauge-derived results. The ICE-3G model agreed better with the gauge-derived gradients than the ICE-4G model and was therefore retained for further analysis. The ICE-3G PGR model is contoured in Figure 6. One can see the smoothness of this global PGR model over the Great Lakes. The ICE-3G-derived velocities over the Great Lakes region were then replaced by our gauge-derived relative velocities (Method 3), referenced to the ICE-3G velocity at Lakeport. These velocities were contoured to obtain the final results in Figure 7, where the ICE-3G PGR surrounds the gauge-derived PGR.

Three gauge sites—Bar Point, Fairport, and Monroe—were not used to produce Figure 7, because their velocities did not agree with the other velocities on Lake Erie (see Fig. 3 and Table 3). These gauges are among those that have the least number of years: 35, 26, and 14 yr, respectively. Also, the least-squares estimates for their velocities have some of the largest standard deviations obtained: 1.4, 2.2, and 5.9 cm/century, respectively.

Finally, the relative rates in Figure 7 provide an estimate of the maximum movement expected in the region, i.e., some 57 cm every 100 yr between Rossport and Calumet Harbor (see Fig. 1).

The relative velocity between two sites on a lake has an average standard deviation of

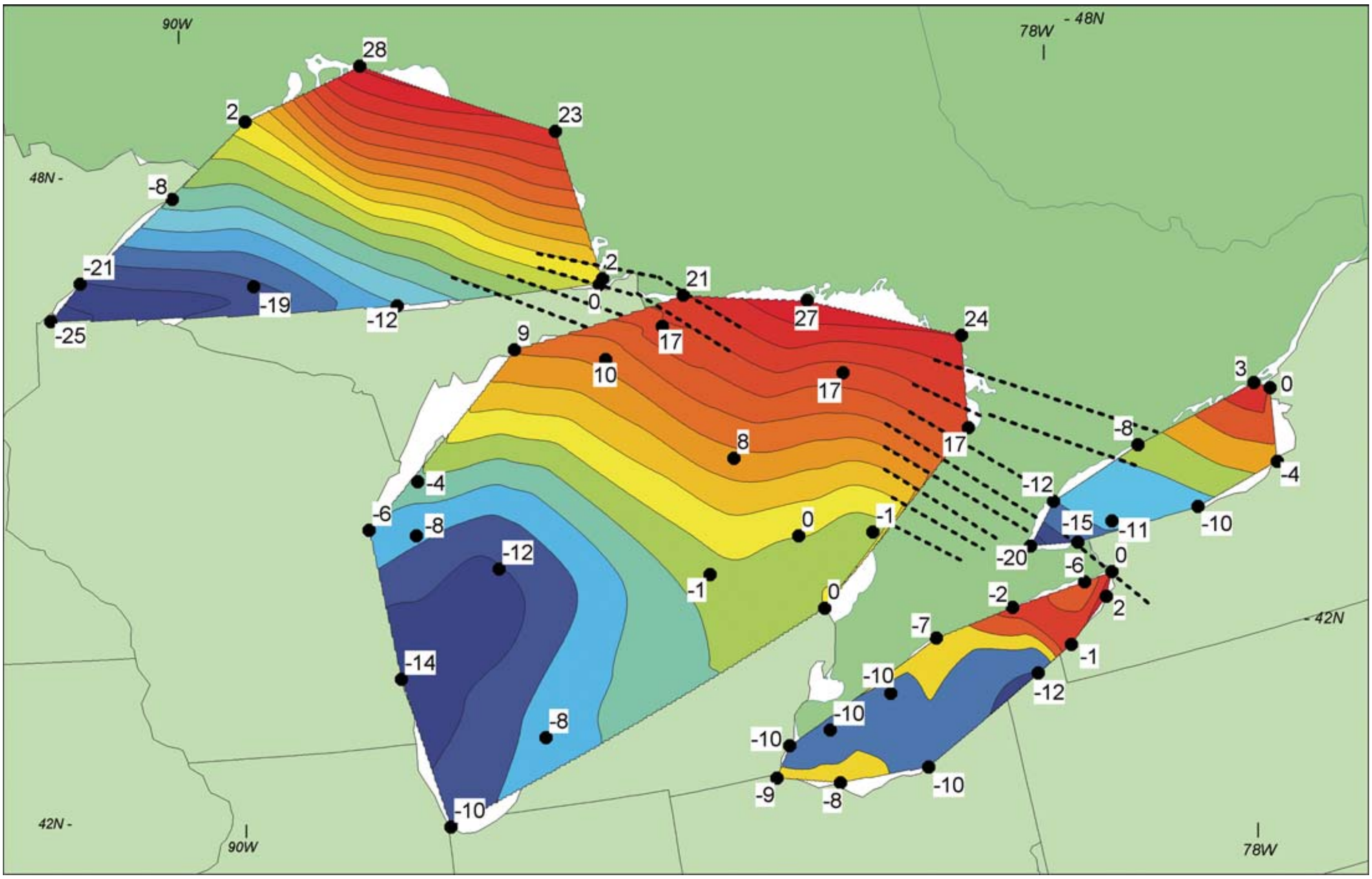


Figure 5. Contour map of relative vertical velocities derived from water level gauges over each lake. Dashed lines indicate extrapolation from each lake. Contour interval—3 cm/century.

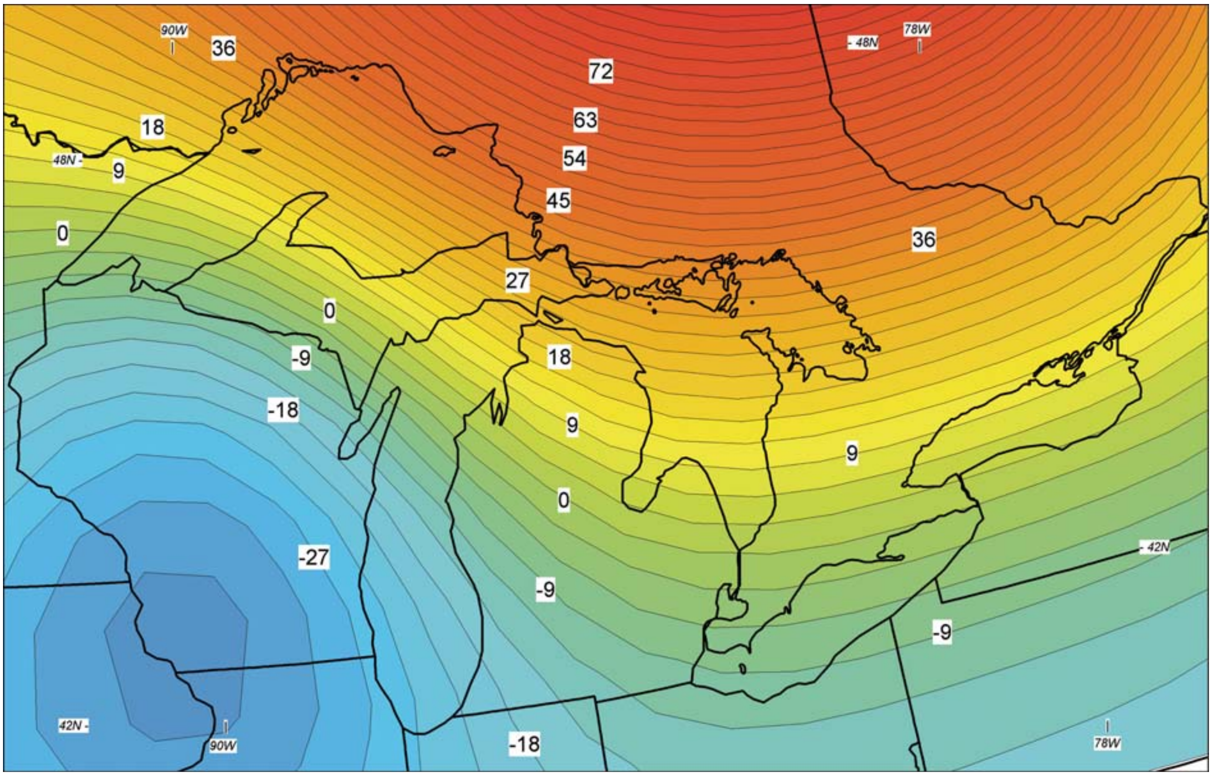


Figure 6. Contour map of ICE-3G global postglacial rebound–derived velocities in the Great Lakes area. Contour interval—3 cm/century.

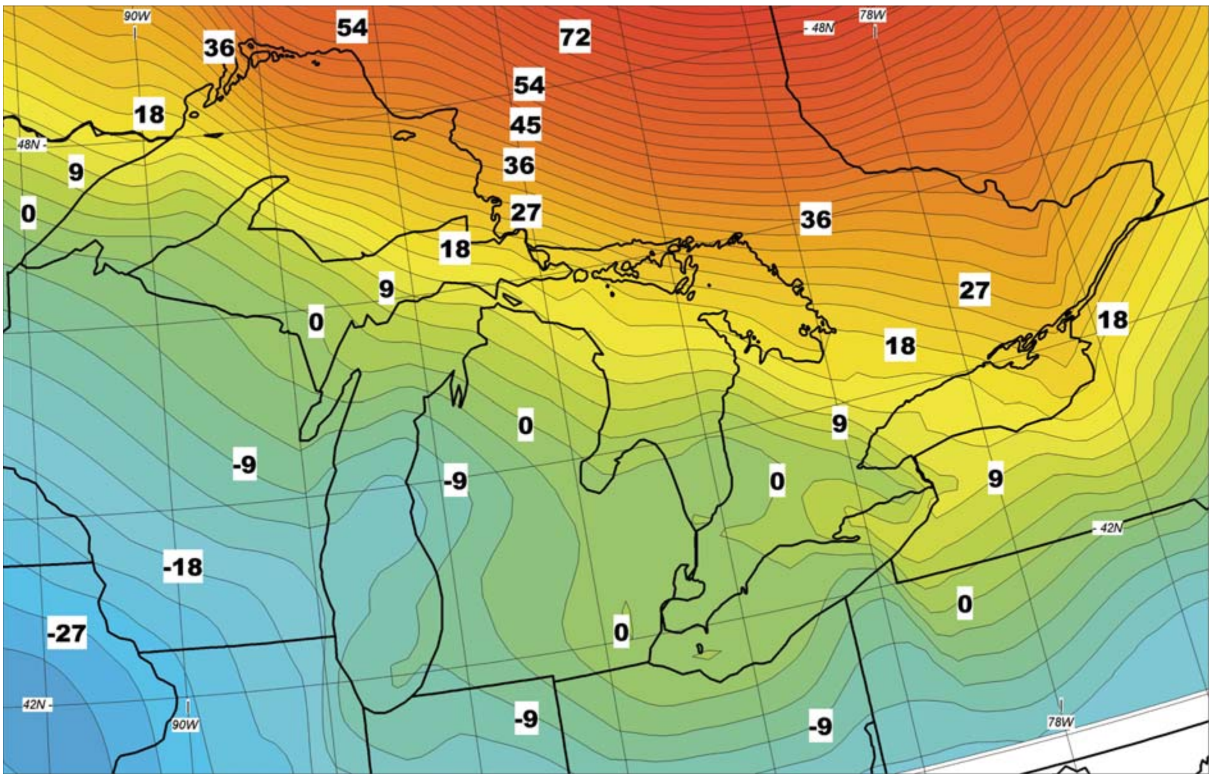


Figure 7. Contour map of vertical velocities derived from water level gauges over the Great Lakes surrounded with ICE-3G–derived velocities. Contour interval—3 cm/century.

±1.2 cm/century (Tables 3 and DR2–DR5 [see footnote 1]). However, the relative velocity between sites on two different lakes likely has a standard deviation on the order of ±6 cm/century. This increased standard deviation is due to the large uncertainty in interpolating the relative velocities between different lakes.

COMPARISON WITH ICE-4G PGR MODELS

As stated previously, the ICE-4G–derived velocities were tested against the gauge-derived velocities. First, Figure 8A displays ICE-3G–derived velocities in dashed lines, overlaid by the gauge-derived regional PGR model (solid lines). Similar maps were produced for ICE-4G(VM1)– and ICE-4G(VM2)–derived velocities also with the gauge-derived velocities overlaid (Fig. 8B, C, respectively). ICE-4G uses a different ice thickness and distribution than ICE-3G. ICE-4G(VM2) has a different viscosity model for the mantle as well as a different lithosphere thickness than ICE-4G(VM1). One can see visually in Figure 8C that the ICE-4G(VM2) contour gradient is too small in comparison with the gauge-derived contours. In Figure 8B, the ICE-4G(VM1) contour gradient agrees better with the gauge-derived contours but not as well as ICE-3G in Figure 8A. The spacing between contour lines is the same for all models. In addition, maps similar to Figure 7 were produced using ICE-4G(VM1) and ICE-4G(VM2), again observing that ICE-4G gradients are too small around the Great Lakes. The ICE-3G contours in Figure 8A therefore agree best with the gauge-derived velocities.

CONCLUSIONS

The relative movements between 55 Canadian and U.S. lake level gauges on the Great Lakes were computed and are listed in Tables DR2–DR5 (see footnote 1), together with their uncertainties. These vertical velocities and standard deviations are summarized in Table 3 and Figure 3 as velocities relative to a reference gauge at each lake outlet. The relative velocity over the whole region was also derived and is shown in Figure 7.

The relative velocities between sites on the same lake have a standard deviation on the order of ±1 cm/century. However, the relative velocities between sites on different lakes is expected to be large because of the interpolation used to connect the velocities from different lakes.

The gauge-derived relative velocities were compared with the global PGR models ICE-3G and two versions of ICE-4G, using viscosity models VM1 and VM2. The agreement was found to be best with ICE-3G.

Note that the global PGR models do not provide standard deviations for their velocities. Hence the rates provided by our PGR model in Figure 7 do not have standard deviations assigned. One must therefore exercise caution when using these velocities.

Systematic trends in the residuals and outliers from our estimation model have not been adequately investigated and may point to errors in the data that could have some influence on the accurate determination of the movement rates. Specifically, more than 5% of the observations on Lakes Erie and Ontario were rejected as outliers, whereas the residuals at Port Weller, Rochester, De Tour, Ludington, and Rossport show undesirable systematic trends. Hence, the data from these sites should be investigated further.

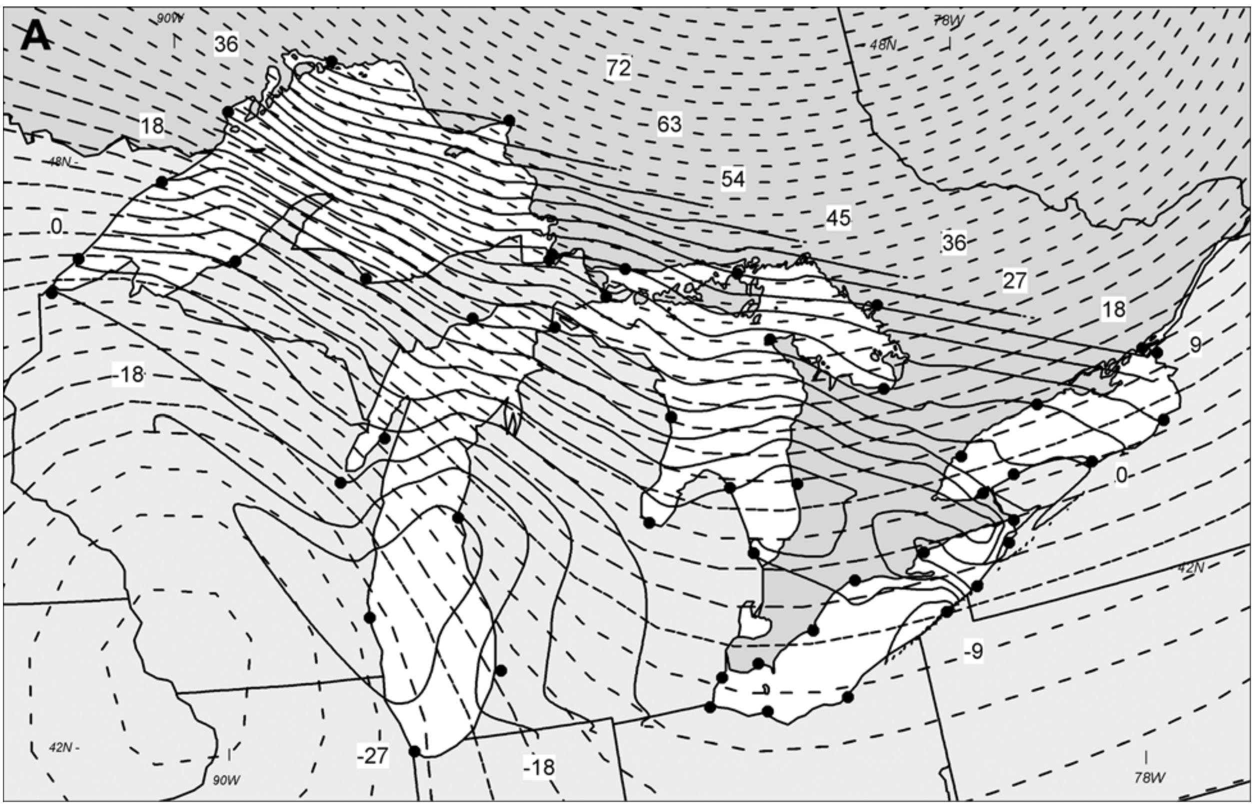
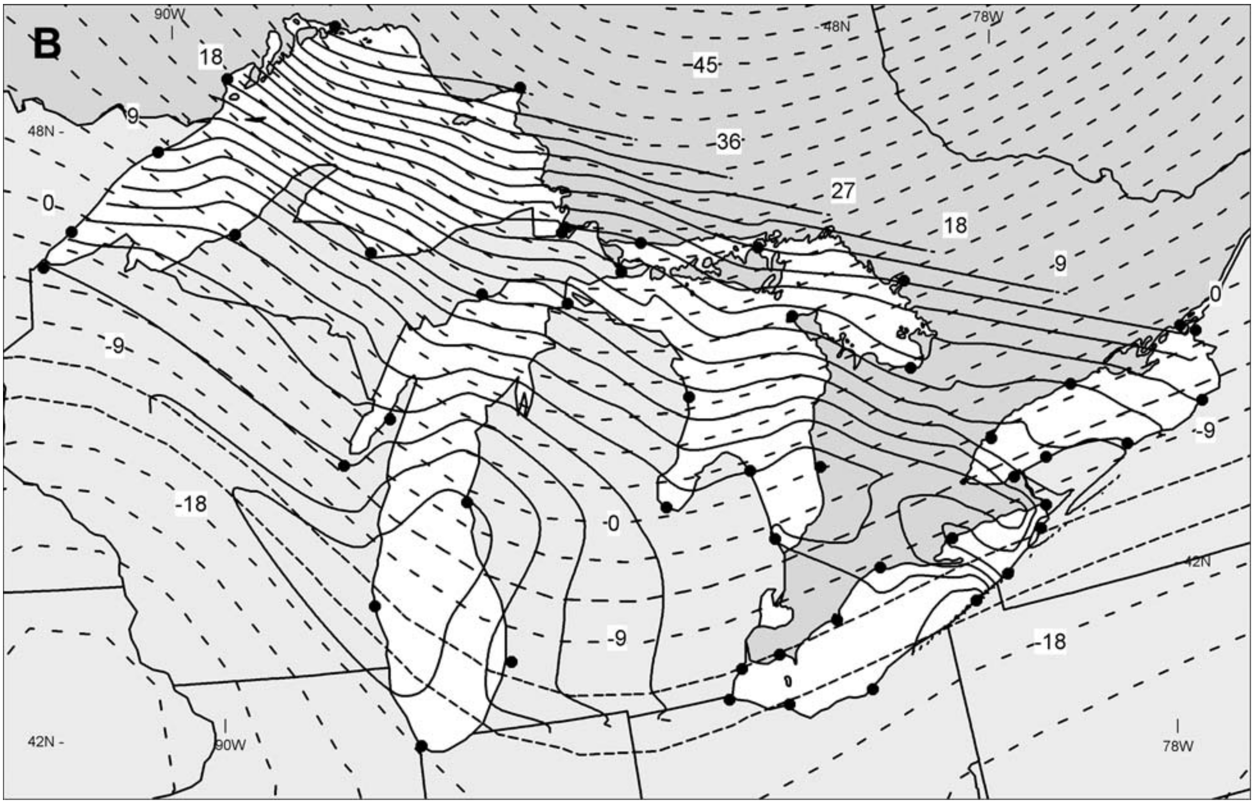


Figure 8. Overlaid contour maps comparing vertical velocities derived from water level gauges (solid contour lines) and those derived from (A) the ICE-3G postglacial rebound model, (B) the ICE-4G(VM1) model, and (C) the ICE-4G(VM2) model. Contour interval—3 cm/century. (*Continued on following page*).



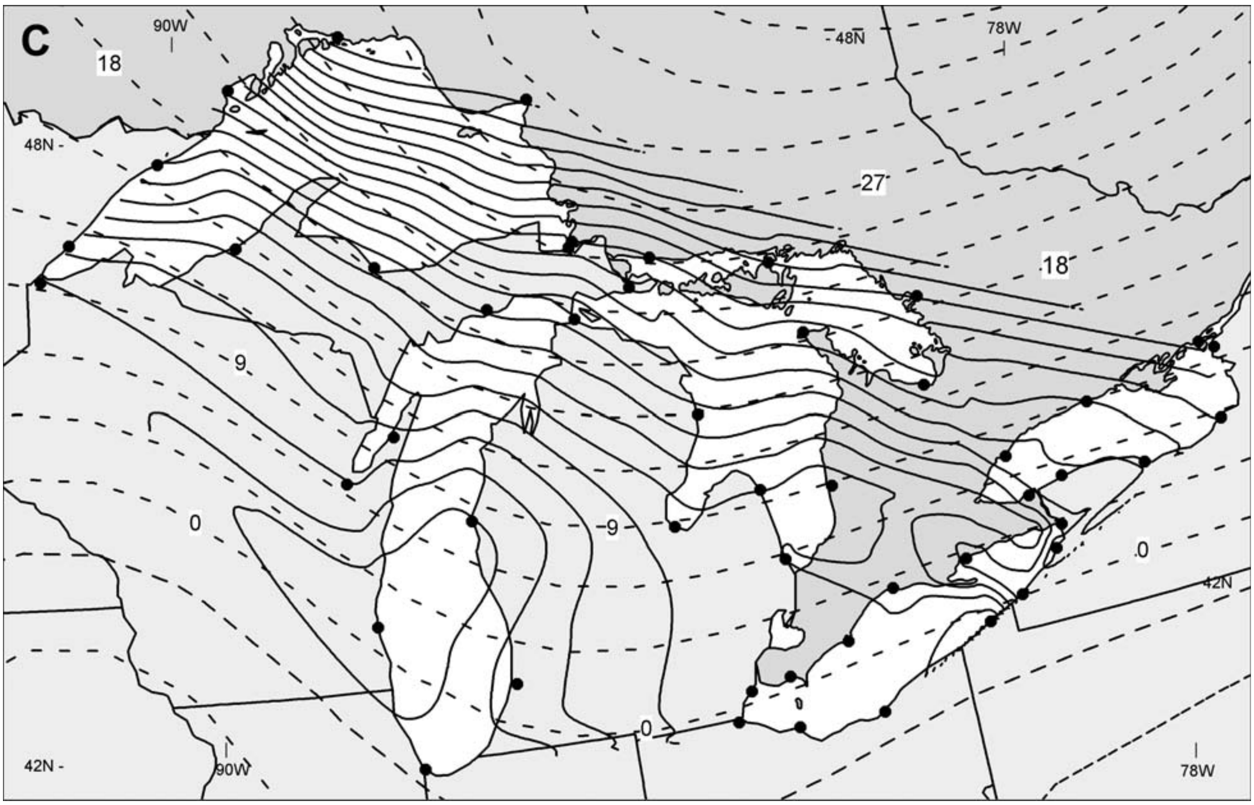


Figure 8 (*continued*).

The GPS satellite positioning technique is seen as the technology for determining the absolute velocities of the Earth's crust around the Great Lakes. Having gauge sites on each lake that are permanently equipped with GPS receivers will allow us, after several years, to accurately link the relative rates of all five lakes (as well as Lake Saint Clair, between Lakes Huron and Erie) and eventually achieve absolute rates of vertical movement over the region. Obtaining absolute velocities is important in view of linking the area to ocean level and upgrading the vertical datum, hydraulic and hydrologic studies, bathymetry, charts, and navigational safety.

The resulting velocities will provide important constraints on future PGR analyses. Crustal tilting rates are key for future safe navigation on the Great Lakes. Precise positioning obtained by GPS will require corrections for crustal tilting, and thus such models, as developed here, are becoming necessary.

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