Physics and Chemistry of the Earth 53–54 (2012) 61–71

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

A model of surface water hydrology of the Great Lakes, North America during the past 16,000 years

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A R T I C L E I N F O

Article history:
Received 12 December 2009
Received in revised form 18 November 2010
Accepted 8 December 2010
Available online 15 December 2010

Keywords:
Great Lakes
Glacial isostatic adjustment
Ice sheet
Outlets
Shorelines
Hydrology

A B S T R A C T

A model of glacial isostatic adjustment (GIA) is combined with GIS methods to predict the surface water history of the Great Lakes region of North America during the past 16,000 years. The extent of lakes continually changed as the Laurentide ice sheet margin fluctuated and GIA affected the elevations of ice-free outlets. Given only a modern digital elevation model, an earth viscoelastic structure and an ice sheet history, the model adequately represents the Great Lakes history that was developed by glacial geologists during more than a century of field studies. The model predicts the location and elevations of the lowest ice-free outlets and the extent and bathymetry of the proglacial and post-glacial lakes. Results indicate that the Lake Algonquin shoreline, formed about 13,000 years ago, plunges below the present level of Lake Michigan rather than becoming subhorizontal as was once thought leading early geologists to conclude the region was stable and not experiencing GIA. Rather our study indicates that the southern region of the Great Lakes is subsiding, a conclusion reinforced by modern GPS and lake level data. GIA also contributed to many avulsions of river channels during the past 10,000 years as post-glacial tilting promoted stream capture.

1. Introduction

The Great Lakes of North America have experienced dramatic and continued changes during the past 16,000 years forced by the retreat of the Laurentide ice sheet and the accompanying glacial isostatic adjustment (GIA). The history of the Great Lakes has been studied for more than a century (Spencer, 1888; Goldthwait, 1908; Leverett and Taylor, 1915) and the early field observations confirmed that ancient lake shorelines tilted upwards towards the north. It was tilting of ancient ocean and lake shorelines that convinced geologists in North America in the late 19th century that ice sheets affected the geoid. Woodward (1888) believed that the tilted strandlines were solely a result of geoid perturbation caused by the great mass of the ice sheet resting on a rigid earth. His calculation was plausible but the tilting of shorelines continuing after the ice mass had retreated well north of the region convinced geologists that the earth's solid surface also deformed. Geophysicists then invoked GIA as the tilt mechanism for Great Lakes shorelines (Gutenberg, 1933; Broecker, 1966; Brotchie and Silvester, 1969; Walcott, 1970). More recent models incorporated both the effects of geoid perturbations and earth deformation forced by the glacial isostatic adjustment process (Clark et al., 1978, 1990, 1994; Wu and Peltier, 1984; Tushingham and Peltier, 1992). The goal of our study is to use a model of glacial isostatic adjustment to reconstruct the late-glacial and post-glacial hydrologic history of the Great Lakes. This endeavor has become possible because of advances in geophysical modeling methods, improved understanding of the earth's viscosity structure and ice sheet thickness history, and availability of a high resolution digital elevation model giving topography throughout the region. It is thus possible to reconstruct the topography during late- and post-glacial times and from this paleotopography to recreate the ancient surface hydrology.

In addition to reconstructing the ancient lake history our study also explores the possibility that river systems in the Great Lakes watersheds have been influenced by glacial isostatic adjustment processes. It is certain that river systems were greatly affected as the ice sheet margin retreated during late-glacial times (Schumm, 1965; Baker, 1983). River channels became ice-free and glacial outwash surged down valleys that are now occupied by underfit streams. Also changes in the levels of the Great Lakes affected river incision and aggradation due to dramatic base level changes (e.g. Kincare, 2007). Because we reconstruct the paleotopography of the region we can also predict surface water drainages and divides. These predictions can then indicate where isostasy may have forced drainage shifts or stream capture.

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doi:10.1016/j.pce.2010.12.005

Finally as warm-based ice sheets retreated the groundwater hydrology of the Great Lakes region was affected by the changes in hydraulic head, lake level fluctuations and isostatic adjustment. Lemieux et al. (2008a,b) have shown how large these groundwater perturbations may have been over Canada, while Hoaglund et al. (2004) have done a similar analysis for the more limited region near Saginaw Bay of Lake Huron. Although our preliminary groundwater simulations for the Great Lakes region suggest that dramatic changes in flow velocity and even reversals in groundwater flow direction occurred, this important part of Great Lakes hydrology is not addressed here.

2. History of the Great Lakes from field observations

Field studies of the Great Lakes have been extensive and intensive. Great Lakes history is extremely complex as advances, retreats and readvances of the ice sheet occurred repeatedly in conjunction with GIA. Even early geologists recognized the influence of a significant amount of GIA, because the very prominent 13,000 year old Lake Algonquin shoreline rises 120 m over a distance of only 300 km. Outlets that controlled the lake levels were thus alternately ice-covered and deglaciated while simultaneously experiencing isostatic uplift or isostatically induced subsidence. Excellent reviews of this field work are given by Hough (1958), Karrow and Calkin (1985), Teller (1987) and most recently by Kincare and Larson (2009). Although details of the history are still attracting attention, the classic interpretations of changing lake levels and shoreline tilting, much of it reported before the advent of radiocarbon dating, has been largely confirmed. From the viewpoint of the geophysicist the detail of the classic lake interpretation that is most in need of revision was the idea that a “hinge line” passing through Lake Michigan separated a dynamically uplifting region to the north from a stable southern region. This interpretation was based upon supposed subhorizontal shorelines in the southern basin in contrast to the large tilt of those same shorelines north of the hinge line. This hinge line concept has been challenged on both observational (Larsen, 1987; Taylor, 1990; Colman et al., 1994a,b) and theoretical grounds (Clark et al., 1994) and modern reviews of GPS data and lake level gauges have not supported the existence of a hinge line (Mainville and Craymer, 2005; Sella et al., 2007; Braun et al., 2008).

3. The modeling process

The first and most important step in predicting past changes in Great Lakes levels is the determination of the amount of isostatic deformation affecting the region. The method we have used is described in detail by Clark et al. (2008). It involves representing global ice sheets by a collection of discrete quadrilateral cells which have prescribed ice thicknesses through time. The earth is assumed to be a spherically symmetric Maxwell viscoelastic material. As the ice sheet retreats meltwater flows into the ocean causing sea level to rise increasing the ocean water load. These changing surface mass loads and accompanying internal mantle flow not only affect the deformation of the earth’s solid surface but also its geoid. Because both sea level and lake levels must lie on gravitational equipotentials our model predicts both geoid perturbation and deformation of the solid surface. Changes in levels of the ocean and lakes are calculated as the difference between these two dynamic surfaces. Whereas the ocean has a water volume constraint that fixes the ocean surface on a unique gravitational equipotential surface, lakes are not similarly constrained. Rather lake levels are on an equipotential parallel to the geoid and selected by outlet elevation. Hence the past levels of a lake are a function of the tilting of the solid earth, the perturbation of a gravitational equipotential surface, and factors affecting the water level at the outlet. Such factors would include the changing elevation of the outlet, any erosion at the outlet and fluctuating outlet discharge which affects the height of water as it enters the outlet channel (Hansel and Mickelson, 1988).

To incorporate self-consistent ocean and ice loads, changes in sea level were calculated for a global change in ice sheet loading. Once the sea level equation of Farrell and Clark (1976) was solved numerically at 1000-year intervals all of the surface loads were fixed and these were used to calculate isostatic adjustment anywhere in the world. We calculated results on a regular grid of 10,000 points with spacing of 0.2° longitude by 0.1° latitude spanning the Great Lakes region. At each point the change between the solid surface and the geoid was predicted at 30 times beginning 29,000 years ago. Although the global load predictions were only at 1000-year intervals, the time-dependent change is smoothly varying so that spline interpolation was used to predict changes at any required time intermediate to the regular 1000-year predictions. All changes were tabulated at times relative to the present deformation. Not only is the deformation smoothly varying in time but it is also smoothly varying laterally. Therefore two-dimensional spline interpolation in the spatial dimension among the grid points yields predictions $d(r, t)$ at any location, r, and time, t for the past 20,000 years.

Tilting and deformation of a former lake plain between locations r and r' at time t in the past is $d(r, t) - d(r', t)$. But the predicted shoreline elevation is only fixed when the present elevation of a point on the lake is known, $e(r, 0)$. The predicted present elevation of the former lake is then $e(r', t) = e(r, 0) + d(r, t) - d(r', t)$. This lake surface can only be observed where it intersects the topography and thus may have left ancient shoreline features. Predicted shorelines can occur wherever $e(r', t)$ equals $\mathrm{DEM}(r', 0)$, the modern digital elevation of the earth’s surface. Although any single point on a shoreline can constrain the lake surface it is common to use the present elevation of the ancient lake outlet.

As ice retreated proglacial lakes flooded the region. The ice load was thus replaced by a water load that persisted to the present. However this water load is not included in the ice and ocean loads of the model. To test the effects of this omission water loads were calculated by Clark et al. (2007) who showed that water loading always contributed less than 10% to the total deformation with values typically much less than that. The present study does not include the lake water loading term.

3.1. Input data

The history of glacial isostatic adjustment is a function of both the ice sheet history and the earth rheology. Although many earth viscoelastic structures have been proposed (e.g. Sabadini et al., 1991) we have chosen to use the VM2 viscoelastic structure determined by Peltier (1985, 1998, 1999) resulting from direct inversion of GIA sea level data. For an ice sheet history we use the ICE-3G model (Tushingham and Peltier, 1991, 1992) but modify it slightly, thinning by 40% that model over the Great Lakes region (Clark et al., 2008). We have done this to improve the fit to lake shorelines of Glacial Lake Oshkosh in eastern Wisconsin. Braun et al. (2008) have compared GIA predictions in the Great Lakes region to modern tide gauge records and to rates of vertical motion from GPS data. They show that the GPS and tide gauge data are highly correlated. Of 70 different combinations of earth structure and ice sheet histories they concluded that the combination of ICE-3G ice sheet and VM2 viscosity structure results in a prediction that best fits the modern rate of vertical motion over the Great Lakes.

In addition to the ice loads it is necessary to include data of the history of ice sheet extent. This is because the ice sheet formed