Technical Appendix 1: Sea level Change

Controls on sea level

Sea level changes that took place during the Palaeolithic were primarily driven by three processes.

First, addition or removal of water from the oceans on a global scale as continental ice sheets grew or shrank (*glacio-eustasy*) in response to alternating glacial and interglacial cycles. Peak glacial lowering has been estimated to be of the order of 120m below present sea level, with interglacial highstands similar to the present, or higher by up to 6-9m (Rohling et al. 2009). Rates of changes were potentially rapid, of the order of several centimetres per year.

Second, isostatic uplift or subsidence of the terrestrial crust induced by changes in the weight of the ice sheets which modified (i.e. accentuated or reduced) the effect of glacio-eustatic changes on a regional-scale (*glacio-isostasy*). As ice sheets grew, their weight depressed the crust beneath them with areas closest to the centre of the sheet, and hence under the greatest mass, experiencing the largest depression (in some instances below contemporary sea level). During deglaciation, the weight was released and the underlying crust rebounded at a rate faster than the meltwater-induced glacio-eustatic rise creating a pattern of RSL fall. On the margins of the ice sheets, crustal depression was also induced by the weight of the ice. However, as the ice was thinner than at the centre, isostatic rebound was only able to dominate the initial stages of deglaciation, whereupon it was overtaken by the global glacio-eustatic rise. This resulted in a RSL history of an initial fall to a lowstand and then a rise, often referred to as a J-shaped sea level curve. In some instances, the rise may have continued to a short-lived highstand that was then terminated by another RSL fall brought about by residual isostatic rebound. Finally, areas outside or on the periphery of the ice sheet were uplifted during glaciation to compensate for the depression under the ice sheet and held there for as long as the ice was present (the *forebulge* effect). The net result was that when the ice retreated they experienced rising sea levels brought about by rising glacio-eustatic sea level and the local collapse of the forebulge as it migrated back into the centre of isostatic recovery.

All three types of RSL history can be observed around the British Isles during the postglacial transition from the Last Glacial Maximum (LGM) to the Holocene interglacial. Scotland, due to its position under the bulk of the British ice sheet is dominated by isostatic rebound and characterized by falling and J-shaped RSL curves. England and Wales however, largely experienced RSL rise with any isostatically-induced fluctuations/reversals occurring below present sea level (Shennan et al. 2002; 2006). Similar patterns probably characterized earlier (i.e. pre-LGM) periods with the exact pattern of RSL change dependant on ice sheet size and growth/decay history.

Third, more minor contributions were driven by crustal uplift or subsidence in response to tectonic forces. Of particular note is the subsidence of the North Sea Basin, which has experienced average subsidence of 0.4m per thousand years over the past 730,000 years (Cameron 1992). Conversely, the region surrounding the English Channel appears to have experienced uplift through the Quaternary at rates averaging 0.1m per thousand years (Lagarde et al. 2003).

Reconstructing past sea-level

The pattern of past sea level change can be built up from two main sources:

1) Dated geological, sedimentological or biological features with a known relationship to past sea-level
2) Numerical models of the Earth's response to ice loading calibrated with observed indicators of past sea level.

Each source has its own advantages and disadvantages. The advantages of dated features is that they can potentially provide a quantitative reconstruction of past sea-level for a given place and time. Their accuracy depends heavily on the nature of the feature. Some, such as submerged tree stumps or raised marine shells, provide only upper or lower limits on past sea level. Others, provide a quantifiable relationship to past sea level, or even a given tide level. This latter category, commonly referred to as Sea Level Index Points (SLIPs), includes microorganisms such as diatoms and foraminiferal communities with very specific habitat requirements (e.g. saltwater, brackish, freshwater). While SLIPs and limits are highly useful, the estimates they provide are generally only applicable locally (i.e. less than several tens of kilometres) due to spatial variations in sea-level history caused by differential isostatic loading/rebound. Moreover, each data point provides only a snapshot for a given time. Long time series records require multiple data points which may not always be available.

In contrast, GIA models cover much larger areas (e.g. the entire British Isles) and allow continuous histories of past sea level change to be generated from anywhere within the model coverage. The main disadvantage of these is accuracy as misfits between model predictions and sea level indicators have been observed (see Edwards et al. 2008, McCabe 2008 for an example from Ireland). However, the models have undergone considerable refinements over the past 15 years. For the British Isles this can be seen in a progression from the models developed by Lambeck et al (1995), to those used by Peltier et al. (2002), Shennan et al (2002) and to the most recent improvements developed by Milne et al (2006). For example, the most recent models are corrected for topography beneath the simulated ice sheets, a fact not taken into account in earlier interactions, which consequently suffered from overestimates in the weight of ice (Shennan et al. 2006). Overall, while the models can generally simulate the overall regional scale RSL well, there are questions over how well this translates to a local scale.

In terms of spatial coverage, RSL data is spread relatively evenly across the British Isles (Shennan et al. 2006). There are over 2000 observations/records of which approximately 1250 were validated index points (Brooks 2007). Data points from the surrounding continental shelf are much sparser and tend to only constrain the shallower portions of RSL signal (i.e. there are relatively few indicators of sea-level change from depths below -20m) (Shennan et al. 2002).

In terms of temporal distribution, the vast majority of RSL records postdate 10 ka (Shennan et al. 2002) with many of the oldest records coming from areas such as Arisaig (Scotland), where RSL never fell below modern levels (Shennan et al. 2006). Older data from submerged shelves are particularly rare. For example, Ward et al. (2006) identified only 9 pre-Holocene dates from sedimentary contexts in the southern North Sea, with the oldest date limited to 14 ka. Moreover, they also identified that the stratigraphic context of many of these submerged samples is often poorly constrained, leading to increased uncertainties in the reconstructed elevations of past sea-level. This distribution is further substantiated by the peat database held by English Heritage (Hazell 2008). Of the c. 340 sites recorded in the database, only 13 had dates or interpretations (based on stratigraphy or fossil remains) that indicated a pre-Holocene age.

Some RSL data have survived from the pre-LGM, chiefly in the form of raised beaches and marine deposits. Examples of these are known along the south coast of England and are particularly clear on the Hampshire-Sussex coastal plain. While the exact chronological sequence of these deposits has yet to be finalized, it has been suggested that they were laid down during interglacial highstands in MIS5e, 7, 9 and possibly 11 and 13 (Bates et al. 2003). Lowstand estimates for the pre-LGM are still poorly known. There are deposits and geomorphologic features offshore (e.g. deltaic sediments and palaeo-channels) which show that sea levels were lower but the precise shelf extent and pattern of flooding/retreat cannot currently be reconstructed.

Since GIA models are calibrated against RSL data, the lack of pre-LGM data prevents their extension into the pre-LGM. Moreover, their use prior to the LGM is also hindered by uncertainties in ice sheet size and deglaciation history and the resultant complex interplay of glacio-eustatic changes and isostatic movements. Even within the post-LGM, the lack of older data from deeper shelf context (i.e. >20-30m water depth) results in greater uncertainty for the earlier Palaeolithic sections of the modelled RSL histories.

References

Bates, M. R., D. H. Keen & J.-P. Latridou. 2003. Pleistocene marine and periglacial deposits of the English Channel. *Journal of Quaternary Science* 18(3-4):319-37.

Brooks, A. J. (2007). Late Devensian and Holocene Relative Sea-Level Change around Ireland. Unpublished PhD thesis. Department of Geography, Trinity College Dublin.

Cameron, T. D., A. Crosby, P. S. Balson, D. H. Jeffery, G. K. Lott, J. Bulat & D. J. Harrison. 1992. *The Geology of the Southern North Sea,* London: Her Majesty's Stationary Office for the British Geological Survey.

Edwards, R., A. J. Brooks, I. Shennan, G. A. Milne & S. L. Bradley. 2008. Reply: Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. A. J. Brooks, S. L. Bradley, R. J. Edwards, G. A. Milne, B. Horton and I. Shennan (2008). Journal of Quaternary Science 23: 175-192. *Journal of Quaternary Science* 23(8):821-5.

Hazell, Z.J. 2008. Offshore and intertidal peat deposits, England - a resource assessment and development of a database. *Environmental Archaeology* 13(2):101-10

Lagarde, J. L., D. Amorese, M. Font, E. Laville & O. Dugue. 2003. The structural evolution of the English Channel area. *Journal of Quaternary Science* 18(3-4):201-13.

Lambeck, K. 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society, London* 152:437-48.

McCabe, A. M. 2008. Comment: Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. A. J. Brooks, S. L. Bradley, R. J. Edwards, G. A. Milne, B. Horton and I. Shennan (2008). Journal of Quaternary Science 23: 175-192. *Journal of Quaternary Science,* 23(8):817-20.

Milne, G. A., I. Shennan, B. A. R. Youngs, A. I. Waugh, F. N. Teferle, R. M. Bingley, S. E. Bassett, C. Cuthbert-Brown & S. L. Bradley. 2006. Modelling the glacial isostatic adjustment of the UK region. *Philosophical Transactions of the Royal Society (Series A)* 364:931-948.

Peltier, W. R., I. Shennan, R. Drummond & B. Horton. 2002. On the postglacial isostatic adjustment of the British Isles and the shallow viscoelastic structure of the Earth. *Geophysical Journal International* 148(3): 443-75

Rohling, E. J., K. Grant, M. Bolshaw, A. P. Roberts, M. Siddall, C. Hemleben & M. Kucera. 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. *Nature Geoscience* 2:500-4.

Shennan, I., W. R. Peltier, R. Drummond & B. Horton. 2002. Global to local scale parameters determining relative sea-level changes and the post-glacial isostatic adjustment of Great Britain. *Quaternary Science Reviews* 21:397-408.

Shennan, I., S. Bradley, G. A. Milne, A. Brooks, S. E. Basset & S. Hamilton. 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* 21(6):585-99.

Ward, I., P. Larcombe & M. Lillie. 2006. The dating of Doggerland — post-glacial geochronology of the southern North Sea. *Environmental Archaeology,* 11(2):207-18.