Continental Shelf Research 85 (2014) 96–105

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research Papers

Impact of flood defences and sea-level rise on the European Shelf tidal regime

Holly E. Pelling*, J.A. Mattias Green

School of Ocean Science, Bangor University, Askew Street, Menai Bridge LL59 5AB, United Kingdom

A R T I C L E   I N F O

Article history:
Received 13 June 2013
Received in revised form
13 April 2014
Accepted 16 April 2014
Available online 12 June 2014

Keywords:
Tidal modelling
Sea level rise
Flood defence
European Shelf

A B S T R A C T

The tidal response of the European Shelf to moderate (<1 m) levels of sea level rise is investigated using a high resolution, well established tidal model. The model is validated for present day conditions and the tidal response to sea level rise by comparing the modelled response to long term tide gauge data. The effects of coastal defence schemes are tested, with three levels of present day coastal defences simulated. Full walls are added at the present day coastline, no coast defence schemes are used and a set of present day coastal defence schemes is simulated. The simulations show that there is a significant tidal response to moderate levels of SLR and that the response is strongly dependant on level of coastal defence simulated. The simulation using coastal defence data resulted in the strongest response as the tide was able to build up behind the coastal defence walls and create a patchwork of sea and land at the coastline. This had a strong impact on the spatial tidal energy dissipation field and in turn this has large effects on the tidal regime throughout the domain.

1. Introduction

Studying the response of the tides to sea level rise is a relatively new area of interest with much of the recent research concerning the European Shelf. Pickering et al. (2012) and Ward et al. (2012) have investigated the effects on the tides of somewhat extreme levels of mean sea level rise and both studies found significant but contrasting results. Pelling et al. (2013a) found that the way SLR was implemented – whether land was allowed to flood (or not) – significantly affected the response of the tides to SLR, as the newly flooded areas change the distribution of tidal energy dissipation. Here we will evaluate if realistic levels of SLR will have an impact on the tidal regime of the European Shelf. Furthermore, using long term tidal gauge data we will attempt to validate the model for any tidal impacts.

The current estimate of present global SLR is approximately 0.18–0.79 mm year^{-1} (Denman et al., 2007) and this is expected to accelerate over the century (Church and White, 2006, 2011; Woodworth et al., 2011). Also due to underestimations of the contribution of land ice melt it is possible that this rate is severely underestimated (Nicholls et al., 2011). Katsman et al. (2011) show that the sea level rise off the coast of the Netherlands is actually closer to the global high end estimates of 0.55–1.15 mm year^{-1}. These moderate levels of SLR estimated may have significant impact on regional tidal systems on the European Shelf (Muller et al., 2011; Pickering et al., 2012; Ward et al., 2012) and other regional systems (Pelling and Green, 2013; Pelling et al., b).

Studies show over the last 100 years that there have been observable secular trends in global tides (Woodworth, 2010; Muller et al., 2011), tides in regional areas (e.g. Flick et al., 2003; Ray, 2009; Jay, 2009) and more specifically the tidal system of the European Shelf (for example Woodworth et al., 1991; Haigh et al., 2010). Trends in observed mean tidal range on the European Shelf fall between -1.8 and 1.3 mm year^{-1} (Woodworth et al., 1991). While by no means conclusive, it has been suggested that this could be due to SLR (Woodworth, 2010; Muller et al., 2011). The UK boasts some of the longest tidal records of the world. This wealth of data allows us to analyse how observations of tides on the European Shelf have changed with SLR and to compare this to our model results.

The response of tidal systems to SLR can be highly nonlinear due to additional shallow water effects such as friction and other effects such as resonance. Pelling and Green (2013) showed that the tides of the Bay of Fundy may increase with SLR as the increasing water depth brings the natural resonance period of the basin closer to the M_2 frequency. However, it was also found that flooding of low lying land dampens this effect as it increases the tidal dissipation. On a global scale, modelling studies have shown that there are tidal impacts of SLR (Egbert et al., 2004; Green, 2010; Muller et al., 2011) but that tidal changes are poorly captured and the model results differ significantly in the magnitude and direction of these changes. However, it is possible that this may be because of the way SLR is implemented or the model resolution.

---

* Corresponding author.

http://dx.doi.org/10.1016/j.csr.2014.04.011

Coastal flood defences are designed to preliminarily defend the coastline against significant storm surges. They are typically concentrated in areas of high populations. In order to prevent flooding from predicted SLR and storm surges, the UK has invested some 358 million on flood defence schemes in 2007 (Monitoring, 2010) and approximately 44% of the UK's coastline is protected by some form of flood defence scheme (Monitoring, 2010). However the Convention for the Protection of the Marine Environment of the North-East Atlantic (the OSPAR Convention) conducted an assessment of the present day coastal defences on the European Shelf (Govarets and Lauwerts, 2009) and Fig. 1 shows the distribution of protected coastline within the European Shelf. The sea defences in use fall in to two main categories. Hard defence techniques which include sea walls and soft techniques which include beach nourishment, wetland management and the creation of artificial reef systems. While hard structures aim to provide a barrier to water inundation, soft defences aim to dissipate the kinetic energy in the incoming waves. By their very nature coastal defence schemes can have a strong impact on the coastline effecting sediment transport pathways and change the way the natural coastline would respond to natural events. This opens for an interesting question, given that the tidal response to SLR on the European Shelf differs whether the land floods or not: how do these flood defences schemes affect the response of the tidal regime on the European Shelf to SLR?

In this paper, we will show how the European Shelf responds to reasonable estimates of SLR and compare the modelled results to observed trends in tidal amplitudes. Furthermore we will investigate how the European Shelf may respond over the next 100 years to realistic levels of SLR. We do not attempt to present predictions, instead we hope to highlight potential processes and mechanisms that may occur. A description of the tidal model and observations used follows this introduction. Results of the control run and validation can be found in Section 3 and of the future simulations in Section 4. Section 5 makes up the discussion and conclusions.

2. Methods

2.1. Modelling

We use the Oregon State University Tidal Model (OTIS), a 2D hydrodynamic numerical model, which has been used a number of times to study regional and global tides (e.g. Egbert et al., 2004; Pelling and Green, 2013). The model solves the shallow water equations with friction:

$$\partial U/\partial t+f\times\mathbf{U}+\mathbf{U}\cdot\nabla\mathbf{u}=-gH\nabla(\eta-\eta_{SAL})-\mathbf{F}+k\nabla^{2}\mathbf{U} \tag{1}$$

$$\partial\eta/\partial t=-\nabla\cdot\mathbf{U} \tag{2}$$

Here $\mathbf{U}=\mathbf{u}H$ is the depth-integrated volume transport given by the velocity $\mathbf{u}$ times the water depth H, t is time, f is the Coriolis vector, η and η_{SAL} is the tidal elevation and the self-attraction and loading (SAL) elevation respectively, $\mathbf{F}$ is the dissipative stress from bed friction and $k\nabla^{2}\mathbf{U}$ is a crude parametrization of horizontal turbulent eddy viscosity, where k is the horizontal eddy viscosity coefficient. The bed-friction is parameterized using the common quadratic law, i.e. $\mathbf{F}=C_d\mathbf{U}|\mathbf{u}|/H$, where $\mathbf{u}$ is the total velocity vector, and $C_d=2.75\times10^{-3}$ is a drag coefficient.

The model was set up for the European Shelf (extent of model domain shown in Figs. 1 and 3) with a resolution of $1/60\ \times1/60^{\circ}$ in latitude and longitude and run for a total of 10 days, with the last 3 days used for harmonic analysis. Only the M_2 tide was simulated. Forcing in the form of tidal elevations from TPXO7.2 was prescribed at the boundary and an intertidal wetting and drying scheme was used in all runs. The original bathymetry was a composite bathymetry (described by Uehara et al., 2006). However to obtain the required resolution this was merged with GEBCO 1 arc-min resolution database (available at http://www.gebco.net). The increased accuracy was achieved by calculating the mean and vertical variation around the mean for each $1/12^{\circ}$ block of GEBCO data. This database was then added into the original KUTM bathymetry. The GEBCO dataset also contains topography, which was retained and added to the composite bathymetry. A similar method was employed by Egbert et al. (2004) to produce high resolution paleo-bathymeteries. In total 12 runs were completed. Initial SLR runs were simulated by adding 250 mm to the water depth and allowing the inundation (flooding) of dry cells.

In order to investigate the possible impact of future SLR on the tidal regime of the European Shelf a total of 12 simulations were made by adding 250, 500, 750 and 1000 mm SLR. SLR was implemented in three ways. The flood runs allow the inundation (flooding) of dry cells, while the no flood runs do not allow any inundation of flood water by adding vertical walls at the coastline. Flood defence schemes were also simulated by adding vertical walls where the flood defence schemes exist according to Govarets

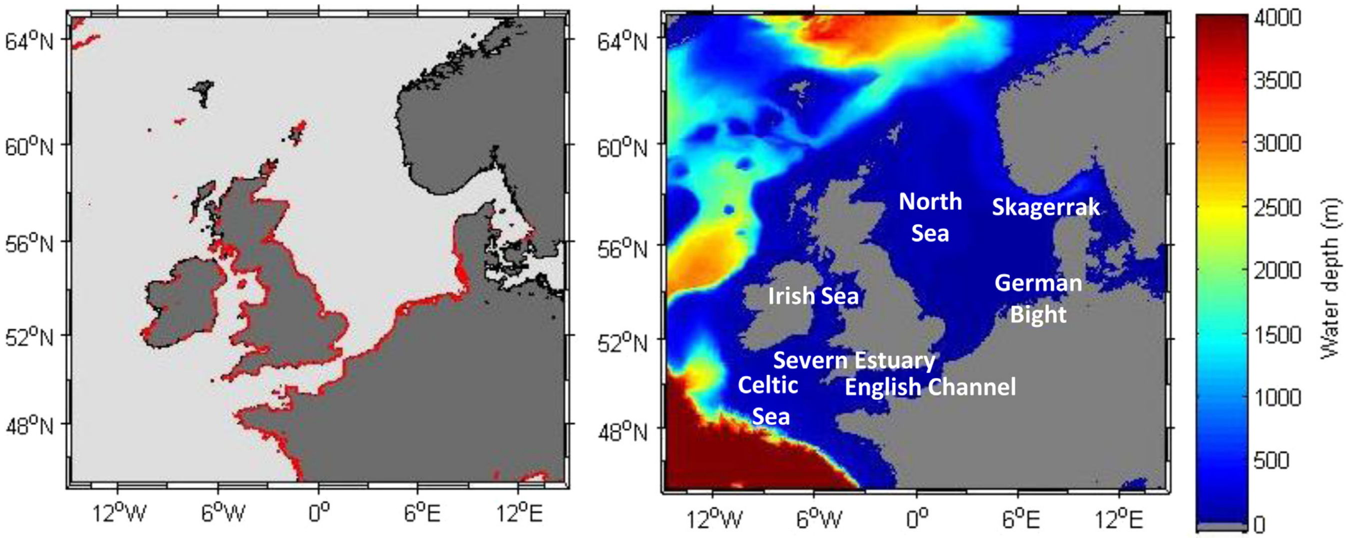

Fig. 1. Extent of model domain and location of the flood defence schemes (red areas) based on OSPAR. Undefended coastline is shown in black. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)