Environmental Science and Policy
Managing estuaries under a changing climate
--Manuscript Draft--

Manuscript Number:	ENVSCI-D-20-00274R1
Article Type:	Review Article
Keywords:	Climate Change; Estuary; Management; legislation
Corresponding Author:	Jemma-Anne Lonsdale Cefas Lowestoft, Suffolk UNITED KINGDOM
First Author:	Jemma-Anne Lonsdale
Order of Authors:	Jemma-Anne Lonsdale
	Chloe Leach, PhD
	Michael Elliott, PhD
	Dan Parsons, PhD
	Andrew Barkwith
	Susan Manson, PhD
Manuscript Region of Origin:	Europe
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.
Suggested Reviewers:	Alice / Newton, PhD Professor, University of Algarve: Universidade do Algarve anewton@ualg.pt Her expertise is aligned to the topic of the paper
	Larissa / Naylor, PhD Professor, University of Glasgow Larissa.Naylor@glasgow.ac.uk She has the expertise relevant to the paper
	Peter / Robins, PhD Lecturer in Physical Oceanography, School of Ocean Sciences, Bangor University, Bangor University p.robins@bangor.ac.uk His work is relevant to the paper
Opposed Reviewers:	
Response to Reviewers:	

Lowestoft, February 2022

Dear Raul Lejano,

We apologise for the delay but we are pleased to send the revision of manuscript ENVSCI-D-20-00274 entitled " Managing estuaries under a changing climate”. We hope that the revised version can make a useful contribution to the journal, by providing an overview of the effects of climate change that can impact estuaries, highlighting the potential bottlenecks to effective management to improve management into the future.

We have, in line with the reviewers’ suggestions, clarified the manuscript by adding text as recommended by the reviewers. The manuscript has undergone major revision, changing the structure, removing superfluous text/detail and making more use of referencing other research and making the links between sections (International to case study) has been made clearer. Since the previous submission, we have in light of the reviewer’s comments, asked a colleague to re-read to ensure no typos or grammatical errors.

We have attached a clean copy of the manuscript as per the instructions on the Editorial Manager, but we do have a track change version available if required. Please see below for our detailed response to all reviewers’ feedback – which we perceived as extremely constructive in helping us improve the text. The references to line numbers appear to the document if ‘simple markup’ is selected under the ‘track changes’ setting.

Kind regards,

Jemma

Jemma Lonsdale
Centre for Environment, Fisheries & Aquaculture Science (Cefas)
Pakefield Road
Lowestoft NR33 0HT
United Kingdom
Tel. +44 1502 524491

Reviewer #1:

I found the paper "Managing estuaries under a climate change" an interesting and useful review article that fits well with Environmental Science and Policy's aim.
We thank the reviewer for their comment. No action required.

I have several suggestions that hopefully will make this paper more relevant to a broad international audience.
We thank the reviewer for their comment. No action required for this point.

Lines 34-36. The article's aims need to be reframed and justified. It is unclear why the authors are doing this review and the knowledge gap to be closed. What is the "novelty" in this review? Please justify.
Additional text has been added in lines 34-43. We have stated the novelty and added justification to show the importance.

Lines 36-39. The description of the sections of the paper can be improved. Readers need to know how you organized your argument.
Lines 34-43 have been updated to reflect the order of the paper including cross referencing.

Sections 2 and 3 are useful, but I am missing quantitative information about the magnitude of the impacts described in the text.
The manuscript has undergone major revision so that the impacts are only summarised and the manuscript now directs the reader to other, more detailed research papers which provides quantitative results on the potential impacts of climate change on estuaries.

Section 3 (what was management and governance) has been incorporated into Section 2 to make clear this section is setting the scene at a more global level.

Subsection 2.4 should be global in scope. Right now, all examples are from the UK.
Thank you for raising this. Additional examples and references have now been added to make this section more globally relevant.

Section 4 i) is limited and needs more work. ii)Authors should have a table summarizing all management frameworks available rather than focus only on one. iii) Again, to be useful for an international audience, this section needs to be global in scope. Right now, the emphasis in Europe and the UK.
i)We have addressed the comments that the reviewer has specified, and added more references however, if the reviewer has any additional suggestions for improvement, we would be happy to consider them.

ii) Rather than provide a table, we have provided a few more additional frameworks that can be used and provided additional references rather than make the paper too lengthy.

iii) Additional references have been added to demonstrate the global relevance and application.

Section 5 is acceptable, but after reading the text, a reader will not learn about the actual bottlenecks regarding climate change policy implementation in the Humber Estuary. More information and analysis are required.
We believe this is now addressed explicitly due to the revisions in the table, but we have also included additional text in lines 729-735 to discuss these bottlenecks.

I believe Table 1 needs additional work. I suggest dividing the "comments" column into three columns: 1) The first column should indicate what is(are) the policy (or policies) addressing each one of the climate change effects, 2) the second column should show what is(are) the agency (or agencies) implementing the policy(policies), 3) the third column should describe what the major bottlenecks that the executing agency (or agencies) face for successful policy implementation are. By doing so, authors could reframe their analysis and show what the significant challenges are.
We have updated this table as per the reviewers' comments. We thank the reviewer for their helpful suggestions.

Section 5 needs to be based on the previous sections and avoid overstatements. For instance, based on section 4, I could not see any strong evidence that the study "demonstrates the importance of vertical and horizontal integration across management levels". Where is the data supporting this statement? Lines 408-417? If so, better data and analysis are required.
We have reviewed this Section to either remove such over statements, or ensure any statements are evidenced either through revisions earlier in the manuscript or through additional references. We have also had a colleague provide a thorough read through to ensure no further unsupported statements remain.

Reviewer #2:

The article is clear and well-written.
We thank the reviewer for their comment. No action required for this point.

It is lacking in terms of depth of treatment of the case study. On the other hand, as a review article, it does not go deeply enough into the literature either. I am not sure what to recommend for this manuscript: either major revision or reject. If the latter, it does not mean that the article itself is not good reading, just that it does not seem to accomplish any clear scholarly objective.
We thank the reviewer for their comment. No action required for this point however we have taken the proceeding comments on board and updated the manuscript which we hope satisfies the reviewers concerns.

The article is an informative review of threats to estuaries. But it is hard to clearly classify this article. As a review, it is not so exhaustive a coverage of the literature on climate and estuaries. Moreover, its treatment of this topic is superficial. It is also an investigation of threats to a particular ecosystem, the Humber Estuary. And, so, the second part of it seems like a case study based research study --so the article is in between a review and case study research. It does not fit either type very well. The authors need to decide how to either deepen and expand the literature review, or deepen the analysis of the Humber case. Perhaps it is possible to do both, but I think easier to just attempt for one (for example, shortening the review and expanding the case study).
We appreciate the reviewer's suggestion and we have taken this on board. The manuscript has now been through a major revision in which we have changed the structure and removed superfluous detail. The manuscript is now much more focussed on the case study. We have updated the research questions in lines 33-38.

If the authors decide to expand the case study and include a deeper analysis, then it has to be clear on what research questions they are answering. It may be that the question is related to the sufficiency or appropriateness of the legislative framework and regional rules for protecting the Humber. And how might policies be modified and improved. In this way, the contribution of this paper to the literature on environmental policy will be clearer. The case study, including relevant regulations, can be seen to start on page 7 onwards in the manuscript (including Management and Governance). Even so, the discussion is a bit superficial --for example, is it necessary to include a description of the IPCC in describing legal frameworks for protecting estuaries?
We thank the reviewer for their very helpful suggestions. We have updated the research questions in lines 33-38. We have revised so that Section 2 is clear about setting the global scene (and linked in Section 3, line 228).

To address the comment regarding international treaties etc, we have added additional text in Lines 490-492 and 539-540 which clarifies the link between these two sections and the reason for their inclusion.

The discussion on page 9 is interesting but not focused. What, exactly, are the national and local rules/regulations that govern the Humber? The authors need to discuss this in specific terms in order for the problems of vertical and horizontal legislation to be understandable and meaningful to policy audiences.
We thank the reviewers for this comment; however section 3 is meant to summarise general management measures including legislation and regulations. The specific regulations for the Humber are brought out in section 5. We have however added additional text in Section 5 in lines 703-725 to explore the vertical and horizontal legislation further for the reader

The discussion of the marine plan in pp. 14-15 is vague --it needs to be discussed in enough detail so that the reader can see exactly what vertical and horizontal issues are found today. What are some pressing problems today, and how can we trace these to lack of vertical or horizontal integration? As it is, the discussion on page 14 is not specific enough to really show any sort of policy analysis.
We have now included a new figure to help visualise the horizontal and vertical governance/management measures.

Would the analysis make use of the DAPSI framework? If so, then the framework needs to be better described, and the methodology for using it and conducting the analysis also described. It is not clear that the DAPSI framework was used in this research.
We recognise that the manuscript has caused confusion through the description of the DAPSI framework in Section 4 and using the term 'analysing' herein Section 5. We have removed the detailed text regarding DAPSI because we have removed the section about 'How can management better address Climate Change' which was a general overview. Instead, this now follows on from the assessment we carried out, so is specific to the Humber Estuary.

If the authors decide that this is not case study research but more of a lit review, then still, what overarching questions guide the review, and what answers do we arrive at? What does the literature say about lack of integration regarding estuaries?

The article concludes that
"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 sitespecific 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 must be taken in the light of inadequate knowledge and data."
but, because the case study was inadequately described, and too little detail given of the governing legislation and rules, it is hard to say that the study demonstrated the importance of integration (or demonstrated the lack of integration of current governance and regulation). It did not seem to demonstrate that the data was coarse nor provide any specific example of how such coarseness hurts the estuary with regard to climate change (or other environmental problem).
The concluding remarks have been updated to relate back to the manuscript more accurately.

"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."
but discussion of such models is vague and, so, the reader is not shown how these models merely highlight uncertainty and how these do not serve governance of the estuary well. There is not enough specific information to see how the findings were arrived at. Perhaps taking up just one thing found in Table 1 might help to show how current rules and management systems and current monitoring data do not suffice. For example, what specific inadequacies do you find in the area of flood protection, etc. As it is now, the discussion is too vague and abstract.
The concluding remarks have been updated to relate back to the manuscript more accurately.

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.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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." (Elliott 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 means that no single definition is suitable (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 economy (Lonsdale *et al.*, 2015; Elliott and Whitfield, 2011). They also support an abundant and functionally large but not necessarily diverse range of flora and fauna and many typically 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; Defeo & Elliott 2021). 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 and challenging 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~~ summarises the relevant impacts from climate change on estuarine systems and how the effects of climate change are currently being managed and governed locally, regionally and globally through legislative measures (Section 2). The sufficiency or appropriateness of the legislative framework and regional rules for protecting an estuary, using the Humber Estuary as a case study, against the effects of climate change are explored (Section 3) and, as a result, recommendations are made as to how policies can, or should be modified or improved (Section 4).

~~, 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 and ~~Climate Change~~

~~Understanding the impact that climate change has on 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 CO_2 is a primary cause of anthropogenic climate change and can lead to other effects, e.g. 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, 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 system to sea level rise is to migrate landward and either erode the shoreline or submerge previous intertidal habitats (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; 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. 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 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 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.

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 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 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 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, including bird watching, walking, sailing routes etc. given their coastal location (Lonsdale et al., 2015) and could see increased visitor numbers as the climate warms and the summer period extends (Rosselló-Nadai, 2014).

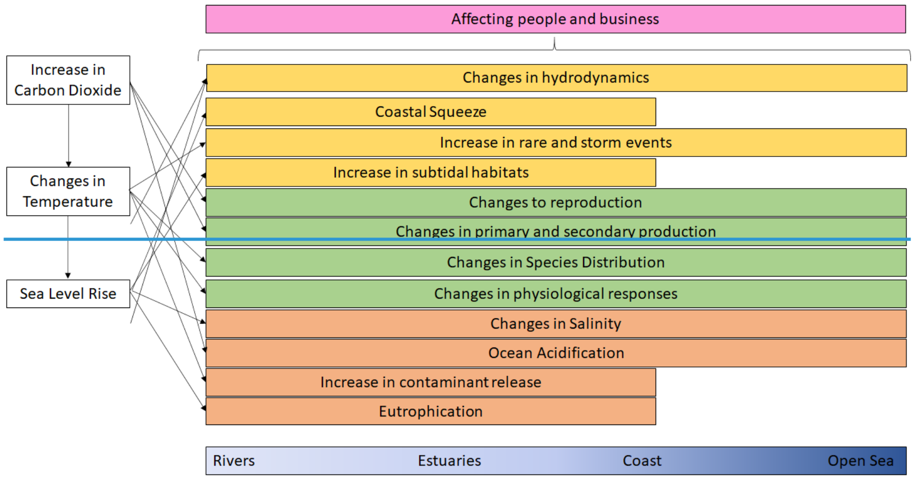

Figure 1 Impacts of climate change showing the drivers (on the left) and where these impacts are most likely to occur or have the greater impact (blue horizontal box along the bottom). Orange boxes represent chemical changes; green represent biological changes; yellow boxes represent physical changes;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

2 Management and Governance: The Global Challenge

~~3~~

Formatted: Heading 2, No bullets or numbering

Understanding the impact that climate change has on 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 and concomitant changes in temperature, sea level rise, and increasing storminess ~~changes in temperature~~ (IPCC, 2013) (see Figure 1).

In addition to these threats, there is a threat to socio-economics (summarised in~~see~~ Figure 1 ~~for a summar~~): the urban and industrialised coastal and estuarine areas ~~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) are likely to ~~may also~~ be affected. The increase in sea level~~s~~ 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 (see Tunstall et al. ~~(~~2006~~)~~).

Wright (2013) noted that 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 (supported by Becker et al., 2018; Hallegatte et al., 2011). Most notably, changes to the physiography and hydrodynamics could alter ~~a~~the system~~'s~~ sediment budget and change the morphology of navigable channels, thereby affecting ~~which could affect~~ shipping 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 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, thus ~~which would~~ positively impacting the economy (Rosselló-Nadai, 2014). For example, along coastlines globally, and particularly in estuaries, these sites are often for recreation, including bird watching, walking, sailing routes etc. given their coastal location (Lonsdale et al., 2015; Agardy and Alder, 2005) and could see increased visitor numbers as the climate warms and the summer period extends (Rosselló-Nadai, 2014).

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 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 creating factors outside the control of local managers (a force majeure) again giving rise to challenges (Elliott et al., 2015; Saul et al., 2016) and ~~. 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).

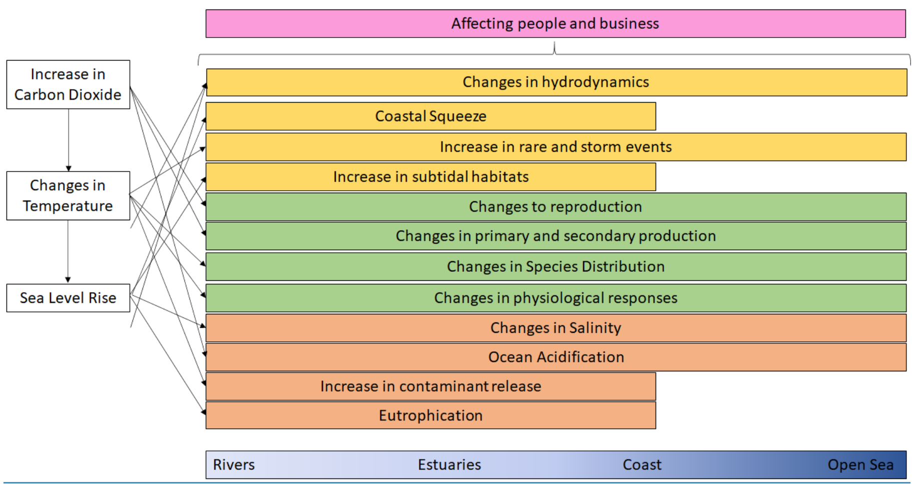

Figure 1 Impacts of climate change showing the drivers (on the left) and where these impacts are most likely to occur or have the greater impact (blue horizontal box along the bottom). Orange boxes represent chemical changes; green represent biological changes; yellow boxes represent physical changes;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

~~Estuaries~~ ~~To support, e~~Estuaries are managed through many legislative instruments at~~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. However, l

~~L~~egislation 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). These international treaties set the minimum standard, for example, for environmental protection. Countries can implement higher standards of [marine] environmental protection, but not less. Here we briefly provide an overview of these overarching protection measures as they influence regional, national and local management measures.

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 'Life below water' 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. However, it is questioned whether these targets are operationally satisfactory (Cormier & Elliott 2017).

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, t~~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. For example, ~~An example of this is~~ the European ~~Union which, under the European~~ Commission~~,~~ sets out Directives which, as with ~~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.~~ Under ~~An example of a European Directive which is applicable to climate change is~~ the European Directive for Environmental Impact Assessments (2014/52/EC)~~. 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).

Similarly, ~~However, there are also other conventions including~~ UNEP Regional Seas Conventions, such as 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~~ marine areas~~ 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 states ~~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~~ marine and coastal governance~~ (those specific to the Humber are explored in Section XXX)~~:

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 treaties set out what is expected, and the national legislation stipulates what can and cannot be done legally to meet the international obligations. For example, in the UK, The the Climate Change Act 2008 is an Act of Parliament under which and makes it the duty of the Secretary of State should to ensure, amongst other provisions, that the net UK carbon emissions (including from all six greenhouses gases targeted by the Kyoto Protocol) by 2050 are at least 10080% lower than the 1990 baseline. Additionally, an independent UK Committee on Climate Change has been created under the Act to provide advice to UK Government on these targets and related policies. The specific aspects relating to the Humber Estuary, eastern England are explored in Section XXX3.

The above Up until this point, all the management measures generally consider have been general in terms of geographic scope and scale, and it is only at the local level where estuarine specific aspects are 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).

Environmental management in estuaries, as with all other environments, needs to cover horizontal integration, across all the stakeholders in an area, and vertical integration Compliance from the local, national and regional to global level obligations. This requires that managers, regulators, and decision makers are in place and that independent reviews of the governance are completed, i.e. a regulatory impact assessment. However, governance structures, especially for the marine environment, are often complex with overlapping roles and responsibilities (Lonsdale et al., 2015; Boyes & Elliott, 2015). 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 environmental (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.

Formatted: Not Highlight

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 stakeholders across 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 (see Section 3 for those relevant to the Humber Estuary) 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 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, 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 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 monitor, 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 as 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 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 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 the effects of individual managed realignment sites at the estuary level.

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

To explore the sufficiency or appropriateness of the legislative framework and regional rules for protecting an estuary against the effects of climate changethe application of this analysis, we take a the 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 (North) sea (Figure 2). It is one of the busiest and fastest growing areas for seaborne trade in ~~the EU~~Europe 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.

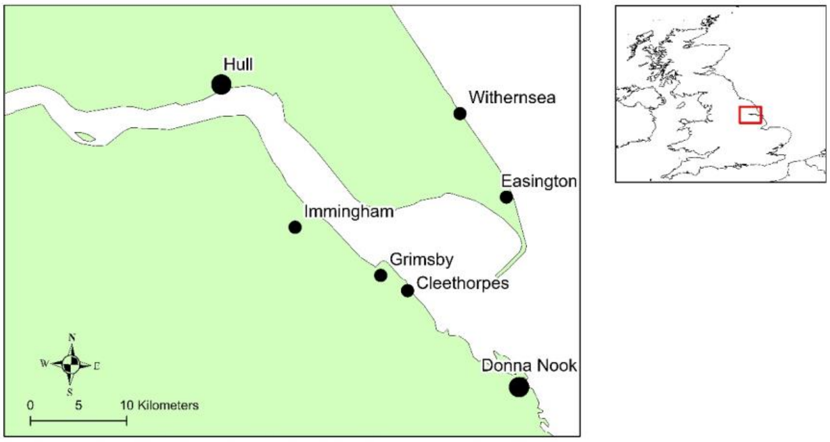

Figure 2 Case Study area

Given the nature conservation importance of the area, t~~T~~he 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 tourism and leisure opportunities (Freestone et al., 1987).

Almost 235 km of defences protect the Humber's environmental, social, and economic assets, including managed realignment sites such as Alkborough Flats and other ecoengineering initiatives

(Winn et al., 2003; Elliott et al., 2016). However, ~~following~~ the storm surge that caused widespread flooding around the estuary in December 2013 (Wragg, 2014), led to the questioning that ~~a question was raised as to whether~~ the estuary management needs improving. The Humber Estuary, like many other estuaries, is susceptible to the effects of climate change and this needs to be considered when management strategies are developed (Wolanski et al., 2019).

3~~5~~.1 Managing Climate Change Impacts

The Humber Estuary is vulnerable to all the potential impacts of Climate Change identified in section 3~~2~~, but it is important to consider how these impacts manifest at the site-specific level. ~~In~~ Table 1 summarises~~,~~ the physical, chemical, and biological effects relevant to the Humber Estuary ~~are summarised~~. The Humber Estuary is managed through many legislative instruments, from international, to European, national, and regional levels, including voluntary codes of conduct. Hence, ~~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 (Elliott et al., 2016). This leads to the ~~; the~~ question of ~~is,~~ how future proof are these methods especially given any time lag and inertia in the system? ~~The impacts of climate change will continue even if we were to stop all greenhouse emissions today due to inertia~~. The efficacy of management measures aimed at tackling climate change impacts is determined by monitoring such as ~~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.~~ In Section 2, we ~~have~~ highlighted the international conventions which set out the requirement for countries to do something, here we look at the specific requirements for managing a relatively small site in comparison to the global treaties jurisdiction~~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- this is important when considering ongoing (e.g., shipping) or new (e.g., power stations) developments. 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

Formatted: Not Highlight

Formatted: Highlight

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 used a cost-benefit analysis to 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). It is of note that those not protected live at sites where the cost-benefit analysis would have indicated that protection is prohibitively expensive given the value of assets protected. See Figure 3 for a visualisation of the Humber relevant management measures.

To determine the sufficiency of the legislative framework and/or the organisations responsible, the potential impacts highlighted in Section 2, were considered in terms of what (legislation) and who (authorities) is responsible for managing these impacts (Table 1).

Many of the responsibilities for monitoring and managing the impacts of climate change within the estuary appear to fall onto the Environment Agency, anthe English environmental protection agency (in the UK, Scotland, Wales and Northern Ireland have their own bodies as devolved agencies) of water ways in the UK. However, some specific responsibility falls to others, such as the Marine Management Organisation (for assessing new development applications) or private organisations or Local Authorities, and even private organisations, for the maintenance of some flood defences (see Figure 3). Vertical and horizontal integration between these legislative instruments and responsible organisations 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.

Formatted: Not Highlight

Formatted: Not Highlight

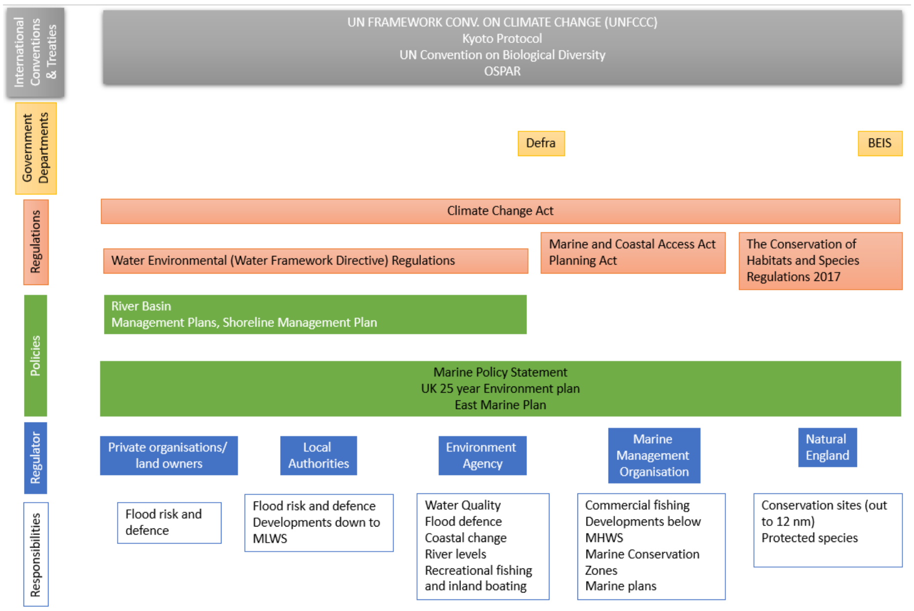

Figure 3 Visualisation of the horizontal and vertical governance of the Humber Estuary specific to estuarine waters management.

By analysingA potential weakness in aAssessing the potential impacts from climate change and the legislative instruments, what appears to be a weakness is the sheer task of monitoring for the potential impacts of climate change which may be prohibitively expensive for many organisations. Ifor very few organisations, in most cases, it falls solely on the Environment Agency, although there is acknowledgement that other forms of monitoring, such as condition monitoring of the nature conservation features and compliance monitoring for ongoing developments (Elliott et al., 2022)that take place. Models can inform how an area may be impacted by climate change (Falconer et al., 2020REF), but they have caveats and their spatial and temporal predictability, both from deterministic and empirical modelling, gives them with their use and the results, therefore on a local level, they have limited use in prioritising areas for monitoring. End-to-end models which link changes to the natural environment with the socio-economic repercussions (Peck et al., 2018) have the potential for use but require expensive parameterisation for individual areas. Hence, tTo inform 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, national policy could be more aligned to the UK's responses (both environmental and management) to climate change impacts.

TFollowing the review in Table 1 also indicates , it also appears that there is little in the way of preparatory or proactive mitigation measures to combat when, and if, thresholds for biological impacts are reached for example, what is to happen when there is a salinity shift? Is there anything that can be done to offset or mitigate the changes?

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, 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~~Potential for impact	What is(are) the policy (or policies) addressing the climate change effects	What is(are) the agency (or agencies) implementing the policy (policies)?	What are the major bottlenecks that the executing agency (or agencies) face for successful policy implementation	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.~~	River Basin Management Plans, Shoreline Management Plan, Water Environmental (Water Framework Directive) Regulations,	Environment Agency. Local Authorities. Private landowners	Funding and man power to monitor, maintain and where required, create or improve sea defences along a vast coastline.	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)	This is likely to be high magnitude.~~Managed/ monitored by the Environment Agency. Some sites are compensation for projects.~~ The Humber estuary has multiple sites	River Basin Management Plans, Shoreline Management Plan, Water Environmental (Water Framework Directive) Regulations,	Environment Agency. Natural England (for compensation sites under Habitats Regulations Assessment)	Funding and man power to monitor coastal squeeze, and then to create, monitor and manage managed realignment 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	There is no consensus on the magnitude of these impacts. ~~Managed/ monitored by the Environment Agency.~~	Water Environmental (Water Framework Directive) Regulations,	Environment Agency	Funding and manpower to monitor pH changes to the extent that natural variability can be included in any assessment. There is currently no precedence for increase pH nor an agreed threshold of when a pH may cause biological impacts.	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

Formatted: Width: 11.69", Height: 8.27"

Formatted Table

		Affect species physiological and behavior responses					
	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	There is no consensus on the magnitude of these impacts. ~~Monitoring under the Water Framework Directive should inform where these saline incursions are occurring.~~	Water Environmental (Water Framework Directive) Regulations,	Environment Agency	Funding and manpower to monitor pH changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing salinty nor an agreed threshold of when a salinity level may cause biological impacts.	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	There is no consensus on the magnitude of these impacts. ~~Monitored by the Environment Agency and can come to light for Marine License applications for dredging whereby sediments may require chemical analysis.~~	Water Environmental (Water Framework Directive) Regulations, Marine and Coastal Access Act	Environment Agency Sediment contamination is also considered by the Marine Management Organization.	Funding and manpower to monitor contaminant changes. Limited resource to tackle increases in water contamination.	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.~~	Water Environmental (Water Framework Directive) Regulations	Environment Agency	Funding and manpower to monitor all potential water quality characteristics and their changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing nor an	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

						agreed threshold of when levels may cause biological impacts.	
	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.~~	Water Environmental (Water Framework Directive) Regulations	Environment Agency	Funding and manpower to monitor all potential water quality characteristics and their changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing nor an agreed threshold of when levels may cause biological impacts.	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	There is no consensus on the magnitude of these impacts. ~~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~~	Water Environmental (Water Framework Directive) Regulations	Environment Agency.	Funding and man power to monitor along a vast coastline and water columns to identify and monitor non-native species presence.	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.

			~~European Union Water Framework Directive 2000/60/EC~~				
	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.	There is no consensus on the magnitude of these impacts. 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	Water Environmental (Water Framework Directive) Regulations	Environment Agency	Funding and manpower to monitor all potential water quality characteristics and their changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing nor an agreed threshold of when levels may cause biological impacts.	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.

4 How can management better address Climate Change?

Formatted: Numbering: Continuous

Climate change is bringing challenges to the effective and sustainable management of estuaries, and these will continue over the long-term. For effective management, we have assessed that the Humber Estuary requires the managers and regulators to work together, even where there are competing targets, but we have also identified (from Table 1) the ~~bottlenecks~~impediments to effective management:

- The funding and manpower to monitor the multiple parameters across a large area.
- That there is ~~lots of~~much monitoring being undertaken to understand trends and potential impacts, but there is comparatively little being done to combat these (with the exception of flood defence, followed by managed realignment sites to combat coastal squeeze).
- Understanding the magnitude of any changes due to natural variation.
- Not having any guidance or precedence for managing or rather mitigating against changes in parameters such as pH and salinity. Given an understanding of estuarine hydrodynamics, there is relatively little that is possible to modify or reverse ~~If the~~ pH or salinity changes~~, what can reasonably and practically be done about it?~~.
- There are many objectives but fewer thresholds about when a change may require intervention, instead relying on expert judgement.

Overall, there appears to be a jump in these management systems: we have policy objectives and regulated targets to meet, and monitoring is being undertaken to inform progress, but there appears to be gaps regarding what these changes mean and what can be done about ~~it~~them. There are already a number of rigorous management and risk assessment frameworks available such as Environmental Impact Assessment (Lonsdale et al., 2017), Decision Support Systems (e.g. Lonsdale et al., 2018; 2015), the DAPSI(W)R(M) cause-consequence-response framework and the ISO standard Bowtie analysis (e.g. Elliott, *et al.*, 2017; Cormier *et al.*, 2019) ~~to name a few (see Lonsdale et al., 2015)~~ to help inform discussions. Despite this, ~~but~~ the regulators and environmental managers~~,~~ require government backing and support to make a difference (see also Lonsdale et al., 2015).

For instance, changes in temperature could increase the likelihood of non-native species inhabiting estuarine waters and this is complex to monitor, 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 become established (Olenin *et al.*, 2011). The relationship between the global and local scales is an ongoing challenge, particularly given the uncertainty surrounding the quantification of 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.

It appears that the Humber Estuary, has good vertical integration of governance from the local to ~~links from~~ global thereby facilitating ~~to local requirements to facilitate the implementation of~~ suitable management measures across all levels. However, ~~but~~ ideally, policies and legislative instruments, ~~including guidance,~~ should include prescriptive guidance for what thresholds indicate an issue e.g. approaching an action points (a reference condition, threshold, trigger or ~~-~~tipping point (Elliott et al., 2022~~REF~~), or what actions can be taken~~can be done about it e.g. changes in pH?~~. To ensure successful and sustainable development, the policies and strategies require to be tested rigourously, for example against ~~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. Hence, ~~As indicated in the 10 tenets,~~ wider education, and engagement of stakeholders (e.g. CEDA, 2012; Newton and Elliott, 2016) 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 the effects of individual managed realignment sites at the estuary level.

~~6~~5 Concluding Remarks

This paper details the potential challenges associated with managing vulnerable estuarine environments in the face of climate change. There are efforts by stakeholders to address some of the effects of climate change, but the ways in which estuaries are managed, from the local to the global scale~~globally to locally~~, needs to be improved~~improvement.~~. Given the complexity of the system, ranging from the natural to the societal, calls for a systems analysis approach (Elliott et al. 2020) and hence r~~R~~ecently developed decision support systems (e.g. Lonsdale *et al.*, 2018) give progress towards this end. The causes and effects of exogenic pressures combined in climate change are relevant from the local to the global, and co-ordination is needed across all levels to encourage effective, suitable, and sustainable management (Wolanski et al., 2019). In particular, while the causes need to be addressed at the global level, the consequence need addressing at the local level. Hence, t

~~T~~he link between the global and local needs to be considered within l~~L~~egislation 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).

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 must 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.~~the ~~bottlenecks~~impediments to effective and long term management against the potential harmful effects of climate change on the marine environment. The main bottleneck being the lack of resources, or rather the current inability to monitor all aspects of the estuarine waters and coastline, and the inability to currently address some of the effects. Many of the effects are wide-ranging and therefore it requires the culmination of mitigation measures on a scale larger than the estuary level to effectively mitigate against the effects. To do this, requires~~-~~ the use of frameworks to assess the potential impacts of any effects, the use of tools such as models, although their use is associated with limitations, and the integration of the governance structures, both vertically and horizontally.

There is extensive monitoring carried out on the Humber but monitoring is not a management measure but rather the means of determining whether management measures have been effective (Wolanski and Elliott, 2015; Elliott et al. 2022), and hence ~~: -~~we need to understand the physical, biological and chemical environment to inform management. A major gap is the availability of data to understand the magnitude of the effects of climate change and what can be done about it.

~~Furthermore, monitoring of change is required to determine whether management measures have had the desired effect.~~

As shown here, there is an increasing understanding of how our climate is changing, how environmental systems such as estuaries are affected, and the ways they can be managed to become more resistant and resilient through informed decision frameworks. Whilst ~~the use of~~ targets, ambitions and goals are useful tools to ensure issues relating to impacts from climate change are tackled, there is the risk that the focus is on meeting targets, will not address the ancillary issues, for example, at local or regional levels. 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.

Acknowledgements

Centre for Environment, Fisheries and Aquaculture Science for their financial support of their doctoral study of the first author and the Environment Agency and British Geological Survey for their financial support of the doctoral study of the second author. Dr Tom Coulthard for his input into the research development.

References

Agardy, T., Alder, J. 2005. Chapter 19 Coastal Systems IN: Sarukhan, J., Whyte, A. [Editors] 2005. Millennium Ecosystem Assessment. ISLAND PRESS Washington, USA. (Available from: https://www.millenniumassessment.org/en/Condition.html#download) [viewed 23/07/2021].

Andrello, M., Mouillot, D., Somot, S., Thuiller, W., Manel, S., 2015. Additive effects of climate change on connectivity between marine protected areas and larval supply to fished areas. Diversity and Distributions, 21(2):139-150.

Andrews, J.E., Burgess, D., Cave, R.R., Coombes, E.G., Jickells, T.D., Parkes, D.J. and Turner, R.K. 2006. Biogeochemical value of managed realignment, Humber estuary, UK. *Science of the total environment*, 371(1): 19-30.

Antonov, J.I., Levitus, S., Boyer, T.P. 2002. Steric sea level variations during 1957–1994: Importance of salinity, *Journal of Geophysical Research*, 107(C12): 14-1-14-8. DOI: 10.1029/2001JC000964

Antonson, H., Isaksson, K., Storbjörk, S., Hjerpe, M. 2016. Negotiating climate change responses: Regional and local perspectives on transport and coastal zone planning in South Sweden, *Land Use Policy*, 52: 297-305.

Apitz, S.E., Elliott, M., Fountain, M., Galloway, T.S. 2006. European environmental management: Moving to an ecosystem approach, *Integrated Environmental Assessment and Management*, 2(1): 80-85.

Australian Government. 2017. 2017 Review of Climate Change Policies December 2017. 54pp. (Available from: https://publications.industry.gov.au/publications/climate-change/system/files/resources/186/2017-review-of-climate-change-policies.pdf) [viewed 13/05/2020].

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R. 2011.The value of estuarine and coastal ecosystem services, *Ecological Monographs*, 81(2): 169-193.

Barnard, S., Elliott, M. 2015. The 10-tenets of adaptive management and sustainability: An holistic framework for understanding and managing the socio-ecological system, *Environmental Science and Policy*, 51: 181-191.

Becker, A., Ng, A.K., McEvoy, D. and Mullett, J., 2018. Implications of climate change for shipping: Ports and supply chains. Wiley Interdisciplinary Reviews: Climate Change, 9(2), p.e508.

Bentley, M.G. 2011. The Global Spread Of The Chinese Mitten Crab *Eriocheir Sinensis*. In in The Wrong Place - Alien Marine Crustaceans: Distribution, Biology And Impacts. Dordrecht: Springer Netherlands, 107–127.

Borja, Á, Elliott. M., Carstensen, J., Heiskanen, A-S., van de Bund, W. 2010. Marine management – towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. *Marine Pollution Bulletin* 60: 2175-2186.

Boyes, S., Elliott, M. 2015. The excessive complexity of national marine governance systems- Has this decreased in England since the introduction of the Marine and Coastal Access Act 2009? *Marine Policy*, 51: 57-65.

Boyes, S., Elliott, M. 2006. Organic matter and nutrient inputs to the Humber Estuary, England. *Marine Pollution Bulletin*, 53(1):136-143.

Brodie, J., Williamson, C.J., Smale, D.A., Kamenos, N.A., Mieszkowska, N., Santos, R., Cunliffe, M., Steinke, M., Yesson, C., Anderson, K.M., Asnaghi, V. 2014. The future of the northeast Atlantic benthic flora in a high CO2 world. *Ecology and Evolution*, 4(13): 2787-2798.

CEDA. 2012. Climate Change Adaptation As It Affects The Dredging Community. CEDA Position Paper. Available from: https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-05-ceda_positionpaper-climatechangeadaptation.pdf [viewed 21/05/2017].

Ciavola, P. 1997. Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK), *Catena,* Vol.30:4, Pages 369-389

Committee on Climate Change. 2019. Net Zero: The UK's contribution to stopping global warming. (Available from: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf) [viewed 23/07/2019]

Committee on Climate Change. 2017. Progress in preparing for climate change. 2017 Report to Parliament. Pp. 234. (Available from: https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf) [viewed 21/08/2017]

Cook, E.J., Jenkins, S., Maggs, C., Minchin, D., Mineur, F., nall, C., Sewell, J. 2013. Impacts of climate change on non-native species, *MCCIP Science Review 2013*, 155-166, doi:10.14465/2013.arc17.155-166

Cormier, R., Elliott, M., Rice, J. 2019. Putting on a Bow-tie to sort out who does what and why in the complex arena of marine policy and management. *Science of the Total Environment*, 648: 293-305. https://doi.org/10.1016/j.scitotenv.2018.08.168.

Cormier, R., Elliott, M. 2017. SMART marine goals, targets and management – is SDG 14 operational or aspirational, is 'Life Below Water' sinking or swimming? Marine Pollution Bulletin 123: 28-33; https://doi.org/10.1016/j.marpolbul.2017.07.060.

Creighton, C., Hobday, A.J., Lockwood, M., Pecl, G.T., 2016. Adapting management of marine environments to a changing climate: a checklist to guide reform and assess progress. Ecosystems, 19(2): 187-219.

Cripps, I.L., Munday, P.L., McCormick, M.I. 2011. Ocean Acidification Affects Prey Detection by a Predatory Reef Fish, *PLOSone*, doi: http://dx.doi.org/10.1371/journal.pone.0022736

Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Dauvin, J.C., De Mesel, I., Derweduwen, J., Gill, A.B., Hutchison, Z.L. 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES Journal of Marine Science, 77(3): 1092-1108.

Defeo, O, Elliott, M., (2021). Editorial - The 'Triple Whammy' of coasts under threat – why we should be worried! Marine Pollution Bulletin, 163: 111832. https://doi.org/10.1016/j.marpolbul.2020.111832

Defra. 2013. A Coastal Concordat for England. (Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256234/coastal-concordat-20131111.pdf). [Viewed 27/12/2017]

Defra. 2010. Adapting to climate change: A guide for local councils. 26pp. (Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/218798/adapt-localcouncilguide.pdf) [viewed 13/05/2020].

De Jonge, V.N., Elliott, M. 2001. Eutrophication. In: J Steele, S Thorpe & K Turekian (Eds.) *Encyclopaedia of Ocean Sciences*. Vol. 2, Academic Press, London.p852-870.

Department for Transport. 2012. National Policy Statement for Ports. 76pp. (available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf) [viewed 15/11/2018].

Dixon, D.L., Munday, P.L., Jones, G.P. 2009. Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues, *Ecology Letters*, 13(1): 68-75.

Donovan, B., Horsburgh, K., Ball, T. and Westbrook, G. 2013. Impacts of climate change on coastal flooding, *MCCIP Science Review 2013*, 211-218, doi:10.14465/2013. arc22.211-218

Ducrotoy, J.-P., Elliott, M., Cutts, N.D., Franco. A., Little. S., Mazik. K., Wilkinson. M. 2019. Temperate Estuaries: their ecology under future environmental changes. In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.), Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

Durant, J.M., Hjermann, D.Ø., Ottersen, G., Stenseth, N.C. 2007 Climate and the match or mismatch between predator requirements and resource availability, C*limate Research*, doi: http://dx.doi.org/doi:10.3354/cr033271

Dürr, H. H., G. G. Laruelle, C. M. van Kempen, C. P. Slomp, M. Meybeck, Middelkoop, H. 2011. Worldwide Typology of Nearshore Coastal Systems: Defining the Estuarine Filter of River Inputs to the Oceans. *Estuaries and Coasts*, 34(3): 441-458, doi:10.1007/s12237-011-9381-y.

Edwards, M., Bresnan, E., Cook, K., Heath, M., Helaouet, P., Lynam, C., Raine, R. and Widdicombe, C. 2013. Impacts of climate change on plankton, *MCCIP Science Review 2013*, 98-112, doi:10.14465/2013.arc12.098-112

Edwards, A.M.C., Winn, P.S.J. 2006. The Humber Estuary, Eastern England: Strategic planning of flood defences and habitats, *Marine Pollution Bulletin*, 53(1-4): 165-174.

Elliott, M., Houde, E.D., Lamberth, S.J., Lonsdale, J.-A., Tweedley, J.R., 2022. Chapter 12, Management of Fishes and Fisheries in Estuaries. In: Fish and Fisheries in Estuaries – A Global Perspective (ed., Whitfield, A.K., Able, K.W., Blaber, S.J.M. & Elliott, M.). John Wiley & Sons, Oxford, UK.

Elliott, M., Borja, A., Cormier, R. 2020. Managing marine resources sustainably: a proposed integrated systems analysis approach. Ocean & Coastal Management, 197, 105315, https://doi.org/10.1016/j.ocecoaman.2020.105315

Elliott, M., Quintino, V.M. 2019. The Estuarine Quality Paradox Concept. Encyclopaedia of Ecology, 2nd Edition, (Editor-in-Chief B Fath), Elsevier, Amsterdam, Volume 1, p78-85; ISBN: 978-0-444-63768-0. https://doi.org/10.1016/B978-0-12-409548-9.11054-1

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K. 2017. "And DPSIR begat DAPSI(W)R(M)!" - a unifying framework for marine environmental management. *Marine Pollution Bulletin*, 118 (1-2): 27-40. http://dx.doi.org/10.1016/j.marpolbul.2017.03.049.

Elliott, M., Mander, L., Mazik, K., Simenstad, C., Valesini, F., Whitfield, A., Wolanski, E. 2016. Ecoengineering with Ecohydrology: Successes and failures in estuarine restoration, *Estuarine, Coastal and Shelf Science*, 176: 12-35. doi: 10.1016/j.ecss.2016.04.003.

Elliott, M., Borja, Á., McWuatters-Gollop, A., Mazik, K., Birchenough, S., Anderson, J.H., Painting, S., Peck, M. 2015. *Force Majeure*: Will climate change affect our ability to attain Good Environmental Status for marine biodiversity, *Marine Pollution Bulletin*, 95(1):7-27.

Elliott, M. 2014. Integrated marine science and management: wading through the morass. *Marine Pollution Bulletin*, 86(1/2): 1-4. doi: 10.1016/j.marpolbul.2014.07.026

Elliott, M., Cutts, N.D., Trono, A. 2014. A typology of marine and estuarine hazards and risks as vectors of change: a review for vulnerable coasts and their management. *Ocean & Coastal Management*, 93: 88-99.

Elliott, M. 2013. The 10-tenets for integrated, successful and sustainable marine management, *Marine Pollution Bulletin*, 74: 1-5.

Elliott, M. 2011. Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures – a numbered guide. *Marine Pollution Bulletin*, 62: 651-655.

Elliott, M., Whitfield, A. 2011. Challenging paradigms in estuarine ecology and management, *Estuarine, Coastal & Shelf Science*, 94:306-314.

Elliott, M., Underwood, G., Wilkinson, M., Mazik, K., de Jonge, V.N., Dodge, G. 2008. Statement by the Expert Panel on the Eutrophic status of the Humber Estuary as Requested by the Environment Agency, December 2008

Elliott, M., McLusky, D.S. 2002 The need for definitions in understanding estuaries. *Estuarine, Coastal & Shelf Science*, 55(6) 815-827.

Environment Agency. 2005a. Humber Estuary Coastal Habitat Management Plan. Available from http://www.discoverysoftware.co.uk/FRaME/pdf/ChaMP.pdf [Viewed 05/08/2020].

Environment Agency. 2008. The Humber Flood Risk Management Strategy: Planning for the Rising Tides. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308281/Humber_Strategy_Summary.pdf [Viewed 17/07/2020].

European Commission. 2013. Guidelines on Climate Change and Natura 2000. 105pp. Available from: http://ec.europa.eu/environment/nature/climatechange/pdf/Guidance%20document.pdf [Viewed 09/02/2018].

Falconer, L., Hjøllo, S.S., Telfer, T.C., McAdam, B.J., Hermansen, Ø. and Ytteborg, E., 2020. The importance of calibrating climate change projections to local conditions at aquaculture sites. Aquaculture, 514, p.734487.

Feely, R.A., Alin, S.R., Newton, J., Sabine, C.L., Warner, M., Devol, A., Krembs, C., Maloy, C. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary, *Estuarine, Coastal and Shelf Science*, 88(4): 442-449.

Freestone, D., Jones, N., North, J., Pethick, J., Symes, D. and Ward, R. 1987. The Humber Estuary, Environmental Background, UK: Shell.

Garcia-de-Lomas, J., Dana, E.D., López-Santiago, J., González, R., Ceballos, G., Ortega, F., (2010) Management of the Chinese mitten crab, *Eriocheir sinensis* (H. Milne Edwards, 1853) in the Guadalquivir Estuary (Southern Spain), *Aquatic Invasions*, 5(3): 323-330.

Giffin, A.L., Brown, C.J., Nalau, J., Mackey, B.G. and Connolly, R.M., 2020. Marine and coastal ecosystem-based adaptation in Asia and Oceania: review of approaches and integration with marine spatial planning. Pacific Conservation Biology, 27(2), pp.104-117.

Gilbey, V., Attrill, M.J., Coleman, R.A. 2008. Juvenile Chinese mitten crabs (*Eriocheir sinensis*) in the Thames estuary: distribution, movement and possible interactions with the native crab *Carcinus maenas*, *Biological Invasions*, 10: 67-77.

Government of Canada. 2020. Policy Context: Considering Environmental Obligations and Commitments in Respect of Climate Change under the Impact Assessment Act. (Available from: https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/considering-environmental-obligations.html) [viewed 13/05/2020].

Government of Canada. 2018. Adaptation and climate resilience. Strengthening our communities to thrive in a changing climate. https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-actions-clean-growth-economy/adaptation-climate-resilience.html

Gross, J.E. 2003. Developing Conceptual Models for Monitoring Programs, (available from http://science.nature.nps.gov/im/monitor/docs/Conceptual_modelling.pdf) [viewed 21/10/13].

Hallegatte S, Ranger N, Mestre O, Dumas P, Corfee-Morlot J, Herweijer C, Wood RM. Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. Climatic change. 2011 Jan;104(1):113-37.

HM Government. 2018a. A Green Future: Our 25 Year Plan to Improve the Environment. 151pp. (Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf) [viewed 13/05/2020].

HM Government. 2018b. Strengthened Local Enterprise Partnerships. 30pp. (available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728058/Strengthened_Local_Enterprise_Partnerships.pdf) [viewed 15/11/2018].

HM Government. 2014. East Inshore and East Offshore Marine Plans. (available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312496/east-plan.pdf) [viewed 27/11/16].

HM Government. 2011. UK Marine Policy Statement, London: The Stationary Office.

Health Protection Agency. 2012. Health Effects of Climate Change in the UK 2012. Current evidence, recommendations and research gaps. Pp. 242. (Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/371103/Health_Effects_of_Climate_Change_in_the_UK_2012_V13_with_cover_accessible.pdf) [Viewed 21/08/3027]

Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung, 2014: The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.

Humber Nature Partnership. 2017. Investing in Natural Capital. Creating the right environment for economic investment. (Available from: http://humbernature.co.uk/admin/resources/investing-in-natural-capital.pdf) [Viewed 21/08/2017]

IMO. 2020. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx

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, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jarvie, H.P., Neal, C., Robson, A.J. 1997. The geography of the Humber catchment, *Science of the Total Environment*, 194: 87-100.

Johns, D., Smalls, M., Maslen, S. 2010. Coastal Schemes with Multiple Funders and Objectives FD2635. Case Study Report 1 Alkborough Flats Tidal Defence Scheme. 10pp.

Jones, L., Garbutt, A., Hansom, J., Angus, S. 2013. Impacts of climate change on coastal habitats, *Marine Climate Change Impacts Partnership: Science Review*, pp. 167-179.

Kelly, C., Gray, L., Shucksmith, R.J., Tweddle, J.F. 2014. Investigating options on how to address cumulative impacts in marine spatial planning, *Ocean and Coastal Management*, 102: 139-148.

Klein, S.A., Soden, B.J. and Lau, N.C. 1999. Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *Journal of Climate*, 12(4): 917-932.

Klemetsen, A., Amundsen, P-A., Dempson, J.B., Jonsson, N., O'Connell, M.F., Mortensen, E. 2003. Atlantic salmon Salmo salar L., brown trout Salmo trutta L. and Arctic charr Salvelinus alpinus (L.): a review of aspects of their life histories*, Ecology of Freshwater Fish*, Vol. 12:1, DOI: 10.1034/j.1600-0633.2003.00010.x

Kroeger, K.D., Anderson, I., Baldwin, S., Brooks, W., Brush, M., Cai, W.J., Canuel, E., Casso, M., Chen, R., Green, A. and McCallister, L., 2012. Fluxes in tidal wetlands. In *Report of The US East Coast Carbon Cycle Synthesis Workshop* (pp. 5-7). Gloucester Point, VA: Virginia Institute of Marine Sciences.

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M. and Gattuso, J.P., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global change biology*, 19(6), pp.1884-1896.Little, S., Wood, P.J, Elliott, M. (in press). Quantifying salinity-induced changes on estuarine benthic fauna: The potential implications of climate change. *Estuarine, Coastal and Shelf Science*, in press.

Lonsdale, J., Nicholson, R., Weston, K., Elliott, M., Birchenough, A., Sühring, R., 2018. A user's guide to coping with estuarine management bureaucracy: An Estuarine Planning Support System (EPSS) tool. *Marine Pollution Bulletin*, 127: 463-477.

Lonsdale, J., Weston, K., Elliott, M., Blake, S., Edwards, R. 2017. The Amended European Environmental Impact Assessment Directive: UK Marine Experience and Recommendations. *Ocean and Coastal Management*, 148: 131-142.

Lonsdale, J-A., Weston, K., Barnard, S., Boyes, S., Elliott, M. 2015. Integrating Management Tools and Concepts to Develop an Estuarine Planning Support System: A case study of the Humber Estuary, Eastern England, Marine Pollution Bulletin, 100(1): 393-405.

Lonsdale, J. 2013. The Potential Uses of Dredged Material in the Humber Estuary, MSc Thesis, University of Hull funded by TiDE (available from: http://www.tide-project.eu/downloads/Pilot_project_Humber_estuary.pdf) [viewed 29/05/2015]

Maitland, P.S. 2003. Ecology of the River, Brook and Sea Lamprey. Conserving Natura 2000 Rivers Ecology Series No. 5. English Nature, Peterborough.

Mander, L., Cutts, N.D., Allen, J., Mazik, K. 2007. Assessing the development of newly created habitat for wintering estuarine birds, *Estuarine, Coastal and Shelf Science*, 75(1-2): 163-174.

Mansanet-Bataller, M. 2010. The Challenges of Adapting to Climate Change. Climate Report. No. 21. Availble from: http://www.cdcclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate_change.pdf [Viewed 21/05/2017]

Masselink, G., Russell, P. 2013. Impacts of climate change on coastal erosion, *MCCIP Science Review 2013*, Psges 71-86, doi:10.14465/2013.arc09.071-086

Mazik, K., Solyanko, E., Elliott, M. & De Jonge, V.N. 2009. Summary of microalgal species composition and water quality in the Humber Estuary, Report to Environment Agency. Institute of Estuarine and Coastal Studies, University of Hull, 26 March 2009, Report: YBB133-D1-2009.

Mazik, K., Thomson, S., Elliott, M., Solyanko, K., Phelps, A. 2008. CASI ground truth surveys — Humber estuary 2008, Report to Environment Agency, Institute of Estuarine and Coastal Studies, University of Hull, 8th December 2008.

MCCIP. 2017. Annual Report Card. (Available from: http://www.mccip.org.uk/media/1770/mccip-report-card-2017-final-artwork-spreads.pdf) [viewed 21/08/2017.

MCCIP. 2013. Annual Report Card. Available from: http://www.mccip.org.uk/annual-report-card/2013/climate-of-the-marine-environment/ [Viewed 21/01/2017].

McCormick, S.D., Hanse, L.P., Quinn, T.P., Saunders, R.L. 1998. Movement, migration, and smelting of Atlantic salmon (*Salmo salar*), Movement, migration, and smolting of Atlantic salmon (*Salmo salar*), *Canadian Journal of Fisheries and Aquatic Sciences*, 55 (1): 77-92.

Mee, L.D., Jefferson, R.L., Laffoley, D., Elliott, M. 2008. How good is good? Human values and Europe's proposed Marine Strategy Directive, *Marine Pollution Bulletin*, 56: 187-204.

Metcalfe, S.E., Ellis, S., Horton, B.P., Innes, J.B., McArthur, J., Mitlehner, A., Parkes, A., Pethick, J.S., Rees, J., Ridgway, J., Rutherford, M.M., Shennan, I., Tooley, M.J. 2000 The Holocene evolution of the Humber Estuary: reconstructing change in a dynamic environment, *Geological Society, London, Special Publications*, 175: 253-279

Mieszkowska, N., Firth, L., Bentley, M. 2013 Impacts of climate change on intertidal habitats, *MCCIP Science Review 2013*, 180-192, doi:10.14465/2013.arc19.180-192

Miller, D.D., Ota, Y., Sumaila, U.R., Cisneros‐Montemayor, A.M., Cheung, W.W.L. 2017. Adaptation strategies to climate change in marine systems. *Global Change Biology*, 24 (1): e1-e14. https://doi.org/10.1111/gcb.13829

MMO. 2016. Potential spatial effects of climate change in the South and East Marine Plan Area. MMO Project Number 1077. 136pp.

Munday, P.L., Dixson, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O., Chivers, D.P. 2010. Replenishment of fish populations is threatened by ocean acidification, *Proceedings of the National Academy of Sciences of the United States of America*, 107(29): 12930-12934.

Munday, P.L., Dixson, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V., Døving, K.B. 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish, *Proceedings of the National Academy of Sciences of the United States of America*, 106(6): 1848-1852.

Newton A and Elliott M (2016) A Typology of Stakeholders and Guidelines for Engagement in Transdisciplinary, Participatory Processes. Front. Mar. Sci. 3:230. doi: 10.3389/fmars.2016.00230

Nunn, A.S., Harvey, J.P., Noble, R.A.A., Cowx, I.G. 2008. Condition assessment of lamprey populations in the Yorkshire Ouse catchment, north-east England, and the potential influence of physical migration barriers; *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18: 175-189.

Olenin, S, Elliott, M, Bysveen, I, Culverhouse, P, Daunys, D, Dubelaar, GBJ, Gollasch, S, Goulletquer, P, Jelmert, A, Kantor, Y, Mézeth, KB, Minchin, D, Occhipinti-Ambrogi, A, Olenina, I, Vandekerkhove, J. 2011. Recommendations on methods for the detection and control of biological pollution in marine coastal waters. *Marine Pollution Bulletin*, 62(12): 2598-2604.

OSPAR Commission. 2010. The North-East Atlantic Environment Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2010–2020 (OSPAR

Agreement 2010-3). Pp27. (Available from: https://www.ospar.org/site/assets/files/1200/ospar_strategy.pdf) [viewed 13/05/2020].

OSPAR. 2009. Eutrophication Status of the OSPAR Maritime Area: Second OSPAR Integrated Report. 108pp. Available from: www.ospar.org/documents?d=7107 [viewed 26/03/2017]

Painting, S., Foden, J., Forster, R., van der Molen, J. Aldridge, J., Best, M., Jonas, P, Walsham, P., Webster, L., Gubbins, M., *et al.* 2013 Impacts of climate change on nutrient enrichment, *MCCIP Science Review 2013*, 219-235, doi:10.14465/2013. arc23.219-235

Pankhurst. N.W., Munday, P.L. 2011. Effects of climate change on fish reproduction and early life history stages, *Marine and Freshwater Research*, 62: 1015-1026.

Passeri, D.L., Hagen, S.C., Medeiros, S.C., Bilskie, M.V., Alizad, K., Wang, D. 2015 The dynamic effects of sea level rise on low-gradient coastal landscapes: A review, *Earth's Future*, 3(6):159-181.

Peck, M.A., Arvanitidis, C., Butenschon, M., et al. 2018. Projecting changes in the distribution and productivity of living marine resources: a critical review of the suite of modelling approaches used in the large European project VECTORS. Estuarine, Coastal and Shelf Science 201, 40–55.

Pinnegar, J.K., Cheung, W.W.L., Jones, M., Merino, G., Turrell, B., Reid, D. 2013 Impacts of climate change on fisheries. *MCCIP Science Review 2013*, 302-317, doi:10.14465/2013. arc32.302-317

Potter, I.C., Chuwen, B.M., Hoeksema, S.D., Elliott, M. 2010. The concept of an estuary: a definition that incorporates systems which can become closed to the ocean and hypersaline. Estuarine, Coastal & Shelf Science, 87: 497–500.

Pörtner, H.O., Knust, R. 2007. Climate Change Affects Marine Fishes Through the Oxygen Limitation of Thermal Tolerance, *Science*, 315(5808): 95-97.

Rasmussen, E. 1973. Systematics and ecology of the Isefjord marine fauna (Denmark). *Ophelia*, 11(1): 1-507.

Raynor, P. 2014. The Humber Estuary Flood Risk Management Strategy: Summary Strategy and Business Case. 54pp. Available at: http://www2.eastriding.gov.uk/EasySiteWeb/GatewayLink.aspx?alId=592095. [Viewed 26/01/2017]

Raynor, P., Chatterton, J. 2014. Flood Defences Cost Money, No Defences Cost More: an Economic Case for the Humber and United Kingdom. Report Prepared on Behalf of the Humber Parlimentarians, Local Authorities and the Humber Local Enterprise Partnership. Available at: http://www.floodcba.eu/main/wp-content/uploads/Flood-Risk-Management-Investing-in-thefuture-of-the-Humber-Estuary.pdf [Accessed January 28, 2016].

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, Wang. F. 2013. Observations: Ocean. 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, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Roberts, D.A., Birchenough, S.N., Lewis, C., Sanders, M.B., Bolam, T., Sheahan, D. 2013. Ocean acidification increases the toxicity of contaminated sediments. *Global change biology*, 19(2): 340-351.

Robins, P. 2019. Changing hydrology. In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.), Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

Robins, P.E., Skov, M.W., Lewis, M.J., Giménez, L., Dacies, A.G., Malham, S.K., Neill, S.P., McDonald, J.E., Whitton, T.A., Jackson, S.E., Jago, C.F. 2016. Impact of climate change on UK estuaries: A review of past trends and potential projections, *Estuarine, Coastal and Shelf Science*, 169: 119-135.

Rosselló-Nadai, J. 2014. How to evaluate the effects of climate change on tourism, *Tourism Management*, 42:334-340.

Santos, C.F., Ehler, C.N., Agardy, T., Andrade, F., Orbach, M.K. and Crowder, L.B., 2019. Marine spatial planning. In World seas: an environmental evaluation (pp. 571-592). Academic Press.

Saul, R, Barnes, R, Elliott, M. 2016. Is climate change an unforeseen, irresistible and external factor – a force majeure in marine environmental law? *Marine Pollution Bulletin*, 113: 25-35.

Secretariat of the Convention on Biological Diversity. 2004. The Ecosystem Approach, ISBN: 92-9225-023-x (available online at: https://www.cbd.int/doc/publications/ea-text-en.pdf) [Viewed 09/07/2017]

Sheahan, D., Maud, J., Wither, A., Moffat, C. and Engelke, C. 2013. Impacts of climate change on pollution (estuarine and coastal). *MCCIP Science Review 2013*, 244-251, doi:10.14465/2013.arc25.244-251

Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., & Rutherford, M. 2000. Holocene isostasy and relative sea-level changes on the east coast of England. *Geological Society*, London, Special Publications, 166(1): 275–298.

Simpson, M. 2013. Impacts of climate change on tourism (and marine recreation), *MCCIP Science Review 2013*, 271- 283, doi:10.14465/2013.arc29.271-283

Skinner, C. J., T. J. Coulthard, D. R. Parsons, J. A. Ramirez, L. Mullen, Mason, S. 2015. Simulating tidal and storm surge hydraulics with a simple 2D inertia based model, in the Humber Estuary, UK, *Estuarine Coastal Shelf Science*., 155, 126–136, doi:10.1016/j.ecss.2015.01.019.

Solomon, Susan, ed. Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC. Vol. 4. Cambridge University Press, 2007.

Townsend, M., Thrush, S.F., Carbines, M.J. 2011 Simplifying the complex: an "Ecosystem Principles Approach" to goods and services management in marine coastal ecosystems, *Marine Ecology Progress Series, Volume* 434: 291-301.

Tunstall, S., Tapsell, S., Green, C., Floyd, P., George, C. 2006. The health effects of flooding: social research results from England and Wales, *Journal of Water and Health*, 4(3):365-380.

Turley, C, Findlay, HS, Mangi, S, Ridgwell, A and Schimdt, DN. 2009. CO2 and ocean acidification in Marine Climate Change Ecosystem Linkages Report Card 2009. (Eds. Baxter JM, Buckley PJ and Frost MT), Online science reviews, 25pp.

Turner, R.K., Schaafsma, M. (Eds.) 2015. Coastal zones ecosystem services: from science to values and decision making. Springer Ecological Economic Series, Springer Internat. Publ. Switzerland, ISBN 978-3-319-17213-2.

UNCLOS. 1982. United Nations Convention on the Law of the Sea of 10 December 1982. Available from: https://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm

United Nations. 2011. Framework Convention on Climate Change Decisions adopted by the Conference of the Parties. 31pp. (Available from: https://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf) [viewed 13/05/2020].

United Nations. 1998. KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. 21pp. (Available from: https://www.kyotoprotocol.com/resource/kpeng.pdf) [viewed 13/05/2020].

United Nations. 1992. UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. (Available from: https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf) [viewed 13/05/2020].

Vézina, A., Hoegh-Guldberg, O. 2008. Effects of ocean acidification on marine ecosystems. *Marine Ecology Progress Series*, 373: 199-201.

Wadey, M.P., Roberts, H. and Harris, J. 2013. Impacts of climate change on built structures (onshore and coastal), *MCCIP Science Review 2013*, 284-294, doi:10.14465/2013. arc30.284-294

Wadhams, P., Munk, W. 2004. Ocean freshening, sea level rising, sea ice melting, *Geophysical Research Letters*, Vol. 31:11. doi:10.1029/2004GL020039

Waterkeyn, A., Vanschoenwinkel, B., Vercampt, H., Grillas, P., Brendonck, L. 2011. Long-term effects of salinity and disturbance regime on active and dormant crustacean communities, *Limnology and Oceanography*, Vol. 56:3, Pages 1008-1022

Whitfield, A.K., Elliott, M., Basset, A., Blaber, S.J.M., West, R.J. 2012. Paradigms in estuarine ecology- A review of the Remane diagram with a suggested revised model for estuaries, *Estuarine, Coastal and Shelf Science*, 97: 78-90.

Whitfield, A.K., Elliott, M. 2011. Chapter 1.07: Ecosystem and Biotic Classifications of Estuaries and Coasts. In: Volume 1, Classification of Estuarine and Nearshore Coastal Ecosystems, C Simenstad and T Yanagi (Eds), In: E Wolanski & McLusky, DS (Eds) *Treatise on Estuarine & Coastal Science*, Elsevier, Amsterdam, pp.99-124.

Winn, P.J.S., Young, R.M., Edwards, A.M.C 2003. Planning for the rising tides: the Humber Estuary Shoreline Management Plan, *Science of The Total Environment*, 314-316: 13-30.

Wittmann, A.C., Pörtner, H.O. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change*, 3(11): 995.

Wright P. Impacts of climate change on ports and shipping. MCCIP Sci. Rev. 2013:263-70.

Woodward, S. (2010). The Economic Potential of Nature Tourism in Eastern Yorkshire. (retrieved 04/10/17 from https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiMq9TpxtbWAhUEaFAKHYtpCpIQFggrMAA&url=http%3A%2F%2Fmediafiles.thedms.co.uk%2FPublication%2FYS-EY%2Fcms%2Fpdf%2FYNT%2520ICRT%2520Report%252C%2520Nature%2520Tourism%2520in%2520Eastern%2520Yorkshire.pdf&usg=AOvVaw1JJ8E-dXhv8qvIO1xDfQAY)

Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.) 2019. Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

Wragg, S. 2014. Hull City Council Flood Investigation Report: December 2013 City Centre Tidal Surge Event. Report to the Environment & Transport Overview and Scrutiny Committee, Hull City Council, 4th February 2014. (accessible from https://cmis.hullcc.gov.uk/cmis/Meetings/tabid/70/ctl/ViewMeetingPublic/mid/397/Meeting/291/Committee/64/SelectedTab/Documents/Default.aspx accessed February 16, 2017)

Wright, P. 2013. Impacts of climate change on ports and shipping, *MCCIP Science Review 2013*, 263-

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.” (Elliott and Whitfield, 2011), with more specific classifications often used to describe the characteristics of individual systems (Potter at al., 2010; Whitfield and Elliott, 2011). Given their location, connections and resources, estuaries are hotspots for many urban, industrial and recreational activities, which can provide a significant contribution to the economy (Lonsdale *et al.*, 2015; Elliott and Whitfield, 2011). They also support an abundant and functionally large but not necessarily diverse range of flora and fauna and many typically 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; Defeo & Elliott 2021). 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 and challenging 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 summarises the relevant impacts from climate change on estuarine systems and how the effects of climate change are currently being managed and governed locally, regionally and globally through legislative measures (Section 2). The sufficiency or appropriateness of the legislative framework and regional rules for protecting an estuary, using the Humber Estuary as a case study, against the effects of climate change are explored (Section 3) and, as a result, recommendations are made as to how policies can, or should be modified or improved (Section 4).

2 Climate Change and Management and Governance: The Global Challenge

Understanding the impact that climate change has on 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 and concomitant changes in temperature, sea level rise, and increasing storminess (IPCC, 2013) (see Figure 1).

In addition to these threats, there is a threat to socio-economics (summarised in Figure 1): the urban and industrialised coastal and estuarine areas 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) are likely to be affected. The increase in sea level 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 (see Tunstall et al. 2006).

Wright (2013) noted that 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 (supported by Becker et al., 2018; Hallegatte et al., 2011). Most notably, changes to the physiography and hydrodynamics could alter the system sediment budget and change the morphology of navigable channels, thereby affecting shipping 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 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, thus positively impacting the economy (Rosselló-Nadai, 2014). For example, along coastlines globally, and particularly in estuaries, these sites are often for recreation, including bird watching, walking, sailing routes etc. given their coastal location (Lonsdale et al., 2015; Agardy and Alder, 2005) and could see increased visitor numbers as the climate warms and the summer period extends (Rosselló-Nadai, 2014).

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 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 creating factors outside the control of local managers (a force majeure) again giving rise to challenges (Elliott et al., 2015; Saul et al., 2016) and lead to moving baselines against which management of static features may be judged. 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).

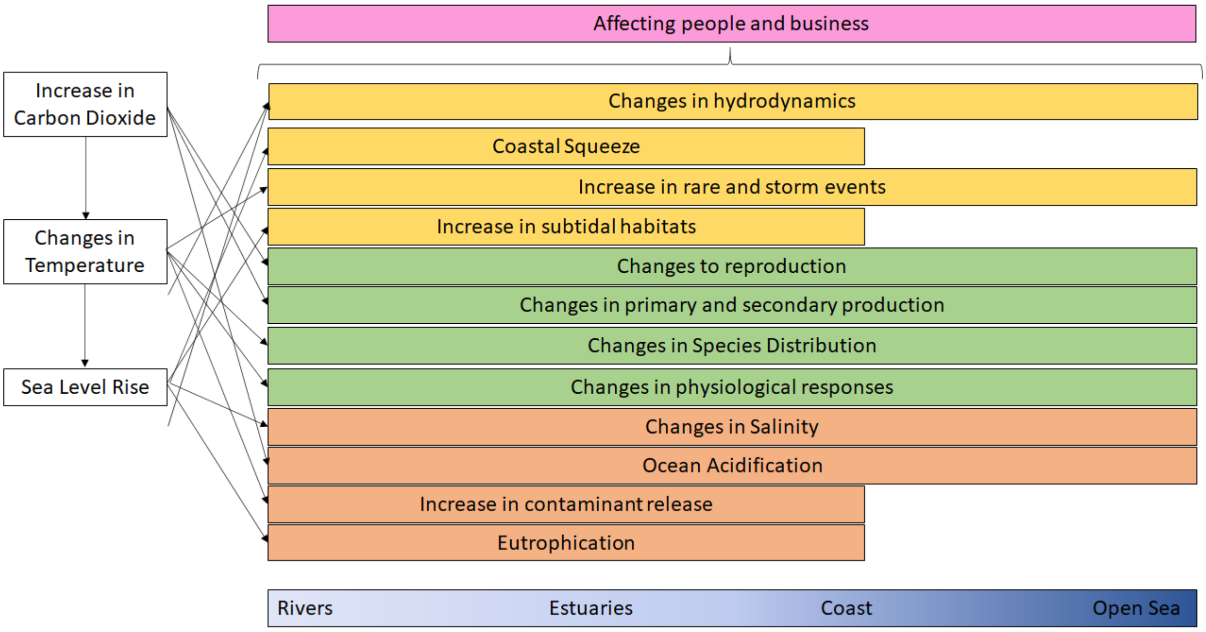

Figure 1 Impacts of climate change showing the drivers (on the left) and where these impacts are most likely to occur or have the greater impact (blue horizontal box along the bottom). Orange boxes represent chemical changes; green represent biological changes; yellow boxes represent physical changes;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

Estuaries are managed through many legislative instruments at 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. However, 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). These international treaties set the minimum standard, for example, for environmental protection. Countries can implement higher standards of [marine] environmental protection, but not less. Here we briefly provide an overview of these overarching protection measures as they influence regional, national and local management measures.

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 ‘Life below water’ 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. However, it is questioned whether these targets are operationally satisfactory (Cormier & Elliott 2017).

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). 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. For example, the European Commission sets out Directives which, as with global treaties, set the minimum requirements. Under the European Directive for Environmental Impact Assessments (2014/52/EC), 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).

Similarly, UNEP Regional Seas Conventions, such as 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), are aimed at protecting marine areas used by multiple countries as a shared resource. The OSPAR North-East Atlantic Environment Strategy 2020 states 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 marine and coastal 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 treaties set out what is expected, and the national legislation stipulates what can and cannot be done legally to meet the international obligations. For example, in the UK, the Climate Change Act 2008 is an Act of Parliament under which the Secretary of State should ensure, amongst other provisions, that the net UK carbon emissions (including from all six greenhouses gases targeted by the Kyoto Protocol) by 2050 are at least 100% lower than the 1990 baseline. Additionally, an independent UK Committee on Climate Change has been created under the Act to provide advice to UK Government on these targets and related policies. The specific aspects relating to the Humber Estuary, eastern England are explored in Section 3.

The above management measures generally consider geographic scope and scale, and it is only at the local level where estuarine specific aspects are 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).

Environmental management in estuaries, as with all other environments, needs to cover horizontal integration, across all the stakeholders in an area, and vertical integration from the local , national and regional to global level obligations. This requires that managers, regulators, and decision makers are in place and that independent reviews of the governance are completed, i.e. a regulatory impact assessment. However, governance structures, especially for the marine environment, are often complex with overlapping roles and responsibilities (Lonsdale et al., 2015; Boyes & Elliott, 2015). 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 environmental (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 stakeholders across 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 (see Section 3 for those relevant to the Humber Estuary) that manage a marine area and activities. Hence, cross-agency communication, with shared visions and agreements is key for effective marine management.

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

To explore the sufficiency or appropriateness of the legislative framework and regional rules for protecting an estuary against the effects of climate change, we take the 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 (North) sea (Figure 2). It is one of the busiest and fastest growing areas for seaborne trade in Europe 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.

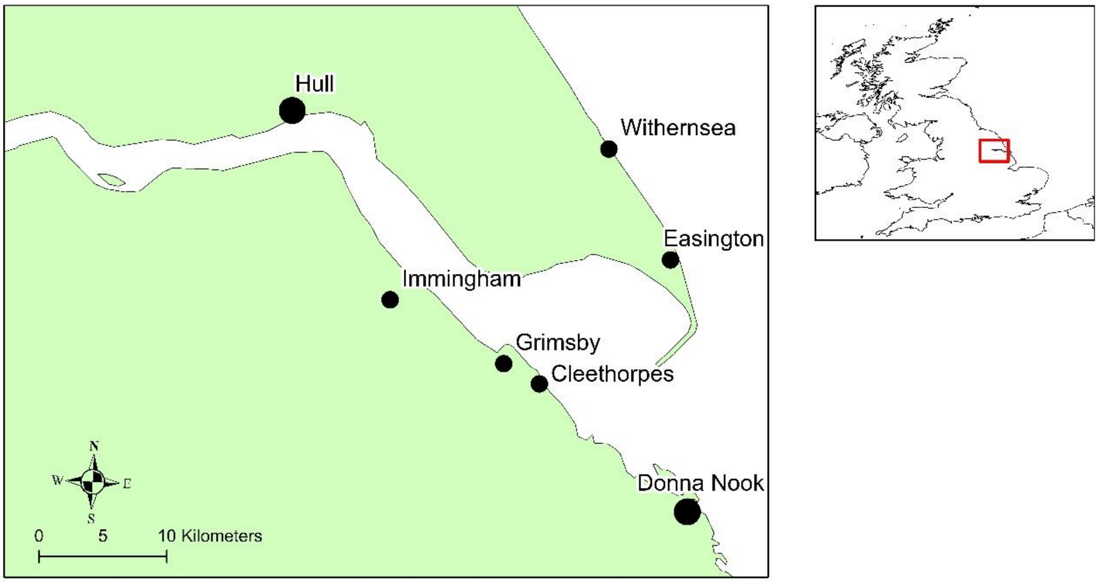

Figure 2 Case Study area

Given the nature conservation importance of the 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 tourism and leisure opportunities (Freestone et al., 1987).

Almost 235 km of defences protect the Humber's environmental, social, and economic assets, including managed realignment sites such as Alkborough Flats and other ecoengineering initiatives (Winn et al., 2003; Elliott et al., 2016). However, the storm surge that caused widespread flooding around the estuary in December 2013 (Wragg, 2014), led to the questioning that the estuary management needs improving. The Humber Estuary, like many other estuaries, is susceptible to the effects of climate change and this needs to be considered when management strategies are developed (Wolanski et al., 2019).

3.1 Managing Climate Change Impacts

The Humber Estuary is vulnerable to all the potential impacts of Climate Change identified in section 3, but it is important to consider how these impacts manifest at the site-specific level. Table 1 summarises the physical, chemical, and biological effects relevant to the Humber Estuary. The Humber

Estuary is managed through many legislative instruments, from international, to European, national, and regional levels, including voluntary codes of conduct. Hence, management measures within the Humber Estuary are designed to combat the effects of climate change, such as management realignment sites or setting back or raising flood defences (Elliott et al., 2016). This leads to the question of how future proof are these methods especially given any time lag and inertia in the system. The efficacy of management measures aimed at tackling climate change impacts is determined by monitoring such as salinity, species distribution or contamination.

In Section 2, we highlighted the international conventions which set out the requirement for countries to do something, here we look at the specific requirements for managing a relatively small site in comparison to the global treaties jurisdiction.

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- this is important when considering ongoing (e.g., shipping) or new (e.g., power stations) developments. 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 used a cost-benefit analysis to implement 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). It is of note that those not protected live at sites where the cost-benefit analysis would have indicated that protection is prohibitively expensive given the value of assets protected. See Figure 3 for a visualisation of the Humber relevant management measures.

To determine the sufficiency of the legislative framework and/or the organisations responsible, the potential impacts highlighted in Section 2, were considered in terms of what (legislation) and who (authorities) is responsible for managing these impacts (Table 1).

Many of the responsibilities for monitoring and managing the impacts of climate change within the estuary appear to fall onto the Environment Agency, the English environmental protection agency (in the UK, Scotland, Wales and Northern Ireland have their own bodies as devolved agencies). However, some specific responsibility falls to others, such as the Marine Management Organisation (for assessing new development applications) or Local Authorities, and even private organisations, for the maintenance of some flood defences (see Figure 3). Vertical and horizontal integration between these legislative instruments and responsible organisations 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.

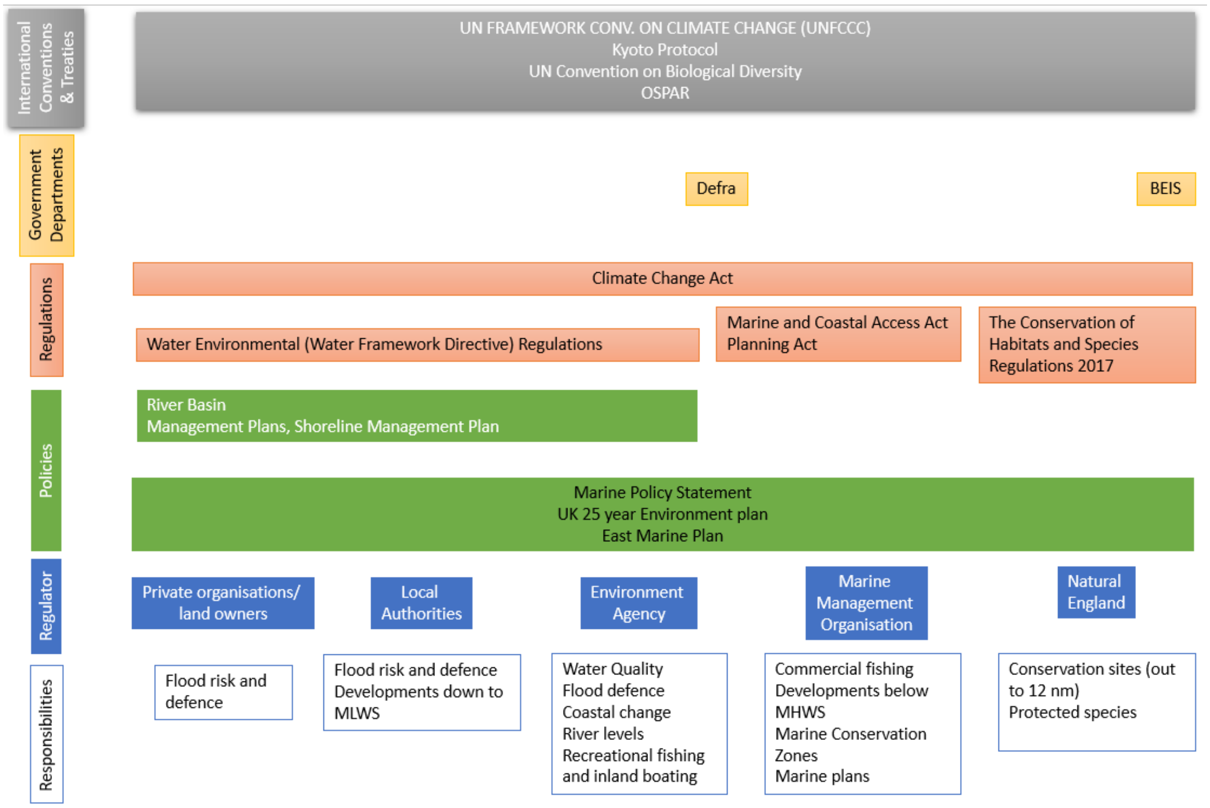

Figure 3 Visualisation of the horizontal and vertical governance of the Humber Estuary specific to estuarine waters management.

A potential weakness in assessing the potential impacts from climate change and the legislative instruments is the task of monitoring for the potential impacts of climate change which may be prohibitively expensive for many organisations. In most cases, it falls solely on the Environment Agency, although there is acknowledgement that other forms of monitoring, such as condition monitoring of the nature conservation features and compliance monitoring for ongoing developments

(Elliott et al., 2022). Models can inform how an area may be impacted by climate change (Falconer et al., 2020), but they have caveats and their spatial and temporal predictability, both from deterministic and empirical modelling, gives them limited use in prioritising areas for monitoring. End-to-end models which link changes to the natural environment with the socio-economic repercussions (Peck et al., 2018) have the potential for use but require expensive parameterisation for individual areas. Hence, to inform management strategies, we need robust modelling 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, national policy could be more aligned to the UK's responses (both environmental and management) to climate change impacts.

The review in Table 1 also indicates that there is little in the way of preparatory or proactive mitigation measures to combat when, and if, thresholds for biological impacts are reached for example, what is to happen when there is a salinity shift? Is there anything that can be done to offset or mitigate the changes?

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?	Potential for impact	What is(are) the policy (or policies) addressing the climate change effects	What is(are) the agency (or agencies) implementing the policy (policies)?	What are the major bottlenecks that the executing agency (or agencies) face for successful policy implementation	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.	River Basin Management Plans, Shoreline Management Plan, Water Environmental (Water Framework Directive) Regulations,	Environment Agency. Local Authorities. Private landowners	Funding and man power to monitor, maintain and where required, create or improve sea defences along a vast coastline.	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)	This is likely to be high magnitude. The Humber estuary has multiple sites	River Basin Management Plans, Shoreline Management Plan, Water Environmental (Water Framework Directive) Regulations,	Environment Agency. Natural England (for compensation sites under Habitats Regulations Assessment)	Funding and man power to monitor coastal squeeze, and then to create, monitor and manage managed realignment 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	There is no consensus on the magnitude of these impacts.	Water Environmental (Water Framework Directive) Regulations,	Environment Agency	Funding and manpower to monitor pH changes to the extent that natural variability can be included in any assessment. There is currently no precedence for increase pH nor an agreed threshold of when a pH may cause biological impacts.	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

		Affect species physiological and behavior responses					
	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	There is no consensus on the magnitude of these impacts.	Water Environmental (Water Framework Directive) Regulations,	Environment Agency	Funding and manpower to monitor pH changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing salinty nor an agreed threshold of when a salinity level may cause biological impacts.	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	There is no consensus on the magnitude of these impacts.	Water Environmental (Water Framework Directive) Regulations, Marine and Coastal Access Act	Environment Agency Sediment contamination is also considered by the Marine Management Organization.	Funding and manpower to monitor contaminant changes. Limited resource to tackle increases in water contamination.	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.	Water Environmental (Water Framework Directive) Regulations	Environment Agency	Funding and manpower to monitor all potential water quality characteristics and their changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing nor an agreed threshold of	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

						when levels may cause biological impacts.	
	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.	Water Environmental (Water Framework Directive) Regulations	Environment Agency	Funding and manpower to monitor all potential water quality characteristics and their changes to the extent that natural variability can be included in any assessment. There is currently no precedence for managing nor an agreed threshold of when levels may cause biological impacts.	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	There is no consensus on the magnitude of these impacts.	Water Environmental (Water Framework Directive) Regulations	Environment Agency.	Funding and man power to monitor along a vast coastline and water columns to identify and monitor non-native species presence.	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	There is no consensus on the magnitude of these impacts. Management is restricted to monitoring the distribution of species and physiological responses	Water Environmental (Water Framework Directive) Regulations	Environment Agency	Funding and manpower to monitor all potential water quality characteristics and their changes to the extent that natural variability can be included in any assessment.	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.

		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.	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			There is currently no precedence for managing nor an agreed threshold of when levels may cause biological impacts.	

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, we have assessed that the Humber Estuary requires the managers and regulators to work together, even where there are competing targets, but we have also identified (from Table 1) the impediments to effective management:

- The funding and manpower to monitor the multiple parameters across a large area.
- That there is much monitoring being undertaken to understand trends and potential impacts, but there is comparatively little being done to combat these (with the exception of flood defence, followed by managed realignment sites to combat coastal squeeze).
- Understanding the magnitude of any changes due to natural variation.
- Not having any guidance or precedence for managing or rather mitigating against changes in parameters such as pH and salinity. Given an understanding of estuarine hydrodynamics, there is relatively little that is possible to modify or reverse pH or salinity changes.
- There are many objectives but fewer thresholds about when a change may require intervention, instead relying on expert judgement.

Overall, there appears to be a jump in these management systems: we have policy objectives and regulated targets to meet, and monitoring is being undertaken to inform progress, but there appears to be gaps regarding what these changes mean and what can be done about them. There are already a number of rigorous management and risk assessment frameworks available such as Environmental Impact Assessment (Lonsdale et al., 2017), Decision Support Systems (e.g. Lonsdale et al., 2018; 2015), the DAPSI(W)R(M) cause-consequence-response framework and the ISO standard Bowtie analysis (e.g. Elliott, *et al.*, 2017; Cormier *et al*., 2019) to help inform discussions. Despite this, the regulators and environmental managers require government backing and support to make a difference (see also Lonsdale et al., 2015).

For instance, changes in temperature could increase the likelihood of non-native species inhabiting estuarine waters and this is complex to monitor, 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 species that become established (Olenin *et al.*, 2011). The relationship between the global and local scales is an ongoing challenge, particularly given the uncertainty surrounding the quantification of 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.

It appears that the Humber Estuary, has good vertical integration of governance from the local to global thereby facilitating suitable management measures across all levels. However, ideally, policies and legislative instruments, should include prescriptive guidance for what thresholds indicate an issue e.g. approaching an action points (a reference condition, threshold, trigger or tipping point (Elliott et al., 2022), or what actions can be taken. To ensure successful and sustainable development, the policies and strategies require to be tested rigourously, for example against 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. Hence, wider education, and engagement of stakeholders (e.g. CEDA, 2012; Newton and Elliott, 2016) 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 the effects of individual managed realignment sites at the estuary level.

5 Concluding Remarks

This paper details the potential challenges associated with managing vulnerable estuarine environments in the face of climate change. There are efforts by stakeholders to address some of the effects of climate change, but the ways in which estuaries are managed, from the local to the global scale, needs to be improved. Given the complexity of the system, ranging from the natural to the societal, calls for a systems analysis approach (Elliott et al. 2020) and hence recently developed decision support systems (e.g. Lonsdale *et al.*, 2018) give progress towards this end. The causes and effects of exogenic pressures combined in climate change are relevant from the local to the global, and co-ordination is needed across all levels to encourage effective, suitable, and sustainable management (Wolanski et al., 2019). In particular, while the causes need to be addressed at the global level, the consequence need addressing at the local level. Hence, the link between the global and local needs to be considered within legislation 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).

Using a case study of the Humber Estuary, this study demonstrates the impediments to effective and long term management against the potential harmful effects of climate change on the marine environment. The main bottleneck being the lack of resources, or rather the current inability to monitor all aspects of the estuarine waters and coastline, and the inability to currently address some of the effects. Many of the effects are wide-ranging and therefore it requires the culmination of mitigation measures on a scale larger than the estuary level to effectively mitigate against the effects. To do this, requires the use of frameworks to assess the potential impacts of any effects, the use of tools such as models, although their use is associated with limitations, and the integration of the governance structures, both vertically and horizontally.

There is extensive monitoring carried out on the Humber but monitoring is not a management measure but rather the means of determining whether management measures have been effective (Wolanski and Elliott, 2015; Elliott et al. 2022), and hence we need to understand the physical, biological and chemical environment to inform management. A major gap is the availability of data to understand the magnitude of the effects of climate change and what can be done about it.

As shown here, there is an increasing understanding of how our climate is changing, how environmental systems such as estuaries are affected, and the ways they can be managed to become more resistant and resilient through informed decision frameworks. Whilst targets, ambitions and goals are useful tools to ensure issues relating to impacts from climate change are tackled, there is the risk that the focus is on meeting targets, will not address the ancillary issues, for example, at local or regional levels. 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.

Acknowledgements

Centre for Environment, Fisheries and Aquaculture Science for their financial support of their doctoral study of the first author and the Environment Agency and British Geological Survey for their financial support of the doctoral study of the second author. Dr Tom Coulthard for his input into the research development.

References

Agardy, T., Alder, J. 2005. Chapter 19 Coastal Systems IN: Sarukhan, J., Whyte, A. [Editors] 2005. Millennium Ecosystem Assessment. ISLAND PRESS Washington, USA. (Available from: https://www.millenniumassessment.org/en/Condition.html#download) [viewed 23/07/2021].

Andrello, M., Mouillot, D., Somot, S., Thuiller, W., Manel, S., 2015. Additive effects of climate change on connectivity between marine protected areas and larval supply to fished areas. Diversity and Distributions, 21(2):139-150.

Andrews, J.E., Burgess, D., Cave, R.R., Coombes, E.G., Jickells, T.D., Parkes, D.J. and Turner, R.K. 2006. Biogeochemical value of managed realignment, Humber estuary, UK. *Science of the total environment*, 371(1): 19-30.

Antonov, J.I., Levitus, S., Boyer, T.P. 2002. Steric sea level variations during 1957–1994: Importance of salinity, *Journal of Geophysical Research*, 107(C12): 14-1-14-8. DOI: 10.1029/2001JC000964

Antonson, H., Isaksson, K., Storbjörk, S., Hjerpe, M. 2016. Negotiating climate change responses: Regional and local perspectives on transport and coastal zone planning in South Sweden, *Land Use Policy*, 52: 297-305.

Apitz, S.E., Elliott, M., Fountain, M., Galloway, T.S. 2006. European environmental management: Moving to an ecosystem approach, *Integrated Environmental Assessment and Management*, 2(1): 80-85.

Australian Government. 2017. 2017 Review of Climate Change Policies December 2017. 54pp. (Available from: https://publications.industry.gov.au/publications/climate-change/system/files/resources/186/2017-review-of-climate-change-policies.pdf) [viewed 13/05/2020].

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R. 2011.The value of estuarine and coastal ecosystem services, *Ecological Monographs*, 81(2): 169-193.

Barnard, S., Elliott, M. 2015. The 10-tenets of adaptive management and sustainability: An holistic framework for understanding and managing the socio-ecological system, *Environmental Science and Policy*, 51: 181-191.

Becker, A., Ng, A.K., McEvoy, D. and Mullett, J., 2018. Implications of climate change for shipping: Ports and supply chains. Wiley Interdisciplinary Reviews: Climate Change, 9(2), p.e508.

Bentley, M.G. 2011. The Global Spread Of The Chinese Mitten Crab *Eriocheir Sinensis*. In in The Wrong Place - Alien Marine Crustaceans: Distribution, Biology And Impacts. Dordrecht: Springer Netherlands, 107–127.

Borja, Á, Elliott. M., Carstensen, J., Heiskanen, A-S., van de Bund, W. 2010. Marine management – towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. *Marine Pollution Bulletin* 60: 2175-2186.

Boyes, S., Elliott, M. 2015. The excessive complexity of national marine governance systems- Has this decreased in England since the introduction of the Marine and Coastal Access Act 2009? *Marine Policy*, 51: 57-65.

Boyes, S., Elliott, M. 2006. Organic matter and nutrient inputs to the Humber Estuary, England. *Marine Pollution Bulletin*, 53(1):136-143.

Brodie, J., Williamson, C.J., Smale, D.A., Kamenos, N.A., Mieszkowska, N., Santos, R., Cunliffe, M., Steinke, M., Yesson, C., Anderson, K.M., Asnaghi, V. 2014. The future of the northeast Atlantic benthic flora in a high CO2 world. *Ecology and Evolution*, 4(13): 2787-2798.

CEDA. 2012. Climate Change Adaptation As It Affects The Dredging Community. CEDA Position Paper. Available from: https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-05-ceda_positionpaper-climatechangeadaptation.pdf [viewed 21/05/2017].

Ciavola, P. 1997. Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK), *Catena,* Vol.30:4, Pages 369-389

Committee on Climate Change. 2019. Net Zero: The UK's contribution to stopping global warming. (Available from: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf) [viewed 23/07/2019]

Committee on Climate Change. 2017. Progress in preparing for climate change. 2017 Report to Parliament. Pp. 234. (Available from: https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf) [viewed 21/08/2017]

Cook, E.J., Jenkins, S., Maggs, C., Minchin, D., Mineur, F., nall, C., Sewell, J. 2013. Impacts of climate change on non-native species, *MCCIP Science Review 2013*, 155-166, doi:10.14465/2013.arc17.155-166

Cormier, R., Elliott, M., Rice, J. 2019. Putting on a Bow-tie to sort out who does what and why in the complex arena of marine policy and management. *Science of the Total Environment*, 648: 293-305. https://doi.org/10.1016/j.scitotenv.2018.08.168.

Cormier, R., Elliott, M. 2017. SMART marine goals, targets and management – is SDG 14 operational or aspirational, is 'Life Below Water' sinking or swimming? Marine Pollution Bulletin 123: 28-33; https://doi.org/10.1016/j.marpolbul.2017.07.060.

Creighton, C., Hobday, A.J., Lockwood, M., Pecl, G.T., 2016. Adapting management of marine environments to a changing climate: a checklist to guide reform and assess progress. Ecosystems, 19(2): 187-219.

Cripps, I.L., Munday, P.L., McCormick, M.I. 2011. Ocean Acidification Affects Prey Detection by a Predatory Reef Fish, *PLOSone*, doi: http://dx.doi.org/10.1371/journal.pone.0022736

Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Dauvin, J.C., De Mesel, I., Derweduwen, J., Gill, A.B., Hutchison, Z.L. 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES Journal of Marine Science, 77(3): 1092-1108.

Defeo, O, Elliott, M., (2021). Editorial - The 'Triple Whammy' of coasts under threat – why we should be worried! Marine Pollution Bulletin, 163: 111832. https://doi.org/10.1016/j.marpolbul.2020.111832

Defra. 2013. A Coastal Concordat for England. (Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256234/coastal-concordat-20131111.pdf). [Viewed 27/12/2017]

Defra. 2010. Adapting to climate change: A guide for local councils. 26pp. (Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/218798/adapt-localcouncilguide.pdf) [viewed 13/05/2020].

De Jonge, V.N., Elliott, M. 2001. Eutrophication. In: J Steele, S Thorpe & K Turekian (Eds.) *Encyclopaedia of Ocean Sciences*. Vol. 2, Academic Press, London.p852-870.

Department for Transport. 2012. National Policy Statement for Ports. 76pp. (available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf) [viewed 15/11/2018].

Dixon, D.L., Munday, P.L., Jones, G.P. 2009. Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues, *Ecology Letters*, 13(1): 68-75.

Donovan, B., Horsburgh, K., Ball, T. and Westbrook, G. 2013. Impacts of climate change on coastal flooding, *MCCIP Science Review 2013*, 211-218, doi:10.14465/2013. arc22.211-218

Ducrotoy, J.-P., Elliott, M., Cutts, N.D., Franco. A., Little. S., Mazik. K., Wilkinson. M. 2019. Temperate Estuaries: their ecology under future environmental changes. In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.), Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

Durant, J.M., Hjermann, D.Ø., Ottersen, G., Stenseth, N.C. 2007 Climate and the match or mismatch between predator requirements and resource availability, *Climate Research*, doi: http://dx.doi.org/doi:10.3354/cr033271

Dürr, H. H., G. G. Laruelle, C. M. van Kempen, C. P. Slomp, M. Meybeck, Middelkoop, H. 2011. Worldwide Typology of Nearshore Coastal Systems: Defining the Estuarine Filter of River Inputs to the Oceans. *Estuaries and Coasts*, 34(3): 441-458, doi:10.1007/s12237-011-9381-y.

Edwards, M., Bresnan, E., Cook, K., Heath, M., Helaouet, P., Lynam, C., Raine, R. and Widdicombe, C. 2013. Impacts of climate change on plankton, *MCCIP Science Review 2013*, 98-112, doi:10.14465/2013.arc12.098-112

Edwards, A.M.C., Winn, P.S.J. 2006. The Humber Estuary, Eastern England: Strategic planning of flood defences and habitats, *Marine Pollution Bulletin*, 53(1-4): 165-174.

Elliott, M., Houde, E.D., Lamberth, S.J., Lonsdale, J.-A., Tweedley, J.R., 2022. Chapter 12, Management of Fishes and Fisheries in Estuaries. In: Fish and Fisheries in Estuaries – A Global Perspective (ed., Whitfield, A.K., Able, K.W., Blaber, S.J.M. & Elliott, M.). John Wiley & Sons, Oxford, UK.

Elliott, M., Borja, A., Cormier, R. 2020. Managing marine resources sustainably: a proposed integrated systems analysis approach. Ocean & Coastal Management, 197, 105315, https://doi.org/10.1016/j.ocecoaman.2020.105315

Elliott, M., Quintino, V.M. 2019. The Estuarine Quality Paradox Concept. Encyclopaedia of Ecology, 2nd Edition, (Editor-in-Chief B Fath), Elsevier, Amsterdam, Volume 1, p78-85; ISBN: 978-0-444-63768-0. https://doi.org/10.1016/B978-0-12-409548-9.11054-1

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K. 2017. “And DPSIR begat DAPSI(W)R(M)!” - a unifying framework for marine environmental management. *Marine Pollution Bulletin*, 118 (1-2): 27-40. http://dx.doi.org/10.1016/j.marpolbul.2017.03.049.

Elliott, M., Mander, L., Mazik, K., Simenstad, C., Valesini, F., Whitfield, A., Wolanski, E. 2016. Ecoengineering with Ecohydrology: Successes and failures in estuarine restoration, *Estuarine, Coastal and Shelf Science*, 176: 12-35. doi: 10.1016/j.ecss.2016.04.003.

Elliott, M., Borja, Á., McWuatters-Gollop, A., Mazik, K., Birchenough, S., Anderson, J.H., Painting, S., Peck, M. 2015. *Force Majeure*: Will climate change affect our ability to attain Good Environmental Status for marine biodiversity, *Marine Pollution Bulletin*, 95(1):7-27.

Elliott, M. 2014. Integrated marine science and management: wading through the morass. *Marine Pollution Bulletin*, 86(1/2): 1-4. doi: 10.1016/j.marpolbul.2014.07.026

Elliott, M., Cutts, N.D., Trono, A. 2014. A typology of marine and estuarine hazards and risks as vectors of change: a review for vulnerable coasts and their management. *Ocean & Coastal Management*, 93: 88-99.

Elliott, M. 2013. The 10-tenets for integrated, successful and sustainable marine management, *Marine Pollution Bulletin*, 74: 1-5.

Elliott, M. 2011. Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures – a numbered guide. *Marine Pollution Bulletin*, 62: 651-655.

Elliott, M., Whitfield, A. 2011. Challenging paradigms in estuarine ecology and management, *Estuarine, Coastal & Shelf Science*, 94:306-314.

Elliott, M., Underwood, G., Wilkinson, M., Mazik, K., de Jonge, V.N., Dodge, G. 2008. Statement by the Expert Panel on the Eutrophic status of the Humber Estuary as Requested by the Environment Agency, December 2008

Elliott, M., McLusky, D.S. 2002 The need for definitions in understanding estuaries. *Estuarine, Coastal & Shelf Science*, 55(6) 815-827.

Environment Agency. 2005a. Humber Estuary Coastal Habitat Management Plan. Available from http://www.discoverysoftware.co.uk/FRaME/pdf/ChaMP.pdf [Viewed 05/08/2020].

Environment Agency. 2008. The Humber Flood Risk Management Strategy: Planning for the Rising Tides. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308281/Humber_Strategy_Summary.pdf [Viewed 17/07/2020].

European Commission. 2013. Guidelines on Climate Change and Natura 2000. 105pp. Available from: http://ec.europa.eu/environment/nature/climatechange/pdf/Guidance%20document.pdf [Viewed 09/02/2018].

Falconer, L., Hjøllo, S.S., Telfer, T.C., McAdam, B.J., Hermansen, Ø. and Ytteborg, E., 2020. The importance of calibrating climate change projections to local conditions at aquaculture sites. Aquaculture, 514, p.734487.

Feely, R.A., Alin, S.R., Newton, J., Sabine, C.L., Warner, M., Devol, A., Krembs, C., Maloy, C. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary, *Estuarine, Coastal and Shelf Science*, 88(4): 442-449.

Freestone, D., Jones, N., North, J., Pethick, J., Symes, D. and Ward, R. 1987. The Humber Estuary, Environmental Background, UK: Shell.

Garcia-de-Lomas, J., Dana, E.D., López-Santiago, J., González, R., Ceballos, G., Ortega, F., (2010) Management of the Chinese mitten crab, *Eriocheir sinensis* (H. Milne Edwards, 1853) in the Guadalquivir Estuary (Southern Spain), *Aquatic Invasions*, 5(3): 323-330.

Giffin, A.L., Brown, C.J., Nalau, J., Mackey, B.G. and Connolly, R.M., 2020. Marine and coastal ecosystem-based adaptation in Asia and Oceania: review of approaches and integration with marine spatial planning. Pacific Conservation Biology, 27(2), pp.104-117.

Gilbey, V., Attrill, M.J., Coleman, R.A. 2008. Juvenile Chinese mitten crabs (*Eriocheir sinensis*) in the Thames estuary: distribution, movement and possible interactions with the native crab *Carcinus maenas*, *Biological Invasions*, 10: 67-77.

Government of Canada. 2020. Policy Context: Considering Environmental Obligations and Commitments in Respect of Climate Change under the Impact Assessment Act. (Available from: https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/considering-environmental-obligations.html) [viewed 13/05/2020].

Government of Canada. 2018. Adaptation and climate resilience. Strengthening our communities to thrive in a changing climate. https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-actions-clean-growth-economy/adaptation-climate-resilience.html

Gross, J.E. 2003. Developing Conceptual Models for Monitoring Programs, (available from http://science.nature.nps.gov/im/monitor/docs/Conceptual_modelling.pdf) [viewed 21/10/13].

Hallegatte S, Ranger N, Mestre O, Dumas P, Corfee-Morlot J, Herweijer C, Wood RM. Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. Climatic change. 2011 Jan;104(1):113-37.

HM Government. 2018a. A Green Future: Our 25 Year Plan to Improve the Environment. 151pp. (Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf) [viewed 13/05/2020].

HM Government. 2018b. Strengthened Local Enterprise Partnerships. 30pp. (available from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728058/Strengthened_Local_Enterprise_Partnerships.pdf) [viewed 15/11/2018].

HM Government. 2014. East Inshore and East Offshore Marine Plans. (available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312496/east-plan.pdf) [viewed 27/11/16].

HM Government. 2011. UK Marine Policy Statement, London: The Stationary Office.

Health Protection Agency. 2012. Health Effects of Climate Change in the UK 2012. Current evidence, recommendations and research gaps. Pp. 242. (Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/371103/Health_Effects_of_Climate_Change_in_the_UK_2012_V13_with_cover_accessible.pdf) [Viewed 21/08/3027]

Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung, 2014: The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir,

M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.

Humber Nature Partnership. 2017. Investing in Natural Capital. Creating the right environment for economic investment. (Available from: http://humbernature.co.uk/admin/resources/investing-in-natural-capital.pdf) [Viewed 21/08/2017]

IMO. 2020. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx

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, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jarvie, H.P., Neal, C., Robson, A.J. 1997. The geography of the Humber catchment, *Science of the Total Environment*, 194: 87-100.

Johns, D., Smalls, M., Maslen, S. 2010. Coastal Schemes with Multiple Funders and Objectives FD2635. Case Study Report 1 Alkborough Flats Tidal Defence Scheme. 10pp.

Jones, L., Garbutt, A., Hansom, J., Angus, S. 2013. Impacts of climate change on coastal habitats, *Marine Climate Change Impacts Partnership: Science Review*, pp. 167-179.

Kelly, C., Gray, L., Shucksmith, R.J., Tweddle, J.F. 2014. Investigating options on how to address cumulative impacts in marine spatial planning, *Ocean and Coastal Management*, 102: 139-148.

Klein, S.A., Soden, B.J. and Lau, N.C. 1999. Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *Journal of Climate*, 12(4): 917-932.

Klemetsen, A., Amundsen, P-A., Dempson, J.B., Jonsson, N., O'Connell, M.F., Mortensen, E. 2003. Atlantic salmon Salmo salar L., brown trout Salmo trutta L. and Arctic charr Salvelinus alpinus (L.): a review of aspects of their life histories, *Ecology of Freshwater Fish*, Vol. 12:1, DOI: 10.1034/j.1600-0633.2003.00010.x

Kroeger, K.D., Anderson, I., Baldwin, S., Brooks, W., Brush, M., Cai, W.J., Canuel, E., Casso, M., Chen, R., Green, A. and McCallister, L., 2012. Fluxes in tidal wetlands. In *Report of The US East Coast Carbon Cycle Synthesis Workshop* (pp. 5-7). Gloucester Point, VA: Virginia Institute of Marine Sciences.

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M. and Gattuso, J.P., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global change biology*, 19(6), pp.1884-1896.Little, S., Wood, P.J, Elliott, M. (in press). Quantifying salinity-induced changes on estuarine benthic fauna: The potential implications of climate change. *Estuarine, Coastal and Shelf Science*, in press.

Lonsdale, J., Nicholson, R., Weston, K., Elliott, M., Birchenough, A., Sühring, R., 2018. A user's guide to coping with estuarine management bureaucracy: An Estuarine Planning Support System (EPSS) tool. *Marine Pollution Bulletin*, 127: 463-477.

Lonsdale, J., Weston, K., Elliott, M., Blake, S., Edwards, R. 2017. The Amended European Environmental Impact Assessment Directive: UK Marine Experience and Recommendations. *Ocean and Coastal Management*, 148: 131-142.

Lonsdale, J-A., Weston, K., Barnard, S., Boyes, S., Elliott, M. 2015. Integrating Management Tools and Concepts to Develop an Estuarine Planning Support System: A case study of the Humber Estuary, Eastern England, Marine Pollution Bulletin, 100(1): 393-405.

Lonsdale, J. 2013. The Potential Uses of Dredged Material in the Humber Estuary, MSc Thesis, University of Hull funded by TiDE (available from: http://www.tide-project.eu/downloads/Pilot_project_Humber_estuary.pdf) [viewed 29/05/2015]

Maitland, P.S. 2003. Ecology of the River, Brook and Sea Lamprey. Conserving Natura 2000 Rivers Ecology Series No. 5. English Nature, Peterborough.

Mander, L., Cutts, N.D., Allen, J., Mazik, K. 2007. Assessing the development of newly created habitat for wintering estuarine birds, *Estuarine, Coastal and Shelf Science*, 75(1-2): 163-174.

Mansanet-Bataller, M. 2010. The Challenges of Adapting to Climate Change. Climate Report. No. 21. Availble from: http://www.cdcclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate_change.pdf [Viewed 21/05/2017]

Masselink, G., Russell, P. 2013. Impacts of climate change on coastal erosion, *MCCIP Science Review 2013*, Psges 71-86, doi:10.14465/2013.arc09.071-086

Mazik, K., Solyanko, E., Elliott, M. & De Jonge, V.N. 2009. Summary of microalgal species composition and water quality in the Humber Estuary, Report to Environment Agency. Institute of Estuarine and Coastal Studies, University of Hull, 26 March 2009, Report: YBB133-D1-2009.

Mazik, K., Thomson, S., Elliott, M., Solyanko, K., Phelps, A. 2008. CASI ground truth surveys — Humber estuary 2008, Report to Environment Agency, Institute of Estuarine and Coastal Studies, University of Hull, 8th December 2008.

MCCIP. 2017. Annual Report Card. (Available from: http://www.mccip.org.uk/media/1770/mccip-report-card-2017-final-artwork-spreads.pdf) [viewed 21/08/2017.

MCCIP. 2013. Annual Report Card. Available from: http://www.mccip.org.uk/annual-report-card/2013/climate-of-the-marine-environment/ [Viewed 21/01/2017].

McCormick, S.D., Hanse, L.P., Quinn, T.P., Saunders, R.L. 1998. Movement, migration, and smelting of Atlantic salmon (*Salmo salar*), Movement, migration, and smolting of Atlantic salmon (*Salmo salar*), *Canadian Journal of Fisheries and Aquatic Sciences*, 55 (1): 77-92.

Mee, L.D., Jefferson, R.L., Laffoley, D., Elliott, M. 2008. How good is good? Human values and Europe's proposed Marine Strategy Directive, *Marine Pollution Bulletin*, 56: 187-204.

Metcalfe, S.E., Ellis, S., Horton, B.P., Innes, J.B., McArthur, J., Mitlehner, A., Parkes, A., Pethick, J.S., Rees, J., Ridgway, J., Rutherford, M.M., Shennan, I., Tooley, M.J. 2000 The Holocene evolution of the Humber Estuary: reconstructing change in a dynamic environment, *Geological Society, London, Special Publications*, 175: 253-279

Mieszkowska, N., Firth, L., Bentley, M. 2013 Impacts of climate change on intertidal habitats, *MCCIP Science Review 2013*, 180-192, doi:10.14465/2013.arc19.180-192

Miller, D.D., Ota, Y., Sumaila, U.R., Cisneros‐Montemayor, A.M., Cheung, W.W.L. 2017. Adaptation strategies to climate change in marine systems. *Global Change Biology*, 24 (1): e1-e14. https://doi.org/10.1111/gcb.13829

MMO. 2016. Potential spatial effects of climate change in the South and East Marine Plan Area. MMO Project Number 1077. 136pp.

Munday, P.L., Dixson, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O., Chivers, D.P. 2010. Replenishment of fish populations is threatened by ocean acidification, *Proceedings of the National Academy of Sciences of the United States of America*, 107(29): 12930-12934.

Munday, P.L., Dixson, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V., Døving, K.B. 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish, *Proceedings of the National Academy of Sciences of the United States of America*, 106(6): 1848-1852.

Newton A and Elliott M (2016) A Typology of Stakeholders and Guidelines for Engagement in Transdisciplinary, Participatory Processes. Front. Mar. Sci. 3:230. doi: 10.3389/fmars.2016.00230

Nunn, A.S., Harvey, J.P., Noble, R.A.A., Cowx, I.G. 2008. Condition assessment of lamprey populations in the Yorkshire Ouse catchment, north-east England, and the potential influence of physical migration barriers; *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18: 175-189.

Olenin, S, Elliott, M, Bysveen, I, Culverhouse, P, Daunys, D, Dubelaar, GBJ, Gollasch, S, Goulletquer, P, Jelmert, A, Kantor, Y, Mézeth, KB, Minchin, D, Occhipinti-Ambrogi, A, Olenina, I, Vandekerkhove, J. 2011. Recommendations on methods for the detection and control of biological pollution in marine coastal waters. *Marine Pollution Bulletin*, 62(12): 2598-2604.

OSPAR Commission. 2010. The North-East Atlantic Environment Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2010–2020 (OSPAR Agreement 2010-3). Pp27. (Available from: https://www.ospar.org/site/assets/files/1200/ospar_strategy.pdf) [viewed 13/05/2020].

OSPAR. 2009. Eutrophication Status of the OSPAR Maritime Area: Second OSPAR Integrated Report. 108pp. Available from: www.ospar.org/documents?d=7107 [viewed 26/03/2017]

Painting, S., Foden, J., Forster, R., van der Molen, J. Aldridge, J., Best, M., Jonas, P, Walsham, P., Webster, L., Gubbins, M., *et al.* 2013 Impacts of climate change on nutrient enrichment, *MCCIP Science Review 2013*, 219-235, doi:10.14465/2013. arc23.219-235

Pankhurst. N.W., Munday, P.L. 2011. Effects of climate change on fish reproduction and early life history stages, *Marine and Freshwater Research*, 62: 1015-1026.

Passeri, D.L., Hagen, S.C., Medeiros, S.C., Bilskie, M.V., Alizad, K., Wang, D. 2015 The dynamic effects of sea level rise on low-gradient coastal landscapes: A review, *Earth's Future*, 3(6):159-181.

Peck, M.A., Arvanitidis, C., Butenschon, M., et al. 2018. Projecting changes in the distribution and productivity of living marine resources: a critical review of the suite of modelling approaches used in the large European project VECTORS. Estuarine, Coastal and Shelf Science 201, 40–55.

Pinnegar, J.K., Cheung, W.W.L., Jones, M., Merino, G., Turrell, B., Reid, D. 2013 Impacts of climate change on fisheries. *MCCIP Science Review 2013*, 302-317, doi:10.14465/2013. arc32.302-317

Potter, I.C., Chuwen, B.M., Hoeksema, S.D., Elliott, M. 2010. The concept of an estuary: a definition that incorporates systems which can become closed to the ocean and hypersaline. Estuarine, Coastal & Shelf Science, 87: 497–500.

Pörtner, H.O., Knust, R. 2007. Climate Change Affects Marine Fishes Through the Oxygen Limitation of Thermal Tolerance, *Science*, 315(5808): 95-97.

Rasmussen, E. 1973. Systematics and ecology of the Isefjord marine fauna (Denmark). *Ophelia*, 11(1): 1-507.

Raynor, P. 2014. The Humber Estuary Flood Risk Management Strategy: Summary Strategy and Business Case. 54pp. Available at: http://www2.eastriding.gov.uk/EasySiteWeb/GatewayLink.aspx?alId=592095. [Viewed 26/01/2017]

Raynor, P., Chatterton, J. 2014. Flood Defences Cost Money, No Defences Cost More: an Economic Case for the Humber and United Kingdom. Report Prepared on Behalf of the Humber Parlimentarians, Local Authorities and the Humber Local Enterprise Partnership. Available at: http://www.floodcba.eu/main/wp-content/uploads/Flood-Risk-Management-Investing-in-thefuture-of-the-Humber-Estuary.pdf [Accessed January 28, 2016].

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, Wang. F. 2013. Observations: Ocean. 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, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Roberts, D.A., Birchenough, S.N., Lewis, C., Sanders, M.B., Bolam, T., Sheahan, D. 2013. Ocean acidification increases the toxicity of contaminated sediments. *Global change biology*, 19(2): 340-351.

Robins, P. 2019. Changing hydrology. In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.), Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

Robins, P.E., Skov, M.W., Lewis, M.J., Giménez, L., Dacies, A.G., Malham, S.K., Neill, S.P., McDonald, J.E., Whitton, T.A., Jackson, S.E., Jago, C.F. 2016. Impact of climate change on UK estuaries: A review of past trends and potential projections, *Estuarine, Coastal and Shelf Science*, 169: 119-135.

Rosselló-Nadai, J. 2014. How to evaluate the effects of climate change on tourism, *Tourism Management*, 42:334-340.

Santos, C.F., Ehler, C.N., Agardy, T., Andrade, F., Orbach, M.K. and Crowder, L.B., 2019. Marine spatial planning. In World seas: an environmental evaluation (pp. 571-592). Academic Press.

Saul, R, Barnes, R, Elliott, M. 2016. Is climate change an unforeseen, irresistible and external factor – a force majeure in marine environmental law? *Marine Pollution Bulletin*, 113: 25-35.

Secretariat of the Convention on Biological Diversity. 2004. The Ecosystem Approach, ISBN: 92-9225-023-x (available online at: https://www.cbd.int/doc/publications/ea-text-en.pdf) [Viewed 09/07/2017]

Sheahan, D., Maud, J., Wither, A., Moffat, C. and Engelke, C. 2013. Impacts of climate change on pollution (estuarine and coastal). *MCCIP Science Review 2013*, 244-251, doi:10.14465/2013.arc25.244-251

Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., & Rutherford, M. 2000. Holocene isostasy and relative sea-level changes on the east coast of England. *Geological Society*, London, Special Publications, 166(1): 275–298.

Simpson, M. 2013. Impacts of climate change on tourism (and marine recreation), *MCCIP Science Review 2013*, 271- 283, doi:10.14465/2013.arc29.271-283

Skinner, C. J., T. J. Coulthard, D. R. Parsons, J. A. Ramirez, L. Mullen, Mason, S. 2015. Simulating tidal and storm surge hydraulics with a simple 2D inertia based model, in the Humber Estuary, UK*, Estuarine Coastal Shelf Science*., 155, 126–136, doi:10.1016/j.ecss.2015.01.019.

Solomon, Susan, ed. Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC. Vol. 4. Cambridge University Press, 2007.

Townsend, M., Thrush, S.F., Carbines, M.J. 2011 Simplifying the complex: an "Ecosystem Principles Approach" to goods and services management in marine coastal ecosystems, *Marine Ecology Progress Series, Volume* 434: 291-301.

Tunstall, S., Tapsell, S., Green, C., Floyd, P., George, C. 2006. The health effects of flooding: social research results from England and Wales, *Journal of Water and Health*, 4(3):365-380.

Turley, C, Findlay, HS, Mangi, S, Ridgwell, A and Schimdt, DN. 2009. CO2 and ocean acidification in Marine Climate Change Ecosystem Linkages Report Card 2009. (Eds. Baxter JM, Buckley PJ and Frost MT), Online science reviews, 25pp.

Turner, R.K., Schaafsma, M. (Eds.) 2015. Coastal zones ecosystem services: from science to values and decision making. Springer Ecological Economic Series, Springer Internat. Publ. Switzerland, ISBN 978-3-319-17213-2.

UNCLOS. 1982. United Nations Convention on the Law of the Sea of 10 December 1982. Available from: https://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm

United Nations. 2011. Framework Convention on Climate Change Decisions adopted by the Conference of the Parties. 31pp. (Available from: https://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf) [viewed 13/05/2020].

United Nations. 1998. KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. 21pp. (Available from: https://www.kyotoprotocol.com/resource/kpeng.pdf) [viewed 13/05/2020].

United Nations. 1992. UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. (Available from: https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf) [viewed 13/05/2020].

Vézina, A., Hoegh-Guldberg, O. 2008. Effects of ocean acidification on marine ecosystems. *Marine Ecology Progress Series*, 373: 199-201.

Wadey, M.P., Roberts, H. and Harris, J. 2013. Impacts of climate change on built structures (onshore and coastal), *MCCIP Science Review 2013*, 284-294, doi:10.14465/2013. arc30.284-294

Wadhams, P., Munk, W. 2004. Ocean freshening, sea level rising, sea ice melting, *Geophysical Research Letters*, Vol. 31:11. doi:10.1029/2004GL020039

Waterkeyn, A., Vanschoenwinkel, B., Vercampt, H., Grillas, P., Brendonck, L. 2011. Long-term effects of salinity and disturbance regime on active and dormant crustacean communities, *Limnology and Oceanography*, Vol. 56:3, Pages 1008-1022

Whitfield, A.K., Elliott, M., Basset, A., Blaber, S.J.M., West, R.J. 2012. Paradigms in estuarine ecology- A review of the Remane diagram with a suggested revised model for estuaries, *Estuarine, Coastal and Shelf Science*, 97: 78-90.

Whitfield, A.K., Elliott, M. 2011. Chapter 1.07: Ecosystem and Biotic Classifications of Estuaries and Coasts. In: Volume 1, Classification of Estuarine and Nearshore Coastal Ecosystems, C Simenstad and T Yanagi (Eds), In: E Wolanski & McLusky, DS (Eds) *Treatise on Estuarine & Coastal Science*, Elsevier, Amsterdam, pp.99-124.

Winn, P.J.S., Young, R.M., Edwards, A.M.C 2003. Planning for the rising tides: the Humber Estuary Shoreline Management Plan, *Science of The Total Environment*, 314-316: 13-30.

Wittmann, A.C., Pörtner, H.O. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change*, 3(11): 995.

Wright P. Impacts of climate change on ports and shipping. MCCIP Sci. Rev. 2013:263-70.

Woodward, S. (2010). The Economic Potential of Nature Tourism in Eastern Yorkshire. (retrieved 04/10/17 from https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiMq9TpxtbWAhUEaFAKHYtpCpIQFggrMAA&url=http%3A%2F%2Fmediafiles.thedms.co.uk%2FPublication%2FYS-EY%2Fcms%2Fpdf%2FYNT%2520ICRT%2520Report%252C%2520Nature%2520Tourism%2520in%2520Eastern%2520Yorkshire.pdf&usg=AOvVaw1JJ8E-dXhv8qvIO1xDfQAY)

Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.) 2019. Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

Wragg, S. 2014. Hull City Council Flood Investigation Report: December 2013 City Centre Tidal Surge Event. Report to the Environment & Transport Overview and Scrutiny Committee, Hull City Council, 4th February 2014. (accessible from https://cmis.hullcc.gov.uk/cmis/Meetings/tabid/70/ctl/ViewMeetingPublic/mid/397/Meeting/291/Committee/64/SelectedTab/Documents/Default.aspx accessed February 16, 2017)

Wright, P. 2013. Impacts of climate change on ports and shipping, *MCCIP Science Review 2013*, 263-