GROUNDWORK
Furthering the Influence of Earth Science

Late Holocene relative land- and sea-level changes: Providing information for stakeholders

Ian Shennan, *Sea Level Research Unit, Dept. of Geography, Durham University, Durham DH1 3LE, UK;* ***Glenn Milne,*** *Dept. of Earth Sciences, University of Ottawa, Ottawa K1N 6N5, Canada; and* ***Sarah Bradley,*** *Dept. of Earth Sciences, Durham University, Durham DH1 3LE, UK*

INTRODUCTION

Throughout history, human societies dependent upon coastal environments have adapted to changes in sea level. Drowned peat layers on the North Sea continental shelf contain artifacts of Mesolithic communities that had no alternative than to migrate or drown as sea level rose up to 10 mm a^{-1}. At the same time, those in western Scotland prospered, as illustrated by analyses of Mesolithic shell middens, when the rate of sea-level rise declined to zero at a mid-Holocene highstand (Shennan et al., 2006). We can explain these contrasts by the process of glacial isostatic adjustment (GIA), which results in variable relative sea-level change around the British Isles. This geological process, driven by the build-up and retreat of the last great ice sheets, continues in and around previously glaciated regions.

The combination of contrasting relative sea-level changes around the British Isles and a large database of paleo–sea-level reconstructions provides a rigorous test for quantitative GIA models. These models offer a spatial picture not easily inferred from field research at individual sites. Two studies demonstrate the recent advances: Brooks et al. (2008) and Shennan et al. (2006). Their model predictions show good agreement with the majority of the geological evidence of relative sea-level change since 16 ka B.P., but unlike Shennan and Horton (2002), did not include a map summarizing current rates.

The approaches outlined here are applicable to the coastlines of other previously glaciated countries where the processes controlling long-term coastal change, ranging from glacial isostatic adjustment to localized sediment consolidation, are similar to the British Isles (Peltier, 1998; Törnqvist et al., 2008). We also present a map showing our best estimates of current relative sea-level change around the British Isles.

MODEL PREDICTIONS AND RECONSTRUCTIONS OF PAST SEA LEVEL

Our GIA model has three key inputs: a model of the Late Pleistocene ice history, an Earth model to reproduce the solid-earth deformation resulting from surface mass redistribution between ice sheets and oceans, and a model of sea-level change to calculate the redistribution of ocean mass (Bradley et al., 2009). For each geographical location, φ, relative sea-level change ($\Delta\xi_{rsl}$) at time, τ, results from these and other factors:

$$\Delta\xi_{rsl}(\tau,\varphi) = \Delta\xi_{eus}(\tau) + \Delta\xi_{iso}(\tau,\varphi) + \Delta\xi_{tect}(\tau,\varphi) + \Delta\xi_{local}(\tau,\varphi), \quad (1)$$

where $\Delta\xi_{eus}(\tau)$ is the eustatic sea-level function derived from the model of ice history, and $\Delta\xi_{iso}(\tau,\varphi)$ is the total isostatic effect, including the glacio-isostatic and hydro-isostatic load contributions and the redistribution of ocean mass. In contrast to areas adjacent to active plate boundaries, we consider the tectonic effect, $\Delta\xi_{tect}(\tau,\varphi)$, negligible over Holocene time scales.

We express local processes as

$$\Delta\xi_{local}(\tau,\varphi) = \Delta\xi_{tide}(\tau,\varphi) + \Delta\xi_{sed}(\tau,\varphi), \quad (2)$$

where $\Delta\xi_{tide}(\tau,\varphi)$ is the total effect of tidal regime changes and the elevation of the sediment with reference to tide levels at the time of deposition (Shennan and Horton, 2002), and $\Delta\xi_{sed}(\tau,\varphi)$ is the total effect of sediment consolidation since the time of deposition.

Sediment consolidation can be both a major process in coastal evolution (Long et al., 2006; Törnqvist et al., 2008) and a key variable in relative sea-level change (van de Plassche, 1982). The net effect for each site is determined by plotting data as either basal or intercalated data points. Basal data points come from samples at the base of the Holocene sequence and have suffered minimal consolidation, whereas intercalated data points, from within the Holocene sediment sequence, are likely to be at a lower elevation than at the time of deposition due to sediment consolidation.

Comparison of model predictions and reconstructions of Holocene relative sea levels at 80 sites shows good agreement (Brooks et al., 2008; Shennan et al., 2006). All meter-scale differences have data points below model predictions, consistent with showing the net effect of sediment consolidation, which lowers the elevation of a data point. Net effects of 3–5 m are not unusual, either in our study or others (Törnqvist et al., 2008; van de Plassche, 1982).

DISCUSSION

Policymakers use estimates of late-Holocene relative sea-level change to modify predictions of sea-level rise according to geographical location (DEFRA, 2006; UKCIP, 2005). We follow their convention and show relative uplift as a positive value and relative subsidence as a negative value (Fig. 1). The

GSA Today, v. 19, no. 9, doi: 10.1130/GSATG50GW.1

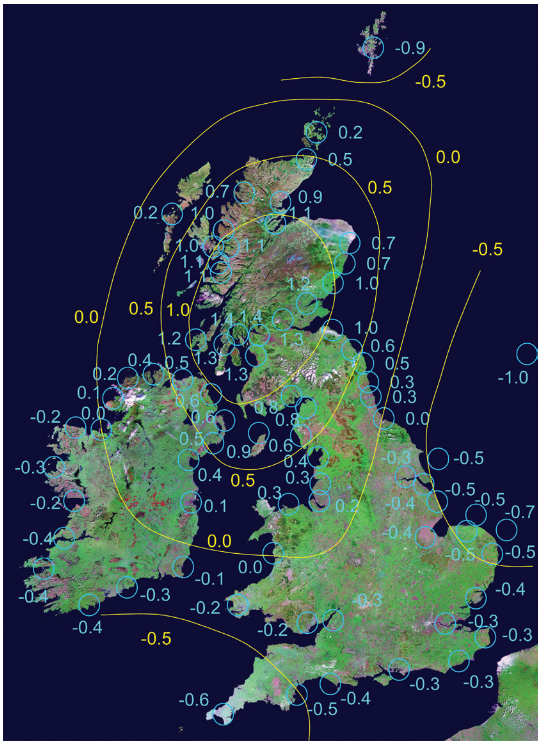

Figure 1. Current rate of relative land- and sea-level change in the British Isles in mm a^{-1}, showing relative land uplift as positive and relative subsidence as negative. Image is ~900 × 1300 km, courtesy of the NASA Scientific Data Purchase Program.

center of relative uplift over central Scotland reflects the continuing impact of glacial isostatic adjustment. Rather than a simple elliptical pattern, three foci of relative subsidence over southwest England, the southern North Sea, and the Shetland Isles show that other factors are important. These include the ocean load on the Atlantic basin and on the continental shelf and the glacial isostatic signal from far-field ice sheets (predominantly Fennoscandinavia).

Our model shows important differences with the 2002 study (Shennan and Horton, 2002). The 2002 study showed greater relative uplift in Scotland and greater relative subsidence in southwest England. We attribute the differences to (1) the availability of more data to test models; (2) model improvements; (3) calculating late Holocene rates for the past 1 ka rather than 4 ka; and (4) greater consideration of sediment consolidation. The 1-ka time frame is important where the relative sea-level trend is distinctly nonlinear. The benefit of our adopted approach to sediment consolidation is borne out by new data from southwest England (Massey et al., 2008). The new data, basal peat data points, fit better with our model, −0.6 mm a^{-1}, compared to intercalated peat data points that gave the 2002 estimate of −1.2 mm a^{-1}.

Figure 1 provides a practical baseline for considering climate-driven sea-level change in different locations. Our calculations use calibrated radiocarbon ages B.P., with A.D. 1950 as 0 B.P., so are independent of debates over any late–twentieth-century acceleration of sea-level rise. Tide gauge–derived trends show a regional sea-level rise of climate change origin on the order of 1.4 mm a^{-1} (Woodworth et al., 2009). The spatial pattern of relative uplift and subsidence is similar to that derived from GPS observations (Bradley et al., 2009) but not identical since they measure different parameters (Eq. 1).

How stakeholders use the baseline rates must be determined by their individual needs. If we consider flood defenses, whether a structure has foundations in Holocene sediment or in basement rock determines the net effect of all components in Equation (1). Many hundreds of kilometers of sea defenses around the world are made up of dirt levees or concrete and steel structures with shallow foundations in Holocene sequences. Their failure or overtopping can cause widespread flooding. Whether in nineteenth-century rural England (Skertchly, 1877) or twenty-first century New Orleans, our understanding of and adaptation to relative land and sea-level change remains intrinsically linked to Holocene geology.

REFERENCES CITED

Bradley, S.L., Milne, G.A., Teferle, F.N., Bingley, R.M., and Orliac, E.J., 2009, Glacial isostatic adjustment of the British Isles: New constraints from GPS measurements of crustal motion: Geophysical Journal International, doi: 10.1111/j.1365-246X.2008.04033.x.

Brooks, A.J., Bradley, S.L., Edwards, R.J., Milne, G.A., Horton, B., and Shennan, I., 2008, Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling: Journal of Quaternary Science, v. 23, no. 2, p. 175–192, doi: 10.1002/jqs.1119.

DEFRA, 2006, Flood and Coastal Defence Appraisal Guidance—FCDPAG3 Economic Appraisal—Supplementary Note to Operating Authorities—Climate Change Impacts: Department for Environment, Food and Rural Affairs, www.defra.gov.uk/environ/fcd/pubs/pagn/climatechangeupdate.pdf (last accessed 21 Apr. 2009).

Long, A.J., Waller, M.P., and Stupples, P., 2006, Driving mechanisms of coastal change: Peat compaction and the destruction of late Holocene coastal wetlands: Marine Geology, v. 225, no. 1–4, p. 63–84.

Massey, A.C., Gehrels, W.R., Charman, D.J., Milne, G.A., Peltier, W.R., Lambeck, K., and Selby, K.A., 2008, Relative sea-level change and postglacial isostatic adjustment along the coast of south Devon, United Kingdom: Journal of Quaternary Science, v. 23, no. 5, p. 415–433, doi: 10.1002/jqs.1149.

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.

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

Shennan, I., Bradley, S., Milne, G., Brooks, A., Bassett, S., and Hamilton, S., 2006, Relative sea-level changes, glacial isostatic modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum: Journal of Quaternary Science, v. 21, no. 6, p. 585–599.

Skertchly, S.B.J., 1877, The geology of the Fenland: Memoirs of the Geological Survey, England and Wales: London, HMSO, 355 p.

Törnqvist, T.E., Wallace, D.J., Storms, J.E.A., Wallinga, J., van Dam, R.L., Blaauw, M., Derksen, M.S., Klerks, C.J.W., Meijneken, C., and Snijders, E.M.A., 2008, Mississippi Delta subsidence primarily caused by compaction of Holocene strata: Nature Geoscience, v. 1, p. 173–176, doi: 10.1038/ngeo129.

UKCIP, 2005, Update to UKCIP02 sea level change estimates, December 2005: UK Climate Impacts Program: www.ukcip.org.uk/index.php?option=com_content&task=view&id=87&Itemid=300 (last accessed 21 Apr. 2009).

van de Plassche, O., 1982, Sea-level change and water movements in the Netherlands during the Holocene: Mededelingen Rijks Geologische Dienst, v. 36, p. 1–93.

Woodworth, P.L., Teferle, F.N., Bingley, R.M., Shennan, I., and Williams, S.D.P., 2009, Trends in UK mean sea level revisited: Geophysical Journal International, v. 176, no. 1, p. 19–30.

Manuscript received 20 March 2009; accepted 27 April 2009.