Sea Level Rise in the Severn Estuary and Bristol Channel and Impacts of a Severn Barrage

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Abstract
Many research projects in recent years have focused on marine renewable energy devices and structures due to the growing interest in marine renewable energy. These devices and structures have very different life spans. Schemes such as the Severn Barrage in the UK, as originally proposed by the Severn Tidal Power Group (STPG), would be the largest tidal renewable energy generation project in the world and would be operational for well over a century if built. Due to the long working life of some of these marine renewable energy schemes, it is important to study the impacts of climate change on such schemes, and particularly sea level rise. This study focuses on investigating the impacts of sea level rise due to climate change on the largest macro-tidal estuary in the UK, namely the Severn estuary and Bristol Channel, and the alterations of the impacts and the performance of the Severn Barrage as a result of climate change. A hierarchy of computer models was implemented to identify the more localised impacts of climate change in the region of the study. Moreover, the potential benefits of the barrage on reducing flood risk, as well as the impact of climate change and the barrage on intertidal mudflats were investigated. The model predictions showed that the barrage would reduce flood risk due to the sea level rise. Furthermore, annual power output and the initial reduction in flood risk of the barrage would not be affected by sea level rise.

Keywords: Sea Level Rise; Climate Change; Severn Barrage; Flood Risk; Severn Estuary; Marine Renewable Energy
Introduction

Marine renewable energy has attracted much interest in recent years as an attractive means of generating low carbon energy and considering the resources available around the world this resource could play a key role in replacing conventional CO$_2$ emitting electricity generation schemes. In the UK the tidal stream resource has been conservatively estimated to be around 12 TWh/year (Binnie and Black & Veatch Ltd. 2001) and the Severn and Mersey Barrages could potentially generate more than 18 TWh/year (Sustainable Development Commission 2007), with there being a further opportunity to generate additional power from a number of tidal lagoons located at key sites around the UK coastline. Meanwhile, researchers have been investigating the hydro-environmental and ecological impacts of such marine renewable energy schemes (Ahmadian et al. 2010; Langhamer et al. 2009; Neill et al. 2009), as well as exploring new devices (Neptune Renewable Energy Ltd. 2011; Verdant Power Ltd. 2011) and the availability of resources (Blunden and Bahaj 2006; Iglesias et al. 2009; Willis et al. 2010), as well as improving the performance of existing devices (Ahmadian and Falconer 2012; Batten et al. 2007; O’Doherty et al. 2009). Nevertheless, where EIA studies have been undertaken these studies have generally focused on evaluating the impacts at the development time and there has been very little research on investigating the impact of the devices and structures for future climate scenarios, using detailed climate change modelling. For instance, Xia et al (Xia et al. 2011) used a hypothetical sea level rise value to study the future coastal flood risk in the Severn Estuary after building the Severn Barrage. Although, this might be considered as an acceptable procedure for schemes with a short life span, the longer life span of some of the projects, e.g. the Severn Barrage a life span of over a century, requires more detailed investigations on the effects of climate change and, in particular, sea level rise, which could change the impact of the structure on the surrounding environment as well as altering the performance of the structure itself. Moreover, the impact of the Severn Barrage on reducing coastal flood risk has been well documented and could be an additional key benefit in building the barrage. Hall et al (Hall et al. 2006) identified a large area around the Severn Estuary which would be susceptible to coastal flooding due to climate change, with mainly high to medium annual damage expected as a result of flooding in 2080. This emphasises the need for further investigation to the impact of a barrage on potential flood risk reduction as a result of climate change.

There has been little research directly focused on investigating the climate change signals in the Severn Estuary and Bristol Channel and most climate change studies in the estuarine
basin use the results from studies focused on the UK or the Irish Sea. In this region, Lowe et al. (Lowe et al. 2001) implemented a storm surge model of the North West European continental shelf region and suggested significant changes in the return periods of extreme storm surge events at many locations around the UK coastline, due to future changes in local meteorology conditions in addition to the effect of rising mean sea level. Wang et al. (Wang et al. 2008), and Lowe and Gregory (Lowe and Gregory 2005) also undertook studies focusing on storm surges and Wolf and Woolf (Wolf and Woolf 2006) have focused on wave climate in this area. Brown et al. (Brown et al. 2010) studied the impact of increased sea levels and enhanced wind velocities on the residual current pattern, as well as the peak surge elevations. Woodworth (Woodworth 1987) employed a number of tide gauge stations to measure the trends in mean sea level (MSL) around the UK coast. Woodworth et al. (Woodworth et al. 2009) also implemented a more accurate analysis method and used a larger tide gauge data set to estimate the rates of mean sea level (MSL) changes around the UK. Their study included a number of sites within the Irish Sea region, including: Liverpool, Holyhead and Douglas, and they reported an MSL change of 1.82 ± 0.13, 2.13 ± 0.26 and −0.21 ± 0.59 for these sites, respectively. Esteves et al. (Esteves et al. 2011) analysed available measured datasets of water level, surge level, wave height, wind speed and barometric pressure for a site located on the Eastern Irish Sea Coast, to find relationship between metocean climate and the existing predictions. They did not find enhanced storminess or increases in surge heights or extreme water levels from the data they analysed as a part of their study. To estimate the probability of future coastal flooding, and considering the uncertainty of possible sea level rise, Purvis et al. (Purvis et al. 2008) used sea level rise magnitudes for 2100, contained in the IPCC Third Assessment Report, and conjecture a plausible probability of this range for a 32 km section of the Bristol Channel. Devoy (Devoy 2008) studied coastal vulnerability around the Irish Coast under sea level rise and climate change. Olbert et al. (Olbert et al. 2012) studied the climate change signals in the Irish Sea using a nested global and regional model and reported an average of 47 cm MSL across the Irish Sea. Recent studies by Pelling et al. (Pelling et al. 2013) discussed the importance of including land in modelling the impact of sea level rise on flooding.

To decrease the uncertainties in the inability of global models to predict sub-scale processes, investigations into the sea level rise in the Severn Estuary and the Bristol Channel were carried out using a nested global, regional and coastal model. Then, a coastal hydro-environmental model has been refined to study the impacts of the Severn Barrage, with the
focus being on including the impacts of the barrage on flood risk variation, tidal currents and intertidal mudflats, as well as the barrage-generated electricity at the end of the 21st century.

2 Severn Estuary and Severn Barrage

The Severn Estuary is the estuary of the Severn River, the longest river in the UK, located in the South-West region of the UK. It is connected to the Atlantic Ocean through the Bristol and Celtic Channels and forms part of the boundary between England and Wales. The estuary has the 2nd highest tidal range in the world, with a peak spring tidal range of over 14m. The site has also been regularly identified as one of the best sites for marine renewable energy projects in the world. A number of proposals to build tidal energy structures in the estuary, based on more conventional and embryonic technologies, have been considered by the UK government over the past few decades with the latest study being reported in 2010 (Department of Energy and Climate Change 2010) and the shortlisted schemes being illustrated in Figure 1.

Figure 1: Latest study short-listed schemes, including the Seven Barrage (B3) (Department of Energy and Climate Change 2010)

One of the most publicised schemes is known as the Severn Barrage. This barrage is 16 km long and spans the Severn Estuary from Lavernock Point, to the South West of Cardiff on the
Welsh Coast, to Brean Down near Weston-super-Mare on the English Coast. This would create an impounded area of over 500 km². As reported by Severn Tidal Power Group (STPG) EP57 report (Department of Energy 1989), the barrage would include: 166 sluice gates and 216 × 9 m diameter bulb turbines (Figure 2), each producing a peak output of 40 MW. The barrage would also provide options for flood defence and rail and road communications and would include ship locks for access to the ports of Cardiff, Newport, Bristol and others.

Ebb tide generation was proposed by STPG as the operating scheme for the barrage, wherein the sluice gates and turbines would be open on the incoming tide and only the turbines would operate on the outgoing tide while the sluice gates would be closed. However, more recent research has indicated that two-way generation could generate a similar amount of electricity, while the environmental impacts could be reduced (Ahmadian et al. 2011; Fenrich et al. 2011; Xia et al. 2010b). Ebb tide generation only has been used as the barrage operation scheme in this study.

Figure 2: The Severn Barrage layout (Courtesy of Severn Tidal Power Group)(Department of Energy 1989)
Modelling Methodology

Global climate models are capable of describing vital climatic processes, however, local changes may not scale with the predicted global climate change. Moreover, the inability of coarse model resolution to determine sub-grid scale processes introduces local uncertainties to the model (Wilby et al. 1998). A lack of appropriate shelf sea physical processes in global ocean climate models, such as tidal mixing which is of great importance in the case of the Irish Sea, is one of the major problems of using large scale global models (Olbert et al. 2012).

Subsequently, to reduce these uncertainties and increase the accuracy of the model in predicting sea level change, a cascade of three one-way nested models was utilized to dynamically downscale the hydrodynamic processes from a global (MPI-OM) model, through a regional (ECOMSED-Irish Sea), to a local coastal scale (FV2DModel – Severn Estuary) model. Large scale boundary conditions of the IPCC A1B emission scenario were derived from the ocean MPI-OM and atmospheric ECHAM5 global models to generate initial and boundary conditions for the ECOMSED regional model of the Irish Sea. Subsequently, water elevations at the outer Bristol Channel were extracted from the Irish Sea model and utilized for the local-scale Severn Estuary model to investigate the impact of sea level rise on the estuary and subsequently as a result of the proposed Severn Barrage. In this study, there was no feedback from the local model to the Irish Sea regional model.

In order to take full account of sea level rise, a temporal evolution transient simulation approach was used with a full time period being simulated. This approach, in contrast to frequently used time-slice approach, provides a good insight into the natural variability of sea level and climate change signals. As a result, global (MPI-OM) and regional (ECOMSED) ocean models were run for 120 years (1980-2100) to provide the Severn Estuary model with a time series of sea level changes due to climate change, driven by moderate economic growth and as defined in the SRES A1B emission scenario.

3.1 Global Modelling
The global Max Plank Institute Ocean Model (MPI-OM) developed by the Max Planck Institute for Meteorology, Hamburg, was utilised for this research in the three-step model nesting cascade to provide boundary conditions for the regional scale model. The MPI-OM model has a long track of application for various climate change studies, such as: sea level changes (Landerer et al. 2007), thermohaline circulation (Jungclaus et al. 2006a) and biogeochemical processes (Kloster et al. 2007; Wetzel et al. 2006). The primitive equations for a hydrostatic Boussinesq fluid are solved for with a free surface (Jungclaus et al. 2006b).
Scalars and vectors are formulated on a C grid in the horizontal plane (Jungclaus et al. 2006b) and on irregularly spaced z-level system in the vertical direction. Model parameterization, with a full description and model performance discussion can be found in Marsland et al. (Marsland et al. 2003).

With regard to the sea level forecasting being pertinent to current analysis, a globally-averaged prognostic sea surface height in the MPI-OM is zero and conservation of volume is confirmed by the continuity equation. The eustatic sources are not included in the simulation and the global mean rates of precipitation, evaporation and river runoff are considered to be negligible and set to zero. Consequently, the net global volume change in the model results solely from changes in ocean temperature (Landerer et al. 2007), derived from the local density structure.

For this research the numerical domain was constructed on a bipolar orthogonal curvilinear grid, with poles placed over Europe and North America, respectively. Such configuration allowed increased resolution over the European Continental Shelf. As a result, the globally-averaged horizontal resolution of 1.5° was refined to approximately 15 km in the Severn Estuary area. The model consisted of 164 meridional by 239 zonal lanes and 30 vertical layers with 20 layers being distributed over the upper 800m of the water column. ETOPO5 dataset (NGDC 1998) was used to construct model bathymetry; the model mesh and bathymetry over the North East Atlantic is illustrated in Figure 3a. The surface forcing was obtained from the ECHAM5 (Roeckner et al. 2006) atmospheric model (T63L31) providing 6-hour instantaneous atmospheric output for the SRESA1B scenario.

![Figure 3](image-url)

Figure 3. Grid and Bathymetry of (a) MPI-OM model for the European Continental Shelf with M5 data buoy location and (b) Irish Sea model.
Regional Modelling
Water temperature and salinity fields extracted from the MPI-OM model were used to force ECOMSED regional model of the Irish Sea. The mathematical formulation, parameterization and technical details of the ECOMSED model can be found in (Blumberg and Moellor 1987). The downscaling ratio used in this study was 10:1, following a good performance shown at the previous hindcast model study of the Irish Sea climate (Olbert et al. 2011). A 2 km by 1.5 km horizontal rectangular grid was used over the modelling domain extending from 51.0°N to 56.0°N and from 7.0 °W to 2.6°W and covering the entire Irish Sea, Bristol Channel and Severn Estuary. Model bathymetry constructed from the Irish National Seabed Data is shown in Figure 3b. Twenty-one sigma terrain-following vertical layers were used to model the hydrodynamic processes over the water column.

The hydrodynamics of the Irish Sea in the model are driven by astronomical tides and baroclinic conditions at the lateral boundaries and atmospheric conditions at the model surface. The tidal input conditions were determined from five tidal constituents: K1, O1, M2, N2 and S2, extracted from the FES2004 dataset (Lyard et al. 2006). Baroclinicity was driven by three-dimensional monthly-averaged temperatures and salinity conditions were obtained from the MPI-OM model, while atmospheric forcing was provided by the ECHAM5 model as discussed above. Global and local components of the sea level changes were obtained from the MPI-OM model and supplied to variable surface elevation at the open boundary of the Irish Sea model.

Estuary Modelling
The flow in the Severn Estuary is primarily in the horizontal plane without any considerable sign of stratification and vertical velocities (Evans et al. 1990; Uncles 1981; Xia et al. 2010a) and consequently, the hydro-environmental processes in the estuary can be modelled using a depth averaged 2D model. The governing depth-integrated 2D shallow water equations and the numerical solution schemes implemented in the FV2DModel used in this study are outlined below, with more details of the model being found in Xia et al. (Xia et al. 2010a; Xia et al. 2010b).

The general conservative form of shallow water equations can be written as:

\[ \frac{\partial u}{\partial t} + \frac{\partial \xi}{\partial x} + \frac{\partial \zeta}{\partial y} = \frac{\partial \zeta}{\partial x} + \frac{\partial \zeta}{\partial y} + S \]  

(1)
where $\mathbf{U} = \text{vector of conserved variables}; \ E$ and $\mathbf{G} = \text{convective flux vectors of flow in the x and y directions, respectively}; \ \vec{E}$ and $\vec{G} = \text{turbulent stress related diffusive vectors in the x and y directions, respectively}; \ \text{and } \mathbf{S} = \text{source term including: bed friction, bed slope and the Coriolis force. Each of the preceding terms can be expressed in more details as below:}

$$
\begin{align*}
\mathbf{U} &= \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \\
\mathbf{E} &= \begin{bmatrix} hu^2 + \frac{1}{2}gh^2 \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix}, \\
\mathbf{G} &= \begin{bmatrix} hv \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix}, \\
\vec{E} &= \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{yx} \end{bmatrix}, \\
\vec{G} &= \begin{bmatrix} \tau_{xy} \\ \tau_{yy} \end{bmatrix}, \\
\mathbf{S} &= \begin{bmatrix} q_s \\ +hf'v + gh(S_{bx} - S_{fx}) \\ -hf'u + gh(S_{by} - S_{fy}) \end{bmatrix}
\end{align*}
$$

(2)

where $h = \text{total water depth (m)}; \ u, v = \text{depth-averaged velocities (m/s) in the x and y directions, respectively}; \ q_s = \text{source (or sink) discharge per unit area (m/s)}; \ g = \text{gravitational acceleration (m/s}^2); \ f = \text{Coriolis acceleration due to the earth’s rotation, in which } f = 2\omega \sin \varphi (\text{rad/s}), \ \omega = \text{earth’s angular velocity (7.29\times10^{-5} \text{ rad/s}) and } \varphi = \text{latitude of study domain (rad)}; \ S_{bx} \text{ and } S_{by} = \text{bed slopes in the x and y directions, respectively (dimensionless)}; \ S_{fx} \text{ and } S_{fy} = \text{friction slopes in the x and y directions (dimensionless), respectively}; \ \text{and } \tau_{xx}, \ \tau_{xy}, \ \tau_{yx} \text{ and } \tau_{yy} = \text{components of the turbulent shear stress over the plane (N/m}^2)$. 

A cell-centred finite volume method over a triangular unstructured mesh was utilised in this study. The average values of the conserved variables were stored at the centre of each cell and the flow flux at the interface of two neighbouring cells was treated as a locally one-dimensional problem perpendicular to the interface. The flow flux between neighbouring cells was obtained using various approximate Riemann Solvers and Roe’s approximate Riemann solver, with the Monotone Upstream Scheme for Conservation Laws (MUSCL) being implemented in the current study (Xia et al. 2010a; Xia et al. 2010c). The predictor-corrector time stepping procedure was used to achieve second order accuracy in time as well as space. Due to extensive flooding and drying processes and large intertidal areas in the estuary, caused by the high tidal range, a robust flooding-drying algorithm was used in the model (Falconer and Chen 1991; Xia et al. 2010c). Furthermore, a non-reflecting boundary flux function based on the theory of characteristics was implemented to estimate the state variables at the seaward boundary to eliminate the reflection of waves generated inside the computational domain at the seaward boundary (Sanders 2002). More details of the
The numerical solution of the governing equations can be found in (Xia et al. 2010a; Xia et al. 2010b).

The model domain was extended from the outer Bristol Channel (A-A) to the River Severn tidal limit close to Gloucester at How Bridge, (D-D) as shown in Figure 4, which is approximately 200km long and covering about 5700 km$^2$. The model included 37,423 unstructured triangular cells and higher resolution was used around the deep channels and at the barrage site. The domain decomposition technique was utilised to model the barrage, wherein two sub models were linked through turbines and sluice gates as internal boundaries.

![Figure 4: Coastal model extent and the calibration sites (Xia et al. 2010a)](image)

4 Results and Discussion

4.1 Severn Barrage Modelling

The coastal model, which was setup for the Severn Estuary and Bristol Channel, was first calibrated and validated using existing data sets at the sites shown in Figure 4, and where it was found that there was very good correlation between the model predictions and existing field data (Xia et al. 2010a). Figures 5 and 6 show typical comparisons between the model predictions and field data.
Figure 5: Typical water level validation at Newport, site- shown in Figure 4 (Xia et al. 2010a)

Figure 6: Typical speed and direction validation at Site R- shown in Figure 4 (Xia et al. 2010a)

The model was then used to predict the hydro-environmental impacts of the Severn Barrage for a typical spring-neap tidal cycle as the base line to study the impacts of climate change. Figures 7 and 8 respectively depict the maximum water levels and maximum velocities across the Severn Estuary and Bristol Channel without and with the barrage, with the maximum water levels along the Severn Estuary and Bristol Channel being illustrated in Figure 9. These figures show that the maximum water levels upstream of the barrage were reduced by more than 1 m, and by up to 1.37m at the Severn River tidal limit. Moreover, the maximum velocity values across the estuary dropped by more than 0.5 m/s in the main channel upstream and downstream of the barrage. This reduction in the velocity values had certain environmental consequences which have been discussed in detail in Ahmadian et al. (Ahmadian et al. 2010).
Figure 7: Comparison of the maximum water levels across the Severn Estuary and Bristol Channel: (a) without, and (b) with the barrage.
Figure 8: Comparison of the maximum velocities across the Severn Estuary and Bristol Channel: (a) without, and (b) with the barrage
4.2 Impact of Climate Change on the Severn Estuary

Before utilising nested models to predict the impact of future climate change on the Severn Estuary, the models were validated by using the hindcast control period (1981-2005) to reproduce past climate conditions. Detailed evaluation of the MPI-OM and ECOMSED simulations under atmospheric forcing of the NCEP Reanalysis 2 model (Kanamitsu et al. 2002) was carried out by the authors and is presented in Olbert et al. (Olbert et al. 2011).

The assessment of the MPI-OM model performance for the European Continental Shelf showed that the model was capable of reproducing water temperatures, both at the surface and throughout the water column. For brevity, only the validation plot for one site in the proximity of the Bristol Channel and Severn Estuary is shown herein (Figure 10).
A performance of the ECOMSED model, forced with ECHAM5 output, was evaluated based on a comparison with the well-validated ECOMSED model, forced with NCEP data. Details of these extensive comparisons can be found in Olbert et al (Olbert et al. 2012). In general, the ECOMSED model demonstrates good ability to resolve small-scale advective and convective processes by using the downscaling procedure. The model is capable of reproducing complex hydrodynamic features, induced by temperature profiles, stratification and flow fields changes induced by hydrographic changes within the regional domain when correct meteorological forcing is applied. However, under the ECHAM5 forcing the ECOMSED model tends to overestimate SSTs. Figure 11 shows a difference between SSTs predicted by the ECOMSED-ECHAM5 and ECOMSED-NCEP models. Over the Seven Estuary and Bristol Channel, the SSTs simulated with ECHAM5 forcing are slightly overestimated with an annual mean bias of approximately 0.11°C, while these values are 0.18°C for the entire regional model domain. This warm bias results directly from the bias in the ECHAM5 model as discussed in Olbert et al (Olbert et al. 2012). Overall, since the bias is relatively insignificant for the region of interest, one could conclude that the ECOMSED model forced by the ECHAM5 atmospheric data are capable of responding to the future climate change.
Figure 11: Difference in sea surface temperature (deg C) between ECOMSED model forced with ECHAM5 output and NCEP data set for the period 1981–2005.

An accurate forecasting of the future changes to sea level is of primary concern to this research. In the MPI-OM model, the sea level changes result only from changes in ocean density (steric changes); eustatic mass sources are not taken into account in the model. The contribution of steric change in the Irish Sea is estimated from the global mean thermosteric sea level rise (global thermal expansion) and change in local sea level calculated as a difference in steric change between the Irish Sea and global mean. As shown in Figure 12a, the MPI-OM model projects a 0.24 m global sea level rise under the SRES A1B climate scenario by 2100, with this result is in line with climate model ensemble projections for this scenario. The local steric signal resulting from changes in the North Atlantic circulation patterns, as explained in Olbert et al. (Olbert et al. 2012), is responsible for a relatively small sea level rise. As shown in Figure 12b, the local sea level in the region of the Severn Estuary is projected to rise by approximately 0.088 m over the 21st century. The effects of changes in ocean mass on the sea level rise were adopted from the research carried out by Katsman et al. (Katsman et al. 2008) for the north-east Atlantic and summarized in Table 1. All steric and eustatic signals contributing to the sea level change in the Severn Estuary region and possibly having an impact on the proposed Severn Barrage are expected to cause the sea level to rise by 0.481 m at the end of the century.
Table 1: Predicted sea level rise at 2100 under SRES A1B scenario at the coastal model boundary

<table>
<thead>
<tr>
<th>Contributing Factor</th>
<th>Value (m)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global mean thermosteric</td>
<td>0.24</td>
<td>MPI-OM model results</td>
</tr>
<tr>
<td>Local steric</td>
<td>0.088</td>
<td>MPI-OM model results</td>
</tr>
<tr>
<td>Glaciers</td>
<td>0.101</td>
<td>Katsman et al. (Katsman et al. 2008)</td>
</tr>
<tr>
<td>Greenland ice sheets</td>
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<td>Katsman et al. (Katsman et al. 2008)</td>
</tr>
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<td>Katsman et al. (Katsman et al. 2008)</td>
</tr>
<tr>
<td>Terrestrial water storage</td>
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<td>Katsman et al. (Katsman et al. 2008)</td>
</tr>
<tr>
<td>Total</td>
<td>0.481</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12: 1-year running mean of global mean sea level changes (a) and 5-year running mean of local sea level changes in the Irish Sea (b)

4.3 Impact of Climate Change on Severn Barrage

The total value of 0.481m, which was calculated as the total sea level rise at 2100 under SRES A1B climate scenario, was added to the coastal model existing boundary to investigate the impact of sea level rise on the Severn Estuary and Bristol Channel as well as the Severn Barrage. In this study, it was assumed that only the mean water level at the boundary was
increased as a result of sea level rise and that the shape of the tidal curve is unlikely to be significantly affected by sea level rise.

Figure 13 shows the maximum water levels and maximum velocities across the estuary without the barrage by the end of the century, while maximum water levels along the estuary pre-barrage in 2100 are shown in Figure 9. It can be seen that the water levels at the end of the century without including the barrage have increased by nearly 0.48 m across the estuary, which virtually corresponds to the sea level rise at the model boundary.
Figure 13: Predicted maximum water levels and maximum velocity across the estuary in 2100 including sea level rise; a: maximum water levels in 2100, b: maximum velocities in 2100

Figure 14 shows the maximum water levels and maximum velocities throughout the estuary in 2100 if the barrage is built. Post-barrage the maximum water levels along the estuary by the end of the century are shown in Figure 9. It is shown that the water levels would increase by about 0.48 m across the estuary which virtually corresponds to the sea level rise at the model boundary. This increase is smaller in the River Severn and the changes in water levels at the end of the century with the barrage showed only about a 0.3 m increase at the Severn River tidal limit, compared with the existing water levels and the barrage included. This means that even further reduction to the sea level rise at the Severn River tidal limit was imposed by the barrage in addition to the initial reduction in water levels. Although, these changes in the water levels have a considerable impact on coastal flooding across the estuary, the changes are relatively insignificant in relation to the total depth in the main channel and consequently there are no appreciable changes in the maximum velocities in the estuary, by the end of the century, as a result of sea level rise.
Figure 14: Predicted maximum water levels and maximum velocity across the estuary in 2100 including sea level rise with the barrage; a: maximum water levels, and b: maximum velocities

The annual power predicted to be generated by the barrage in the existing conditions without including the losses was 18.32 TWhr/year. This was calculated using the available hill charts.
and by extending the simulation period over the year. More information on the power calculations can be found in (Xia et al. 2010b). The amount of power generated by the barrage at the end of the 21st century would be 18.43 TWhr/year which indicates very little difference.

Decreased maximum and increased minimum water levels throughout the estuary after building the barrage in the current climate would cause a reduction of about 127 km$^2$ in intertidal mudflats based on the model results. This reduction is considered to be significant from an ecological and environmental viewpoint as the intertidal mudflats provide an important part of the food cycle in the coastal eco-system. However, model predictions for the water levels at 2100 indicate a reduction of about 35 km$^2$ can be expected in these intertidal mudflats just as a result of sea level rise and in comparison with the extent of the existing mudflats. In contrast, the intertidal mudflats would be reduced across the estuary by about 133 km$^2$ by the end of the century as a result of building the barrage comparing to the mudflats at that time without the barrage. This indicates that the reduction in the intertidal habitats after building the barrage would not change significantly by the end of the century.

5 Conclusion
The ocean MPI-OM and atmospheric ECHAM5 global models were linked one-way to run the ECOMSED Irish Sea regional model for future climate scenarios. The global ocean and the Irish Sea conditions were simulated for the period 1980 to 2100, under the moderate economic growth SRES A1B emission scenario, to acquire the future climate conditions at the end of the century. To ensure the applicability of the regional Irish Sea model, forced by the ECHAM5 model, results from this model were compared with the well-validated ECOMSED model, driven by the NCEP data. The annual mean bias of SSTs simulated with the ECHAM5 forcing over the Seven Estuary and the Bristol Channel were very close and were only 0.11°C higher than the values generated using the NCEP dataset. This model was then used to predict the sea level rise for the outer Bristol Channel by the end of the century. This is the location where the coastal model seaward boundary was located and the sea level rise predicted by the regional model at this location due to global mean thermosteric and local steric was 0.24 m and 0.088 m, respectively. These values were added to the changes in Antarctica and Greenland ice sheets, as well as the glaciers and terrestrial water storage from the literature. The total value of the sea level rise at the location of the outer Bristol Channel was implemented at the coastal model boundary, which included the Severn Barrage. The
new boundary was used to predict the impact of sea level rise in the Severn Estuary and Bristol Channel at the end of the century, both without and with the barrage. The simulations showed that the barrage would reduce the water levels by up to 1.40 m upstream of the barrage for the existing conditions, which resulted in a significant reduction of flood risk as well as a reduction of around 0.5 m/s in velocity values in the main channel. Applying the predicted 0.48 m sea level rise for 2100 at the model boundary for the case without the barrage scenario, would result in a similar increase in the water levels across the estuary and no significant change in velocity values. However, the maximum water level increase due to the climate change after including the barrage showed a similar increase across the estuary, but a smaller increase in the river. The increase in the maximum water levels in the vicinity of the River Severn tidal limit for the barrage scenario at 2100 showed only 0.30 m rise, in comparison with the maximum water level for the barrage scenario and the existing conditions. This corresponds to a 0.18 m decrease in the maximum water levels compared to the sea level rise at the boundary, thereby confirming that the barrage would reduce flood risk due to climate change further. This reduction is in addition to the initial reduction in the flood risk caused by the barrage due to the decline in the maximum water levels for the existing conditions. The model predictions therefore showed no significant change in the barrage electricity output in 2100 due to the predicted sea level rise. Moreover, the loss in inter-tidal mudflat areas in 2100 due to climate change alone was predicted to be around 35 km², and the inter-tidal areas in 2100 with a barrage was reduced by about a further 41 km² when compared to the barrage scenario for the existing conditions.

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