Managing estuaries under a changing climate

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Abstract

Estuaries are globally important zones for urban, recreational and commercial activities as well as supporting a range of habitats and species of significant ecological importance. The role of estuaries is recognised by the legislative framework that has been developed to protect and manage these areas as well as those species and resources in adjoining habitats. However, estuaries worldwide are subject to a number of major threats, including increasing industrialisation and urbanisation, increasing resource scarcity notably for space and energy, and the impacts of climate change, sea-level rise and related increases in vulnerability and decreases in resilience. In addition to local pressures, climate change is now increasingly recognised as having a range of severe impacts on estuarine ecosystem functions and services, but current legislation and associated management may not necessarily be wholly appropriate to deal with these longer-term changes. Here we consider how the current legislation and management addresses the potential impacts of climate change on a large estuarine system. Alongside a set of recommendations, we emphasise that the implementation of governance

instruments needs to be underpinned by continued monitoring, improved modelling and enhanced predictive capabilities and integration and collaboration across management levels.

Highlights

- We provide a review of the potential impacts from climate change on estuaries.
- The current management measures for managing these impacts are presented.
- Future approaches to legislation are recommended.
- A reference of impacts and management of coastal and estuarine environments is provided.

Keywords

Climate change; Estuary; Management; Legislation

1. Introduction

Estuaries cover over 400,000 km of the global coastline (Dürr *et al.*, 2011) and are dynamic environments that form a transition zone between rivers, the open sea and terrestrial systems. They are most commonly defined as ‘‘a semi-enclosed coastal body of water which is connected to the sea either permanently or periodically, has a salinity that is different from that of the adjacent open ocean due to freshwater inputs, and includes a characteristic biota” and being “transitional waters, a term which includes lagoons, rias, etc.” (Elliot and Whitfield, 2011), with more specific classifications often used to describe the characteristics of individual systems (Potter at al., 2010; Whitfield and Elliott, 2011). Their transitional nature requires that no single definition is suitable and legal, geomorphic, ecological and societal definitions are often required (Elliott and McLusky 2002). Given their location, connections and resources, estuaries are hotspots for many urban, industrial and recreational activities, which can provide a significant contribution to the local and regional economy (Lonsdale *et al.*, 2015; Elliott and Whitfield, 2011). They also support a large but not necessarily diverse range of flora and fauna and many hold statutory environmental designations to protect their unique ecological characteristics.

Estuaries are increasingly regarded as facing three major threats worldwide: increasing industrialisation and urbanisation, increasing resource scarcity notably for both space and energy, and the impacts of climate change (Wolanski et al, 2019). Many of the activities and pressures within these categories are *endogenic,* i.e. occurring inside the estuarine area and where the causes and consequences of change, such as navigation and fisheries, need to be managed. However, they are also subject to *exogenic unmanaged pressures,* the causes of which originate within the wider catchment (e.g. abstraction) or are globally mediated (e.g. climate change) and where it is the consequences (not sources) inside the estuary that need to be managed (Elliott, 2011). These pressures affect both the natural and socio-economic systems and they therefore require a robust and defendable risk assessment and risk management framework to be managed sustainably (Cormier *et al.*, 2019; Elliott, *et al.*, 2014).

Sustainably managing estuarine environments is complex as there are numerous managers, planners, statutory bodies, industries and stakeholders that are required to meet international, national and local obligations (Boyes and Elliott, 2015; Lonsdale *et al.*, 2015). There is also a need for transdisciplinary and holistic approaches covering governance, socio-economics, physical sciences and ecology (Elliott, 2014). The overall aim of each management layer is to sustainably manage these environments and where possible, reduce pressures on them in order to prevent state change and to lessen the impacts on environmental and human receptors (Barnard and Elliott 2015; Lonsdale *et al.*, 2015; Gross, 2003; Barbier *et al.*, 2011; Townsend *et al.*, 2011).

This study identifies the relevant impacts from climate change, relevant legislation and outlines strategic improvements for future estuarine management to counter or accommodate the potential effects of climate change on estuarine environments. Furthermore, we highlight how current management is successfully addressing these issues and where improvements could be made. Whilst the Humber Estuary (northeast England) is used as the primary case study, the themes and recommendations are applicable globally.

2. Climate Change

Understanding the impact that climate change has on these transitional systems is crucial to developing management strategies that will be sustainable over the long-term (Donovan *et al.*, 2013; Jones *et al.*, 2013; Mieszkowska *et al.*, 2013). There are many recognised impacts and similarities of climate change worldwide which increase the vulnerability and decrease the resilience of estuaries (Wolanski *et al.*, 2019). Elliott *et al.* (2015) summarises a conceptual framework relating to all the coastal effects of climate change and Robins *et al.*, (2015), Robins (2019) and Ducrotoy *et al.* (2019) focus on the natural science aspects within estuaries. Some of the most prominent threats to estuarine environments highlighted within this literature are related to: increased carbon dioxide, sea level rise, and changes in temperature (IPCC, 2013). The predicted impact these effects may have on estuarine environment, including the socio-economic impacts, is explored below.

2.1 Increased Carbon Dioxide

Increased atmospheric $C0_2$ is a primary cause of anthropogenic climate change and can lead to other effects, such as ocean acidification. The oceans have absorbed 27-34% of the CO_2 from the atmosphere since the industrial revolution (Turley et al., 2009) and consequently, ocean surface water pH has decreased by 0.1 units; further decreases of approximately 0.3-04 units by 2100 are predicted (Feely et al., 2010).

Ocean acidification is likely to have direct and indirect impacts on the reproduction, growth and survival of commercially exploited fish stocks (Dixon et al., 2009; Munday et al., 2009; 2010; Cripps et al., 2011). Series of meta-analyses have indicated that whilst some species may be affected on their physiological and behavioural responses (including development, viability and mortality rates), others may potentially benefit from such change in pH conditions (Kroeger et el., 2012; 2013; Wittman and Portner, 2013; Brodie et al., 2014).

Changes in pH and water chemistry are likely to impact marine organisms from plankton, to carbonate utilising species (Orr *et al.*, 2005), to fish species. The timing of life stages such as migration and spawning may be altered due the physiochemical properties of the water systems. Such changes may even become a barrier to migration if conditions are significantly outside of their tolerances (Munday *et al.*, 2010, Klemetsen *et al.*, 2003; Maitland, 2003; McCormick *et al.*, 1998).

2.2 Sea Level Rise

According to the IPCC's Fifth Assessment Report (AR5), sea level is predicted to rise by 0.26-0.82 m by 2100 relative to 1986-2005 levels (IPCC, 2013). Sea level rise is likely to alter the hydrodynamics and tidal characteristics in these environments, affecting estuarine circulation patterns, sediment transport processes, erosion-deposition cycles and flood and erosion potentials along the banks (Passeri et al., 2015).

The natural response of a marine systems to sea level rise is to migrate landward and either erode the shoreline or submerge previous intertidal habitats, extending the subtidal area (Passeri et al., 2015). This alters the shape and location of the shoreline, resulting in the loss of land or an increased risk of flooding in vulnerable locations; this is of particular concern where people and assets are likely to be affected. The ability of a system to change naturally in this way is influenced by the presence of fixed boundaries or engineered structures; where these prevent a shoreline migrating, 'Coastal Squeeze' occurs (Andrews et al., 2006). Coastal squeeze can subsequently lead to a decrease in intertidal and increase in subtidal habitats.

Changes in sea level could also lead to increased saline incursions into estuaries, through the penetration of saline waters further upstream. This may affect the fish and benthic species that migrate and inhabit these areas, alongside other determining factors such as substratum type and food web interactions. Saline intrusion could also alter the chemical properties of estuarine environments leading to increased nutrient release into the estuarine waters, freshwater and groundwater reserves (Robins *et al.*, 2016), potentially leading to eutrophication. Eutrophication is defined as "*the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned, and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients* ….", (OSPAR, 2009) which can cause algal mats, harmful algal blooms, fish kills, hypoxia and benthic changes in these waters (e.g. de Jonge and Elliott, 2001). This may also affect the fish and benthic species that migrate and inhabit these areas, alongside other determining factors such as substratum type and food web interactions. However, given the variability of salinity species in estuaries, the effect of salinity on estuarine species is currently unknown (Elliott *et al.*, 2016; Waterkeyn *et al.*, 2011; Little *et al.*, in press).

2.3 Changes in Temperature

Due to the increase in greenhouse gases into the atmosphere, the sea surface temperature has shown an overall global increase, predominantly within the upper 700 m of the ocean (Hoegh-Guldberg *et al.*, 2014). Changes to oceanic temperatures can affect all components of my cryosphere, contribute to sea level rise, shift storm tracks, alter circulation patterns and affect the transport of nutrients around the oceans (Hoegh-Guldberg *et al.*, 2014).

Increased oceanic temperatures can expand the area suitable for various species to habituate and cause others to retreat (Edwards *et al.* 2013; Mieszkowska *et al.*, 2013; Pinnegar *et al.*, 2013; Elliott *et al.*, 2015). Changes in water chemistry and temperature may impact the species timing for migrating and spawning or be a barrier to migration if conditions are outside of their tolerances (Klemetsen *et al.*, 2003; Maitland, 2003; McCormick *et al.*, 1998). Conversely, non-native species may increase their distribution due to conditions becoming more favourable to their establishment, i.e. changes in sea temperature.

Due to increases and improvements of technologies, there could be an increase in the introduction of non-native species due to bio-fouling and ballast water transport (Cook *et al.*, 2013). The growth of these species could change the structure and function of the ecosystem and consequently, the goods and services the ecosystem provides (Sheahan *et al.*, 2013). For example, the establishment of the Chinese Mitten Crab (*Eriocheir sinensis*) in the Humber Estuary, which burrows into and undermines estuarine seawalls, has led to increased erosion and failure of these structures (Bentley, 2011; Gilbey *et al.*, 2008).

An increase in sea temperature can affect the metabolic rate of species (Pankhurst and Munday, 2011; Pörtner and Knust, 2007). Most marine and estuarine species have well-defined temperature thresholds for maturation and spawning (Rasmussen, 1973) and climate change induced temperature changes in any given area. This change in the timing of reproduction can affect the higher trophic level species which prey on these seasonally reproducing species (Lonsdale *et al.*, 2013; Nunn *et al.*, 2008; Klemetsen *et al.*, 2003; Maitland, 2003; McCormick *et al.*, 1998).

2.4 Socioeconomics

The people and industries found along the coastlines of estuarine environments will become increasingly exposed to the effects of climate change. As sea levels rise, storm activity intensifies and the physiography and biology of these environments change, the lives and livelihoods of people, properties and assets will be threatened (Simpson, 2013; Wadey et al., 2013). Other coastal structures, such as coastal protection measures (e.g. sea walls), and infrastructure (notably energy and transport) may also be affected.

The increase in sea levels and storm surges can increase the risk of coastal properties being affected and damaged due to flooding (Raynor, 2014). However, there are also wellbeing impacts from flooding; Tunstall et al. (2006) found that two thirds of respondents from the General Health Questionnaire indicated that their mental health was at its worst after the flooding occurred (although some form of mental health concerns continued over the long term) when compared to those not affected by flooding (Tunstall et al., 2006).

Wright (2013) noted that UK ports will be particularly affected by climate change associated impacts such as enhanced storm surge activity, sea-level rise, temperature change, precipitation and high winds. Most notably, changes to the physiography and hydrodynamics could alter a system's sediment budget and change the morphology of navigable channels, which could affect shipping routes and capabilities. If channels are deepened through increased erosion, larger vessels could be accommodated but if channels infill, the size of ships could be restricted, and dredging may be necessary to maintain water depths. For estuaries, where there is generally a lot of activity in terms of industry and recreation, this could have a significant impact on the national economy.

Other climate change effects however, such as a warmer climate, could increase tourism opportunities with people staying within country for holidays rather than travelling abroad, which would positively impact the economy (Rosselló-Nadai, 2014). For example, along the UK coastline, and particularly in estuaries, these sites are often for recreation and tourism, including bird watching, walking routes, sailing routes etc. given their coastal location (Lonsdale et al., 2015). These sites could see increased visitor numbers as the climate warms and the summer period extends (Rosselló-Nadai, 2014).

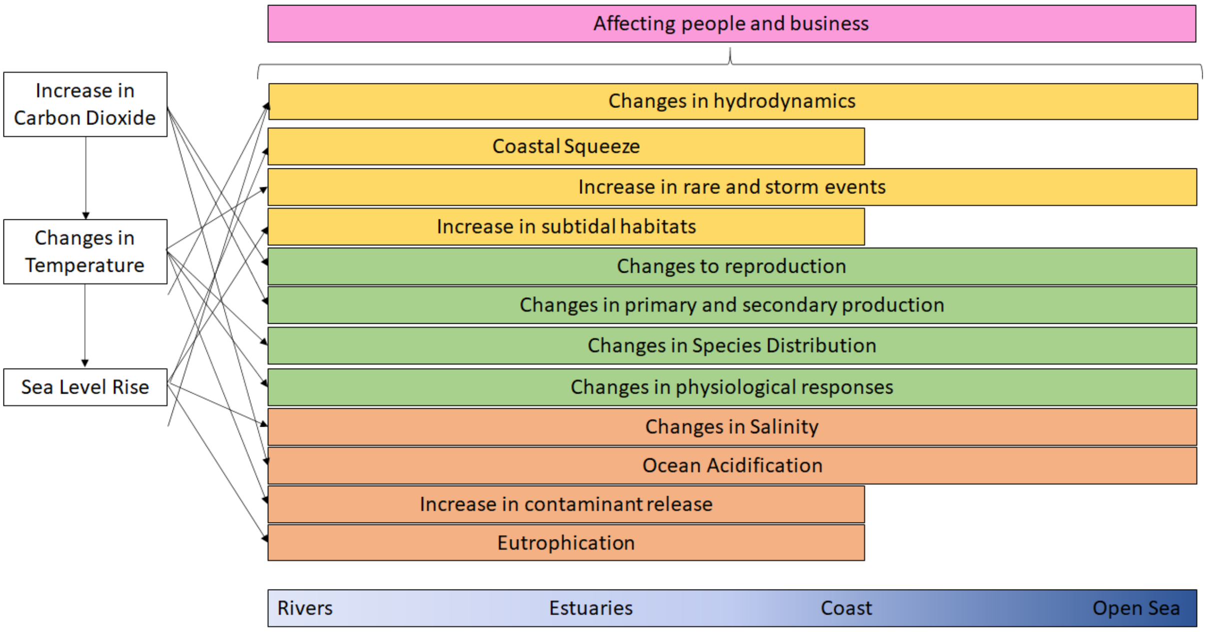

Figure 1 Impacts of climate change showing the drivers (on the left) and where these impacts are most likely to occur or have the greater impact (blue horizontal box along the bottom). Orange boxes represent chemical changes; green represent biological changes; yellow boxes represent physical changes; and pink box represent socio-economic changes.

These hazards and risks may be exacerbated by direct human actions, for example removing natural vegetation (e.g. mangroves, reedbeds) that increases the severity of natural hazards such as storm-surges, which in themselves may be increased by climate alterations (Wolanski et al., 2019). These external, climate-forced vectors thus add complexity to the estuarine management challenges. These changes have the potential to influence processes that control the behaviour (e.g. geomorphological), physical properties (e.g. sea level), biological receptors (e.g. species distribution), economic benefits and uses (e.g. recreation) of these systems (Donovan et al., 2013; Masselink and Russel, 2013; Painting et al., 2013; Sheahan et al., 2013; Simpson et al., 2013). Furthermore, climate change may be regarded in legal terms as factors outside the control of local managers (a force majeure) again giving rise to challenges. For example, climate change will lead to moving baselines against which management of static features may be judged (Elliott et al., 2015; Saul et al., 2016). It is therefore important that strategies and governance are designed and implemented to protect and enhance estuarine environments over the long-term, fully considering the likely impacts of climate change on the uses and users of these systems (Lonsdale et al., 2015).

3 Management and Governance

Estuaries are managed through many instruments from international, national and regional levels, including voluntary codes of conduct (Boyes and Elliott, 2014). Across all these levels, the legislation, policies, administration and management strategies are designed to safeguard ecosystems whilst allowing for sustainable development and the management of ongoing and proposed activities.

Importantly, legislation does not tell us how to do something but rather permits what can and cannot be done (Cormier et al., 2019). At a global level, there are international treaties and conventions, many of which are legally binding for countries that have formally ratified them e.g. the United Nations Convention on the Law of the Sea (UNCLOS, 1982) and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention/ London Protocol) (IMO, 2020). These international treaties set the minimum standard, for example, for environmental protection. Countries can implement higher standards of [marine] environmental protection, but not less.

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development and the Sustainable Development Goals. There are 17 Sustainable Development Goals (SDGs) and associated targets, with SDG 14 focused on the oceans. The aim of SDG 14 is to “Conserve and sustainably use the oceans, seas and marine resources for sustainable development”. Of its seven targets, Target 14.3 is to “Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels” is the most relevant when considering how estuaries are responding to climate change and how these impacts can be managed.

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty, adopted in 1992, whose objective is to stabilise “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (United Nations, 1992). Unlike the aforementioned treaties, the UNFCCC sets non-binding limits on greenhouse gas emissions and contains no enforcement mechanisms. Rather, it sets out a framework for how specific treaties could be negotiated to meet the objectives in a legally binding manner. The parties to the convention meet annually to assess progress towards the objectives and in tackling climate change.

However, in 1997, the Kyoto Protocol established legally binding obligations for developed countries to reduce their greenhouse gas emissions in the period 2008–2012 (United Nations, 1998). These were superseded by the 2010 United Nations Climate Change Conference which produced an agreement stating that future global warming should be limited to below 2.0 °C (3.6 °F) relative to the pre-industrial level (United Nations, 2011).

Below this level, there are regional commissions, where multiple countries who share common seas and/or coastline agree to management measures. An example of this is the European Union which, under the European Commission, sets out Directives which, similar to the global treaties, set the minimum requirements. Countries can either adopt as is, adopt through national legislation using same thresholds, or with stricter thresholds. An example of a European Directive which is applicable to climate change is the European Directive for Environmental Impact Assessments (2014/52/EC) which states that any development must be assessed against its potential impacts on the marine environment. Under this Directive, developers have a duty to consider the effects their development may have on the repercussions of climate change and vice versa (Lonsdale et al., 2017). Comparable Legislation is found globally, such as the Canadian Impact Assessment Act, 2019, which states that the assessment must consider "the extent to which the effects of the designated project hinder or contribute to the Government of Canada's ability to meet its environmental obligations and its commitments in respect of climate change" (Government of Canada, 2020).

However, there are also other such conventions including the Convention for the Protection and Development of the Marine Environment and Coastal Region of the Mediterranean Sea (Barcelona Convention) and Convention for the Protection of the Marine Environment of the North-east Atlantic (OSPAR Convention), to name but two, which are aimed at protecting an area of the marine environment which is used by multiple countries as a shared resource. The OSPAR Convention is concerned with impacts on the marine environment and in OSPAR's North-East Atlantic Environment Strategy 2020 it is stated that "*first effects of climate change and ocean acidification are apparent throughout the OSPAR Maritime Area and that pressures on the marine environment from climate change and ocean acidification are set to grow*" (OSPAR Commission, 2010). As such, and in accordance with this strategy, the OSPAR Secretariat has committed to monitor and assess the nature, rate and extent of the effects of climate change and ocean acidification on the marine environment and consider appropriate ways of responding to such developments.

At the national level, there are three levels of ocean governance:

1) The government sets **policy** objectives (not thresholds) and priorities for both present day and into the future (e.g. HM Government, 2011; HM Government, 2018a for the UK; Australian Government, 2017 for Australia; Government of Canada, 2018 for Canada);
2) Regulators and/or Governments **identify tasks** to meet the objectives and priorities produced in step 1. An example is maritime spatial planning which aims to support management decisions, which support the policies.
3) **Legislation** is required to implement the tasks identified in step 2.

The global and regional treaties set out what is expected, and the national legislation stipulates what can and cannot be done legally in order to meet the international obligations. For example, in the UK, The Climate Change Act 2008 is an Act of Parliament and makes it the duty of the Secretary of State to ensure, amongst other provisions, that the net UK carbon emissions (including from all six greenhouses gases targeted by the Kyoto Protocal) by 2050 are at least 80% lower than the 1990 baseline. Additionally, an independent Committee on Climate Change has been created under the Act to provide advice to UK Government on these targets and related policies. In the Act, 'Secretary of State' refers to then 'Secretary of State for Energy and Climate Change'.

Up until this point, all the management measures have been general in terms of geographic scope and scale, it is only at the local level where estuarine specifics can be considered. At this local level, the administrators can only enact current law and regulations; and the law may be more focussed on the repercussions of not acting. Local management measures can be binding such as byelaws (which manage certain activities in a certain area), or non-binding, such as codes of conduct or local policies related to, amongst others, climate change adaptation (Defra, 2010).

Compliance from local to global level obligations requires that managers, regulators and decision makers are in place and that independent reviews of the governance structure are completed. However, governance structures, especially for the marine environment, are often complex with overlapping roles and responsibilities (Lonsdale et al., 2015). Different areas of government can be responsible for policymaking whilst others are responsible for implementation. There are often perceived conflicts in this approach as the Government may set a policy e.g. increasing reliance on renewable energy, but this requires renewable infrastructure to be built, and the infrastructure may not be permitted to be built either for environment (too large an impact) or societal (objections based on impact to local amenities or economy) grounds. Therefore, it is questioned what happens if targets are not met despite all departments acting lawfully.

The vertical integration from having international and regional agreements, conventions and protocols which feed into the national and local governance as described above, is generally accepted and well-implemented. However, there is also the need for horizontal integration which requires the coordination of environmental goals and objectives with those of marine sectors (Cormier et al., 2019). For example, constructing an offshore structure could only be permitted if the goals/objectives of a marine protected area were not threatened. As demonstrated by Cormier et al. (2019) and Lonsdale et al. (2015), this horizontal integration is complex: there are usually several regulators that manage a marine area and activities. Hence, cross agency communication, with shared visions and agreements is key for effective marine management.

Whilst the use of targets, ambitions and goals are a useful tool to ensure issues relating to impacts from climate change are tackled, there is the risk that the focus is on meeting targets, and not the ancillary issues, for example, what this means in terms of environmental impact due to an increase in hard structures in the marine environment (see Dannheim et al., 2020). Due to the global-reaching impacts of climate change, a national strategy for harmonising targets and combatting climate change impacts may be an effective solution, albeit, costly to coordinate, implement and monitor.

4 How can management better address Climate Change?

Climate change is bringing challenges to the effective and sustainable management of estuaries and these will continue over the long-term. For effective management to be achieved, managers, regulators and planners will benefit from working together to develop strategies that consider key stakeholders and legislative requirements from global to local levels as well as potentially competing targets (Lonsdale *et al.*, 2015).

To do this there needs to be a rigorous management and risk assessment framework to help in estuarine management, such as DAPSI(W)R(M) and the ISO standard Bowtie analysis (e.g. Elliott, *et al.*, 2017; Cormier *et al*., 2019). The unifying DAPSI(W)R(M) management framework developed by Elliott *et al.* (2017) accommodates the **D**rivers (of change are the economic and social forces that result from government policies, markets and activities of the private industry, e.g. the basic needs of society, determine the needs for the development of land) as the basic human needs (for food, space, etc), the resulting **A**ctivities which lead to **P**ressures which are the mechanisms of change. These pressures change both the natural **S**tate and also have an **I**mpact on human **W**elfare. Finally, these require **R**esponses (using management **M**easures) (Elliott, *et al.*, 2017) when assessed against the defined baseline. A more flexible and responsive management framework(s) may minimise adverse effect on receptors and therefore, it is important that legislation and regulations allow for adaptation as our understanding of climate change impacts becomes more comprehensive. This further requires that changes to the pressures and impacts be monitored, in order to determine the ongoing suitability of management measures. However, a key question will be at what scale? The perfect monitoring programme will have 100% coverage with real time data, but this would be a huge financial burden, and therefore a balance must be struck between what we want (scale, temporal, variables) and what can be afforded to answer the specific question.

The link between the global and local needs to be considered within Legislation in order to facilitate the implementation of suitable management measures across all levels. This would enable scientists, managers and decision makers to address site-specific climate change effects, relevant to the areas they manage whilst remaining within the boundaries of more global-based guidance (Elliott *et al.*, 2015; Robins *et al.*, 2016; Wolanski *et al.*, 2019). For instance, changes in temperature could increase the likelihood of non-native species inhabiting estuarine waters and this is complex to monitoring, map and manage. There are few, if any effective measures to address this at present and requires management at the local level, relevant to site-specific conditions and the types of species that establish (Olenin *et al.*, 2011). The relationship between the global and local is an ongoing challenge, particularly given the uncertainty surrounding the potential impacts of climate change. Cross departmental strategies, which consider multiple targets, need to be sufficiently flexible to allow targets and mitigation/adaptation methods to be updated according to site-specific conditions and increasing knowledge.

Alignment of the different levels of management is encouraged through the implementation of the Marine Plans, that are found globally (HM Government, 2014). In the UK, the Marine Plans are supported by policies to ensure the development of coastal infrastructure both in terms of how new developments can affect climate change (through emissions), how the effects of climate change can affect the infrastructure (through increasing sea levels) and potential mitigation measures (HM Government, 2018b; 2011; Department for Transport, 2012). However, implementing these policies and practices is challenging. The cost of implementing measures which may not have an instantaneous reduction in the vulnerability to climate change (due to the time lag between management measures being implemented and the levels of greenhouse gases responding). Uncertainties in how the effects of climate change may impact an area at a local level and the potential need to cut across multiple legislative drivers, policies and strategies as well as the regulators and planners is also a challenge to overcome (Mansanet-Bataller, 2010). Effective management requires centralised coordination and implementation to ensure that each of these players are involved in decision making and issues at all levels, vertically (local to global) and horizontally (cross agency and sector), are considered.

Monitoring in itself is not a management measure but rather the means of determining whether management measures have been effective (Wolanski and Elliott, 2015): we need to understand the physical, biological and chemical environment to inform management. A major gap is the availability of data to understand the effects of climate change, including site specific and fine resolution monitoring that is comparable across regions. Gathering these data requires multi-national and inter-disciplinary collaborations, which would provide a greater baseline understanding. There is also a need to better understand these data and use them to predict likely mid- to long-term effects of climate change; this would allow more informed decisions to be made. Numerical models are increasingly being used for such tasks, as they can simulate decadal to centennial evolution of environmental systems over relatively short time-periods, including minutes to days. These tools and their predictive capabilities are continually being improved but are not yet sufficient for small scale changes and responses to the effects of management measures. Hence, further investment in the technology and the quality of data used is required if we are to inform suitable and sustainable management over the mid- to long-term. Furthermore, monitoring of change is required in order to determine whether management measures have had the desired effect.

To ensure successful and sustainable development, the policies and strategies would benefit from adhering to the ten-tenets of sustainable management (Elliott, 2013; Barnard and Elliott, 2015). These cover the ecological, economic, technological, societal, administrative, legislative, political, ethical (moral), cultural and communication aspects of sustainable solutions. As indicated in the 10-tenets, wider education and engagement of stakeholders (e.g. CEDA, 2012) is required to address these issues and ensure adaptive capacity is recognised and built into plans, policies and existing developments. In line with the coordination of climate change adaptation, this requires ensuring adaptive capacity is maintained through all levels of the estuary stakeholders. The collation and dissemination of evidence and monitoring data will become increasingly important to identify whether the effects and trends of climate change are apparent. By ensuring the monitoring data and evidence are shared, the effects and adaptive management strategies can be fed into marine plans to provide long-term resilience to climate change and allow a greater integration, awareness and understanding of the effects of climate change into policy and infrastructure changes. For example, this includes the need to consider all of the effects of individual managed realignment sites at the estuary level.

5 What does this mean in reality? A Case Study of the Humber Estuary, UK

To explore the application of this analysis in reality, we take a well-studied case study of the Humber Estuary in the North East of England. It is one of the largest coastal plain estuaries in the EU, extending approximately 62 km from Trent Falls to the open sea (Figure 2). It is one of the busiest and fastest growing areas for seaborne trade in the EU and provides an important contribution to the UK economy (Ciavola, 1997; Jarvie, et al., 1997; Metcalfe et al., 2000). It supports four major ports: Goole, Hull, Grimsby and Immingham, that import >20% of the UK's total inward tonnage per year (Figure 2) and is rapidly growing as a national base for offshore wind installation and operations in the North Sea. Many industries, cities and towns are clustered near these ports, with much of the remaining land bordering the system used for agriculture. Much of the low-lying farmland was claimed from saltmarshes and is predominantly arable farmland, with some grassland that is grazed by cattle (Freestone et al., 1987).

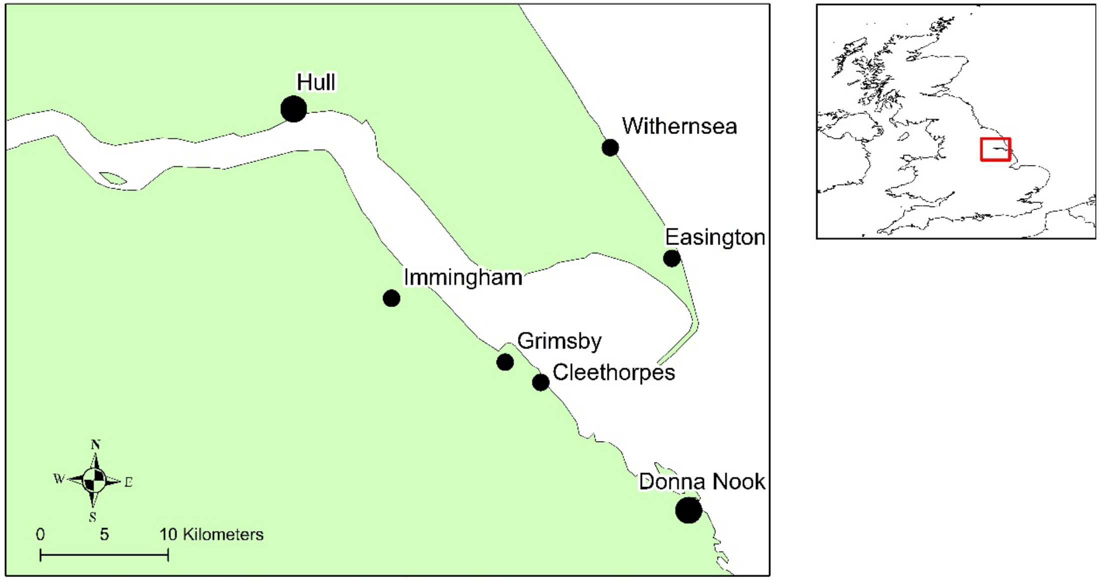

Figure 2 Case Study area

The Humber's various habitats and waterways constitute a European Marine Site within the Natura 2000 framework (Lonsdale, 2015). This includes Special Areas of Conservation (SAC), Special Protection Areas (SPA), Sites of Special Scientific Interest (SSSI) and a Heritage Coast site (see Lonsdale, 2015). These designations protect a wide variety of rare and sensitive biological components, including the seabed habitats, benthic communities, seabed features (e.g. sandbanks), mobile fish species (e.g. lamprey), marine mammals (e.g. the grey seal population) and bird species (e.g. the breeding Great bittern, Botaurus stellaris). Many of these sites provide ecosystem services and societal goods and benefits (Turner and Schaafsma, 2015) including many tourism and leisure opportunities, including bird watching, walking and educational benefits (Freestone et al., 1987).

Almost 235 km of defences protect and enhance the Humber's environmental, social and economic assets, including managed realignment sites such as Alkborough Flats (Winn et al., 2003). However, following the storm surge that caused widespread flooding around the estuary in December 2013 (Wragg, 2014) a question was raised as to whether management needs to be improved. The Humber Estuary, like many other estuaries, is susceptible to the effects of climate change and this needs to be taken into consideration when management strategies are developed and evolved into the future (Wolanski et al., 2019).

5.1 Managing Climate Change Impacts

The Humber Estuary is vulnerable to all the potential impacts of Climate Change identified in section 2, but it is important to consider how these impacts manifest at the site-specific level. In Table 1, the physical, chemical and biological effects relevant to the Humber Estuary are summarised.

There are management measures within the Humber Estuary that are designed to combat the effects of climate change, such as management realignment sites or setting back or raising flood defences; the question is, how future proof are these methods? The impacts of climate change, including sea level rise, will continue even if we were to stop all greenhouse emissions today due to inertia. Most other measures are designed to monitor the impacts and effects within the estuary, such as changes to salinity, species distribution or contamination. These are a means to inform management measures.

The Humber Estuary is managed through many legislative instruments, from international, to European, national and regional levels, including voluntary codes of conduct. At the International level, management of the Humber must be considered according to the policies and guidance outlined in Section 4, whilst considering national and local level regulations. Nationally, The UK Climate Change Act (2008), amended in 2019, is the UK's response to reducing and mitigating against climate change. It requires the UK to act to tackle climate change and reduce greenhouse gas emissions by 100% of 1990 levels by 2050. The UK Marine Policy statement, as required by the Marine and Coastal Access Act 2009, sets out guidelines for maintaining marine environments in healthy, productive and resilient conditions, without compromising the ecosystem services and societal goods and benefits (Kelly at al., 2014; Turner and Schaafsma, 2015). The East Marine Plan (within which the Humber Estuary sits) aims 'to facilitate action on climate change adaptation and mitigation' by identifying areas for renewable energy generation (wave and tidal energy) and carbon capture storage, in line with the European Renewable Energy Directive (2009/28/EC) and the UK Climate Change Act, 2008. Local-level estuarine management is prominent in the Humber Estuary in acknowledging that climate change increases the risk of flooding. The Environment Agency has implemented the Humber Flood Risk Management Strategy to manage flood risk, aiming to ensure that 99% of people who live close to the Estuary have a good level of protection against tidal flooding for 25 years following the implementation of the strategy (Environment Agency, 2008). The Humber Flood Risk Strategy complements a range of regional plans, including Shoreline Management Plans (SMP) and Coastal Habitat Management Plans (CHaMP).

Many of the responsibilities for monitoring and managing the impacts of climate change within the estuary appear to fall onto the Environment Agency. However, some specific responsibility falls to others, such as the Marine Management Organisation (for assessing sediment contamination for dredge and disposal to sea applications) or private organisations or Local Authorities for the maintenance of some flood defences. Vertical and horizontal integration is therefore imperative to ensure effective management that is compliant with international, regional and national legislation whilst taking into consideration specific challenges within the Humber Estuary. How this can be achieved is not always clear or straightforward to achieve.

By analysing the potential impacts from climate change and the legislative instruments, what appears to be a weakness in the management of the Humber Estuary is the lack of a cross-departmental long-term planning of adaptability to the effects of climate change. For instance, what is to happen when there is a salinity shift? Is there anything that can be done to offset or mitigate? To inform such management strategies, we need to have robust modelling in place to predict potential scenarios and determine harmonised specific responses based on the site-specific information, for instance the modelling results and management responses for the south coast may not be appropriate or applicable to the Humber Estuary. This would allow for a local policy to be developed, but by learning from local examples such as this, national policy could be more aligned to the UK's responses (both environmental and management) to climate change impacts.

Table 1 summary of climate change impacts on estuarine environments, using the Humber Estuary as a case study

	Effect	How it will affect Humber features?	Comments	References
Physical	Changes in coastal hydrodynamics	Increases in storm events Changes to tidal currents, range, prism and patterns Changes in erosion and sedimentation Changes in sediment budget Changes to Estuarine morphology	This is likely to be high magnitude. Managed/ monitored by the Environment Agency. Some flood defenses are owned by local authorities or private organizations.	Andrews et al., 2006; Elliott et al., 2016; Wolanski and Elliott 2015; Lonsdale, 2013; Mori et al., 2010; Passeri et al., 2015; Rhein et al., 2013; Raynor and Chatterton, 2014; Wragg, 2014; Wolf 2009; Woolf & Wolf 2013
	Coastal squeeze	Reduction in intertidal habitat (and species) Changing of land use function (managed realignment sites)	Managed/ monitored by the Environment Agency. Some sites are compensation for projects. The Humber estuary has multiple sites	Wolanski and Elliott 2015; Elliott et al., 2016; Lonsdale, 2013
Chemical	Ocean Acidification	Buffering capacity of estuarine water, Change to pH via run-off Barrier to species migration Reduce the occurrence of recreation fishing Affect organisms with calcareous shells Increase in mortality Affect species physiological and behavior responses	There is no consensus on the magnitude of these impacts. Managed/ monitored by the Environment Agency.	Brodie et al., 2014; Cripps et al., 2011; Dixon et al., 2009; Feely et al., 2010; Orr et al., 2005; Klemetsen et al., 2003; Maitland, 2003; McCormick et al., 1998; Munday et al., 2009; 2010; Pinnegar et al., 2013; Roberts et al., 2013; Wittman and Portner, 2013
	Changes in salinity	Saline incursions of rivers. Barrier to migration Increase in mortality for freshwater species Increase distribution of saline tolerant species Linked to changes in rainfall and run-off patters Balance with greater water use and evaporation in the catchment	Monitoring under the Water Framework Directive should inform where these saline incursions are occurring.	Basset et al., 2013; Elliott and Quintino 2006; Little et al., 2017; Long et al., 1998; Shennan et al., 2000; Whitfield et al., 2012
	Increase in contamination release	Increase erosion and rainfall can increase the release of contaminants in water column Changes in system to retain and/or recycle nutrients Can lead to increase mortality of species	Monitored by the Environment Agency and can come to light for Marine License applications for dredging whereby sediments may require chemical analysis.	Robins et al., 2016; Sheahan et al., 2013; Simpson, 2013; Wither et al., 2013

Biological	Changes in reproduction	Any changes in water chemistry may impact the timing for fisheries migrating and spawning or even become a barrier to migration if conditions are outside of their tolerances	There is no consensus on the magnitude of these impacts. Managed/ monitored by the Environment Agency.	Brodie et al., 2014; Cripps et al., 2011; Dixon et al., 2009; Feely et al., 2010; Orr et al., 2005; Klemetsen et al., 2003; Maitland, 2003; McCormick et al., 1998; Munday et al., 2009; 2010; Pinnegar et al., 2013; Roberts et al., 2013; Wittman and Portner, 2013
	Changes in primary and secondary production	Any changes in water chemistry may impact plankton and benthic species timing for reproducing	There is no consensus on the magnitude of these impacts. Managed/ monitored by the Environment Agency.	Brodie et al., 2014; Cripps et al., 2011; Dixon et al., 2009; Feely et al., 2010; Orr et al., 2005; Klemetsen et al., 2003; Maitland, 2003; McCormick et al., 1998; Munday et al., 2009; 2010; Pinnegar et al., 2013; Roberts et al., 2013; Wittman and Portner, 2013
	Changes in species distribution	Increase in tolerant species and extend distribution Decrease in species intolerant of temperature Increase likelihood of non-native species Change of ecosystem structure and function Change to ecosystem goods and services	Environment Agency have measures that are required to address the presence of non-native species namely: mitigation to control and eradicate. building awareness and understanding of the non-native species and the negative impacts of the presence. to undertake early detection and monitoring to provide a rapid response to reduce the risk of the species of becoming established European Union Water Framework Directive 2000/60/EC	Bentley, 2011; Cook et al., 2013; Edwards et al. 2013; Elliott et al., 2015; Gilbey et al., 2008; Klemetsen et al., 2003; Lonsdale et al., 2013; Maitland, 2003; McCormick et al., 1998; Mieszkowska et al., 2013; Nunn et al., 2008; Olenin et al., 2011; Pinnegar et al., 2013; Sheahan et al., 2013; Turner and Schaafsma, 2015.
	Changes in physiological responses	Affect physiological behaviours (e.g. oxygen metabolism, adult mortality, reproduction, respiration, reproductive development), Affect seasonal reproduction Affect the higher trophic level species which prey on the plankton Repercussions of encouraging migration of species into higher latitudes, or due to changes into the composition of their prey.	Management is restricted to monitoring the distribution of species and physiological responses e.g. spawning areas and timing, Managing other stressors to reduce the overall stress species may be subject to e.g. enforcing timing restrictions during construction projects	Durant et al., 2007; Lonsdale et al., 2013; Nunn et al., 2008; Klemetsen et al., 2003; Maitland, 2003; McCormick et al., 1998; Pankhurst and Munday, 2011; Pörtner and Knust, 2007.

6 Concluding Remarks

This paper details the potential challenges associated with managing vulnerable estuarine environments in the face of climate change. There are efforts by planners, managers and industries to address some of the effects of climate change, but the ways in which estuaries are managed from a global to local level needs to be improved. Recently developed decision support systems (e.g. Lonsdale *et al.*, 2018) give progress towards this end. The causes and effects of climate change are relevant from the local to the global, and so co-ordination is needed across all levels to encourage effective, suitable and sustainable management (Wolanski et al., 2019).

Using a case study of the Humber Estuary, this study demonstrates the importance of vertical and horizontal integration across management levels. It also shows the relevance of developing site-specific assessments, as each estuary and its component habitats and species will be impacted by climate change in different ways and to differing degrees. This is challenging due to the coarse coverage of data and so there is a need for enhanced monitoring and research but also the realisation that action has to be taken in the light of inadequate knowledge and data. Numerical models are increasingly being used to understand the behaviour of these systems and the effect that climate change may have over decadal to centennial timescales. Despite this, the models often highlight the uncertainty both in our understanding and in the predictive capability. However, there is scope to utilise these tools further and improve their predictive capabilities, to inform sustainable management and policies.

As shown here, there is an increasing understanding of how our climate is changing, how these environmental systems are affected, and the ways they can be managed to become more resistant and resilient through an informed decision framework into the future.

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