Holocene relative sea-level changes and glacial isostatic adjustment of the U.S. Atlantic coast

S.E. Engelhart[1], W.R. Peltier[2], and B.P. Horton[1]*
[1]Sea Level Research, Department of Earth and Environmental Science, University of Pennsylvania, Hayden Hall, 240 South 33rd Street, Philadelphia, Pennsylvania 19104, USA
[2]Department of Physics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 1A7, Canada

ABSTRACT

The first quality-controlled Holocene sea-level database for the U.S. Atlantic coast has been constructed from 686 sea-level indicators. The database documents a decreasing rate of relative sea-level (RSL) rise through time with no evidence of sea level being above present in the middle to late Holocene. The highest rates of RSL rise are found in the mid-Atlantic region. We employ the database to constrain an ensemble of glacial isostatic adjustment models using two ice (ICE-5G, ICE-6G [global ice sheet reconstructions]) and two mantle viscosity (models VM5a,VM5b [VM—radial variation of viscosity in the sublithospheric mantle]) variations to assess whether the spherically symmetric viscoelastic models are able to survive intercomparison with a more refined database of postglacial RSL history. We identify significant misfits between observations and predictions using ICE-5G with the VM5a viscosity profile. ICE-6G provides some improvement for the northern Atlantic region, but misfits remain elsewhere. Decreasing the upper mantle and transition zone viscosity by a factor of 2 to 0.25 × 10^{21} Pa s (VM5b) removes significant discrepancies between observations and predictions along the mid-Atlantic coastline, although misfits remain in the southern Atlantic region. These may be an indication of the importance of laterally heterogeneous viscosity in the upper mantle.

INTRODUCTION

Relative sea-level (RSL) change is related to the redistribution of mass from ice sheet growth and decay, inducing isostatic compensation of the underlying solid Earth. Our understanding of current rates of sea-level rise from tide gauge (e.g., Church and White, 2006) and satellite (e.g., Cazenave et al., 2009) data, and of the ongoing mass loss from the major ice sheets by the Gravity Recovery and Climate Experiment (GRACE) (e.g., Velicogna and Wahr, 2006) requires correction for glacial isostatic adjustment (GIA) effects that are both calibrated to, and independently tested by, observations of former sea levels. Holocene RSL data are used to infer mantle viscosity (e.g., Mitrovica and Peltier, 1995) and lithospheric thickness (e.g., Tushingham and Peltier, 1992). The Atlantic coast of the United States is a key region for the comparison of model predictions and sea-level observations because it provides an independent constraint for GIA models such as ICE-5G VM5a (Peltier and Drummond, 2008) that are tuned to data sets from Canada, Fennoscandia, and Barbados (Peltier and Fairbanks, 2006). It is significant that the GIA of the U.S. Atlantic coast is dominated by the collapse of the large-amplitude proglacial forebulge of the massive Laurentide ice sheet.

The earliest GIA models (Clark et al., 1978) did not fit the observational data from the U.S. Atlantic coast when the viscosity of the mantle was assumed to be independent of depth (Cathles, 1975). While the VM1 (VM is radial variation of the viscosity of the sublithospheric mantle) model improved the fit between observations and model predictions (Tushingham and Peltier, 1992), a better agreement was achieved with the combination of ICE-4G (global ice sheet reconstructions) and the more complex VM2 viscosity profile (Peltier, 1996). Since the publication of Peltier (1996), however, there have been advances in the reconstruction of RSL (e.g., Horton et al., 2009) and the development of improved ice models, including ICE-5G (Peltier, 2007) and ICE-6G (Peltier, 2010). The incorporation of rotational feedback in GIA models (e.g., Wu and Peltier, 1984) is an especially important recent advance. Here we focus on whether a new sea-level database is able to confirm the good quality of fit between observations and predictions previously obtained using simpler models, and reveal significant systematic deviations.

CONSTRUCTION OF A SEA-LEVEL DATABASE

The sea-level database is created from published and unpublished samples of organic sediment (salt and fresh-water marshes) and shells of marine gastropods and foraminifera. The samples are converted into sea-level index points (see Supplementary Methods in the GSA Data Repository[1]) when they meet three criteria: (1) the location of the sample is established to within 1 km; (2) the age of the sample is calibrated to sidereal years using the latest ^{14}C calibration curve; and (3) a relationship between the sample and a known tidal level (i.e., indicative meaning; van de Plassche, 1986) is identified. For samples that cannot be directly related to former sea level, we produce marine (e.g., marine shells) and terrestrial (e.g., freshwater peat) limiting data from samples that must have been deposited below and above mean sea level, respectively. Every sample has an error calculated from a variety of factors inherent to sea-level research (van de Plassche, 1986). We minimized the influence of compaction of sediment by excluding intercalated index points (organic sediments that were underlain and overlain by different sedimentary units) and subdivide the remaining into "base of basal" and "basal" (e.g., Horton and Shennan, 2009). To account for spatial variations, the database was subdivided into 16 geographical regions (1–16 in Fig. 1) based on a combination of the availability of data, the distance from the former center of the Laurentide Ice Sheet, and GIA reconstructions. The addition of new RSL data may allow further subdivision. For all observational data (radiocarbon dates, calibrated age ranges, RSL reconstructions with associated errors, and references to the original publications), see the Data Repository.

PREDICTIONS OF RSL

The model analyses are based on the full gravitationally self-consistent form of the GIA theory and include the effects of rotational feedback (e.g., Milne and Mitrovica, 1996; Peltier, 1998; Wu and Peltier, 1984). The RSL predictions are based on the ICE-5G (Peltier and Drummond, 2008) and ICE-6G (Peltier, 2010) ice models. The ice models are coupled to the VM5a viscosity model (Peltier and Drummond, 2008) that reduces the misfit between predicted and observed horizontal motions of the North American plate (Argus and Peltier, 2010). VM5a

[1]GSA Data Repository item 2011226, Appendix DR1 (data presented in this study including location, material dated, ^{14}C and calibrated ages, relative sea level ± error, original reference, and evidence used for classification), Figure DR1 (example of a sea-level index point from New Jersey), Figure DR2 (mantle viscosity profiles for models VM1, VM5a, and VM5b), and Figure DR3 (plots of residuals between model predictions and sea-level index points for three sites), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

*E-mail: bphorton@sas.upenn.edu.

Geology, August 2011; v. 39; no. 8; p. 751–754; doi:10.1130/G31857.1; 3 figures; Data Repository item 2011226.

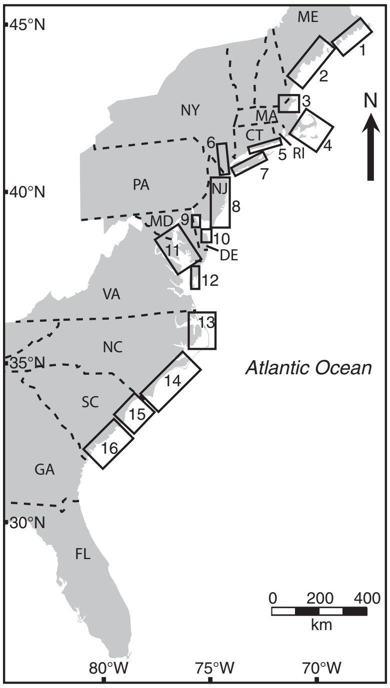

Figure 1. Location map of United States Atlantic coast showing 16 study areas from Maine to South Carolina. Numbers correspond to reconstructions in Figure 3. ME—Maine; MA—Massachusetts; RI—Rhode Island; CT—Connecticut; NY—New York; NJ—New Jersey; PA—Pennsylvania; DE—Delaware; MD—Maryland; VA—Virginia; NC—North Carolina; SC—South Carolina; GA—Georgia; FL—Florida.

includes a 100-km-thick lithosphere, consisting of a 60-km-thick elastic upper layer, beneath which there is a 40-km-thick layer with a viscosity of 10^{22} Pa s. Here we revise the Earth model by reducing the viscosity of the upper mantle and transition zone above the 660 km phase transformation from 0.5×10^{21} Pa s (VM5a) to 0.25×10^{21} Pa s (VM5b) (Fig. DR2 in the Data Repository). This is similar to the value calculated by Wolf et al. (2006) of 0.32×10^{21} Pa s but represents a 50% reduction compared to the viscosity of 0.53×10^{21} Pa s provided by Paulson et al. (2007). However, Paulson et al. (2007) noted that a lower upper mantle viscosity could be supported if associated with a stronger lower mantle viscosity. In Tushingham and Peltier (1992) it was shown that reducing the viscosity of the upper mantle and transition zone substantially increases the width of the proglacial forebulge, and therefore raises the predicted RSLs along the U.S. Atlantic coast without increasing the number of free parameters. VM5b continues to fit RSL data from northern Canada because they are insensitive to upper mantle and transition zone viscoelastic structure (Peltier, 1998).

HOLOCENE SEA-LEVEL OBSERVATIONS

The new Holocene RSL database for the U.S. Atlantic coast consists of 342 sea-level index points, 189 marine limiting dates, and 155 terrestrial limiting dates (Fig. 2A). The RSL database previously used to constrain GIA models (Peltier, 1996) contained fewer index points (n = 175) and marine limiting data (n = 85), but a greater number of terrestrial limiting data (n = 395). The increase in the number of index points in the new database is due to both the addition of new data (e.g., Horton et al., 2009; Miller et al., 2009) and the reinterpretation of terrestrial limiting dates as index points on the basis of the macrofossil and microfossil sea-level indicators. The elevation errors are index-point specific, in contrast to the standard vertical error term employed in the previous database. The new database has good temporal coverage from 6 ka to present; however, only 7% of the index points are older. The early Holocene record is primarily defined by limiting data. Spatially, RSL is well constrained by index points between Maine and South Carolina, although there is an absence of index points in Georgia and the Atlantic coast of Florida. The validation of observations strongly affects the interpretation of a GIA model. For example, the New Jersey predictions must now plot through index points, rather than being below a host of samples previously interpreted as limiting data (Fig. 2B). The North Carolina site demonstrates the importance of the addition of new data (Horton et al., 2009) to constrain models of GIA (Fig. 2C).

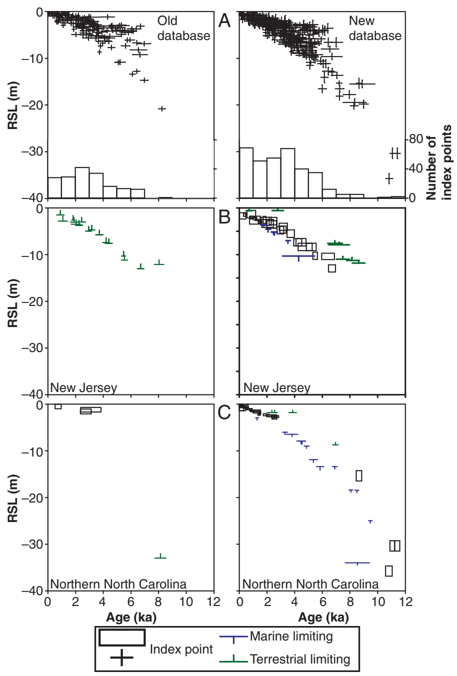

Figure 2. Age-altitude plots of relative sea-level (RSL) observations for Peltier (1996) and new database. A: Highlighting all index points; inset is histogram showing temporal distribution. B, C: Differences in New Jersey and northern North Carolina. Index points in new database are plotted as boxes with 2σ vertical and calibrated age errors, whereas in previous database only age errors are 2σ.

Analysis of the full database from eastern Maine to southern South Carolina (regions 1–16 in Fig. 3) demonstrates that RSL has not risen above present during the middle and late Holocene. In Maine and northern Massachusetts, limiting data suggest that RSL may have dropped from above present prior to a slowstand between 11.5 and 7.5 ka (e.g., Kelley et al., 2010). Rates of RSL change were highest during the early Holocene and have been decreasing over time, due to the exponential form of the GIA process following deglaciation and the reduction of ice equivalent meltwater input from 7 ka onward. The maximum rate of Holocene RSL rise (e.g., ~15 m since 6 ka) occurred in New Jersey and Delaware (regions 8–10), coincident with the area of greatest ongoing GIA related subsidence. The RSL histories of the northeastern Atlantic region (regions 1–5) are constrained by sea-level index points from 7 ka to present; all five areas reveal a rise in sea level of <10 m since 6 ka. Index points from southern North Carolina to southern South Carolina (regions 14–16) similarly support a rise in RSL of <10 m during the past 6 k.y.

IMPLICATIONS FOR GLACIAL ISOSTATIC ADJUSTMENT MODELS

The ICE-5G VM5a model is in good agreement with the Holocene RSL observations in eastern (region 1) and southern Maine (region 2) for the past 6 k.y. The model is above marine limiting dates from southern Maine between 8 and 11 ka. For the remaining study areas (regions 3–16), the model fits the observations in the late Holocene (0–3 ka), but with increasing age there is a systematic disagreement between the model and the data. The misfit is most pronounced along the mid- and southern Atlantic coastlines (New York, 6, to southern South Carolina, 16) with observations of RSL ~10 m higher than model predictions at 6 ka. The predictions are invalidated by marine limiting dates at southern Massachusetts (4), New Jersey (8), Chesapeake Bay (11), and northern North Carolina (13). ICE-6G VM5a is an improvement over ICE-5G VM5a for northern Massachusetts to New York (regions 3–6). However, the model now underpredicts RSL in eastern Maine (1) and overpredicts in southern Maine (2). There is little difference between ICE-5G and ICE-6G from Long Island (7) to southern South Carolina (16), because both ice models have similar mass and cover exactly the same surface area of the North American continent.

For both ice models, decreasing the upper mantle viscosity in VM5a to produce VM5b results in a considerable improvement (Fig. DR3) in the quality of fit along the U.S.

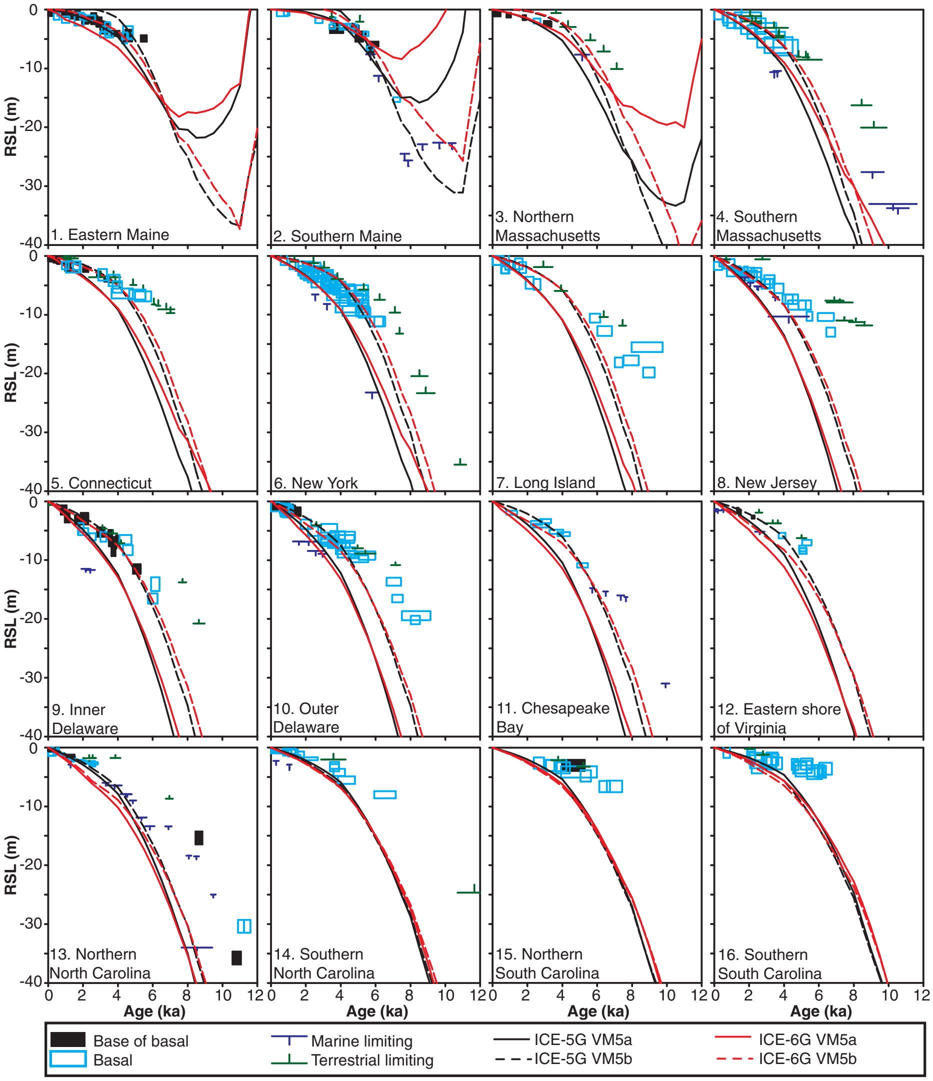

Figure 3. Age-altitude plots of relative sea-level (RSL) observations and model predictions for 16 different areas from Maine to South Carolina. Index points are plotted as boxes with 2σ vertical and calibrated age errors. Predictions shown are from ICE-5G (black line) and ICE-6G (red line) ice models, coupled to either the original VM5a (solid lines) or modified VM5b (dashed lines) viscosity profiles (see text).

Atlantic coast in the area of greatest GIA-related subsidence (regions 4–12). Earlier model iterations that also increased the upper mantle/lower mantle contrast ratio from 1:1 to 1:4 resulted in a similar decrease in variance (Tushingham and Peltier, 1992). However, by reducing the value of both the upper mantle and the transition zone viscosity, we may have significantly violated the model fit to the McConnell (1968) spectrum of Fennoscandian rebound. This would suggest that we have directly detected a requirement for lateral viscosity variation in the upper mantle from two independent data sets associated with the near-field Fennoscandia region and intermediate-field U.S. Atlantic coast (e.g., Kaufmann and Lambeck, 2002). It has previously been noted that one-dimensional viscosity structure derived from global postglacial rebound observations is heavily weighted toward the viscosity structure beneath the loaded region and not the global average (Paulson et al., 2005).

While the VM5b viscosity profile results in a significant improvement, there remain two outstanding issues. First, the incorporation of the VM5b viscosity profile with ICE-5G predicts late Holocene highstands of RSL in the northeastern United States (regions 1–3), because the softening of the upper mantle and transition zone produces a time-dependent shift of the boundary between uplift and subsidence. The highstand is removed at eastern Maine (region 1) by using ICE-6G because of a change in the thickness of the proximal ice load. Therefore, the remaining highstands in southern Maine (region 2) and northern Massachusetts (region 3) may also be eliminated through further thickening of the ice load in proximity to these two locations. Alternatively, a slight increase in the thickness of the elastic lithosphere would accomplish the same improvement of fit (Tushingham and Peltier, 1992).

Second, and more important, are the continuing misfits between the VM5a/VM5b RSL predictions and observations in the southern Atlantic region (regions 13–16). We must consider that changes to other aspects of the Earth model may be necessary to fit the data, including lithospheric thickness (e.g., Tushingham and Peltier, 1992) and/or the incorporation of lateral heterogeneity in the mantle (e.g., Wu, 2006) and lithosphere (e.g., Wang and Wu, 2006). In Tushingham and Peltier (1992), it was demonstrated that changes in lithospheric thickness from 71 to 245 km have little effect on the variance between model predictions and sea-level observations during the Holocene along the U.S. Atlantic coast. Three-dimensional mantle viscosity may be required to incorporate the effects of the subduction of the Farallon plate 80 m.y. ago, which has now penetrated the top half of the lower mantle beneath the Atlantic (e.g., Bunge and Grand, 2000). Changes to the viscosity of the upper part of the lower mantle in the one-dimensional model (e.g., Davis and Mitrovica, 1996) are usually ruled out by the strong constraints of the RSL data from Canada. However, Wang and Wu (2006) produced a model supported by seismic velocity anomalies from global tomography models that showed lateral variations at all depths of the mantle performed better than a model with no lateral variations.

RSL observations may also be subject to changes from processes such as compaction, tidal range variations, and tectonics (e.g., Shennan and Horton, 2002). The database shows no discernable difference between basal and base of basal samples; compaction would only lower the elevation of index points, artificially improving the fit to the model. If the tidal range has not remained constant through time, sea-level chronologies based upon tide-level indicators will differ from true sea level. Modern tidal range along much of the southeastern Atlantic coast is <2.5 m. Therefore, an unrealistic tenfold increase in tidal range is needed to lower the elevation of sea-level observations and remove the misfit at 7 ka. The rate of tectonic uplift necessary to achieve a fit between model and data (>1 mm yr^{-1}) disagrees with global positioning system (Sella et al., 2007) and tide-gauge (e.g., Douglas, 1991) observations. Uplift rates of this magnitude are more typically associated with seismic coastlines such as Cascadia (e.g., Burgette et al., 2009). There is evidence for tectonic activity in North Carolina and South Carolina. However, the calculated long-term uplift rate of ~0.02–0.05 mm yr^{-1} along the Orangeburg Scarp (South Carolina) (Dowsett and Cronin, 1990) is not sufficient. The rate of uplift along the Cape Fear Arch (North Carolina) is poorly constrained (0.14–1.8 mm yr^{-1}) and may be highly localized (Marple and Talwani, 2004). Rates of change due to mantle upwelling and downwelling show no spatial pattern along the U.S. Atlantic coast and are likely to be <0.1 mm yr^{-1} (Conrad and Husson, 2009). It is unfortunate that there are currently no RSL data available from the Atlantic coast of Florida or Georgia to allow us to ascertain whether the misfit between observations and predictions is a regional phenomenon. This limitation currently prevents us from confirming that the internal viscoelastic structure must be laterally heterogeneous on a scale that influences ongoing GIA.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation (grant EAR-0717364), the U.S. Department of Agriculture Forest Service Global Change Research Program of the Northern Research Station, the Natural Sciences and Engineering Research Council of Canada (A9627), the Thouron family, and the University of Pennsylvania. This work is a contribution to International Geoscience Programme (IGCP) Project 588, PALeo-constraints on SEA-level rise (PALSEA), and the Polar Climate Stability Network. We thank I. Shennan, T. Törnqvist, O. van de Plassche, P. Cowie, and two anonymous reviewers for comments that greatly improved the quality of the manuscript.

REFERENCES CITED

Argus, D.L., and Peltier, W.R., 2010, Constraining models of postglacial rebound using space geodesy: A detailed assessment of model ICE-5G (VM2) and its relatives: Geophysical Journal International, v. 181, p. 697–723, doi:10.1111/j.1365-246X.2010.04562.x.

Bunge, H.-P., and Grand, S.P., 2000, Mesozoic plate-motion history below the northeast Pacific Ocean from seismic images of the subducted Farallon slab: Nature, v. 405, p. 337–340, doi:10.1038/35012586.

Burgette, R.J., Weldon, R.J., and Schmidt, D.A., 2009, Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone: Journal of Geophysical Research, v. 114, B01408, doi:10.1029/2008JB005679.

Cathles, L.M., 1975, The viscosity of the Earth's mantle: Princeton, New Jersey, Princeton University Press, 386 p.

Cazenave, A., Dominh, K., Guinehut, S., Berthier, E., Llovel, W., Ramillien, G., Ablain, M., and Larnicol, G., 2009, Sea level budget over 2003–2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo: Global and Planetary Change, v. 65, p. 83–88, doi:10.1016/j.gloplacha.2008.10.004.

Church, J.A., and White, N.J., 2006, A 20th century acceleration in global sea-level rise: Geophysical Research Letters, v. 33, L01602, doi:10.1029/2005GL024826.

Clark, J.A., Farrell, W.E., and Peltier, W.R., 1978, Global changes in postglacial sea level: A numerical calculation: Quaternary Research, v. 9, p. 265–287, doi:10.1016/0033-5894(78)90033-9.

Conrad, C.P., and Husson, L., 2009, Influence of dynamic topography on sea level and its rate of change: Lithosphere, v. 1, p. 110–120, doi:10.1130/L32.1.

Davis, J.E., and Mitrovica, J.X., 1996, Glacial isostatic adjustment and the anomalous tide gauge record of eastern Northern America: Nature, v. 379, p. 331–333, doi:10.1038/379331a0.

Douglas, B.C., 1991, Global sea-level rise: Journal of Geophysical Research, v. 96, p. 6981–6992, doi:10.1029/91JC00064.

Dowsett, H.J., and Cronin, T.M., 1990, High eustatic sea level during the middle Pliocene—Evidence from the southeastern United States Atlantic coastal plain: Geology, v. 18, p. 435–438, doi:10.1130/0091-7613(1990)018<0435:HESLDT>2.3.CO;2.

Horton, B.P., and Shennan, I., 2009, Compaction of Holocene strata and the implications for relative sea-level change: Geology, v. 37, p. 1083–1086, doi:10.1130/G30042A.1.

Horton, B.P., Peltier, W.R., Culver, S.J., Drummond, R., Engelhart, S.E., Kemp, A.C., Mallinson,D., Thieler, E.R., Riggs, S.R., Ames, D.V., and Thomson, K.H., 2009, Holocene sea-level changes along the North Carolina coastline and their implications for glacial isostatic adjustment models: Quaternary Science Reviews, v. 28, p. 1725–1736, doi:10.1016/j.quascirev.2009.02.002.

Kaufmann, G., and Lambeck, K., 2002, Glacial isostatic adjustment and the radial viscosity profile from inverse modeling: Journal of Geophysical Research, v. 107, doi:10.1029/2001JB000941.

Kelley, J.T., Belknap, D.F., and Claesson, S., 2010, Drowned coastal deposits with associated archaeological remains from a sea-level "slowstand": Northwestern Gulf of Maine, USA: Geology, v. 38, p. 695–698, doi:10.1130/G31002.1.

Marple, R., and Talwani, P., 2004, Proposed Shenandoah fault and east coast Stafford fault system and their implications for eastern U.S. tectonics: Southeastern Geology, v. 43, p. 57–80.

McConnell, R.K., 1968, Viscosity of the mantle from relaxation time spectra of isostatic adjustment: Journal of Geophysical Research, v. 73, p. 7089–7105, doi:10.1029/JB073i022p07089.

Miller, K.G., Sugarman, P.J., Browning, J.V., Horton, B.P., Stanley, A., Kahn, A., Uptegrove, J., and Aucott, M., 2009, Sea-level rise in New Jersey over the past 5000 years: Implications to anthropogenic changes: Global and Planetary Change, v. 66, p. 10–18, doi:10.1016/j.gloplacha.2008.03.008.

Milne, G.A., and Mitrovica, J.X., 1996, Postglacial sea-level change on a rotating Earth: First results from a gravitationally self-consistent sea-level equation: Geophysical Journal International, v. 126, p. F13–F20, doi:10.1111j.1365-246X.1996.tb04691.x.

Mitrovica, J.X., and Peltier, W.R., 1995, Constraints on mantle viscosity based upon the inversion of postglacial uplift data from the Hudson Bay region: Geophysical Journal International, v. 122, p. 353–377, doi:10.1111/j.1365-246X.1995.tb07002.x.

Paulson, A., Zhong, S., and Wahr, J., 2005, Modelling post-glacial rebound with lateral viscosity variations: Geophysical Journal International, v. 163, p. 357–371, doi:10.1111/j.1365-246X.2005.02645.x.

Paulson, A., Zhong, S., and Wahr, J., 2007, Inference of mantle viscosity from GRACE and relative sea level data: Geophysical Journal International, v. 171, p. 497–508, doi:10.1111/j.1365-246x.2007.03556.x.

Peltier, W.R., 1996, Mantle viscosity and ice-age ice sheet topography: Science, v. 273, p. 1359–1364, doi:10.1126/science.273.5280.1359.

Peltier, W.R., 1998, Postglacial variations in the level of the sea: Implications for climate dynamics and solid-Earth geophysics: Reviews of Geophysics, v. 36, p. 603–689, doi:10.1029/98RG02638.

Peltier, W.R., 2007, History of Earth rotation, *in* Schubert, G., ed., Treatise on geophysics, Volume 9: Oxford, Elsevier, p. 243–293.

Peltier, W.R., 2010, Closing the budget of global sea level rise: The GRACE correction for GIA over the oceans, *in* Stocker, T.F., et al., eds., Workshop report of the Intergovernmental Panel on Climate Change Workshop on Sea Level Rise and Ice Sheet Instabilities: Bern, Switzerland, University of Bern, IPCC Working Group Technical Support Unit, p. 157–159.

Peltier, W.R., and Drummond, R., 2008, Rheological stratification of the lithosphere: A direct inference based upon the geodetically observed pattern of the glacial isostatic adjustment of the North American continent: Geophysical Research Letters, v. 35, doi:10.1029/2008GL034586.

Peltier, W.R., and Fairbanks, R.G., 2006, Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record: Quaternary Science Reviews, v. 25, p. 3322–3337, doi:10.1016/j.quascirev.2006.04.010.

Sella, G.F., Stein, S., Dixon, T.H., Craymer, M., James, T.S., Mazzotti, S., and Dokka, R., 2007, Observation of glacial isostatic adjustment in "stable" North America with GPS: Geophysical Research Letters, v. 34, doi:10.1029/2006GL027081.

Shennan, I., and Horton, B., 2002, Holocene land- and sea-level changes in Great Britain: Journal of Quaternary Science, v. 17, p. 511–526, doi:10.1002/jqs.710.

Tushingham, A.M., and Peltier, W.R., 1992, Validation of the Ice-3g model of Wurm-Wisconsin deglaciation using a global data-base of relative sea-level histories: Journal of Geophysical Research, v. 97, p. 3285–3304, doi:10.1029/91JB02176.

van de Plassche, O., 1986, Sea-level research: A manual for the collection and evaluation of data: Norwich, UK, Geobooks, 618 p.

Velicogna, I., and Wahr, J., 2006, Measurements of time-variable gravity show mass loss in Antarctica: Science, v. 311, p. 1754–1756, doi:10.1126/science.1123785.

Wang, H., and Wu, P., 2006, Effects of lateral variations in lithospheric thickness and mantle viscosity on glacially induced relative sea levels and long wavelength gravity field in a spherical, self gravitating Maxwell Earth, v. 249, p. 368–383, doi:10.1016/j.epsl.2006.07.011.

Wolf, D., Klemann, V., Wunsch, J., and Zhang, F.-P., 2006, A reanalysis and reinterpretation of geodetic and geological evidence of glacial-isostatic adjustment in the Churchill region, Hudson Bay: Surveys in Geophysics, v. 27, p. 19–61, doi:10.1007/s10712-005-0641-x.

Wu, P., 2006, Sensitivity of relative sea-levels and crustal velocities in Laurentide to radial and lateral viscosity variations in the mantle: Geophysical Journal International, v. 165, p. 401–413, doi:10.1111/j.1365-246X.2006.02960.x.

Wu, P., and Peltier, W.R., 1984, Pleistocene deglaciation and the Earth's rotation: A new analysis: Geophysical Journal of the Royal Astronomical Society, v. 76, p. 753–791.

Manuscript received 26 October 2010
Revised manuscript received 8 March 2011
Manuscript accepted 16 March 2011

Printed in USA