

## **A review of climate change impacts on UK estuaries**

Peter E. Robins, Martin W. Skov, Matt J. Lewis, Alan G. Davies, James E. McDonnald, Shelagh K. Malham, Suzie Jackson, Tim A. Whitton, Luis Gimenez, and Colin F. Jago.

*Centre for Applied Marine Sciences, School of Ocean Sciences, Bangor University, LL59 5AB*

### *Abstract*

Global climate change over the 21<sup>st</sup> century will result in rising sea levels, rising ocean temperatures, and may intensify and cluster atmospheric events such as storm surges, storm waves, and river flows. As such, climate change will have a great impact at the land-ocean interface: on estuarine environments. In the UK, of serious concern is adaptation to changing estuarine functioning and services. This paper reviews historic observations and current anthropogenic climate change projections for the 21<sup>st</sup> century, and summarises the expected impacts to UK estuarine systems, including both physical and environmental changes.

Complex interactions between tidal and wave and surge dynamics, freshwater-seawater mixing, sediment transport, habitat composition, biodiversity, and the fluxes of nutrients, pollutants, pathogens, and viruses are likely to be modified due to climate change and affect the total estuarine environment. The long-term morphodynamic response to climate change is unknown, and there are several biophysical implications of climate change that require further research; but habitat loss due to sea-level rise is one major consequence that is expected. Additionally, altered river flows will likely have negative impacts of eutrophication, hypoxia and harmful algal blooms, increased temperatures might increase microbial pathogen concentrations and increase public health risk, and changes to the salt balance may impact species reproduction and have implications on the conservation status of UK estuaries. Future research relating to the impacts of climate change on estuaries, and the associated mitigation, will require an integrated approach that considers the catchment-river-estuary-coast system as a whole.

*Key words: Climate Change; Estuaries; Hydrological cycle; Sea-level rise; Water quality; Biodiversity; UK*

## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) is ‘virtually certain’ that global precipitation and temperatures will increase during the 21<sup>st</sup> century, and has ‘high confidence’ that inter-regional and inter-seasonal variability in precipitation will increase throughout the world (IPCC 2013). All areas of the UK are projected to warm by between 1.5°C and 5.4°C by 2100 (Jenkins et al. 2009). Global sea levels are expected to rise by between 44 and 74 cm, depending on our future carbon dioxide emissions (IPCC 2013). According to the UK’s 2012 Climate Change Risk Assessment, three potential risks due to climate change that will require primary action are: flood and coastal risk management; the management of soils, water and biodiversity; and management of water resources (CCRA 2012: 8).

Estuaries represent a globally significant frontier linking riverine and coastal regimes. Crucially, estuarine processes play a critical role in the hydrological and carbon cycles, and in food production and catchment services. Estuaries rank along with tropical rainforests and coral reefs as the world's most productive ecosystems; as regions of high primary productivity and biodiversity, and are often characterised by their outstanding natural beauty and high socio-economic value. Estuaries are known to trap, filter and recycle suspended particulate matter (SPM), composed of lithogenic and biogenic components, as well as components that are potentially harmful to human health, such as nutrients and pathogenic viruses. The majority of terrestrially derived SPM reaches the coastal ocean via estuaries, including 50% of the global annual organic carbon (Ittekkot 1988). In the UK, these processes are often complicated further by anthropogenic activity, such as aquaculture and shellfisheries, intensive catchment farming and agriculture, forestation/deforestation, urbanisation, changing ecosystem services, and coastal management. One third of the UK’s population live near estuaries (Austin et al. 2010). Further, we do not yet understand to what extent climate change will affect estuarine processes.

In this review, we amalgamate current knowledge from published literature on estuarine processes and environments throughout the UK, on climate change projections for the UK, and how climate change will impact upon estuaries. This review paper is structured as follows: In the following sub-sections, we define and classify UK estuaries based on several physical and environmental controls, and then briefly summarise the inherent estuarine processes. In Section 2 we review current global and UK climate trends and climate change projections, in terms of the physical alterations to estuaries; Sections 3 and 4 provide summaries of observed trends and projected impacts of climate change to UK Estuaries, in terms of physical and environmental processes; Finally, discussions and conclusions are made in Sections 5 and 6, respectively.

### 1.1. UK Estuaries

Due to the complex interactions of physical and bio-geochemical processes occurring in the estuarine environment, the definition of an estuary is not a simple task. Many attempts have been made over the years to produce an accurate definition of estuaries. One of the most widely accepted is by Dyer (1997), adapted from Cameron and Pritchard (1963): “*An estuary is a semi-enclosed coastal body of water which has free connection to the open sea, extending into the river as far as the limit of tidal influence and within which seawater is measurably diluted with freshwater derived from land drainage*”. This description highlights the main characteristics of an estuary with respect to the mixing of fresh and salt water, tidal influences and a connection to the coastal ocean.

Typically, the landward limit of an estuary is defined by the extent of the salt water intrusion (Fig. 1). However, the limit of tidal influence exceeds salt water advection. The term River Estuary Transition Zone (RETZ) can be employed to better describe the limits of the estuarine environment. The RETZ is comprised of the upper part of the estuary including the Estuarine Turbidity Maximum (ETM), and the Tidally-Influence River (TIR), found above the limit of salt intrusion, where the surface height and velocity field are still tidally modulated. The ETM is an area of elevated turbidity, indicated by a rise (sink) in suspended particulate material (SPM) and associated biogeochemical components, located at the fresh-saline water interface. The ETM supports seasonal biological production and plays an influential role in estuarine biogeochemical processes. Although biological production is widespread throughout the turbidity gradient. We define the seaward estuary limit at the intersection with the coastline, although this is sometimes difficult to isolate (e.g., the Severn Estuary merges into the South Wales and North Devon coasts) and, also, a region of fresh water influence (ROFI) may extend further offshore, such as in Liverpool Bay (Palmer and Polton 2011). Further, a sedimentary delta may extend beyond our defined estuary limit.

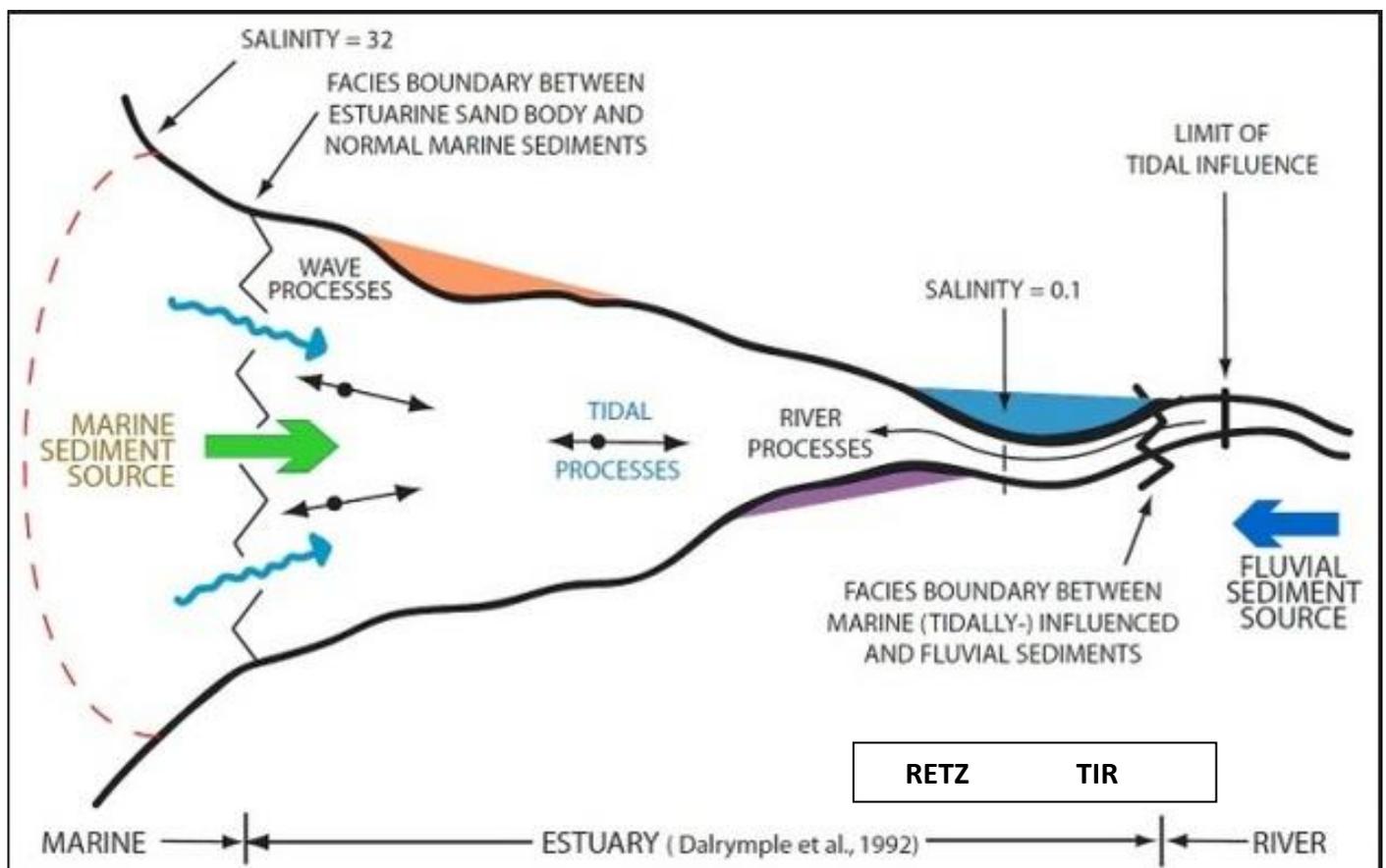


Figure 1. Schematic representation of estuarine processes and definitions taken from Dalrymple et al. (1992).

### 1.2. Estuarine classification

There are a multitude of ways to classify estuaries, based on water balance, geomorphology, salinity structure, and tidal energy. Firstly, estuaries can be classified as positive or negative with respect to the water balance. A positive estuary experiences freshwater input that exceeds the rate of evaporation; typically the freshwater input in positive estuaries induces gravitational circulation – caused by density gradients between lighter, fresher water and heavier, salty water. Conversely, evaporation rates exceed freshwater

input via precipitation in negative estuaries and the freshwater input via rivers is negligible or non-existent. All UK estuaries are positive estuaries, since annual freshwater input exceeds evaporation.

The geomorphology, or shape, of an estuary can be separated into four categories: coastal plain, bar-built, fjords and tectonic (Prandle 2009). Coastal plain (or 'unrestricted entrance') estuaries are essentially drowned river mouths caused by the latest post-glacial Pleistocene rise in sea level; they are typically wide and shallow (e.g., The Thames, Southampton Water and Mersey in England (Dyer 1997)). Bar-built (or 'restricted entrance') estuaries were originally tidal embayments which became semi-closed due to littoral drift forming sand bars or spits restricting the mouth (e.g., Taf and Dyfi in Wales). Fjords are associated with high latitudes and glacial activity; they are characteristically elongated and deep with a sill formed at the mouth. UK fjords are found in Scotland (e.g., Loch Etive). Finally, tectonic estuaries are formed through tectonic activity creating faults causing parts of the Earth's crust to sink and thus fill in with water. In this review, we are not considering fjords and tectonic estuaries. The size and geometry of the estuary mouth exerts a critical influence on hydrodynamics, wave action, sediment transport and morphological evolution (Pye and Blott 2014).

The vertical salinity structure is a useful way to classify estuaries as the extent of vertical stratification can infer considerable information on the state of mixing and, thus, estuarine circulation patterns. The extent of stratification is largely the competition between buoyancy forcing from freshwater inflow and the mixing forces from the tidal influence. The tidal mixing is directly proportional to the water exchange into/out of the estuary (known as the tidal prism and defined as the product of the tidal range and the area of the tidal basin). Following Pye and Blott (2014), an estuary can be classified into four types, based on the salinity water gradient: (1) salt wedge; (2) strongly stratified; (3) weakly stratified; and (4) well mixed. A salt wedge estuary has a large river discharge and low tidal forcing which results in two distinct water layers: a fresh water layer overlying a salty layer. As tidal forcing increases and river discharge weakens, the stratification weakens and the estuary becomes progressively more mixed with respect to salinity; thus, portraying vertically uniform profiles of salinity in the well-mixed case.

In terms of tidal energy, estuaries have been classified by tidal range as follows (Davies 1964): microtidal (tidal range < 2 m), mesotidal (2 m < tidal range < 4 m), macrotidal (4 m < tidal range < 6 m), and hypertidal (tidal range > 6 m). In the UK, examples of each estuary type are (Prandle 2009): Christchurch (microtidal), Dyfi (mesotidal), Humber (macrotidal), and the Severn (hypertidal).

Estuaries can be further classified with respect to acting as a sink or source for sediments or nutrients. This depends on the cross-sectional area and the tidally active water volume of the estuary. The net sediment/nutrient flux can be influenced by tidal forcing, wind stress, wave action, freshwater discharge and extreme weather such as storm surges. Quantifying suspended sediment/nutrient fluxes in estuaries is difficult and usually involves assumptions of vertical homogeneity with respect to velocity. A coastal plain estuary, which becomes shallower towards the head such as the Humber Estuary, is likely to be flood-tide-dominated (producing a net influx (sink) of sediments or nutrients), especially if it has a large tidal range. Whereas a bar-built estuary, which widens and becomes deeper towards the head such as the Alde-Ore Estuary, is more likely to display ebb-tide-dominance (net export of sediments and nutrients), especially if it has a relatively small tidal range. Wide-mouthed estuaries are more influenced by wave processes than estuaries with a narrow mouth.

Sediment types found in UK estuaries can vary greatly. At the estuary mouth, tidal and wave energy acts to sort sediment deposition into mainly medium/coarse sands (Fig. 2), forming deltas (e.g., Exe Estuary, Devon), sand banks and dunes (e.g., Camel Estuary, Cornwall), and spits restricting the estuary mouth (e.g., Ynylas Spit of the Dyfi Estuary, Wales). Within an estuary, finer sands form sub-tidal channels and silts/muds form inter-tidal flats and saltmarshes (Fig. 2). Fig. 3 shows examples of the spatial variability of sediment composition in the Taf Estuary, South Wales (which is hypertidal, with a tidal range up to 10 m): sand ripples and banks at the mouth and in the main channel, and extensive intertidal mudflats at the fringes.

Estuarine classification can be complicated by anthropogenic activities altering the bio-physical environment. Changes to the classification of UK estuaries have occurred by man-made interventions since the industrial period. For example, managed coastal realignment traditionally arose for land reclamation for farming, agriculture, and transport; but more recently has been a mitigation measure against flood risk and climate change (Pye and Blott 2014). Urbanisation, transport and engineering activities have further affected estuarine shape and, hence, their classification (Lee et al. 2006). Similarly, changes to marine services (e.g., the fisheries and shellfisheries industry) and catchment services (e.g., forestation, agriculture, and conservation) have been shown to alter the function and classification of estuaries (Kennish 2002).

There are approximately 90 estuaries in the UK, which is a quarter of the estuaries of northwest Europe. UK estuaries, excluding fjords, are mainly bar-built or coastal plain (Prandle 2009). Although several of the larger estuaries, such as the Severn and Milford Haven are classified as rias (drowned glaciated river valleys). Mesotidal estuaries are typical in the eastern UK, whereas macrotidal or hypertidal estuaries occur in the west, and are connected to catchments that react quickly to rainfall events (Brown et al. 1991). A comprehensive list and characterisation of UK estuaries, as they stand today, can be found on-line (ABPmer and HR Wallingford (2007); [www.estuary-guide.net](http://www.estuary-guide.net)).

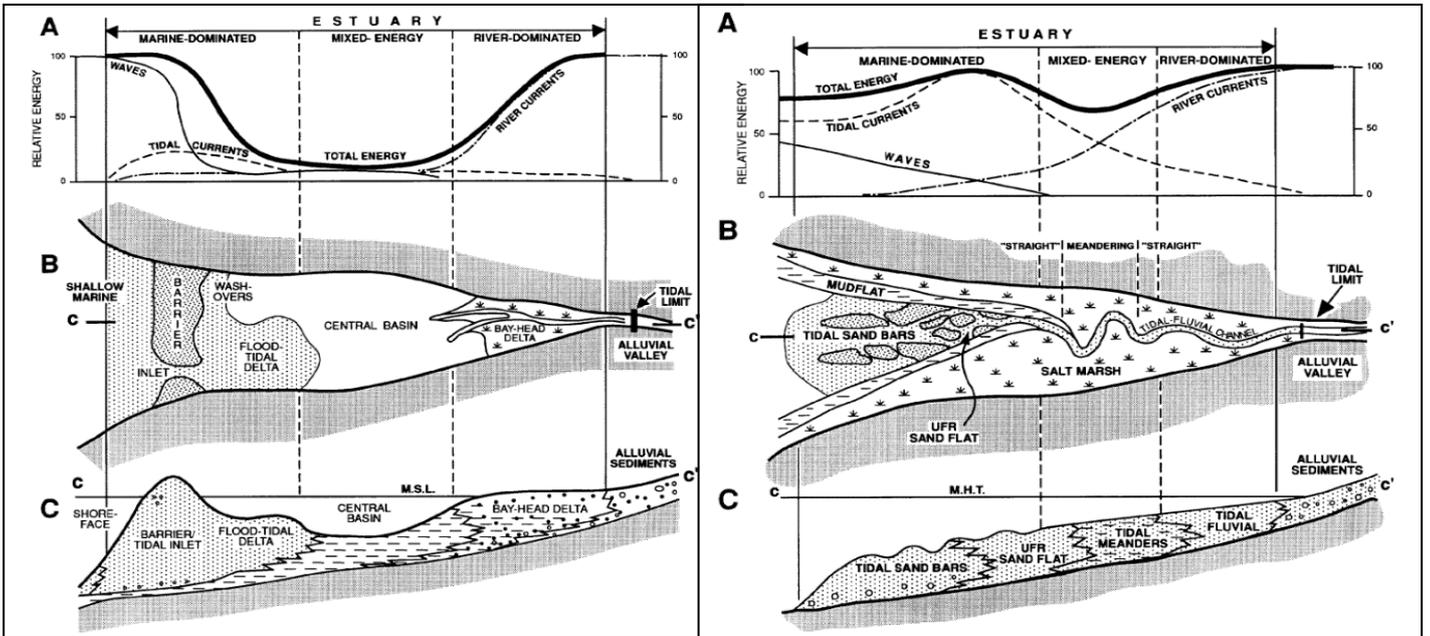


Figure 2. Idealised wave-dominant (left) and tide-dominant (right) estuaries. Distribution of (A) energy types, (B) morphological elements, and (C) sedimentary facies. UFR = Upper Flow Regime, M.H.T. = mean high tide. The along-channel section in (C) does not show the marginal mudflats and saltmarshes; it illustrates the onset of sediment filling (progradation) following transgression (e.g., sea-level rise).



Figure 3. Sediment composition and substrate morphology in the Taf Estuary, South Wales, UK. Moderately sandy substrates, sand ripples and sand banks situated at the estuary mouth (top); fine sandy channels (bottom left) and muddy tidal flats (bottom right) situated within the estuary. Photos: Ben Powell, Bangor University.

### 1.3. *Estuarine processes*

The principal physical processes that are inherent to UK estuaries are briefly summarised. Tidal forcing, surges and waves act to mix the seaward water body and advect saline water up-estuary, in competition with freshwater seaward flow acting to stratify the water column (Dyer 1997). At the saline-freshwater interface, high turbidity attracts high biodiversity and productivity, but also acts as a barrier to persistent tracers or suspended materials (Prandle 2009). Tides are generally the main energy sources for UK estuaries. Tides create vertical and horizontal velocity shear, which generates turbulence and determines the overall rate of mixing, although there is much temporal and spatial variation in tidal amplitude (Pingree and Griffith 1979; Robins et al. 2015). Nonlinear shallow water dynamics, such as tidal amplification (Robins and Davies 2010) and higher harmonics (Robins and Elliott 2009) complicate the tidal forcing/mixing further. Pronounced seasonal and inter-annual cycles often occur in wind (surge and wave variability; Wolf et al. 2011), temperature, light, river flows, stratification (Simpson et al. 2001), nutrient concentrations (Robins et al. 2014), oxygen, and plankton (Prandle 2009). Seasonal variability in river flows control estuarine salinity gradients and stratification (Brown et al. 2014), secondary density-driven circulation (Nunes and Simpson 1985; Brown et al. 1991), and the overall fate of river-borne materials and solutes (Robins et al. 2014). Coastal sediment transport and estuarine morphology are influenced by variabilities in the above processes, together with localised sediment size classes and chemical and biological processes (Soulsby 1997; Moore et al. 2009). Controls on sediment regimes in estuaries are tides and storms, enhanced by wave activity in shallow water (Van-Rijn 1993; Soulsby 1997).

These natural variations, alongside extreme episodic events and projected climate change, play a major role in estuarine ecology (Bulling et al. 2008), coastal flooding and erosion (Lewis et al. 2013), morphology (Milne et al. 2012), and water quality (Maier et al. 2009). The physical (hydrodynamic and morphodynamic) estuarine processes are not independent of the biological processes, as biology moderates physical forcing, for instance, with implications for estuarine morphology (Murray et al. 2008). Conversely, the biological processes are not independent of the physics. Consideration of bio-physical interaction is one of the major gaps in estuarine research. Estuarine processes on large temporal and spatial scales are physically-driven, whereas some intermediate scale processes become bio-physically-driven. Climate change will act on both the physics and the biology, and thus biology will influence physical processes.

## 2. Climate changes to physical forcing

We summarise past trends and future projections of climate change that will impact on UK estuaries. We focus on sea surface temperature, sea-level rise and atmospheric shifts as the main drivers that influence the physical environment and ecosystems, and their interactions. Table 1 summarises the main climate change trends and projections, and estimates the level of confidence associated with each trend/projection. The level of confidence (low, medium, or high) has been ascribed, based on the amount of evidence and the level of agreement of the evidence.

### 2.1. Temperature

Data reveals that global ocean temperatures (upper 700 m) have warmed since the 1970s, and there is some evidence that temperatures have warmed since the 1870s (IPCC 2013). The strongest warming occurred in the upper 75 m, 0.11°C per decade between 1971 and 2010 (IPCC 2013). Sea surface temperatures (SST) around the UK have risen over the past three decades by about 0.7 °C (Jenkins et al. 2009). There has been a 1–3°C rise in freshwater temperatures over the past 100 years in large rivers across Europe (Whitehead et al. 2009).

Global average air temperatures are projected to increase by between 1.4°C and 5.8°C over the 21<sup>st</sup> century, depending on emission scenarios, location, and season – temperatures over land are likely to increase more than over sea (IPCC 2013). Consequently, global mean SST (upper 100 m) are projected to increase by 0.6–2°C, by 2100 (IPCC 2013). All areas of the UK are projected to become warmer, with the summers especially so – a mean increase in summer air temperature of 5.4°C is projected by 2100, for southern England with winter increases of 1.5°C, across most of the UK (Jenkins et al. 2009). Over the UK shelf seas, in shelf edge regions and northern North Sea, temperature increases of 1.5–2.5°C are projected to occur this century. Larger increases of 2.5–4°C are projected for the Celtic, Irish and southern North Sea. The latter amounts to a trend of 0.3°C per decade (Lowe et al. 2009). Whilst, overall, global air temperatures and SST are projected to increase, a potential shutdown of the North Atlantic current (Gulf Stream) would result in much lower winter SST in the UK (Durrell et al. 2006), although this is thought to be very unlikely (Murphy et al. 2010).

### 2.2. Sea-level rise

Global mean sea level has risen at a rate of 1-2 mm yr<sup>-1</sup> since the last century (Church et al. 2004; IPCC 2007; IPCC 2013), with an apparent acceleration to 3 mm yr<sup>-1</sup> during the past 30 years, determined from satellite altimetry measurements (Cazanave and Nerem 2004; Church and White 2006) and analysis of tide gauges worldwide (Woodworth and Blackman 2004; Menendez and Woodworth 2010). Climate models (*see* Appendix) simulate climatic sea-level change, assuming different carbon dioxide emission scenarios (Lowe and Gregory 2006). The 5<sup>th</sup> assessment of the IPCC projected, with medium confidence, that global mean sea-levels will increase by 44-74 cm by 2100 (IPCC 2013); an increase on the 18-59 cm previously projected (IPCC 2007). Alternative estimates based on parametric relationships between sea level and air temperature suggest, with low confidence, that sea-level could rise by up to 1.9 m by 2100 (Rahmstorf 2007; Grinsted et al. 2009; Jevrejeva et al. 2010).

As carbon dioxide emissions lead to increased global temperatures, it is very likely that sea-level will continue to rise in more than 95% of the ocean area (IPCC 2013). Sea-level rise is not uniform, with spatial

variability due to steric and eustatic processes (IPCC 2013), as well as vertical land movements such as isostatic adjustment (e.g., Shennan and Horton 2002). It is this relative mean sea-level which is most important for coastal communities (Lewis et al. 2011). In the UK, observed sea level trends are broadly consistent with the global average (Woodworth et al. 2009; Lewis et al. 2011). Although, vertical land movements will reduce this trend in the far southwest UK (by  $-1.5 \text{ mm yr}^{-1}$ ) and augment this trend in parts of Scotland (by  $+2 \text{ mm yr}^{-1}$ ) (Shennan and Horton 2002).

### 2.3. *Storm surges, rainfall, and river flow*

Atmospheric warming is believed to intensify the hydrological cycle (IPCC 2013; Hannaford 2015; Watts et al. 2015). Future incidences of rainfall and river flow will, therefore, be affected by changes to atmospheric warming (IPCC 2007). Additionally, storm surges around the UK are projected to increase due to climate change (Weisse et al. 2014).

#### *Past changes*

Analysis of observed atmospheric data, and application of this data to drive models, show that the second half of the twentieth century experienced a pole-ward shift in the majority of storm tracks across the Northern Hemisphere (McCabe et al. 2001). Further, there was an increase in intensity, but a decrease in frequency, of extra-tropical cyclones (Paciorek et al. 2002; Geng and Sugi 2003). However, storm surge incidents in the UK were un-related with changes to extra-tropical cyclones: extreme water-levels were driven by a rise in mean sea-level, rather than an increase in storminess (Woodworth et al. 1999; Woodworth and Blackman 2004; Woodworth et al. 2009; Menendez and Woodworth 2010). Therefore, it is uncertain whether the UK storm surge frequency has changed beyond natural levels of variability (Allan et al. 2009) – yet, some evidence is now emerging of clustering of extreme sea-levels (Wadey et al. 2014). For instance, there was an exceptional number of extreme high waters during the 2013/14 winter in the UK, arising from an unusually strong westerly phase of the stratospheric Quasi-biennial oscillation (QBO), which in turn has driven a deep polar vortex and strong polar night jet (Wadey et al. 2014).

Data from extensive river-gauge networks show the relationship between river flow and precipitation is spatially variable (Keef et al. 2009). While annual average rainfall in the UK is unchanged since the 1960's, winter rainfall has intensified and increasingly occurred in clustered events (Jenkins et al. 2008; Burt and Ferranti 2011; Jones et al. 2013; Watts et al. 2015). For the same period, river-flows increased in winter, especially in upland western areas; autumn flows rose and spring flows decreased slightly, while there was no consistent change in the summer (Hannaford and Buys 2012; Hannaford 2015; Watts et al. 2015).

#### *Future changes*

Mean sea-level rise will change the dynamics of storm surge generation and propagation (McInnes et al. 2003) and estuarine flood risk and inundation (Senior et al 2002). Circulation and storm surge models (*see* Appendix) indicate future centennial changes in extreme water levels, which pose the greatest flood risk to estuaries, will be moderate and of the same order as the natural climatological variability (Lowe et al. 2001; Woth et al. 2006; Debernard and Roed 2008; Lewis et al. 2011). Uncertainty within model simulations is high due to the parameterization of sub grid-scale processes, such as cloud formations and quantifying inter-decadal variability (Howard et al. 2010; Lowe et al. 2009), and quantification of decadal variability of storm surge climates (Bijl et al. 1999; Alexandersson et al. 2000; Wakelin et al. 2003).

The UKCP09 report explains that little change is expected in the median precipitation amount across the UK by 2100, but significant changes in the trends of winter and summer precipitation are projected (Jenkins et al. 2009). The report generally found a slight increase in the winter mean precipitation and a decrease in summer mean precipitation for the western UK (Jenkins et al. 2009). River catchment models indicate river flows are projected to reduce in summer (by 40-80%) and increase in winter (by up to 25%), particularly in mountainous regions of western UK (Fowler and Wilby 2010; Christerson et al. 2012; Prudhomme et al. 2012). These projections were biased through inability to capture monthly precipitation climates (Prudhomme and Davies 2009; Smith et al. 2013).

#### 2.4. *Combined extreme events*

In the UK, low pressure systems (extra-tropical cyclones) that are responsible for storm surges and coastal flooding also produce heavy rainfall in the catchment, which ultimately influence estuarine processes (Maskell et al. 2013). The relation of storm surge climate with rainfall has become the focus of a number of studies (e.g., Coles et al. 1999; Senior et al. 2002; Svansson and Jones 2002). For a catchment in south Wales, there was no correlation between sea-level and daily peak river flows (Samuels and Burt 2002), but there was a positive relation between storm surge and daily peak flows (Svensson and Jones 2004).

Storm surge can clearly be associated with extreme rainfall (Svensson and Jones 2004; 2006; Hawkes 2008) and, while spatially and temporally variant with meteorological conditions and catchment characteristics (Svensson and Jones 2006; Keef et al. 2009; Zheng et al. 2013), the relationship should to be taken into account for flood risk estimation. Further research is required to investigate the factors that give rise to the surge-rainfall association (Zheng et al. 2014). Research on extreme event dependence has concentrated on the implications of extreme events to estuarine flood risk (*see* Section 3). There has been much less focus on the implications to other estuarine conditions and processes, such as biology, water quality and sediment transport processes (Lowe et al. 2009; Robins et al. 2014).

**Table 1.** Observed trends and future projections of climate change to UK estuaries

Process	Observed trend	<i>CONFIDENCE</i> and information sources	Projected 21 <sup>st</sup> century change	<i>CONFIDENCE</i> and information sources
<b>Sea surface temperature</b>	+0.7°C (1971 – 2010)	<i>HIGH</i> IPCC (2013) Jenkins et al. (2009)	+1.5°C to +4°C	<i>HIGH</i> Lowe et al. (2009)
<b>Sea-level rise</b>	+1 to +3 mm yr <sup>-1</sup> during last century	<i>HIGH</i> Cazanave and Nerem (2004) Church et al. (2004) Woodworth and Blackman (2004) Church and White (2006) Menendez and Woodworth (2010) IPCC (2013)	+0.44 m to +0.74 m (Steric and eustatic processes)	<i>HIGH</i> Worth et al. (2006) Lowe et al. (2009) Woodworth et al. (2009) Lewis et al. (2011) IPCC (2013)
			+1.9 m (Parametric relationships between sea level and air temperature)	<i>LOW</i> Rahmstorf (2007) Grinsted et al. (2009)
<b>Storm surge</b>	Pole-ward shift of storm tracks.	<i>MED</i> McCabe et al. (2001)	Centennial changes in extreme water levels are marginally significant (i.e., are of the same order as the natural climatological variability).	<i>LOW</i> Bijl et al. (1999) Alexandersson et al. (2000) Wakelin et al. (2003) Woth et al. (2006) Debernard and Roed (2008) Lowe et al. (2009) Howard et al. (2010) Lewis et al. (2011)
	Increased intensity / decreased frequency extra-tropical cyclones.	<i>HIGH</i> Paciorek et al. (2002) Geng and Sugi (2003) Woodworth and Blackman (2004) Woodworth et al. (2009) Menendez and Woodworth (2010)		
	High variability in storm surges	<i>MED</i> Allan et al. (2009)		
	Clustering of extreme sea-levels	<i>LOW</i> Wadey et al. (2014).		
<b>River flows</b>	1969-2008: Increased flow during autumn and winter, decreased flow during spring, no trends during summer	<i>HIGH</i> Keef et al. (2009) Hannaford and Buys (2012) Hannaford (2015) Watts et al. (2015)	Increase in winter mean flow by up to 25%	<i>MED</i> Fowler and Kilsby (2007) Jenkins et al. (2009) Prudhomme and Davies (2009) Fowler and Wilby (2010) Christierson et al. (2012) Prudhomme et al (2012) Smith et al. (2013) Kay et al. (2013a,b)
	Rainfall (river flows) occurring in clustered events	<i>LOW</i> Jenkins et al. (2008) Burt and Ferranti (2011) Jones et al. (2013) Watts et al. (2015)	Decrease in summer mean flow by 40-80%	

### 3. Climate impacts on the physical environment

#### 3.1. Flooding and inundation

The primary climatic drivers of changes to estuarine flood risk and inundation occurrence are caused by a combination of increased sea-level (sea-level rise and/or storm surge, and their nonlinear propagation within estuaries), changes to the wave climate and wave overtopping, and changes to incidences of high river flow events (Lewis et al. 2013; Quinn et al. 2014). Both sea-level and river flow climates appear to be changing due to climate change, resulting in increased flood risk to estuaries (Worth et al. 2006). The impacts of coastal flooding, in the absence of mitigation, are severe (Batstone et al. 2013). They include loss of life (Jonkman et al. 2009), damage to property and infrastructure (Hanson et al. 2011), increased coastal erosion and loss of land to the sea (Zhang et al. 2004), potential population displacement (Nicholls et al. 2011), pollution and increased human health risk, and significant loss of wetland habitats and ecosystems (Day et al. 1995; Nicholls et al. 1999).

There is some past evidence of increased frequency of high storm surges around the UK (*see* Table 1), however, historical surge observations cannot infer future flood risk. Therefore, modelling approaches are key to flood risk assessments (*see* Appendix), where risk is generally defined as the probability of the occurrence multiplied by the consequences. Joint extreme surge-wave-river events can increase the impact (cost) of flooding three-fold, compared with sea-level-only events (Prime et al. 2015). Using published climate change scenarios, a combination of sea-level rise and increased storminess will allow storm surges to reach much further inland, so that UK estuaries will be subject to both higher water levels and more energetic wave attack (King 2004). In the highest IPCC emission scenario for this century, flood levels that are now expected only once in 100 years could be recurring every 3 years (King 2004). Although the likelihood of extreme sea level rise (up to 1.9 m over the 21<sup>st</sup> century) due to rapid ice sheet mass loss is low, the resulting hazard can be large, resulting in a significant increase (of 30%) to the projected risk, for the case of the UK's largest estuary – the Severn (Quinn et al. 2013).

Other drivers of changes to estuarine flood risk and inundation occurrence, which can be considered climatic or non-climatic, are changes to sediment transport (i.e., the sediment flux into or out of an estuary) and the nearshore and estuarine morphology (erosion and accretion). A key consideration under accelerating rates of sea-level rise is the potential for geomorphological features and flood depths to adjust, through longshore transport, progressive flood-dominance, and sediment compaction and subsidence (Dickson et al. 2007; Shennan et al. 2012; Nicholls et al. 2013). In such circumstances, flood risk will increase incrementally over long (decadal) timescales, in which case mitigation measures can be foreseen and employed in advance to reduce risk. However, much greater flood risk will result from rapid morphological changes following extreme storm (wave and/or river flow) events (Pye and Blott 2006). In addition to the natural trends, shoreline protection has greatly reduced the input of new sediment sources, resulting in much contemporary coastal erosion (Nicholls et al. 2013). The capacity for estuaries to respond to sea-level rise will depend on landward constraints to transgression, available accommodation space and available sediment supply (marine and fluvial) (Nicholls et al. 2013). Some studies have suggested that estuaries can cope with relatively high rates of sea-level rise (e.g., Rossington et al. 2007), whilst studies of intertidal and saltmarsh areas suggest far less resilience (e.g., Orford and Pethick 2006; French 2006; Marani et al. 2007).

Projected increases in global average temperatures of 1.4-5.8°C over the 21<sup>st</sup> century will increase evapotranspiration throughout the catchment, and alter vegetation types and reduce soil moisture – all of

which will reduce runoff into estuaries and potentially dampen flood risk slightly. Modelled catchment runoff from several climate change scenarios (up to 2100) in the Ouse-Humber Estuary showed increased evapotranspiration (5% in winter, 15% in summer), although total runoff generally increased by up to 30% in winter due to increased rainfall (Boorman 2003).

Several anthropogenic drivers, which are partly a consequence of climate change, will either directly or indirectly influence flooding and inundation in UK estuaries. For instance, growth in coastal urbanisation and migration is expected to both increase flood risk (through increased water usage and increased rainfall runoff) and introduce higher value assets near coasts (Quinn et al. 2014). Changes in rural land management, agriculture and managed habitats, and environmental regulations, such as biodiversity and habitat protection, will influence vegetation type, catchment morphology, water management and storage, and ultimately catchment runoff into estuaries ([www.gov.uk/government/publications/future-flooding](http://www.gov.uk/government/publications/future-flooding)).

### 3.2. *Hydrodynamics and mixing*

In the UK, the majority of the largest estuaries are either mesotidal or macrotidal, meaning that circulation and mixing are controlled by oscillatory tidal energy (Prandle 2009). A consequence of the shallow nature of many UK estuaries is that the tide is asymmetric, often taking significantly less time to flood than to ebb, producing stronger flood flows and weaker ebb flows (Robins and Davies 2010). The strong tidal flows in these shallow environments often produce vertically well-mixed water, though weak vertical stratification is sometimes evident during the tidal cycle, e.g., at slack water (Howlett et al. 2015). Of particular importance for estuarine dynamics are extreme river flows and their variability. Most UK estuaries react rapidly to rainfall events from relatively small catchments and, as such, are often in a state of non-equilibrium in terms of turbulent mixing, stratification and salt balance, and solute/material fluxes; processes which are reported to be critical for estuarine functioning, water quality, and coastal ecology (Prandle 2009; Robins et al. 2014). The fate of solutes such as carbon and nitrogen within an estuary depends on tidal/wave mixing in conjunction with nonlinear river flows (rivers tend to rise very quickly after rainfall but flowrates reduce more slowly) and the morphology of the estuary (Struyf et al. 2004; Robins et al. 2014).

Under low river flow conditions, which are projected to become more common in summer in the UK (Prudhomme et al. 2012; Christerson et al. 2012), up-estuary tidal-pumping predominates the transport of salt to the upper reaches of the estuary and retains river-borne substances in the estuary for extended periods. Following high rainfall events, there is rapid downstream transport, which potentially flushes freshwater and nutrients and pollutants offshore (Simpson et al. 2001). Slower responding catchments, with longer and flatter rivers or considerable snow storage (e.g., Firth of Tay, Scotland), are more likely to be in equilibrium. Accordingly, estuarine recovery after a rainfall event restores a steady state salt distribution (Kranenburg 1986; MacCready 1998; Hetland and Geyer 2004). Few observations of estuarine tidal-pumping/recovery have been documented (e.g., Simpson et al. 2001; Robins et al. 2014) and there is generally a lack of knowledge about how estuarine hydrodynamics react to extreme climatic events.

Altered river flows due to climate changes could have significant and, as yet, unquantified implications for estuarine functioning (Whitehead et al. 2009). Modelling shows interaction of sea-level rise with altered river flow will increase the length scale of the estuarine salt distribution: sea-level rise combined with low flow conditions will force the saline intrusion (and estuarine turbidity maximum) further up-estuary, whilst increased river flows will push the saline intrusion further offshore (Robins et al. 2014; Yang et al. 2015). In other words, the extent of the pumping effect is dependent on the strength of river flow, which is to be more

variable with climate change. The sum effect is that a projected 20-25% increase in winter river flow in the UK by 2100 (Fowler and Wilby 2010; Christerson et al. 2012; Prudhomme et al. 2012) will increase saline intrusion length scales by up to 5 km (Prandle 2009).

### 3.3. *Sediment transport and morphology*

Many UK estuaries tend to be tidally asymmetric, the flood phase of the tide often taking significantly less time than the ebb phase (Moore et al. 2009). As the tide propagates up an estuary, greater frictional resistance at low tide slows the propagation of water level changes relative to those occurring at high tide (Dronkers 1986). Thus, the time delay between low tide at the mouth and at the head of an estuary is greater than the corresponding time delay for high tide. This results in a longer, weaker ebb tide and a shorter, stronger flood tide (due to conservation of mass). According to Lanzoni and Seminara (1998), weakly dissipative (deep) estuaries tend to generate ebb-tide asymmetry (of the tidal velocities), whereas in strongly dissipative (shallow) estuaries, flood-tide asymmetry tends to occur, which affect sediment transport patterns. But classification of flood/ebb (flow) asymmetry (e.g., Friedrichs and Aubrey 1988) does not necessarily give an accurate indication of the net sediment transport.

Therefore, Robins and Davies (2010) classified an estuary or region within an estuary as ‘flood-dominant’ if the asymmetry in the tide causes a net, up-estuary, sediment accumulation (because the stronger flood flow may be above the threshold of sediment motion for longer than the ebb flow). They referred to the opposite case as ‘ebb-dominant’. Therefore, an estuary is likely to become more flood-dominant as the tidal wave travels landward; however, understanding is insufficient to predict where this occurs with much confidence (Robins and Davies 2010). Modelling suggests that, for idealised estuary shapes that represent the UK coast, flood-dominance in the transport occurs in shallower water where  $a/h > 1.2$  ( $a$  = local tidal amplitude,  $h$  = local water depth), and ebb-dominance occurs in deeper water where  $a/h < 1.2$  (Robins and Davies 2010). However, in terms of transport magnitude the net ebb-dominance was less pronounced than the flood-dominance. Sea-level rise caused the critical value of the parameter  $a/h$  to be reduced, with the estuary tending to shift from ebb-dominance towards flood-dominance, with less sediment transport occurring overall. Reducing the sediment grain size increased both the gross and net sediment transport but did not significantly affect the general pattern of flood/ebb-dominance in the transport. The inclusion of an ebb channel promoted ebb-dominance and increased the transport locally. Applying these outcomes to a Welsh estuarine case (the Dyfi estuary), Robins and Davies (2010) concluded that, due to a projected sea-level rise by 1 m in the next 100 years, greater flood-dominance but less sediment transport overall would occur in the estuary in the future.

### 3.4. *Fluxes of nutrients*

Estuaries provide key ecosystem service benefits and are crucial in processing and cycling nutrients - essential for the growth of plants and animals, through the RETZ to the coast (Nedwell et al. 1999; Malham et al. 2014). Estuarine nutrient fluxes follow highly complex transport patterns, due to the competing nature of the physical drivers, together with the biogeochemistry of the nutrients and their interaction with the estuary (Statham 2012). Processing of nutrients such as nitrogen (N), Phosphorus (P) and Carbon (C) involves several organic and inorganic compounds in both the dissolved or particulate state (Jarvie et al. 2012), as well as interactions with the physical (e.g., tidal flushing, stratification and mixing, extreme river

events (Robins et al. 2014)), biological (e.g., benthic fauna) and chemical (e.g., pH) environment of the estuary.

Current trends have indicated that there has been a general increase in nutrients such as N, P and C in European rivers over time, as a result of changing land-use and fertilizer application, with consequent negative impacts including eutrophication and poor water quality (Whitehead et al. 2009; Statham 2012; Malham et al. 2014). However, river-to-estuary pollution from point source discharges has decreased in recent years, due to more stringent regulations and water treatment facilities (Watts et al. 2015).

Although the underlying processes are complex and forecasting is difficult, nutrient input to UK estuaries is generally projected to increase with climate change and the negative impacts of eutrophication, hypoxia and harmful algal blooms will be augmented as a consequence (Tappin 2002; Statham 2012). The main climatic changes, that will impact on nutrients fluxes through UK estuaries, are thought to be: projected drier summers and wetter winters, more extreme rainfall events and increased rainfall duration, clustered rainfall events, increased temperatures, modified wind patterns, changes to the hydrological cycle and sea-level rise (Kennish 2002; Whitehead et al. 2009). Based on one case study of the Conwy Estuary, the up-estuary extension of the estuarine turbidity maximum, due to sea-level rise during low flow conditions, will diminish the down-estuary transport of nutrients, promoting estuarine trapping and reducing offshore nutrient dispersal (Robins et al. 2014). Assuming these findings hold throughout UK estuaries, reduced river flows associated with drier summers are projected to heighten the likelihood of estuarine nutrient trapping, in between freshwater flushing events (Robins et al. 2014). Nutrient retention is less likely during winter when increased river flow will counteract the effects of sea-level rise (Struyf et al. 2004). Nitrification in summer is more prone to cause eutrophication than in winter: only summer production is nutrient limited; winter production is light limited. Thus, the dry summer effect has the greatest potential for augmenting eutrophication.

Overall, more is known about fluxes of inorganic than organic nutrients (Jarvie et al. 2012). Further research is needed on bacterial cycling of organic nutrients (Asmala et al. 2014), nutrient reactivity (Valdemarsen et al. 2014), speciation and interaction with fresh and salt water under different pH and dissolved organic matter conditions (Morgan et al. 2012). Much research is required on broad-scale processes, such as biogeochemistry processing in estuaries (Jickells et al. 2000; Andrews et al. 2006; Najjar et al. 2010). Catchment-estuary model coupling methods are improving (Tappin 2002; Uncles 2003; Huang et al. 2013) and there is currently a UK drive in data generation (e.g., NERC Macronutrients Cycles Programme) which will prove valuable to model validation. The potential for biological interaction with nutrient cycling is discussed in Section 4.4.

## 4. Climate impacts on estuarine ecosystems

The long-term natural and human impacts that estuaries face can compromise their ecological integrity, habitat composition, and water quality (Kennish 2002). Trends suggest that, over the next few decades and beyond, estuarine ecosystems will be mostly impacted by habitat loss, due to climate change and urban expansion. Other projected high priority problems include excessive nutrient and sewage inputs to estuaries, leading to eutrophication, hypoxia, and anoxia (Kennish 2002). Further damaging problems will arise from over-fishing, chemical contaminant fluxes in urbanised regions, freshwater diversions, the introduction of invasive species, and coastal subsidence and erosion. Although it is difficult to quantify, these impacts on estuarine ecosystems are, at least in-part, linked to climate change.

### 4.1. Human health: pollutants, pathogens, and viruses

Climate change and climate variability in UK estuaries will ultimately have impacts upon human health via ecological disruption in the estuarine environment and the transmission of water-borne and food-borne diseases caused by microbial pathogens (McMichael et al. 2006). By 2100, an increase in the global average temperature of 1.4-5.8°C is projected, together with an increase in global average annual rainfall, with more severe precipitation events and flooding in some regions and drier conditions in others (McMichael et al. 2006; IPCC 2013). These climate changes may increase public health risk associated with water-borne and food-borne pathogens from the estuarine zone.

There are over 100 recognised types of microbial pathogen found in contaminated water used for recreation and as potable water (Rose et al. 2001), with the potential for food-borne transmission if associated with seafood (Marques et al. 2010). Increased precipitation and flooding result in the discharge of untreated sewage via combined sewer overflows (CSOs) and increased runoff from agricultural land. It is estimated that, in the United States, 50% of contamination in estuarine environments is derived from CSOs and runoff from precipitation events (Perciasepe 1998; Rose et al. 2001). In addition to microbiological agents associated with human and industrial wastes in CSOs, toxic pollutants, ammonia, organic solids and oxygen-demanding substances are also discharged into receiving waters (Perciasepe 1998; Friedman-Huffman and Rose 1999; Stachel et al. 2004). There are precedents for precipitation events preceding outbreaks of water-borne disease (Rose et al. 2005; Curriero et al. 2001); for example, outbreaks of the protozoan pathogen *Cryptosporidium* have been observed following extreme precipitation events, which decrease the efficiency of water treatment processes resulting in the incomplete removal of oocysts from discharging waters (reviewed by Rose et al. 2001). In addition, faecal indicator organism concentrations in a Florida estuary were several-fold greater during a winter of high precipitation caused by El-Niño, when compared with the rest of that year (Lipp et al. 2001). It is also well established that climate change may influence the concentrations of toxic metals, organic chemicals, algal toxins derived from harmful algal blooms (HABs) and human pathogen contaminants in seafood (Marques et al. 2010).

Conversely, drought conditions will prevail in some areas, resulting in decreased water flow and the concentration of microbial contaminants (Rose et al. 2001). Sea-level rise will affect the coastal zone via the salinization of land and freshwater, and the loss of coastal wetlands which filter nutrients, microbial agents and chemicals, and help protect the coast from storm surges (McMichael et al. 2006). However, the implications of sea-level rise on the fate of microbial, nutrient and chemical agents and their interactions with the wider ecological dynamics of the system are poorly understood and should be addressed by integrated catchment-river-estuary models (Rose et al. 2001).

The cholera model represents a well-characterised mechanism for understanding the role of climate on infectious disease transmission (Lipp et al. 2002). *Vibrio cholerae* (the bacterial species responsible for cholera) and other *Vibrio* spp. are endemic in marine and coastal environments and demonstrate strong associations with warmer sea surface temperatures (summer and early autumn) that drive their seasonality and ecological distribution (Rose et al. 2001). Furthermore, favourable environmental conditions (e.g., nutrients and temperature) promote the formation of algal blooms that act as a reservoir for *Vibrio* spp. and can cause reversion from a quiescent to infectious state (Rose et al. 2001). Future temperature shifts, therefore, have the potential to expand the prevalence of *V. cholera* at both temporal and geographical scales (Lipp et al. 2002) – although there is no projected cholera risk to the UK. In contrast, several studies report the enhanced survival of faecal indicator organisms at lower temperatures (Lipp et al. 2001; Malham et al. 2014).

#### 4.2. *Estuarine Habitats*

Estuaries are rich in biological diversity and harbour a number of habitats, many of which have statutory protection and all of which have roles in prolific estuarine foodwebs and the cycling of organic material (Kaiser et al. 2005). Estuarine habitats can be classified by submergence into intertidal and subtidal (e.g., intertidal rocky shores and subtidal rocky reefs), by the hardness of the substrate into soft sediment (salt marshes, seagrass beds, mudflats, etc) and hard substrates (rocky shores and reefs), by the salinity regime (full salinity, estuarine brackish, tidally influenced river: TIR) and by whether the habitat is biogenic (biologically formed, e.g., mussel beds, *Sabellaria* reefs) or non-biogenic (e.g., sandy shores, sand banks). There is little evidence-based research on the effects of most of climate change agents on estuarine systems, with the exception of temperature (Mieszkowska et al. 2013). The following review highlights the current knowledge for the most researched habitats, the majority of which are intertidal.

##### *Salt marshes*

There are relatively good nation-wide records of the historical changes to the areal extent of UK salt marshes. Large expanses of marshes were historically lost to agricultural expansion and coastal development (EA 2011). Losses have since abated, although there are concerns about marsh erosion for some regions (EA 2011). A survey commissioned by the Environment Agency showed marshes declined by <100 ha per year between 1989 to 2009 (EA 2011); the survey reported some spatial differences in the patterns of areal change – strongest declines in the south and none or increases in the northwest - but it is not clear if, or how, these changes are associated with emergent climate change. Global evidence suggest marshes are well-capable of keeping pace with sea-level rise if given the space to transgress inland, and in the absence of exceptional land subduction and altered sediment supply (Fagherazzi et al. 2012). Coastal squeeze remains the greatest threat to salt marshes in terms of sea-level rise (Fagherazzi et al. 2012), the elimination of which is linked to policy decisions, such as shoreline management planning. Sea-level rise is not the only climate-linked risk to salt marshes. Marsh vertical and horizontal growth is strongly dependent on sediment supply, which, if diminished, can switch marshes from accreting to eroding and preclude their keeping pace with sea-level rise (Bouma et al 2014).

Section 2 showed sediment supply in the absence of human intervention is governed by hydrological conditions, determining for instance the up-estuary transport of marine sediments, as well as the down-estuary transport of catchment and riverine particles. Tendencies of increased fluvial down-estuary transport

of sediments bode well for the capacity of marshes to keep pace with sea-level rise. Emergent evidence for the past 70 years show many estuarine marshes on the west coast of England and Wales have undergone dynamical changes to area extent, but the collective area has expanded, particularly since the 1950s (Martin Skov, *pers. comm.*). These changes are not linked to isostatic adjustment, which is commonly invoked as a cause for national variation in marsh erosion rates (EA 2011). Future projections of changes to estuarine function might do well to carefully consider the causes for such regional differences in ecosystem change, and the implications to estuarine management.

### *Intertidal rocky shores*

Intertidal habitats are excellent systems for tracking changes to community composition in response to climate change and rocky shores are the most well-studied intertidal system in the UK. Throughout the UK a number of rocky shore species have been gradually moving north in response to a rise in temperature, punctuated by cool years in which the advance has ceased, or reversed (Mieszkowska et al. 2013). The tendency is for northern species that are intolerant to warming to retreat northwards to remain in cooler conditions, while Mediterranean/Lusitanian species are coming up from the south, facilitated by an increasingly benign climate (Mieszkowska et al. 2013). Similar changes are occurring in other estuarine habitats, such as *Sabellaria* reefs (Frost et al. 2004), as well as in terrestrial and marine systems (Hiddink and Hofstede 2008). Changes to community composition brings with it the potential for change in local biodiversity, and thereby to ecological functioning (what ecosystems do: organic production, degradation, habitat provisioning, etc), as altered species composition and biodiversity changes the interactions between species and the portfolio of ecological roles performed by these (Balvanera et al. 2006) (*see also* Section 4.3-4.4). Rocky shores are governed by competition between algae and grazing molluscs, and the relative dominance is determined by environmental conditions: increased wave exposure and temperature tends to favour animals over algae (Hawkins et al. 2008), and predictions are that algae will become less prevalent in a warming and more hydrologically energetic future, which could diminish overall biological production of estuarine rocky shores (Hawkins et al. 2008; 2009).

### *Seagrass*

Seagrasses have dramatically declined in global cover in the past centuries, in Europe by 50-80% (Short and Wyllie-Echeverria 1996). In the UK, declines were severe at the beginning of the 19<sup>th</sup> century and the cover has not recovered since then. There has been minimal monitoring of the areal extent of British seagrass beds and there is no research-based evidence on how they will respond to climate change in the UK (Mieszkowska et al. 2013). Areal cover has declined in England, but there are indications of areal increases in Scotland and Wales (Smith et al. 2002; Howsen 2009). Seagrasses elsewhere have suffered from climate-related changes in temperature, storminess and prevailing winds (Bjork et al. 2008). Whether or not similar patterns will be seen in the UK is unknown. Current climate related research has focused on seagrass beds in other countries that are exposed to less variable environmental conditions than those experienced in the UK. Systems adapted to variable conditions do tend to be more resilient, although whether this principle applies to climate-related influences on seagrasses in the UK remains to be seen.

### *Sedimentary estuarine habitats*

Sedimentary estuarine habitats are already undergoing geomorphological change from climatic drivers including increasing wave height, storm surges and water depth (Lowe et al. 2009), and are likely to respond

to changes in river flow, although there are no detailed studies to support this presumption in the UK. Increased hydrological forcing is likely to steepen beach profiles (Mieszkowska et al. 2013), a geomorphological change that is normally associated with diminishing abundance and diversity of sediment living animals (McLachlan and Brown 2006). Intertidal mudflats are rich in animal diversity and abundance and support a large estuarine foodweb including fish and birds (Kaiser et al. 2005). Mudflats are thought to be particularly sensitive to climate change, through an assortment of drivers, including hydrological forcing driving geomorphological change and changed sediment supply and coarsening, in conjunction with increased temperature and salinity (Gubay et al. 2010; Jones et al. 2011). Modelling indicates communities of soft sediment habitats will respond negatively to additional pressures, such as increased temperature, with estuarine stressors such as eutrophication (Lenihan et al. 2003).

### *Biogenic reefs*

The honeycomb worm *Sabellaria* sp. makes bulky biogenic reefs in intertidal and subtidal stony and rocky areas. Reefs are colonised by an array of invertebrates and are a priority habitat for protection in the UK and Europe. *Sabellaria* is a 'warm' water genus and the reefs have been extending northwards in the UK in recent decades, as a response to less severe winter temperatures (Frost et al 2004) - a pattern which is likely to continue into the future (Mieszkowska et al. 2013). Dr Andrew Davies of Bangor University is leading a team currently researching how *Sabellaria* colonisation and growth will respond to changes in sediment supply; the results are still pending. Mussel beds are found in mixed substrate areas (rock; rock and sediment) throughout the UK. Indications are that temperature rise is unlikely to markedly affect mussel distribution in the UK in the coming century, because mussels are found within their temperature tolerance in the UK; although interactions of temperature with multiple estuarine stressors (e.g., eutrophication) might affect mussel condition and thereby the expanse of mussel beds (Mieszkowska et al. 2013).

### *Caveats and overarching issues*

The potential for impact of climate change on an estuarine habitat is somewhat determined by the physical nature of its habitat (biogenic, non-biogenic; hard, soft) and its relative position (intertidal, subtidal; location in estuary). The persistence of biogenic habitats is strongly governed by the physiological tolerance and condition of the foundation species that generates the habitat; if conditions are sub-optimal, the habitat might disappear. Non-biogenic systems can continue to exist despite climate change, although some might become biologically unavailable. Thus, rocky shores will persist as a habitat, but are projected to decrease in area due to coastal squeeze (Jackson and McIlvenny 2011). Intertidal habitats are naturally more influenced by short-term changes in weather than sub-tidal habitats that are well buffered by seawater. Ultimately, changes in community composition induced by climate change might affect the resilience of systems to other environmental change, although research for UK estuaries in this area is limited. Major research gaps also exist on how biological feedbacks that affect physical conditions in estuaries will be affected by sea-level rise. For instance, saltmarsh colonisation alters the forcing and distribution of hydrological energy, which facilitates further expansion of marshes and ultimately influences the tidal prism and estuarine sediment distribution. Whether or not such biological feedback mechanisms will be enhanced or reduced by change in climatic conditions is currently not known.

### 4.3. *Physiological and behavioural responses*

Environmental cues synchronize the reproductive cycle of many marine invertebrates and fish (Kingsford et al. 2002). A broad diversity of taxa have the capacity to detect variations in current direction, magnetism, water pressure, water chemistry (biotic sources such as amino acids and abiotic sources such as salinity), sound and vibration (e.g., waves breaking or fish assemblages), and light gradients (Shanks 1995, Forward et al. 2001; Kingsford et al. 2002). These cyclic cues may affect a number of reproductive parameters, including sex determination, gametogenesis, spawning, transport, settlement, retention, connectivity, and metamorphosis (Lawrence and Soame 2004).

Primary environmental cues for species that use estuaries for part of their reproductive cycle are tidal currents and photoperiod. For example, European shore crab larvae in estuaries within the North Sea use selective tidal stream transport to swim to the surface during the flood tidal phase, which aids in-shore dispersal towards estuarine feeding grounds (Moksnes et al. 2014). Conversely, decapod crustacean larvae may swim to the surface during the ebb tidal phase and migrate offshore (Queiroga and Blanton 2005). In other regions, shore crab display nocturnal (diel) vertical migration to avoid predation (Moksnes et al. 2014). Some organisms can detect multiple cues (e.g., decapods and fishes) and are likely to have integrated sensory responses (Kingsford et al. 2002). The type of response may be endogenous and regulated by an internal clock (e.g., tidal stream transport), or a direct response to the environment (e.g., diel transport) (Queiroga and Blanton 2005). Further, the phasing and extent of all kinds of vertical migration both change throughout ontogeny (Queiroga and Blanton 2005).

Estuarine species live in a highly dynamic environment where recruitment variability is a key determinant of population dynamics. Environmental requirements for successful recruitment may differ between co-occurring species, and therefore species may be advantaged or disadvantaged under climate change (Allen et al. 2008; Jenkins et al. 2015). Climate change impacts on UK estuaries are likely to alter the environmental cues, which in turn will affect their reproductive parameters. For example, the phase relationship between temperature of the water column and photoperiod directly controls the metabolism and lifecycles of aquatic organisms, with most biological processes operating faster at higher temperatures, leading to shorter pelagic larval durations and time to metamorphosis (Whitehead et al. 2009; Gonzalez-Ortegon and Giménez 2014).

Natural variability in salinity (of the order 10) has been documented to both slightly increase and slightly decrease time to metamorphosis, depending on estuarine species (Forward et al. 2001). The estuarine copepod *Eurytemora affinis* (which exhibits a combination of tidal and salinity cues) will change its migration in response to the location of the estuarine salinity maximum (Hough and Naylor 1991; Robins et al. 2012). The presence of aquatic vegetation and increased humic acids (a decomposition product of terrestrial plant material; Fox 1981), both accelerate the time to metamorphosis of brachyuran crabs (Forward et al. 2001). Alternatively, cues that delay metamorphosis include adverse environmental factors, such as hypoxia and chemical odors from potential predators (Forward et al. 2001).

Thus, species that cue reproduction based on these signals are likely to be particularly vulnerable in the future (Lawrence and Soame 2004). Consequently, climate change may cause local extirpations of populations in the extreme, or more likely impact fecundity, spawning success and recruitment significantly. However, change will ultimately depend on the relative speed of adaptation to climate change (Allen et al. 2008) and the degree of mixing between populations across the Metapopulation (Lawrence and Soame 2004). Eventually, climate change will have implications on the conservation status of UK estuaries.

Besides the hypothesised effect of environmental factors as cues, such factors operate as stressors, in particular in the early life history stages of marine invertebrates. Meteorological forcing, such as extreme rain events, promote salinity decreases in estuaries. Thus, low salinities can reduce growth rates especially during the larval stages, if these are weak osmoregulators or osmoconformer (e.g., decapod crustaceans: Anger 2003; Torres et al. 2011). Low salinity, experienced by parents or at the egg/embryo stage, can have knock-on effects along the life cycle of estuarine organisms (Giménez 2006; Jensen et al. 2014; Chaparro et al. 2014). For instance, low salinity at the embryonic stage can affect the capacity of larvae to osmoregulate (Charmatier et al. 2002) the salinity tolerance (Giménez and Anger 2003) and the larval tolerance to food limitation (Giménez 2002). Exposure of larvae to low salinity also affects juvenile size and growth rate (Giménez et al. 2004, Rey et al. 2015).

It is likely that multiple stressors will operate on estuarine organisms in a synergistic way (Dolbeth et al. 2011; Gonzalez-Ortegon et al. 2013; Przeslawski et al. 2015). As a consequence of warming, temperature may modify the sensitivity to other environmental stressors, but also thermal sensitivity should be modulated by exposure to additional stressors (Sokolova and Portner 2007). For instance, under low salinity, larvae may be more vulnerable to pollutants (Gonzalez-Ortegon et al. 2013) or food limitation (Gonzalez-Ortegon and Giménez 2014). On the other hand, increased temperatures may increase the tolerance of low salinities (Gonzalez-Ortegon and Giménez 2014). Overall, the evaluation of multiple stressor effects suggest that an assessment of the impact of changes in estuaries will require an understanding of the correlated changes in environmental variables such as salinity and temperature.

#### 4.4. *Biota*

Estuaries provide important habitats for species that are either permanent or temporary residents, such as migratory fish and sea bird species (Austin and Rehfisch 2003) or those using estuaries as a nursery (Vasconcelos et al. 2011). The reason for these ecological functions (habitat and nursery provisioning) is attributed to the difference in productivity (Nixon and Oviatt 1986), sediment characteristics and turbidity (Power et al. 2000), when compared with the surrounding coastal environments. Species living in estuaries already live in a naturally highly variable physical environment and often experience conditions close to their physiological tolerances (Attrill and Rundle 2002), with estuaries commonly being highly impacted by extreme events and human interventions.

Covariates and synergistic effects make observing and understanding climate change impacts complex (Field and Aalst 2014). Despite the natural adaptation to the variable physical environment, projected changes due to climate change may have significant impacts on species found in estuaries and the ecosystem of which they are a part. Moreover, invasive species to estuaries have increased in frequency during the last 20 years, due to global temperature warming (Austin et al. 2010), leading to some dramatic effects on native assemblages (Thompson et al. 2002). Problems associated with invasive species, especially pathogens, will continue to increase over the next few decades.

The projected climate changes of sea-level rise and increased winter river discharge, and their associated effects in estuaries (Booij 2005), are thought to be the most important impacts of climate change on species, principally through the habitat changes (Kimmerer 2002; Field and Aalst 2014). Benthic habitat loss from sea-level rise, such as coastal squeeze in the absence of managed retreat, is likely to have important implications for estuarine food webs (Fujii and Raffaelli 2008). In the same way, estuarine food webs will be impacted by habitat modification from increased high river discharge events; for example: changes in

river-borne material, variations in the position and intensity of estuarine turbidity maxima (Kirby 2010; Uncles et al. 2014), and altered salinity stratification and structure (Howlett et al. 2015). Changes in the salinity experienced by fauna in estuaries is likely to have an impact on species diversity: a projected increase in salinity range will reduce species diversity, as found in the Thames estuary (Attrill 2002). Additionally, the occurrence of hypoxic events and the vulnerability of species in estuaries to these events is likely to increase (Rabalais et al. 2009; Vaquer-Sunyer and Duarte 2011). Key components such as benthic filter and deposit feeders have been overserved, and are predicted to be negatively affected through these changes (Fujii and Raffaelli 2008). These functional groups are important for nutrient cycling and supporting higher trophic levels such as predatory fish and birds in estuaries (Austin and Rehfishch 2003), and so can have far reaching implications if affected beyond natural variation. Turbidity has been suggested to be important for survival and behaviour of mid-water organism such as juvenile fish through food supply and vulnerability to visual predators, which may present further implications to changes in river discharge and sediment suspension (Blaber and Blaber 1980; Power et al. 2000).

In addition to these habitat modifications, climate changes to temperature, excluding range shifts, may also affect populations and food webs indirectly, as commonly observed in marine systems (Walther et al. 2002). For example, mild winters are projected to increase in occurrence in the UK as a result of climate change (IPCC 2013) and have been shown to negatively impact infaunal bivalve reproductive output and recruitment directly and through affecting predator phenology (Philippart et al. 2003; Beukema and Dekker 2014). Predatory shore crabs *Carcinus maenas* and brown shrimp *Crangon crangon* recruit earlier after mild winters, which can result in a greater overlap with their post-larval bivalve prey and reduces bivalve and flatfish recruitment success when compared with periods with preceding 'cold' winters ( Power et al. 2000; Beukema and Dekker 2014).

Due to the multiple of indirect effects due to climate change, over a background of high natural variability and human disturbances, identifying and predicting impacts on UK biota in estuaries is admittedly challenging. However, long-term data sets looking at multiple variables (e.g., McMellor and Underwood 2014) and experimentally assessing population and ecosystem processes/changes can help achieve this.

## 5. Conclusions

We have reviewed published literature of historic observations and current anthropogenic climate change projections for the 21<sup>st</sup> century, and summarised the expected impacts to UK estuarine systems, including both physical and environmental changes.

*UK climate observed trends and future projections over the 21<sup>st</sup> century:*

- *Sea surface temperatures:* Increased globally by 0.7°C over the past 30 years. Projected (with high confidence) to increase from present values, by between 1.5°C and 4°C, by 2100.
- *Sea-levels:* Risen globally by 1-3 mm per year during the 20<sup>th</sup> century. Projected (with high confidence) to rise from present levels, by between 0.44 m and 0.74 m, by 2100.
- *Storm surges:* High variability observed over the past few decades, with a general pole-ward shift and increased intensity / decreased frequency of events. Future projections show high variability, with increased surge clustering (low confidence).
- *River flows:* Increased in the UK during autumn and winter, and decreased during spring (past 50 years) with no detectable trends in summer. Future projections are for more clustering of events, with increased winter flow and decreased summer flow (low confidence).

*Impacts on the physical estuarine environment:*

- *Flooding:* Primary climatic drivers are increased sea-level, changing surge and wave climates, and changing river flow events. The capacity for estuaries to respond to flooding will depend in the short term on landward constraints to transgression and available accommodation space (i.e., coastal squeeze), and in the long term on available sediment supply (marine and fluvial) relative to sea-level rise (medium confidence?).
- *Mixing:* Although most UK estuaries have a strong tidal energy input, estuarine mixing – critical for water quality and coastal ecology – is often controlled by river flow variability. Climate change, especially altered river flow, will therefore increase the temporal variability and length scales of estuarine mixing (i.e., longer dry periods in summer combined with sea-level rise will push the salinity maximum further up-estuary, and clustering of storm events will alter the temporal mixing variability in winter) (low confidence?).
- *Sediments:* Many UK estuaries experience stronger flooding tides than ebbing tides, which greatly affects sediment transport patterns (sediment transport is a function of velocity cubed) – resulting in sediment accretion in shallow regions and sediment export in deeper regions. Sea-level rise will likely cause a shift towards accretion everywhere, but with reduced transport overall (low confidence?).
- *Nutrients:* Nutrients in rivers have increased over time, because of changing land-use, with negative impacts on water quality and eutrophication. But pollution from point sources has decreased, due to improved water treatment. Nutrient input to UK estuaries are projected to increase, due to sea-level rise but especially due to altered river flows, with negative impacts of eutrophication, hypoxia and harmful algal blooms (low or medium confidence?). Nutrifaction in summer, during extended periods of low river flow, will likely have the greatest potential for augmenting eutrophication (low confidence?).

*Impacts on the estuarine ecosystem:*

- *Human health:* Increased temperatures and altered river flows may increase public health risk associated with ecological disruption and water-borne and food-borne microbial pathogens (low confidence?). Climate change is likely to influence the concentrations of toxic metals, organic chemicals, algal toxins, and human pathogen contaminants in seafood (low or medium confidence?).

- *Habitats*: Salt marshes are declining in areal extent?. Coastal squeeze due to sea-level rise is the greatest threat to salt marshes. Some intertidal habitats and biogenic reefs – often priority habitats for protection in the UK – have gradually moved north in response to rising temperatures, bringing changes in biodiversity and ecological functioning – for example, algae will likely become less prevalent. However, temperature rise is unlikely to affect species that live within their temperature tolerances, such as mussels. Sedimentary habitats, particularly mudflat-living species, are sensitive to an assortment of climate change drivers including wave attack and sediment coarsening.
- *Physiology and behaviour*: Climate change is likely to alter environmental cues, such as tides and photoperiod, which synchronize the reproductive cycle of many marine invertebrates and fish. Estuarine species that cue reproduction based on salinity signals are likely to be particularly vulnerable to climate change. Eventually, climate change may have implications on the conservation status of UK estuaries (confidence?).
- *Biota*: Climate change-induced habitat alteration/loss will likely affect species diversity and food webs, and the vulnerability of species to the occurrence of hypoxic events (confidence?). Projected increases in mild winters may negatively impact infaunal bivalve reproduction (confidence?). Invasive species to estuaries have increased, due to temperature warming (medium confidence?), affecting native assemblages and introducing pathogens (confidence?).

## **Acknowledgements**

This review paper was commissioned by the Environment Agency of behalf of the Natural Environment Research Councils (NERC) Living with Environmental Change Programme (LWEC). Some authors also wish to acknowledge the support of the SEACAMS (Sustainable Expansion of the Applied Coastal and Marine Sectors; [www.seacams.ac.uk](http://www.seacams.ac.uk), Grant Number 80366) research project at Bangor University, the Welsh Government, the Higher Education Funding Council for Wales, the Welsh European Funding Office, and the European Regional Development Fund Convergence Programme.

## REFERENCES

- ABPmer and HR Wallingford. 2007. The Estuary-Guide: A website based overview of how to identify and predict morphological change within estuaries. Website prepared for the joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme. November 2007.
- Alexandersson H, Tuomenvirta H, Schmith T, Iden K. 2000. Trends of storms in NW Europe derived from an updated pressure data set. *Climate Research* 14: 71-73.
- Allen RM, Buckley YM, Marshall DJ. 2008. Offspring Size Plasticity in Response to Intraspecific Competition: An Adaptive Maternal Effect across Life-History Stages. *The American Naturalist* 171: 225-237.
- Allan R, Tett S, Alexander L. 2009. Fluctuations in autumn–winter severe storms over the British Isles: 1920 to present. *Int. J. Climatol.* 29: 357–371.
- Anger K. 2003. Salinity as a key parameter in the larval biology of decapod crustaceans *Invertebr. Reprod. Dev.* 43: 29–45.
- Andrews JE, Burgess D, Cave RR, Coombes EG, Jickells TD, Parkes DJ, Turner RK. 2006. Biogeochemical value of managed realignment, Humber estuary, UK. *Sci. Tot. Env.* 371: 19-30.
- Attrill MJ. 2002. A testable linear model for diversity trends in estuaries. *J. Anim. Ecol.* 71: 262–269.
- Attrill MJ, Rundle SD. 2002. Ecotone or ecocline: Ecological boundaries in estuaries. *Est. Coast. Shelf Sci.* 55: 929–936.
- Austin GE, Rehfish MM. 2003. The likely impact of sea level rise on waders (Charadrii) wintering on estuaries. *J. Nat. Conserv.* 11: 43–58.
- Austin J, Zhang L, Jones RN, Durack P, Dawes W, Hairsine P. 2010. Climate change impact on water and salt balances: An assessment of the impact of climate change on catchment salt and water balances in the Murray-Darling Basin, Australia. *Climatic change* 100: 607-631.
- Asmala E, Bowers DG, Autio R, Kaartokallio H, Thomas DN. 2014. Qualitative changes of riverine dissolved organic matter at low salinities due to flocculation. *Journal of Geophysical Research: Biogeosciences* 119: 1919-1933.
- Balvanera P, Pfisterer AB, Buchmann N, He JS, Nakashizuka T, Raffaelli D, Schmid B. 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecology Letters* 9: 1146-56.
- Batstone C, Lawless M, Tawn J, Horsburgh K, Blackman D, McMillan A, Worth D, Laeger S, Hunt T. 2013. A UK best-practice approach for extreme sea-level analysis along complex topographic coastlines. *Ocean Eng.* 71: 28–39.
- Beukema J, Dekker R. 2014. Variability in predator abundance links winter temperatures and bivalve recruitment: Correlative evidence from long-term data in a tidal flat. *Mar. Ecol. Prog. Ser.* 513: 1-15.
- Blaber SJM, Blaber TG. 1980. Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal of Fish Biology* 17: 143-162.
- Bijl W, Flather R, de Ronde JG, Schmith T. 1999. Changing storminess? an analysis of long-term sea level data sets. *Climate Research* 11: 161-172.
- Bjork M, Short F, McLeod E, Beer S. 2008. Managing seagrasses for resilience to climate change. IUCN, Gland, Switzerland.
- Booij MJ. 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. *J. Hydrol.* 303: 176–198.
- Boorman LA. 2003. Saltmarsh Review. An overview of coastal saltmarshes, their dynamic and sensitivity characteristics for conservation and management. JNCC Report No. 334, pp. 114. ISSN 0963-8091.
- Bouma TJ, van Belzen J, Balke T, Zhu Z, Airoidi L, Blight AJ, Davies AJ, Galvan C, Hawkins SJ, Hoggart SPG, Lara JL, Losada IJ, Maza M, Ondiviela B, Skov MW, Strain EM, Thompson RC, Yang S, Zanuttigh B, Zhang L, Herman PMJ. 2014. Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities & steps to take. *Coastal Engineering* 87: 147-157.
- Brown J, Turrell WR, Simpson JH. 1991. Aerial surveys of axial convergent fronts in UK estuaries and the implications for pollution. *Marine Pollution Bulletin* 22: 397-400.
- Brown JM, Bolaños R, Souza AJ. 2014. Process contribution to the time-varying residual circulation in tidally dominated estuarine environments. *Estuaries and Coasts* 37: 1041-1057.

- Bulling MT, Solan M, Dyson KE, Hernandez-Milian G, Luque P, Pierce GJ, Raffaelli D, Paterson DM, White PC. 2008. Species effects on ecosystem processes are modified by faunal responses to habitat composition. *Oecologia* 158: 511-520.
- Burt TP, Ferranti EJS. 2012. Changing patterns of heavy rainfall in upland areas: a case study from northern England. *International Journal of Climatology* 32: 518-532.
- Cameron WM, Pritchard DW. 1963. Estuaries. In MN Hill (editor): *The Sea* vol. 2, John Wiley and Sons, New York, 306-324.
- Cazenave A, Nerem RS. 2004. Present-day sea level change: observations and causes. *Reviews of Geophysics* 42: doi:10.1029/2003RG000139.
- CCRA (UK Climate Change Risk Assessment: Government Report). 2012. ISBN: 9780108511257.
- Chaparro OR, Segura CJ, Osorio SJA, Pechenik JA, Pardo LM, Cubillos VM. 2014. Consequences of maternal isolation from salinity stress for brooded embryos and future juveniles in the estuarine direct-developing gastropod *Crepidatella dilatata*. *Marine Biology* 161: 619-629.
- Charmantier G, Giménez L, Charmantier-Daures M, Anger K. 2002. Ontogeny of osmoregulation, physiological plasticity, and larval export strategy in the grapsid crab *Chasmagnathus granulata* (Crustacea, Decapoda). *Mar. Ecol. Prog. Ser.* 229: 185-194.
- Christierson BV, Vidal J-P, Wade SD. 2012. Using UKCP09 probabilistic climate information for UK water resource planning. *J. Hydrol.* 424-425: 48-67.
- Church JA, White NJ, Coleman R, Lambeck K, Mitrovica JX. 2004. Estimates of the regional distribution of sea level rise over the 1950-2000 period. *Journal of Climate* 17: 2609-2625.
- Church JA, White NJ. 2006. A 20th Century acceleration in global sea level rise. *Geophysical Research Letters* 33: doi:10.1029/2005GL024826.
- Coles SG, Heffernan J, Tawn JA. 1999. Dependence measures for extreme value analysis. *Extremes* 2: 339-365.
- Curriero FC, Patz JA, Rose JB, Lele S. 2001. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American journal of public health* 91: 1194-1199.
- Dalrymple RW. 1992. Tidal depositional systems. In: Walker RG, James NP. (Eds.), *Facies Models: Response to Sea Level Change*. Geological Association of Canada, St. John's, pp. 195-218.
- Davies 1964. A morphogenic approach to world shorelines. *Z. Geomorphol.* 8: 27-42.
- Day JW, Pont D, Hensel PF, Ibañez C. 1995. Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. *Estuaries* 18: 636-647.
- Debernard J, Røed LP. 2008. Future wind, wave and storm surge climate in the Northern Seas: a revisit. *Tellus* 60A: 427-438.
- Dickson ME, Walkden MJ, Hall JW. 2007. Systemic impacts of climate change on an eroding coastal region over the twenty-first century. *Climatic Change* 84: 141-166.
- Dolbeth M, Cardoso PG, Grilo TF, Bordalo MD, Raffaelli D, Pardal MA. 2011. Long-term changes in the production by estuarine macrobenthos affected by multiple stressors. *Est. Coast. Shelf Sci.* 92: 10-18.
- Dronkers J. 1986. Tidal asymmetry and estuarine morphology. *Neth J. Sea Res.* 20:117-131.
- dit Durell SELV, Stillman RA, Caldow RW, McGrorty S, West AD, Humphreys J. 2006. Modelling the effect of environmental change on shorebirds: A case study on Poole Harbour, UK. *Biological Conservation* 131: 459-473.
- Dyer KR. 1997. *Estuaries: A physical introduction*. 2nd edition. John Wiley and Sons/Wiley & Sons: Chichester. ISBN 0-471-9741-4. 195 pp.
- EA. 2011. *The extent of saltmarsh in England and Wales: 2006-2009*. Environment Agency, ISBN: 978-1-84911-233-8.
- Fagherrazzi S, Kirwan ML, Mudd SM, Guntenspergen GR, Temmerman S, D'Alpaos A, van de Koppel J, Rybczyk JM, Reyes E, Craft C, Clough J. 2012. Numerical models of salt marsh evolution: ecological, geomorphic and climatic factors. *Reviews of Geophysics* 50: 2011RG000359.
- Field C, Van Aalst M. 2014.
- Forward RB, Tankersley RA, Rittschof D. 2001. Cues for Metamorphosis of Brachyuran Crabs: An Overview. *American Zoologist* 41: 1108-1122.

- Fowler HJ, Wilby RL. 2010. Detecting changes in seasonal precipitation extremes using regional climate model projections: Implications for managing fluvial flood risk. *Water Resources Research* 46: doi:10.1029/2008WR007636.
- Fowler HJ, Kilsby CG. 2007. Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change* 80: 337-367.
- Fox LR. 1981. Defence and dynamics in plant-herbivore systems. *Am. Zool.* 21: 853-86.
- French, J. (2006). Tidal marsh sedimentation and resilience to environmental change: exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems. *Marine Geology*, 235(1), 119-136.
- Friedman-Huffman DE, Rose JB. 1999. The continuing threat of waterborne pathogens. *Providing Safe Drinking Water in Small Systems: Technology, Operations, and Economics (1999)*: 11.
- Friedrichs CT, Aubrey DG. 1988 Non-linear tidal distortion in shallow well-mixed estuaries: A synthesis. *Est. Coast Shelf. Sci.* 27: 521-545 .
- Frost MT, Leaper R, Mieszkowska N, Moschella P, Murua J, Smyth C, Hawkins SJ. 2004. Recovery of a biodiversity action plan species in northwest England: possible role of climate change, artificial habitat and water quality amelioration. *Sabellaria alveolata*. *English Nature*.
- Fujii T, Raffaelli D. 2008. Sea-level rise, expected environmental changes, and responses of intertidal benthic macrofauna in the Humber estuary, UK. *Mar. Ecol. Prog. Ser.* 371: 23-35.
- Geng Q, Sugi M. 2003. Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols-study with a high-resolution AGCM. *Journal of Climate* 16: 2262-2274.
- Giménez L. 2002. Effects of prehatching salinity and initial larval biomass on survival and duration of development in the zoea 1 of the estuarine crab, *Chasmagnathus granulata*, under nutritional stress. *J. Exp. Mar. Biol. Ecol.* 270: 93-110.
- Giménez L. 2006. Phenotypic links in complex life cycles: conclusions from studies with decapod crustaceans. *Int. Comp. Biol.* 46: 615-622.
- Giménez L, Anger K, Torres G. 2004. Linking life history traits in successive phases of a complex life cycle: effects of larval biomass on early juvenile development in an estuarine crab *Chasmagnathus granulata*. *Oikos* 104: 570-580.
- Giménez L, Anger K. 2003. Larval performance in an estuarine crab, *Chasmagnathus granulata*, is a consequence of both larval and embryonic experience. *Mar. Ecol. Prog. Ser.* 249: 251-264.
- González-Ortegón E, Blasco J, Le Vay L, Giménez L. 2013. A multiple stressor approach to study the toxicity and sub-lethal effects of pharmaceutical compounds on the larval development of a marine invertebrate. *Journal of Hazardous Materials* 263: 233-238.
- González-Ortegón E, Giménez L. 2014. Environmentally mediated phenotypic links and performance in larvae of a marine invertebrate. *Mar. Ecol. Prog. Ser.* 502: 185-195.
- Grinsted A, Moore JC, Jevrejeva S. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100AD. *Climate Dynamics* 34: 461-472.
- Gubbay S, Earll R (2010) Assessing the vulnerability of marine biodiversity in Wales to the impacts of climate change. Workshop report. CCW contract Science Report no 934, Countryside Council for Wales, Bangor.
- Hannaford, J. 2015. Climate-driven changes in UK river flows A review of the evidence. *Progress in Physical Geography* 39: 29-48.
- Hannaford J, Buys G. 2012. Seasonal trends in UK river flow regimes and extremes in the UK. *Journal of Hydrology* 475: 158-174.
- Hawkes PJ. 2008. Joint probability analysis for estimation of extremes. *Journal of Hydraulic Research* 46: 246-256.
- Hawkins SJ, Moore PJ, Burrows MT, Poloczanska E, Mieszkowska N, Herbert RJH, Jenkins SR, Thompson RC, Genner MJ, Southward AJ. 2008. Complex interactions in a rapidly changing world: responses of rocky shore communities to recent climate change. *Climate Research* 37: 123-133.
- Hawkins SJ, Sugden HE, Mieszkowska N, Moore PJ, Poloczanska E, Leaper R, Herbert RJH, Genner MJ, Moschella PS, Thompson RC, Jenkins SR, Southward AJ, Burrows MT. 2009. Consequences of climate-driven biodiversity changes for ecosystem functioning of North European rocky shores. *Mar. Ecol. Prog. Ser.* 396: 245-259.

- Hanson S, Nicholls R, Ranger N, Hallegatte S, Corfee-Morlot J, Herweijer C, Chateau J. 2011. A global ranking of port cities with high exposure to climate extremes. *Clim. Change* 104: 89-111.
- Hiddink JG and Hofstede RT. 2008. Climate induced increases in species richness of marine fishes. *Global Change Biology* 14: 453–460.
- Hetland RD, Geyer WR. 2004. An idealized study of the structure of long, partially mixed estuaries. *J. Phys. Oceanogr.* 34: 2677-2691.
- Hough AR, Naylor E. 1991. Field studies on retention of the planktonic copepod *Eurytemora affinis* in a mixed estuary. *Mar. Ecol. Prog. Ser.* 76: 115-122.
- Howlett ER, Bowers DG, Malarkey J, Jago CF. 2015. Stratification in the presence of an axial convergent front: Causes and implications. *Est. Coast. Shelf Sci.* 161: 1-10.
- Howard T, Lowe J, Horsburgh K. 2010. Interpreting century-scale changes in North Sea storm surge climate derived from coupled model simulations. *Journal of Climate* 23: 6234–6247.
- Howsen C. 2009. Intertidal SAC monitoring, Camarthen Bay and Estuaries SAC. CCW Marine Monitoring Report no 79, Countryside Council for Wales, Bangor.
- Huang G, Zhou J, Lin B, Chen Q, Falconer R. 2013. Distributed Numerical Hydrological and Hydrodynamic Modelling for Large River Catchment. *Proceedings of the 35th IAHR World Congress*: 2420-2431.
- IPCC. 2007. Synthesis Report: Contribution of Working Groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change, IPCC Geneva, 104pp.
- IPCC. 2013. Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. Cambridge University Press, United Kingdom and New York, NY, USA
- Ittekkot V. 1988. Global trends in the nature of organic matter in river suspensions, *Nature* 332: 436-438.
- Jackson AC, McIlvenny J. 2011. Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts. *Journal of Experimental Marine Biology and Ecology* 400: 314-321.
- Jarvie HP, Jickells TD, Skeffington RA, Withers PJA. 2012. Climate change and coupling of macronutrient cycles along the atmospheric, terrestrial, freshwater and estuarine continuum. *Sci. Total Environ.* 434: 252-258.
- Jenkins GJ, Perry MC, Prior MJO. 2008. The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, UK.
- Jenkins G, Murphy J, Sexton D, Lowe J. 2009. UK Climate Projections: Briefing Report. Met Office Hadley Centre. <http://ukclimateprojections.defra.gov.uk/>.
- Jenkins GP, Spooner D, Conron S, Morrongiello JR. 2015. Differing importance of salinity stratification and freshwater flow for the recruitment of apex species of estuarine fish. *Mar. Ecol. Prog. Ser.* 523: 125-144.
- Jensen N, Allen RM, Marshall DJ. 2014. Adaptive maternal and paternal effects: gamete plasticity in response to parental stress. *Functional Ecology* 28: 724-733.
- Jevrejeva S, Moore JC, Grinsted A. 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophysical Research Letters* 37: doi:10.1029/2010GL042947.
- Jickells T, Andrews J, Samways G, Sanders R, Malcolm S, Sivyer D, Parker R, Nedwell D, Trimmer M, Ridgway J. 2000. Nutrient fluxes through the Humber estuary-Past, present and future. *AMBIO: A Journal of the Human Environment* 29: 130-135.
- Jones D, Bain V, Dawson S, Watt T. 2011. Assessing the vulnerability of marine biodiversity in Wales to the impacts of climate change. Workshop report. CCW contract Science Report no 934, Countryside Council for Wales, Bangor.
- Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. 2013. An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology* 33: 1178-1194.
- Jonkman SN, Maaskant B, Boyd E, Levitan ML. 2009. Loss of life caused by the flooding of New Orleans after Hurricane Katrina: Analysis of the relationship between flood characteristics and mortality. *Risk Analysis* 29: 676-698.

- Kaiser MJ, Attrill MJ, Jennings S, Thomas DN, Barnes DKA, Brierley AS, Hiddink JG, Kaartokallio H, Polunin NVC, Raffaelli DG. 2005. *Marine Ecology, processes, systems and impacts*. Oxford University Press, Oxford.
- Keef C, Svensson C, Tawn JA. 2009. Spatial dependence in extreme river flows and precipitation for Great Britain. *Journal of Hydrology* 378: 240-252.
- Kennish MJ. 2002. Environmental threats and environmental future of estuaries. *Environmental Conservation* 29: 78-107.
- Kimmerer WJ. 2002. Effects of freshwater flow on abundance of estuarine organisms: Physical effects or trophic linkages? *Mar. Ecol. Prog. Ser.* 243: 39-55.
- King DA. 2004. Climate change science: adapt, mitigate, or ignore? *Science* 303: 176-177.
- Kingsford MJ, Leis JM, Shanks A, Lindeman KC, Morgan SG, Pineda J. 2002. Sensory environments, larval abilities and local self-recruitment. *Bulletin of Marine Science*, 70: 309-340.
- Kirby R. 2010. Distribution, transport and exchanges of fine sediment, with tidal power implications: Severn Estuary, UK. *Marine pollution bulletin* 61: 21-36.
- Kranenburg C. 1986. A time scale for long-term salt intrusion in well-mixed estuaries. *J. Phys. Oceanogr.* 16: 1329-1332.
- Lanzoni S, Seminara G. 1998. On tide propagation in convergent estuaries. *J Geophys. Res.* 103: 30793-30812.
- Lawrence AJ, Soame JM. 2004. The effects of climate change on the reproduction of coastal invertebrates. *Ibis* 146: 29-39.
- Lee SY, Dunn RJK, Young RA, Connolly RM, Dale PER, Dehayr R, Lemckert CJ, Mckinnon S, Po Well B, Teasdale PR, Welsh DT. 2006. Impact of urbanization on coastal wetland structure and function. *Austral Ecology* 31: 149-163.
- Lenihan HS, Peterson CH, Kim SL, Conlan KE, Fairey R, McDonald C, Grabowski JH, Oliver JS. 2003. Variation in marine benthic community composition allows discrimination of multiple stressors. *Mar. Ecol. Prog. Ser.* 261: 63-73.
- Lewis M, Horsburgh K, Bates P, Smith R. 2011. Quantifying the uncertainty in future coastal flood risk estimates for the UK. *Journal of Coastal Research* 27: 870-881.
- Lewis M, Bates P, Horsburgh K, Neal J, Schumann G. 2013. A storm surge inundation model of the northern Bay of Bengal using publicly available data. *Quarterly Journal of the Royal Meteorological Society* 139: 358-369.
- Lipp EK, Kurz R, Vincent R, Rodriguez-Palacios C, Farrah SR, Rose JB. 2001. The effects of seasonal variability and weather on microbial fecal pollution and enteric pathogens in a subtropical estuary. *Estuaries* 24: 266-276.
- Lipp EK, Huq A, Colwell R. 2002. Effects of global climate on infectious disease: The cholera model. *Clin. Microbiol. Rev.* 15: 757-770.
- Lowe JA, Gregory JM. 2006. The effects of climate change on storm surges around the United Kingdom. *Philosophical Transactions of the Royal Society of London A* 363: 1313-1328.
- Lowe JA, Gregory JM, Flather R. 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm model driven by the Hadley Centre climate models. *Climate Dynamics* 18: 179-188.
- Lowe JA, Howard TP, Padaens A, Tinker J, Holt J, Wakelin S, Milne G, Leake J, Wolf J, Horsburgh K. 2009. UK Climate change projections science report: Marine and coastal projections. Met Office, Hadley Centre, Exeter.
- MacCready P. 1998. Estuarine adjustment to changes in river flow and tidal mixing. *J. Phys. Oceanogr.* 29: 708-726.
- Maier G, Glegg, Gillian A, Tappin AD, Worsfold PJ. 2009. The use of monitoring data for identifying factors influencing phytoplankton bloom dynamics in the eutrophic Taw Estuary, SW England. *Marine Pollution Bulletin* 58: 1007-1015.
- Malham SK, Rajko-Nenow P, Howlett E, Tuson KE, Perkins TL, Pallett DW, Wang H, Jago CF, Jones DL, McDonald JE. 2014. The interaction of human microbial pathogens, particulate material and nutrients in estuarine environments and their impacts on recreational and shellfish waters. *Environ. Sci.: Processes Impacts* 16: 2145.

- Marani M, D'Alpaos A, Lanzoni S, Carniello L, Rinaldo A. 2007. Biologically-controlled multiple equilibria of tidal landforms and the fate of the Venice lagoon. *Geophys. Res. Lett.* 34: L1140
- Marques A, Nunes ML, Moore SK, Strom MS. 2010. Climate change and seafood safety: Human health implications. *Food Research International* 43: 1766-1779.
- Maskell J, Horsburgh K, Lewis M, Bates P. 2013. Investigating River-Surge Interaction in Idealised Estuaries. *Journal of Coastal Research* 30: 248-259.
- McCabe GJ, Clark MP, Serreze MC. 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. *Journal of Climate* 14: 2763-2768.
- McInnes KL, Walsh KJE, Hubbert GD, Beer T. 2003. Impact of sea-level rise and storm surges on a coastal community. *Natural Hazards* 30: 187-207.
- McLachlan A, Brown A. 2006. *The ecology of sandy shores*. Academic Press, Amsterdam
- McMellor S, Underwood GJC. 2014. Water policy effectiveness: 30 years of change in the hypernutrified Colne Estuary, England. *Mar. Pollut. Bull.* 81: 200-209.
- McMichael AJ, Woodruff RE, Hales S. 2006. Climate change and human health: Present and future risks. *Lancet* 367: 859-869.
- Menendez M, Woodworth PL. 2010. Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *Journal of Geophysical Research* 115: C10011.
- Mieszewska N, Firth L, Bentley M. 2013. Impacts of climate change on intertidal habitats. *Marine climate change impacts partnership: Scientific review 2013*: 180-190.
- Milne FD, Dong P, Davidson M. 2012. Natural variability and anthropogenic effects on the morphodynamics of a beach-dune system at Montrose Bay, Scotland. *J. Coast. Res.* 28: 375-388.
- Moksnes P-O, Tryman HCK, Hordoir R, Jonsson PR. 2014. Larval behavior and dispersal mechanisms in shore crab larvae (*Carcinus maenas*): Local adaptations to different tidal environments? *Limnology and Oceanography* 59: 588-602.
- Moore RD, Wolf J, Souza AJ, Flint SS. 2009. Morphological evolution of the Dee Estuary, Eastern Irish Sea, UK: A tidal asymmetry approach. *Geomorphology* 103: 588-596.
- Morgan B, Rate AW, Burton ED. 2012. Water chemistry and nutrient release during the resuspension of FeS-rich sediments in a eutrophic estuarine system. *Sci. Tot. Env.* 432: 47-56.
- Murphy DM, Forster PM. 2010. On the accuracy of deriving climate feedback parameters from correlations between surface temperature and outgoing radiation. *Journal of climate* 23: 4983-4988.
- Murray AB, Knaapen MAF, Tal M, Kirwan ML. 2008. Biomorphodynamics: Physical-biological feedbacks that shape landscapes. *Water Resour. Res.* 44: W11301.
- Najjar RG, Pyke CR, Adams MB, Breitburg D, Hershner C, Kemp M, Howarth R, Mulholland MR, Paolisso M, Secor D, Sellner K, Wardrop D, Wood R. 2010. Potential climate-change impacts on the Chesapeake Bay. *Est. Coast. Shelf Sci.* 86: 1-20.
- Herman PMJ, Middelburg JJ, Van De Koppel J, Heip CHR. 1999. Ecology of estuarine macrobenthos. *Advances in Ecological Research; Estuaries Book Series: Advances in Ecological Research* 29: 195-289
- Nicholls RJ, Hoozemans FMJ, Marchand M. 1999. Increasing flood risk and wetland losses due to global sea-level rise: Regional and global analyses. *Global Environmental Change-Human and Policy Dimensions* 9: S69-S87.
- Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, de Gusmão D, Hinkel J. 2011. Sea-level rise and its possible impacts given a 'beyond 4 degrees C world' in the twenty-first century. *Phil. Trans. R. Soc. A* 369: 161-181.
- Nicholls RJ, Townend IH, Bradbury AP, Ramsbottom D, Day SA. 2013. Planning for long-term coastal change: Experiences from England and Wales. *Ocean Engineering* 71: 3-16.
- Nixon S, Oviatt C. 1986. Nutrients and the productivity of estuarine and coastal marine ecosystems. *J. Limnol. Soc. Southern Africa* 12: 1-2.
- Nunes RA, Simpson JH. 1985. Axial convergence in a well-mixed estuary. *Est. Coast. Shelf Sci.* 20: 637-649.
- Orford JD, Pethick JS. 2006 Challenging assumptions of coastal habitat formation in the 21st century. *Earth Surface Processes and Landforms* 31: 1625-42.

- Paciorek CJ, Risbey JS, Ventura V, Rosen RD. 2002. Multiple indices of Northern Hemisphere cyclone activity, winters 1949-99. *Journal of Climate* 15: 1573-1590.
- Palmer MR, Polton JA. 2011. A strain induced freshwater pump in the Liverpool Bay ROFI. *Ocean Dynamics* 61: 1905-1915.
- Perciasepe R. 1998. EPA: Ocean protection challenges - 'Daunting but manageable'. *Sea Technology* 39: 25-29.
- Philippart CJM, van Aken HM, Beukema JJ, Bos OG, Cadée GC, Dekker R. 2003. Climate-related changes in recruitment of the bivalve *Macoma balthica*. *Limnol Oceanogr.* 48: 2171–2185.
- Pingree RD, Griffiths DK. 1979. Sand transport paths around the British Isles resulting from M2 and M4 tidal interactions. *Journal of the Marine Biological Association of the United Kingdom* 59: 497-513.
- Power M, Attrill MJ, Thomas RM. 2000. Environmental factors and interactions affecting the temporal abundance of juvenile flatfish in the Thames Estuary. *J Sea Res* 43: 135-149.
- Prandle D. 2009. *Estuaries: Dynamics, mixing, sedimentation, and morphology*. University Press, Cambridge.
- Prime T, Brown JM, Plater AJ. 2015. Physical and economic impacts of sea-level rise and low probability flooding events on coastal communities. *PLOS ONE* 10: e0117030.
- Prudhomme C, Davies H, 2009. Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 2: future climate. *Clim. Change* 93: 197-222.
- Prudhomme C, Dadson S, Morris D, Williamson J, Goodsell G, Crooks S, Boelee L, Davies H, Buys G, Lafon T, Watts G. 2012. Future flows Climate: An ensemble of 1-km climate change projections for hydrological application in Great Britain. *Earth Syst. Sci. Data* 4: 143-148.
- Przeslawski R, Byrne M, Mellin C. 2015. A review and meta-analysis of the effects of multiple abiotic stressors on marine embryos and larvae. *Global Change Biology* 21: 2122-2140.
- Pye K, Blott SJ. 2006. Coastal processes and morphological change in the Dunwich-Sizewell area, Suffolk, UK. *J. Coast. Res.* 22: 453-473.
- Pye K, Blott SJ. 2014. The geomorphology of UK estuaries: The role of geological controls, antecedent conditions and human activities. *Est. Coast. Shelf Sci.* 150: 196-214.
- Quinn ND, Bates PD, Siddall M. 2013. The contribution to future flood risk in the Severn Estuary from extreme sea level rise due to ice sheet mass loss. *J. Geo. Res.* 118: 5887–5898.
- Quinn ND, Lewis M, Wadey M, Haigh I. 2014. Assessing the variability in extreme storm-tide time-series for coastal flood risk assessment. *J. Geo. Res.* 119: 4983-4998.
- Queiroga H, Blanton J. 2005. Interactions between behaviour and physical forcing in the control of horizontal transport of decapod crustacean Larvae. *Advances in Marine Biology* 47: 107-214.
- Rabalais NN, Turner RE, Diaz RJ, Justic D. 2009. Global change and eutrophication of coastal waters. *ICES J. Mar. Sci.* 66: 1528-1537.
- Rahmstorf S. 2007. A semi-empirical approach to projecting future sea level rise, *Science* 315: 368–370
- Rey F, Neto GMS, Rosa R, Queiroga H, Calado R. 2015. Laboratory trials reveal that exposure to extreme raining events prior to metamorphosis affect the post-settlement performance of an estuarine crab. *Est. Coast. Shelf Sci.* 154: 179-183.
- Robins PE, Davies AG. 2010. Morphological controls in sandy estuaries: the influence of tidal flats and bathymetry on sediment transport, *Ocean Dynamics* 60: 503-517.
- Robins PE, Elliott AJ. 2009. The internal tide of the Gareloch, A Scottish fjord. *Estuarine, Coastal and Shelf Science* 81: 130-142.
- Robins PE, Neill SP, Giménez L. 2012 A numerical study of marine larval dispersal in the presence of an axial convergent front. *Estuarine, Coastal and Shelf Science* 100: 172-185.
- Robins PE, Lewis MJ, Simpson JH, Howlett ER, Malham SK. 2014. Future variability of solute transport in a macrotidal estuary, *Estuarine, Coastal and Shelf Science* 151: 88-99.
- Robins PE, Neill SP, Lewis MJ, Ward SL. 2015. Characterising the spatial and temporal variability of the tidal-stream energy resource over the northwest European shelf seas. *Applied Energy* 147: 510-522.
- Rose JB, Epstein PR, Lipp EK, Sherman BH, Bernard SM, Patz JA. 2001. Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. *Environmental Health Perspectives* 109: 211-221.

- Rose JB. 2005. Identification and characterization of biological risks for water. *Management of Intentional and Accidental Water Pollution*. Springer Netherlands, 2006. 85-101.
- Rossington SK, Nicholls RJ, Knaapen MAF, Wang ZB. 2007. Morphological behaviour of UK estuaries under conditions of accelerating sea-level rise. In, *River, coastal and estuarine morphodynamics*, Enchede, Netherlands.
- Samuels PG, Burt N. 2002. A new joint probability appraisal of flood risk, *Proceeding of International Civil Engineering – Water and Marine Engineering* 154: 109-115
- Senior CA, Jones RG, Lowe JA, Durman CF, Hudson D. 2002. Predictions of extreme precipitation and sea-level rise under climate change. *Phil. Trans. R. Soc.* 360: 1301-1311.
- Shanks A. 1995. Mechanisms of cross-shelf dispersal of larval invertebrates and fish, p. 323–367. In L. McEdward [ed.], *Ecology of marine invertebrate larvae*. CRC Press.
- Shennan I, Horton B. 2002. Holocene land and sea level changes in Great Britain. *Journal of Quaternary Science* 17: 511-526.
- Shennan I, Milne G, Bradley S. 2012. Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *Journal of Quaternary Science* 27: 64-70.
- Short FT, Wyllie-Echeverria S. 1996. Natural and human-induced disturbance of seagrasses. *Environmental Conservation* 23: 17-27
- Simpson JH, Vennell R, Souza AJ. 2001. The salt fluxes in a tidally energetic estuary. *Estuar. Coast. Shelf Sci.* 52: 131-142.
- Smith PM, Dixon ROD, Cochrane MP. 2002. *Plant life of Edinburgh and the Lothians*. Edinburg University Press, Edinburgh.
- Smith A, Bates P, Freer J, Wetterhall F. 2013. Future flood projection: Investigating the application of climate models across the UK. *Hydrological Process* 28: 2810-2823.
- Sokolova IM, Portner HO. 2007. The role of thermal environment in stress adaptation and tolerance: Integration of multiple stressors. *Journal of Thermal Biology* 32: 117.
- Soulsby RL. 1997. *Dynamics of marine sands: A manual for practical applications*. Telford, London, p 249.
- Stachel B, Götz R, Herrmann T, Krüger F, Knoth W, Pöpke O, Rauhut U, Reincke H, Schwartz R, Steeg E, Uhlig S. 2004. The Elbe flood in August 2002 - Occurrence of polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans (PCDD/F) and dioxin-like PCB in suspended particulate matter (SPM), sediment and fish. *Water Sci. Technol.* 50: 309-16.
- Statham PJ. 2012. Nutrients in estuaries – An overview and the potential impacts of climate change. *Science of the Total Environment* 434: 213-227.
- Struyf E, Damme SV, Meire P. 2004. Possible effects of climate change on estuarine nutrient fluxes: A case study in the highly nitrified Schelde estuary (Belgium, The Netherlands). *Estuar. Coast. Shelf Sci.* 52: 131-142.
- Svensson C, Jones DA. 2002. Dependence between extreme sea surge, river flow and precipitation in eastern Britain. *International Journal of Climatology* 22: 1149-1168.
- Svensson C, Jones DA. 2004. Dependence between sea surge, river flow and precipitation in south and west Britain. *Hydrology and Earth System Sciences* 8: 973-992.
- Svensson C, Jones DA. 2006. Joint probability: Dependence between sea surge, river flow and precipitation: A study in south west Britain. R&D Technical Report FD2308/TR3, DEFRA.
- Tappin AD. 2002. An examination of the fluxes of nitrogen and phosphorus in temperate and tropical estuaries: Current estimates and uncertainties. *Estuar. Coast. Shelf Sci.* 55: 885-901.
- Thompson RC, Crowe TP, Hawkins SJ. 2002. Rocky intertidal communities: Past environmental changes, present status and predictions for the next 25 years. *Environmental Conservation* 29: 168-191.
- Torres G, Giménez L, Anger K. 2011. Growth, tolerance to low salinity, and osmoregulation in decapod crustacean larvae. *Aquatic Biology* 12: 249-260.
- Uncles RJ. 2003. From catchment to coastal zone: Examples of the application of models to some long-term problems. *Science of the Total Environment* 314: 567-588.
- Uncles RJ, Stephens JA, Harris C. 2014. Freshwater, tidal and wave influences on a small estuary. *Estuar. Coast. Shelf Sci.* 150: 252-261.
- Van-Rijn L. 1993. *Principles of sediment transport in rivers, estuaries, and coastal seas*. Amsterdam, Aqua Publications.

- Vaquer-Sunyer R, Duarte CM. 2011. Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. *Global Change Biology* 17: 1788–1797.
- Vasconcelos RP, Reis-Santos P, Costa MJ, Cabral HN. 2011. Connectivity between estuaries and marine environment: Integrating metrics to assess estuarine nursery function. *Ecol. Indic.* 11: 1123-1133.
- Wadey MP, Haigh ID, Brown JM. 2014. A century of sea level data and the UK's 2013/14 storm surges: An assessment of extremes and clustering using the Newlyn tide gauge record. *Ocean Science Discussions* 11: 1995-2028.
- Wakelin SL, Woodworth PL, Flather RA, Williams JA. 2003. Sea level dependence on the NAO over the NW European Continental Shelf. *Geophysical Research Letters* 30: doi:10.1029/2003GL017041.
- Watts G, Battarbee R, Bloomfield JP, Crossman J, Daccache A, Durance I, Elliott JA, Garner G, Hannaford J, Hannah D, Hess T, Jackson C, Kay A, Kernan M, Knox J, Mackay J, Monteith D, Ormerod S, Rance J, Stuart M, Wade A, Wade S, Weatherhead K, Whitehead P, Wilby R. 2015. Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography* 39: 6-28.
- Weisse R, Bellafiore D, Menéndez M, Méndez F, Nicholls RJ, Umgiesser G, Willems P. 2014. Changing extreme sea levels along European coasts. *Coastal Engineering* 87: 4-14.
- Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade AJ. 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* 54: 101-123.
- Wolf J, Brown JM, Howarth MJ. 2011. The wave climate of Liverpool Bay - observations and modelling. *Ocean Dynamics* 61: 639-655.
- Woodworth PL, Blackman DL. 2004. Evidence for systematic changes in extreme high water since the mid-1970s. *Journal of Climate* 17: 1190-1197.
- Woodworth PL, Tsimplis MN, Flather RA, Shennan I. 1999. A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysical Journal International* 136: 651-670.
- Woodworth PL, Teferle FN, Bingley RM, Shennan I, Williams SD. 2009. Trends in UK mean sea level revisited. *Geophysical Journal International* 176: 19-30.
- Woth K, Weisse R, von Storch H. 2006. Climate change and North Sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models. *Ocean Dynamics* 56: 3-15.
- Yang ZQ, Wang TP, Voisin N, Copping A. 2015. Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science* 156: 19-30.
- Zhang KQ, Douglas BC, Leatherman SP. 2004. Global warming and coastal erosion. *Climatic Change* 64: 41-58.
- Zheng F, Westra S, Sisson SA. 2013. Quantifying the dependence between extreme rainfall and storm surge in the coastal zone. *Journal of Hydrology* 505: 172-187.
- Zheng F, Westra S, Leonard M, Sisson SA. 2014. Modeling dependence between extreme rainfall and storm surge to estimate coastal flooding risk. *Water Resources Research* 50: 2050-2071.