Relative sea level change in the Forth and Tay Estuaries, Scotland

University of Chester

Dr Victoria Powell University of Chester, v.powell@chester.ac.uk
Prof Robert Duck University of Dundee
Dr Derek McGlashan University of Dundee

University of Dundee

Forth Ports Ltd

Introduction

With increasing sea levels projected until beyond 2100, localised studies of relative sea level change are recommended (Solomon *et al.*, 2007; Lowe *et al.*, 2009). The Forth and Tay Estuaries are valuable ecologically and economically, with several environmental designations, large cities and industrial areas. Since 1897 tide gauges have been periodically located at sixteen locations within the Forth and Tay Estuaries (Figure 1), including several previously unseen tide gauge.

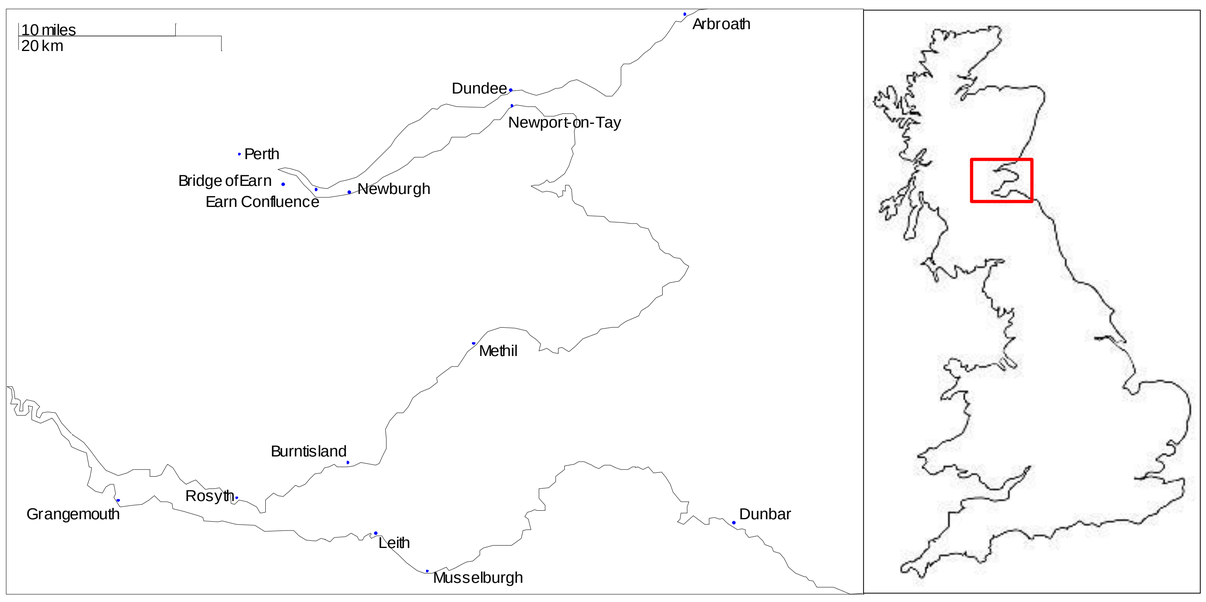


Figure 1. Map of the Tay and Forth Estuaries. Tide gauge data have been collected from all named locations. Data were also collected from Aberdeen and Stannergate, near Dundee.

Glacio-isostatic adjustment (GIA) -induced land movement is typically causing land-level rise in Scotland, but some peripheral areas are experiencing subsidence (Shennan *et al.*, 2011; Milne *et al.*, 2006). As a consequence, most of the Scottish coastline is experiencing decreased levels of relative sea level rise compared to southern England and Wales (Figure 2).

Considering the reduced rates of relative sea level rise predicted along the Forth and Tay Estuaries, this localised study of the region provides greater insight into the contrast between the UK-wide, global and regional sea level trends. It also poses a question, what rate of sea level change could the region have experienced if the GIA had been negligible? A simple model is provided here.

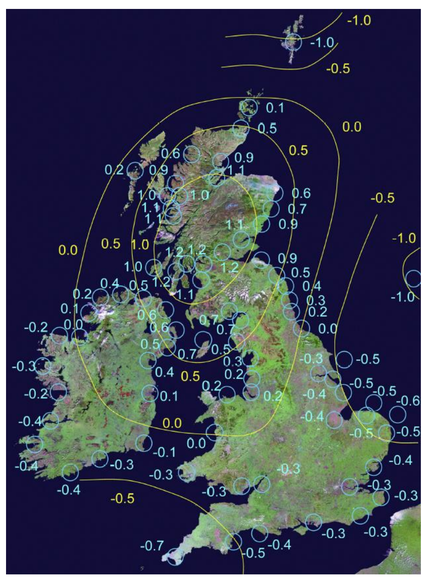


Figure 2. 'Rate of relative land-level change 1,000 years BP to the present day in the British Isles (Ireland and the UK) (mm per year). Relative land uplift is shown as positive and relative subsidence as negative' Shennan *et al.* (2012:68).

Method of correcting and collating data

Data were collected from various international, national and local institutions including the Permanent Service for Mean Sea Level, British Oceanographic Data Centre, National Tidal and Sea Level Facility, UK Hydrographic Office, Perth Harbour Authority, Scottish Environment Protection Agency, Tay Estuary Research Centre and Forth Ports Limited. Data were converted into the same temporal format and validated with neighbouring sites.

The relative sea level rate was calculated for each site and then 5 stable sites were chosen to form a 'Combined Forth and Tay Estuaries' dataset spanning 1900 to 2010. The data are compared here with a modelled GIA-adjusted dataset, the method for which is explained further in the next section.

As part of the lead-author's PhD, these tide gauge data, at different frequencies, were used to analysis storm surge events and adapt two relative sea level projection models.

Relative sea level rates across the Forth and Tay Estuaries

Douglas (1997), Jevrejeva *et al.* (2008) and Church and White (2006) identified the average global sea level rise to be between 18.5 and 19.5 cm between 1900 and 1995/2004. Church and White (2011), using a tide gauge dataset from 1880 to 2009, suggested the global sea level rise has been 1.7 mm a^{-1} (Solomon *et al.*, 2007). These rates are considerably higher than those observed in the study region. Data from individual sites within the study region are presented in Figure 3.

Individual Site Datasets

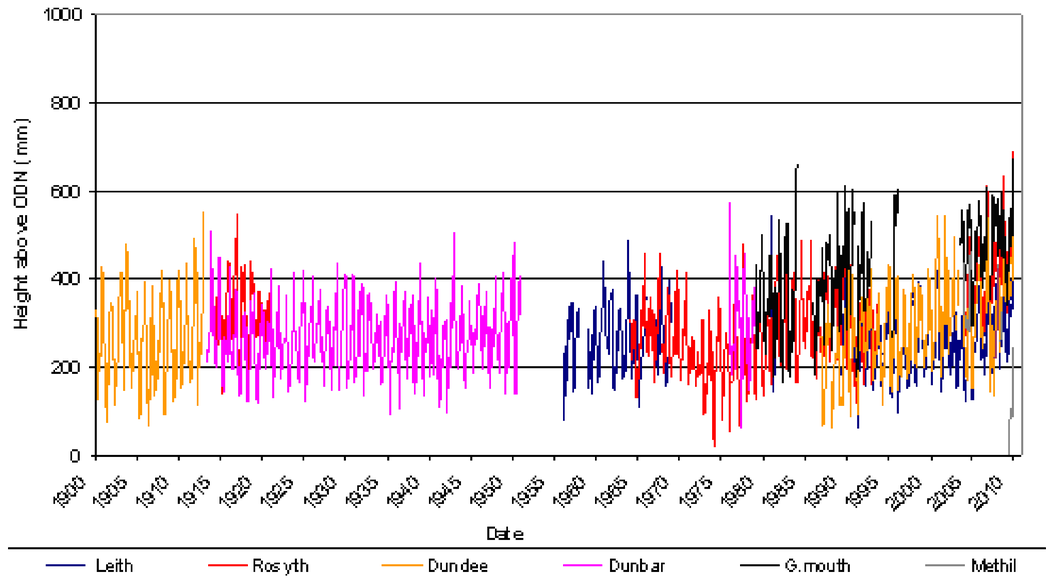


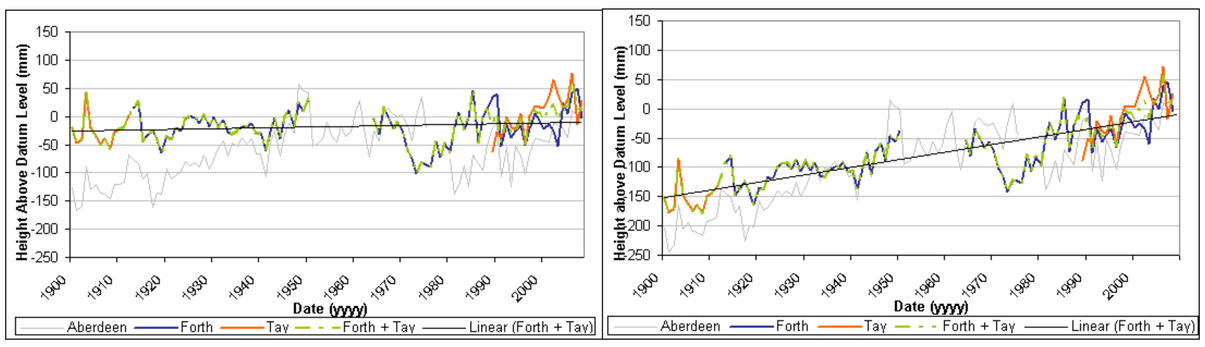
Figure 3. *Relative sea level changes* in Leith, Rosyth, Dundee, Dunbar, Grangemouth and Methil between 1900 and 2010. Grangrmouth and Methil sre excluded from long-term analyses. These sites (excluding Grangemouth and Methil) have long term trends of between 0.27 and 1.06 mm a^{-1}, over the dataset timescales; considerably shorter than the global average (Church and White, 2011).

A Combined Dataset

A Forth and Tay Estuaries region relative sea level dataset was constructed by merging data from tide gauge data recorded between 1900 and 2010 (Figure 4). This dataset represents a near continuous regional tidal record with a linear trend of 0.33 mm per year (36 mm total). This trend is significantly lower than the 1.7 mm a^{-1} calculated by Church and White (2011) as the average global sea level trend (93 mm lower over the time period).

Over the same timescale, GIA rate were removed from the historical sea level records for a simple comparison with global trends. The aim was to illustrate the impact GIA can have on regional trends. This method would ideally be implemented using site-specific, long-term GPS recordings at tide gauge sites to include all forms of land movement, which is why this model is described as simplistic. The GIA rates were taken from the Shennan *et al.* (2011; 2012) land-level change model (Figure 2), which includes three data points in the region.

GIA-adjusted rates plotted in Figure 5 present a linear sea level trend of 1.26 mm a^{-1} (126 mm total). The minor difference between the GIA-corrected rate and the Church and White (2011) rate may be due to the global variations in sea level (Gehrel and Long, 2008); global sea level is not level, but fluctuates across each oceanic basin. The variation could be due to local land level changes not represented by the Shennan *et al.* (2011; 2012) model.



Above left: ***Figure 4***. *Relative sea level changes* in Aberdeen, the Tay Estuary, the Forth Estuary and a combined dataset covering both the Tay and Forth Estuaries.
Above right: ***Figure 5***. *GIA-adjusted sea level changes* in Aberdeen, the Tay Estuary, the Forth Estuary and a combined dataset covering both the Tay and Forth Estuaries, calculated by subtracting GIA from relative sea level data.

Conclusions

- Historically, relative sea levels in the Forth and Tay Estuaries have risen by an average of 3.6 cm since 1900
- GIA has potentially inhibited 5.7 cm of regional relative sea level rise since 1900
- This model follows a simplistic method and would benefit from long-term GPS records

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