Institution: Durham University

Unit of Assessment: 17B

Title of case study: Sea-level change and coastal planning

1. Summary of the impact

DU researchers have used innovative techniques for reconstructing past sea levels to compile a comprehensive database of evidence on recent and current UK sea-level change, and have developed an improved model of vertical land movement which is consistent with the historical data on sea-level change. The model and database underpin the sea-level component of the UK Climate Projections 09 (UKCP09) climate modelling tool, and thereby inform a wide range of coastal planning and management activities around the UK. DU researchers have also applied these methodological advances in detailed work on coastal stability at existing and proposed sites for nuclear power stations and nuclear waste repositories in England and Sweden.

2. Underpinning research

Whether the shoreline is advancing, retreating or stable at a particular location depends on the balance between two factors. The first of these is that the total volume of water in Earth's oceans varies as continental ice masses grow and shrink ('glacio-eustatic' sea-level change), and to a lesser extent through thermal expansion and contraction caused by ocean warming or cooling. The second factor is that the land may itself be rising or falling; in northern Europe this is occurring in response to unloading of the Earth's crust as ice masses shrank from their maximum extent around 20,000 years ago ('glacial isostatic adjustment', or GIA). The rate of GIA is highly variable, with the fastest uplift where the ice was thickest. Because of this, different parts of Britain have distinct recent sea-level histories and different rates of modern sea-level change. DU researchers have made major contributions to documenting the interplay of these factors, particularly (but not only) around the British Isles, and also to modelling GIA. These two strands of research, jointly and individually, have had impact on end users concerned about future sea-level change in Britain and other parts of northern Europe.

The first strand of research, on quantifying recent and past relative sea-level change around Britain, has been pursued over many years by Geography staff Shennan (DU staff 1991-), Lloyd (1994-), Long (1996-), Innes (2002-), Horton (PDRA 1998-2000, L 2000-2004), and Zong (1991-2008) and their PhD students and research staff. The group developed and exploited new sea-level reconstruction techniques (Reference 1), leading to a pioneering high-quality database of UK sea-level evidence (Reference 2) and reconstructions of shoreline evolution at local (site-specific), regional, and national scales (Reference 3). This work has unlocked new and previously-unavailable archives of sea-level change, and has disentangled global glacio-eustatic sea-level change from critical regional and local factors such as GIA, land lowering caused by sediment compaction, variations in sediment supply and, more recently, human impacts. It has also identified rates and patterns of past coastline change that provide plausible scenarios for future evolution (Reference 2). The novelty of this research includes the database itself (which is unique at the national scale) and the methodologies used to quantitatively reconstruct and model past sea levels.

Concurrently, an improved GIA model was developed by Milne (Earth Sciences staff 1999-2008), Whitehouse (Earth Sciences PDRA 2004-2007, Geography PDRA 2009-2013, now NERC PDRF based in Geography), and Bradley (Earth Sciences PhD 2005-2011), working in close collaboration with the DU Geography staff whose database was used to constrain the values of key parameters in the model (References 2, 4, 5). The model accounts explicitly for the 3-D variability of the Earth's internal structure, which has been shown to affect the rates of both vertical and horizontal land motions, and thus predicted rates of sea-level change (Reference 6). The comparison of model predictions with field evidence has, in turn, resulted in improved estimates of Earth model parameters, including lithospheric thickness and the viscosity profile of the Earth's interior, that influence GIA (Reference 5), and has allowed incorporation of state-of-the-art ice sheet dimensions and retreat history into the GIA model framework (Reference 2). The resultant model has enabled spatially comprehensive estimates of relative land and sea-level change for the UK and adjacent areas (Reference 2).

3. References to the research

(**Bold** denotes Durham University staff at time of research, underline denotes DU research student. Journal impact factors and citations are from Web of Science as of 31/8/2013.)

1. **Horton** BP, Edwards RJ, **Lloyd** JM (2000) Implications of a microfossil-based transfer function in Holocene sea- level studies. In **Shennan** I, Andrews J E (eds.) Holocene land ocean interactions and environmental change around the North Sea. *Geological Society of London Special Publication* 166, 41-54 (35 ISI citations)
2. **Shennan** I, **Horton** B (2002) Holocene land- and sea-level changes in Great Britain: *J. Quaternary Science* 17, 511-526 (Journal Impact Factor 2.94, 161 citations); updated as **Shennan** I, Milne G, Bradley S (2012) Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *J. Quaternary Science* 27, 64-70. (JIF 2.94, 5 citations)
3. **Lloyd** JM, **Zong** Y, Fish P, **Innes** JB (2013) Holocene and Late glacial relative sea-level change in north-west England: implications for glacial isostatic adjustment models. *J. Quaternary Science* 28, 59-70 (JIF 2.94, 0 citations)
4. Bradley SL, **Milne** GA, Teferle FN, Bingley RM, Orliac EJ (2009) Glacial isostatic adjustment of the British Isles: new constraints from GPS measurements of crustal motions. *Geophys. J. Int*. 178, 14-22 (JIF 2.85, 22 citations) – *note, incorrectly cited as Bradley et al (2008) by Source 1.*
5. **Milne** GA, **Shennan** I, Youngs BAR, Waugh A I, Teferle FN, Bingley RM, Bassett SE, Cuthbert-Brown C, Bradley SL (2006) Modelling the glacial isostatic adjustment of the UK region. *Phil. Trans. Royal Society, Part A*, 364, 931-948 (JIF 2.89, 25 citations)
6. **Whitehouse** P, Latychev K, **Milne** GA, Mitrovica JX, Kendall R (2006) Impact of 3-D Earth structure on Fennoscandian glacial isostatic adjustment: implication for space-geodetic estimates of present-day crustal deformations. *Geophysical Research Letters* 33, L13502, (JIF 3.98, 12 citations)

4. Details of the impact

DU research on sea-level change and GIA has had significant impact through incorporation in UK Government best-practice guidance and modelling tools, and through detailed assessment of past and future sea-level change at specific sites under consideration for nationally-important nuclear infrastructure developments in the UK and Sweden.

UKCP09: DU research underpins how future sea-level rise is predicted within the UK Government's climate projection modelling tool, UKCP09. Different parts of UKCP09 have been phased in starting in 2009. The sea level component uses the DU model of GIA (Reference 5) with DU data on past sea level (Reference 2) to generate vertical land velocities, which are then combined with global sea-level change scenarios from the Intergovernmental Panel on Climate Change to estimate ranges of future relative sea-level rise at any point in Britain and Ireland. The Defra web pages on UKCP09 explain that

> 'Future land level movements are an important component of projections of relative sea level change. The relative sea level projections reported in previous UK climate change scenarios have been based solely on historical data. This approach is likely to be unreliable in regions where little data exists … The UKCP09 relative sea level projections are based on the results of a geophysical model that has been constrained by observational data' (Source 1)

and go on to cite References 4 & 5 and other DU-author papers as the basis for this tool.

UKCP09 is open-access with no comprehensive record of usage, but its sea-level component has at least two major nationwide applications:

(1) It is the starting point for the National Coastal Erosion Risk Mapping project (NCERM;

www.halcrow.com/Our-projects/Project-details/National-coastal-erosion-risk-mapping-England-and-Wales/) undertaken by Halcrow for the Environment Agency (EA); and

(2) It is the recommended basis for the 22 second-generation Shoreline Management Plans (SMPs; www.environment-agency.gov.uk/research/planning/104939.aspx) that cover the entire coastline of England and Wales and are being developed jointly by local authorities and the EA. These high level, non-statutory plans establish policy for coastal management, including the necessary height of coastal defences. According to the EA the eleven SMP2s completed prior to UKCP09 are required to “check that the latest climate change projections do not change any of the policy decisions … All SMP2 Action Plans will … consider the plan findings in respect of key new information, with UKCP09 being one of the key issues (EA; http://www.scopac.org.uk/meeting_15.09.09/Appendix%204%20EA%20Managing%20the%20UK%20Climate%20Change%20Projections%202009.pdf)

The North West England and North Wales SMP is a good example of how DU research has contributed a regional understanding of sea level to the technical studies which underpin specific plans (Source 2). In this context, a general impact of the DU research has been increased recognition on the part of planners that rates of sea-level rise are not the same throughout the UK.

Nuclear infrastructure: DU sea-level researchers have also contributed directly to site-specific environmental safety assessments for major proposed infrastructure developments by the nuclear industry. Work has been done at three UK coastal sites and one in Sweden. These safety assessments are comprehensive and highly detailed, and thus involve many different contracts and sub-contracts, but in each of the cases described DU was the only UK HEI to be contracted to work on sea-level change which is a key consideration when designing installations with an exceptionally long planned lifespan.

(1) **Drigg**: The sole UK repository for low-level nuclear waste, at Drigg (near Sellafield) in Cumbria, is almost full. Its operator, Low Level Waste Repository Ltd (LLWRL), has applied to the EA for permission to extend the repository. LLWRL commissioned the infrastructure design consultancy Halcrow to prepare the required Environmental Safety Case (ESC), and Halcrow contracted Lloyd and Zong to determine the history of sea-level and coastal change in the vicinity (reported in Reference 4) and assess the likelihood of wave overtopping or erosion before the radioactivity has decayed to a safe level (i.e. within a few centuries for this low-level waste). Halcrow have affirmed (Source 3) that ‘an understanding of coastal response to sea-level change is critical’ (to the ESC), that DU ‘was the logical choice for collaboration’, and that the ‘understanding of the sea-level history provided by this research formed an important input to the conceptual model for projecting coastal change, which itself forms an integral part of the ESC’. The ESC stated that the site is very likely to be subject to coastal erosion, but only after a period of between several hundred and a few thousand years. The EA is still reviewing the proposal but has recently stated (Source 4) that it sees the coastal erosion prediction provided by DU as ‘central to our technical review...’, and that ‘we have examined the evidence carefully and agree with this conclusion’. Our work is thus central to the evidence base for the eventual decision on this nationally-important infrastructure project.

(2) **Sizewell and Bradwell**: British Energy (subsequently taken over by EDF) commissioned Lloyd and Zong, in collaboration with Defra’s Centre for Environment, Fisheries, and Aquaculture Science (CEFAS), to investigate past sea-level and coastline change at Sizewell (Suffolk) and Bradwell (Essex) as part of the British Energy Estuarine and Marine Studies (BEEMS) project, whose goal is to generate informed scientific positions on marine issues affecting potential nuclear power station sites in England. The study constrained the millennial-scale rate of sea-level change and confirmed that high-energy waves have had limited impact in the area since 4000 years ago. This information formed part of the environmental report on the development of Sizewell (Source 5) and the decision by EDF to propose a new Sizewell C power station. CEFAS (Source 6) have confirmed that

> “[DU] research [on] the Blackwater estuary … formed part of the major synthesis report produced by CEFAS for EDF. This report had an impact in terms of informing EDF’s decision with regard to how Bradwell should be prioritised among its roster of potential new-build sites. The research along the Suffolk coastline involved reconstruction of the relative sea-level changes and investigation of marine inundation events and coastal evolution in the Sizewell/Minsmere area. This research has been submitted to EDF as a stand-alone report,

and has also informed CEFAS's synthesis work on the physical science aspects of Sizewell. This research has informed EDF's decision to propose Sizewell C as one of the sites for new build nuclear plant and on the design/construction of Sizewell C in due course"

(3) **Sweden**: Whitehouse used the model of Reference 6 in a state-of-the-art assessment of GIA and shoreline change over multiple glacial cycles (the last 230 000 years) at a coastal site (Forsmark) which was proposed as the sole final repository for spent nuclear fuel in Sweden, a country that generates 40% of its electricity from nuclear power stations. This assessment was used by SKB, the agency responsible for all nuclear waste disposal in Sweden, as part of its site safety assessment and pending license application for nuclear fuel storage at Forsmark (Source 7a). SKB (Source 7b) have affirmed that

'This work was crucial because it established the potential accessibility of the repository under future climate scenarios, e.g. following sea-level rise or lake formation. It also provided an important baseline for ground- and surface-water flow modelling under glacial and permafrost conditions, which was used to assess the potential for freezing throughout the repository under various climate scenarios. Your research informed the decision-making process with regard to determining the preferred site location, and following the decision to site the repository in Forsmark additional safety assessment work was carried out, specific to this site, including quantification of the potential impact of future Greenland ice loss.'

In each of these cases our sea-level research has been critical, despite being only a small part of the total effort, because without approval of the long-term environmental safety case no such infrastructure project can go ahead.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Source 1: Documentation of the DU contribution to UKCP09 is available in Section 3.4.1 of http://ukclimateprojections.defra.gov.uk/22993.

Source 2: Halcrow (2010) *North West England and North Wales Shoreline Management Plan SMP2 Supporting Studies Cell Eleven Tidal and Sediment Transport Study (CETaSS) Phase 2 (ii) Main Report – Summary of findings*, See section on *Regional understanding – sea level*, pp 25-31. Available at http://www.mycoastline.org/documents/CETaSS/CETaSS2ii.pdf

Source 3: Testimonial from Principal Geomorphologist at Halcrow and Site Characterisation Manager at LLWR). [Participant and Reporter in impact delivery]

Source 4: Environment Agency (2013) *Low Level Waste Repository: Our review of the Environmental Safety Case*, April 2013, esp. pp 2-3 (available at www.environment-agency.gov.uk/static/documents/Business/LLWR_update_April_2013.pdf). See also end of p.2 in www.environment-agency.gov.uk/static/documents/Business/LLWR_update_April_2013.pdf . The technical part of the ESC itself is available at http://llwrsite.com/national-repository/key-activities/esc/esc-documentation/ and the full report (2011) is at http://llwrsite.com/wp-content/uploads/2013/04/Environmental-Safety-Case-–-Full-Report.pdf.

Source 5: EDF (2012) *Sizewell C proposals – Environmental Report* (available at http://sizewell.edfenergyconsultation.info/wp-content/uploads/SzC-Stage-1-Environmental-Report.pdf); specific reference to the BEEMS project is on pp 73 and 77.

Source 6: Testimonial from Senior Contracts Manager, CEFAS (April 2013). [Participant in impact delivery].

Source 7: (a) Application of the GIA model to Forsmark and implications for site stability over the next 230,000 years is documented in section 3.3 of SKB Report TR-10-49 *Climate and climate-related issues for the safety assessment SR-Site*, available at www.skb.se/upload/publications/pdf/TR-10-49.pdf . Also (b) testimonial from (Research Coordinator and Company Specialist for Climate Questions, SKB). [Participant in impact delivery].