

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 is 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 1. Introduction

2 Estuaries cover over 400,000 km of the global coastline (Dürr *et al.*, 2011) and are dynamic
3 environments that form a transition zone between rivers, the open sea and terrestrial systems. They
4 are most commonly defined as “a semi-enclosed coastal body of water which is connected to the sea
5 either permanently or periodically, has a salinity that is different from that of the adjacent open ocean
6 due to freshwater inputs, and includes a characteristic biota” and being “transitional waters, a term
7 which includes lagoons, rias, etc.” (Elliott and Whitfield, 2011), with more specific classifications often
8 used to describe the characteristics of individual systems (Potter *et al.*, 2010; Whitfield and Elliott,
9 2011). ~~Their transitional nature requires means that no single definition is suitable (Elliott and McLusky
10 2002).~~ Given their location, connections and resources, estuaries are hotspots for many urban,
11 industrial and recreational activities, which can provide a significant contribution to the economy
12 (Lonsdale *et al.*, 2015; Elliott and Whitfield, 2011). They also support an abundant and functionally
13 large but not necessarily diverse range of flora and fauna and many typically hold statutory
14 environmental designations to protect their unique ecological characteristics.

15 Estuaries are increasingly regarded as facing three major threats worldwide: increasing
16 industrialisation and urbanisation, increasing resource scarcity notably for both space and energy, and
17 the impacts of climate change (Wolanski *et al.*, 2019; Defeo & Elliott 2021). Many of the activities and
18 pressures within these categories are endogenic, i.e. occurring inside the estuarine area and where
19 the causes and consequences of change, such as navigation and fisheries, need to be managed.
20 However, they are also subject to exogenic unmanaged pressures, the causes of which originate within
21 the wider catchment (e.g. abstraction) or are globally mediated (e.g. climate change) and where it is
22 the consequences (not sources) inside the estuary that need to be managed (Elliott, 2011). These
23 pressures affect both the natural and socio-economic systems and they therefore require a robust and
24 defendable risk assessment and risk management framework to be managed sustainably (Cormier *et*
25 *al.*, 2019; Elliott, *et al.*, 2014).

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

34 This study identifies and summarises the relevant impacts from climate change on estuarine systems and
35 how the effects of climate change are currently being managed and governed locally, regionally and
36 globally through legislative measures (Section 2). The sufficiency or appropriateness of the legislative
37 framework and regional rules for protecting an estuary, using the Humber Estuary as a case study,
38 against the effects of climate change are explored (Section 3) and, as a result, recommendations are
39 made as to how policies can, or should be modified or improved (Section 4).

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

45 2. Climate Change and Climate Change

46 Understanding the impact that climate change has on transitional systems is crucial to developing
47 management strategies that will be sustainable over the long term (Donovan *et al.*, 2013; Jones *et al.*,
48 2013; Mieszkowska *et al.*, 2013). There are many recognised impacts and similarities of climate change
49 worldwide which increase the vulnerability and decrease the resilience of estuaries (Wolanski *et al.*,
50 2019). Elliott *et al.* (2015) summarises a conceptual framework relating to all the coastal effects of
51 climate change and Robins *et al.* (2015), Robins (2019) and Ducrotoy *et al.* (2019) focus on the natural
52 science aspects within estuaries. Some of the most prominent threats to estuarine environments
53 highlighted within this literature are related to: increased carbon dioxide, sea level rise, and changes
54 in temperature (IPCC, 2013). The predicted impact these effects may have on estuarine environment,
55 including the socio-economic impacts, is explored below.

56 2.1 Increased Carbon Dioxide

57 Increased atmospheric CO₂ is a primary cause of anthropogenic climate change and can lead to other
58 effects, e.g. ocean acidification. The oceans have absorbed 27-34% of the CO₂ from the atmosphere
59 since the industrial revolution (Turley *et al.*, 2009) and consequently, ocean surface water pH has
60 decreased by 0.1 units; further decreases of approximately 0.3-0.4 units by 2100 are predicted (Feely
61 *et al.*, 2010).

62 Ocean acidification is likely to have direct and indirect impacts on the reproduction, growth and
63 survival of commercially exploited fish stocks (Dixon *et al.*, 2009; Munday *et al.*, 2009; 2010; Cripps *et al.*,
64 2011). Series of meta-analyses have indicated that whilst some species may be affected on their
65 physiological and behavioural responses (including development, viability and mortality rates), others

66 may potentially benefit from such change in pH conditions (Kroeger et al., 2012; 2013; Wittman and
67 Portner, 2013; Brodie et al., 2014).

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

73 **2.2 Sea Level Rise**

74 According to the IPCC's Fifth Assessment Report, sea level is predicted to rise by 0.26-0.82 m by 2100
75 relative to 1986-2005 levels (IPCC, 2013). Sea level rise is likely to alter the hydrodynamics and tidal
76 characteristics in these environments, affecting estuarine circulation patterns, sediment transport
77 processes, erosion-deposition cycles and flood and erosion potentials along the banks (Passeri et al.,
78 2015).

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

86 Changes in sea level could also lead to increased saline incursions into estuaries, through the
87 penetration of saline waters further upstream. Saline intrusion could also alter the chemical properties
88 of estuarine environments leading to increased nutrient release into the estuarine waters, freshwater
89 and groundwater reserves (Robins et al., 2016), potentially leading to eutrophication. Eutrophication
90 is defined as "the enrichment of water by nutrients causing an accelerated growth of algae and higher
91 forms of plant life to produce an undesirable disturbance to the balance of organisms present in the
92 water and to the quality of the water concerned, and therefore refers to the undesirable effects
93 resulting from anthropogenic enrichment by nutrients", (OSPAR, 2009) which can cause algal mats,
94 harmful algal blooms, fish kills, hypoxia and benthic changes in these waters (e.g. de Jonge and Elliott,
95 2001). This may also affect the species that migrate and inhabit these areas, alongside other
96 determining factors such as substratum type and food web interactions. However, given the variability

97 of salinity species in estuaries, the effect of salinity on estuarine species is currently unknown (Elliott
98 *et al.*, 2016; Waterkeyn *et al.*, 2011; Little *et al.*, in press).

99 **2.3 Changes in Temperature**

100 Due to the increase in greenhouse gases into the atmosphere, the sea surface temperature has shown
101 an overall global increase, predominantly within the upper 700 m of the ocean (Hoegh-Guldberg *et al.*,
102 2014). Changes to oceanic temperatures can contribute to sea level rise, shift storm tracks, alter
103 circulation patterns and affect the transport of nutrients around the oceans (Hoegh-Guldberg *et al.*,
104 2014).

105 Increased oceanic temperatures can expand the area suitable for various species to habituate and
106 cause others to retreat (Edwards *et al.* 2013; Mieszkowska *et al.*, 2013; Pinnegar *et al.*, 2013; Elliott *et al.*,
107 2015). Changes in water chemistry and temperature may impact the species timing for migrating
108 and spawning or be a barrier to migration if conditions are outside of their tolerances (Klemetsen *et al.*,
109 2003; Maitland, 2003; McCormick *et al.*, 1998). Conversely, non native species may increase their
110 distribution due to conditions becoming more favourable to their establishment.

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

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

124 **2.4 Socioeconomics**

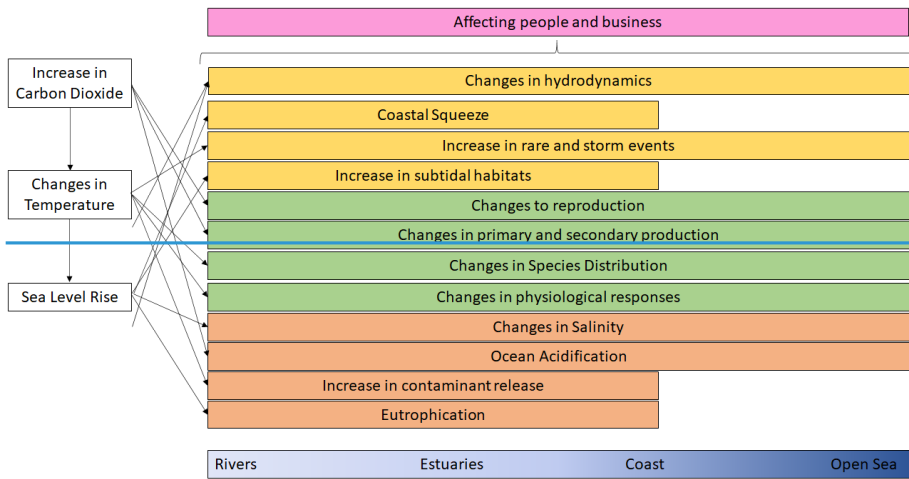
125 The people and industries found along the coastlines of estuarine environments will become
126 increasingly exposed to the effects of climate change. As sea levels rise, storm activity intensifies and
127 the physiography and biology of these environments change, the lives and livelihoods of people,
128 properties and assets will be threatened (Simpson, 2013; Wadey *et al.*, 2013). Other coastal structures,

129 such as coastal protection measures (e.g. sea walls), and infrastructure (notably energy and transport)
130 may also be affected.

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

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

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



151
 152 Figure 1 Impacts of climate change showing the drivers (on the left) and where these impacts are most likely to occur or have
 153 the greater impact (blue horizontal box along the bottom). Orange boxes represent chemical changes; green represent
 154 biological changes; yellow boxes represent physical changes; and pink box represent socio-economic changes.

155 These hazards and risks may be exacerbated by direct human actions, for example removing natural
 156 vegetation (e.g. mangroves, reedbeds) that increases the severity of storm surges, which in
 157 themselves may be increased by climate alterations (Wolanski et al., 2019). These external, climate-
 158 forced vectors thus add complexity to the estuarine management challenges. These changes have the
 159 potential to influence processes that control the behaviour (e.g. geomorphological), physical
 160 properties (e.g. sea level), biological receptors (e.g. species distribution), economic benefits and uses
 161 (e.g. recreation) of these systems (Donovan et al., 2013; Masselink and Russel, 2013; Painting et al.,
 162 2013; Sheahan et al., 2013; Simpson et al., 2013). Furthermore, climate change may be regarded in
 163 legal terms as factors outside the control of local managers (a force majeure) again giving rise to
 164 challenges. For example, climate change will lead to moving baselines against which management of
 165 static features may be judged (Elliott et al., 2015; Saul et al., 2016). It is therefore important that
 166 strategies and governance are designed and implemented to protect and enhance estuarine
 167 environments over the long term, fully considering the likely impacts of climate change on the uses
 168 and users of these systems (Lonsdale et al., 2015).

169 2 Management and Governance: The Global Challenge

170 3

171 Understanding the impact that climate change has on transitional systems is crucial to developing
172 management strategies that will be sustainable over the long-term (Donovan *et al.*, 2013; Jones *et al.*,
173 2013; Mieszkowska *et al.*, 2013). There are many recognised impacts and similarities of climate change
174 worldwide which increase the vulnerability and decrease the resilience of estuaries (Wolanski *et al.*,
175 2019). Elliott *et al.* (2015) summarises a conceptual framework relating to all the coastal effects of
176 climate change and Robins *et al.*, (2015), Robins (2019) and Ducrottoy *et al.* (2019) focus on the natural
177 science aspects within estuaries. Some of the most prominent threats to estuarine environments
178 highlighted within this literature are related to: increased carbon dioxide and concomitant changes in
179 temperature, sea level rise, and increasing storminess changes in temperature (IPCC, 2013) (see Figure
180 1).

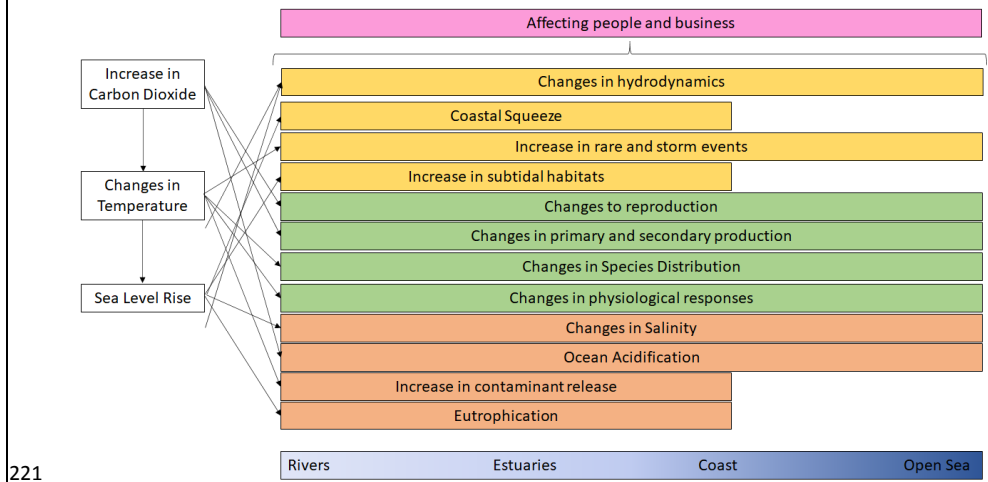
181 In addition to these threats, there is a threat to socio-economics (summarised in see Figure 1 for a
182 summary): the urban and industrialised coastal and estuarine areas people and industries found along
183 the coastlines of estuarine environments will become increasingly exposed to the effects of climate
184 change. As sea levels rise, storm activity intensifies and the physiography and biology of these
185 environments change, the lives and livelihoods of people, properties and assets will be threatened
186 (Simpson, 2013; Wadey *et al.*, 2013). Other coastal structures, such as coastal protection measures
187 (e.g. sea walls), and infrastructure (notably energy and transport) are likely to ~~may also~~ be affected.
188 The increase in sea levels and storm surges can increase the risk of coastal properties being affected
189 and damaged due to flooding (Raynor, 2014). However, there are also wellbeing impacts from flooding
190 (see Tunstall *et al.* (2006)).

191 Wright (2013) noted that ports will be particularly affected by climate change associated impacts such
192 as enhanced storm surge activity, sea-level rise, temperature change, precipitation and high winds
193 (supported by Becker *et al.*, 2018; Hallegatte *et al.*, 2011). Most notably, changes to the physiography
194 and hydrodynamics could alter ~~at the system's~~ sediment budget and change the morphology of
195 navigable channels, ~~thereby affecting which could affect~~ shipping capabilities. If channels are
196 deepened through increased erosion, larger vessels could be accommodated but if channels infill, the
197 size of ships could be restricted, and dredging may be necessary to maintain water depths. For
198 estuaries, where there is generally a lot of activity in terms of industry and recreation, this could have
199 a significant impact on the economy.

Formatted: Heading 2, No bullets or numbering

200 [Other climate change effects however, such as a warmer climate, could increase tourism opportunities](#)
 201 [with people staying within country for holidays rather than travelling abroad, ~~thus which would~~](#)
 202 [positively impacting the economy \(Rosselló-Nadai, 2014\). For example, along coastlines globally, and](#)
 203 [particularly in estuaries, these sites are often for recreation, including bird watching, walking, sailing](#)
 204 [routes etc. given their coastal location \(Lonsdale et al., 2015; Agardy and Alder, 2005\) and could see](#)
 205 [increased visitor numbers as the climate warms and the summer period extends \(Rosselló-Nadai,](#)
 206 [2014\).](#)

207 [These hazards and risks may be exacerbated by direct human actions, for example removing natural](#)
 208 [vegetation \(e.g. mangroves, reedbeds\) that increases the severity of storm-surges, which in](#)
 209 [themselves may be increased by climate alterations \(Wolanski et al., 2019\). These external, climate-](#)
 210 [forced vectors thus add complexity to the estuarine management challenges. These changes have the](#)
 211 [potential to influence processes that control the behaviour \(e.g. geomorphological\), physical](#)
 212 [properties \(e.g. sea level\), biological receptors \(e.g. species distribution\), economic benefits and uses](#)
 213 [\(e.g. recreation\) of these systems \(Donovan et al., 2013; Masselink and Russel, 2013; Painting et al.,](#)
 214 [2013; Sheahan et al., 2013; Simpson et al., 2013\). Furthermore, climate change may be regarded in](#)
 215 [legal terms as ~~creating~~ factors outside the control of local managers \(a force majeure\) again giving rise](#)
 216 [to challenges \(Elliott et al., 2015; Saul et al., 2016\) and ~~–For example, climate change will~~ lead to](#)
 217 [moving baselines against which management of static features may be judged \(Elliott et al., 2015; Saul](#)
 218 [et al., 2016\).](#) It is therefore important that strategies and governance are designed and implemented
 219 [to protect and enhance estuarine environments over the long-term, fully considering the likely](#)
 220 [impacts of climate change on the uses and users of these systems \(Lonsdale et al., 2015\).](#)



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

225 ~~Estuaries To support, e~~[Estuaries](#) are managed through many [legislative](#) instruments ~~atfrom~~
226 international, national and regional levels, including voluntary codes of conduct (Boyes and Elliott,
227 2014). Across all these levels, the legislation, policies, administration and management strategies are
228 designed to safeguard ecosystems whilst allowing for sustainable development, and the management
229 of ongoing and proposed activities. [However, l](#)

230 ~~Legislation~~ does not tell us how to do something but rather permits what can and cannot be done
231 (Cormier et al., 2019).

232 At a global level, there are international treaties and conventions, many of which are legally binding
233 for countries that have formally ratified them e.g. the United Nations Convention on the Law of the
234 Sea (UNCLOS, 1982). These international treaties set the minimum standard, for example, for
235 environmental protection. Countries can implement higher standards of [marine] environmental
236 protection, but not less. [Here we briefly provide an overview of these overarching protection](#)
237 [measures as they influence regional, national and local management measures.](#)

238 In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development and the
239 Sustainable Development Goals. There are 17 Sustainable Development Goals (SDGs) and associated
240 targets, with SDG 14 focused on the oceans. The aim of SDG 14 '[Life below water](#)' is to "Conserve and
241 sustainably use the oceans, seas and marine resources for sustainable development". Of its seven
242 targets, Target 14.3 is to "Minimize and address the impacts of ocean acidification, including through
243 enhanced scientific cooperation at all levels" is the most relevant when considering how estuaries are
244 responding to climate change and how these impacts can be managed. [However, it is questioned](#)
245 [whether these targets are operationally satisfactory \(Cormier & Elliott 2017\).](#)

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

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

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

271 ~~Similarly, However, there are also other conventions including UNEP Regional Seas Conventions, such~~
272 ~~as~~ the Convention for the Protection and Development of the Marine Environment and Coastal Region
273 of the Mediterranean Sea (Barcelona Convention) and Convention for the Protection of the Marine
274 Environment of the North-east Atlantic (OSPAR Convention), ~~to name but two, which~~ are aimed at
275 protecting ~~an marine~~ areas ~~of the marine environment which is~~ used by multiple countries as a shared
276 resource. The OSPAR ~~Convention is concerned with impacts on the marine environment and in~~
277 ~~OSPAR's~~ North-East Atlantic Environment Strategy 2020 ~~states it is stated~~ that “*first effects of climate*
278 *change and ocean acidification are apparent throughout the OSPAR Maritime Area and that pressures*
279 *on the marine environment from climate change and ocean acidification are set to grow*” (OSPAR
280 Commission, 2010). As such, and in accordance with this strategy, the OSPAR Secretariat has
281 committed to monitor and assess the nature, rate and extent of the effects of climate change and
282 ocean acidification on the marine environment and consider appropriate ways of responding to such
283 developments.

284 At the national level, there are three levels of ~~ocean-marine and coastal~~ governance. ~~(those specific to~~
285 ~~the Humber are explored in Section XXX):~~

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

293 The treaties set out what is expected, and the national legislation stipulates what can and cannot be
294 done legally to meet the international obligations. For example, in the UK, ~~The the~~ Climate Change Act
295 2008 is an Act of Parliament ~~under which and makes it the duty of~~ the Secretary of State ~~should to~~
296 ensure, amongst other provisions, that the net UK carbon emissions (including from all six
297 greenhouses gases targeted by the Kyoto Protocol) by 2050 are at least ~~10080~~ 100% lower than the 1990
298 baseline. Additionally, an independent UK Committee on Climate Change has been created under the
299 Act to provide advice to UK Government on these targets and related policies. The specific aspects
300 relating to the Humber Estuary, eastern England are explored in Section XXX3.

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

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

313 There are often perceived conflicts in this approach as the Government may set a policy e.g. increasing
314 reliance on renewable energy, but this requires renewable infrastructure to be built, and the
315 infrastructure may not be permitted to be built either for environment-environmental (too large an
316 impact) or societal (objections based on impact to local amenities or economy) grounds. Therefore, it
317 is questioned what happens if targets are not met despite all departments acting lawfully.

Formatted: Not Highlight

318 The vertical integration from having international and regional agreements, conventions and
319 protocols which feed into the national and local governance as described above, is generally accepted
320 and well-implemented. However, there is also the need for horizontal integration which requires the
321 coordination of environmental goals and objectives with those of [stakeholders across](#) marine sectors
322 (Cormier et al., 2019). For example, constructing an offshore structure could only be permitted if the
323 goals/objectives of a marine protected area were not threatened. As demonstrated by Cormier et al.
324 (2019) and Lonsdale et al. (2015), this horizontal integration is complex: there are usually several
325 regulators ([see Section 3 for those relevant to the Humber Estuary](#)) that manage a marine area and
326 activities. Hence, cross-agency communication, with shared visions and agreements is key for
327 effective marine management.

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

334 **4—How can management better address Climate Change?**

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

340 ~~To do this there needs to be a rigorous management and risk assessment framework to help in
341 estuarine management, such as DAPSI(W)R(M) and the ISO standard Bowtie analysis (e.g. Elliott, et
342 al., 2017; Cormier et al., 2019). The unifying DAPSI(W)R(M) management framework developed by
343 Elliott et al. (2017) accommodates the Drivers (of change are the economic and social forces that result
344 from government policies, markets and activities of the private industry, e.g. the basic needs of
345 society, determine the needs for the development of land) as the basic human needs (for food, space,
346 etc), the resulting Activities which lead to Pressures which are the mechanisms of change. These
347 pressures change both the natural State and have an Impact on human Welfare. Finally, these require
348 Responses (using management Measures) (Elliott, et al., 2017) when assessed against the defined
349 baseline. A more flexible and responsive management framework(s) may minimise adverse effect on~~

350 receptors and therefore, it is important that legislation and regulations allow for adaptation as our
351 understanding of climate change impacts becomes more comprehensive. This further requires that
352 changes to the pressures and impacts be monitored, to determine the ongoing suitability of
353 management measures. However, a key question will be at what scale? The perfect monitoring
354 programme will have 100% coverage with real time data, but this would be a huge financial burden,
355 and therefore a balance must be struck between what we want (scale, temporal, variables) and what
356 can be afforded to answer the specific question.

357 The link between the global and local needs to be considered within Legislation to facilitate the
358 implementation of suitable management measures across all levels. This would enable scientists,
359 managers and decision makers to address site-specific climate change effects, relevant to the areas
360 they manage whilst remaining within the boundaries of more global-based guidance (Elliott *et al.*,
361 2015; Robins *et al.*, 2016; Wolanski *et al.*, 2019). For instance, changes in temperature could increase
362 the likelihood of non-native species inhabiting estuarine waters and this is complex to monitor, map
363 and manage. There are few, if any, effective measures to address this at present and requires
364 management at the local level, relevant to site specific conditions and the types of species that
365 establish (Olenin *et al.*, 2011). The relationship between the global and local is an ongoing challenge,
366 particularly given the uncertainty surrounding the potential impacts of climate change. Cross
367 departmental strategies, which consider multiple targets, need to be sufficiently flexible to allow
368 targets and mitigation/adaptation methods to be updated according to site specific conditions and
369 increasing knowledge.

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

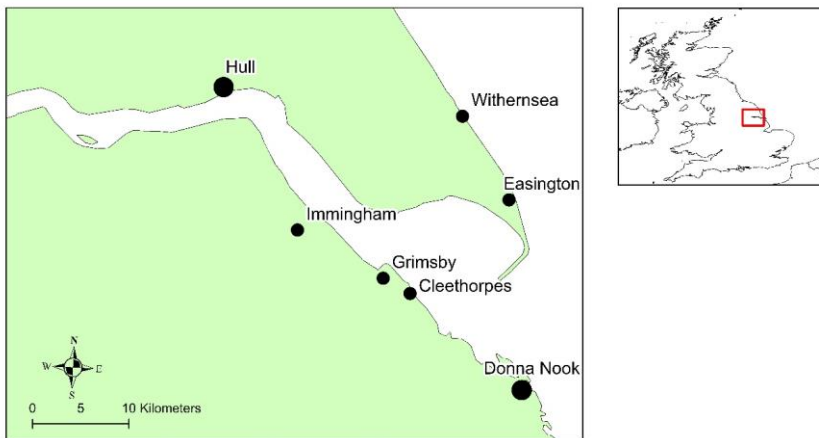
384 Monitoring is not a management measure but rather the means of determining whether management
385 measures have been effective (Wolanski and Elliott, 2015): we need to understand the physical,
386 biological and chemical environment to inform management. A major gap is the availability of data to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

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

414 53 What does this mean in reality? A Case Study of the Humber Estuary, UK

415 To explore the sufficiency or appropriateness of the legislative framework and regional rules for
416 protecting an estuary against the effects of climate change the application of this analysis, we take a

417 [the](#) well-studied case study of the Humber Estuary in the North East of England. It is one of the largest
418 coastal plain estuaries in the EU, extending approximately 62 km from Trent Falls to the open [\(North\)](#)
419 sea (Figure 2). It is one of the busiest and fastest growing areas for seaborne trade in [the EU](#) [Europe](#)
420 and provides an important contribution to the UK economy (Ciavola, 1997; Jarvie, et al., 1997;
421 Metcalfe et al., 2000). It supports four major ports: Goole, Hull, Grimsby and Immingham, that
422 import >20% of the UK's total inward tonnage per year (Figure 2) and is rapidly growing as a national
423 base for offshore wind installation and operations in the North Sea. Many industries, cities and towns
424 are clustered near these ports, with much of the remaining land bordering the system used for
425 agriculture.



426
427 Figure 2 Case Study area

428 [Given the nature conservation importance of the area,](#) ~~t~~The Humber's various habitats and waterways
429 constitute a European Marine Site within the Natura 2000 framework (Lonsdale, 2015). This includes
430 Special Areas of Conservation (SAC), Special Protection Areas (SPA), Sites of Special Scientific Interest
431 (SSSI) and a Heritage Coast site (see Lonsdale, 2015). These designations protect a wide variety of rare
432 and sensitive biological components, including the seabed habitats, benthic communities, seabed
433 features (e.g. sandbanks), mobile fish species (e.g. lamprey), marine mammals (e.g. the grey seal
434 population) and bird species (e.g. the breeding Great bittern, *Botaurus stellaris*). Many of these sites
435 provide ecosystem services and societal goods and benefits (Turner and Schaafsma, 2015) including
436 tourism and leisure opportunities (Freestone et al., 1987).

437 Almost 235 km of defences protect the Humber's environmental, social, and economic assets,
438 including managed realignment sites such as Alkborough Flats [and other ecoengineering initiatives](#)

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

444 35.1 Managing Climate Change Impacts

445 The Humber Estuary is vulnerable to all the potential impacts of Climate Change identified in section
446 32, but it is important to consider how these impacts manifest at the site-specific level. In Table 1
447 summarises the physical, chemical, and biological effects relevant to the Humber Estuary are
448 summarised. The Humber Estuary is managed through many legislative instruments, from
449 international, to European, national, and regional levels, including voluntary codes of conduct. Hence,
450 there are management measures within the Humber Estuary that are designed to combat the effects
451 of climate change, such as management realignment sites or setting back or raising flood defences
452 (Elliott et al., 2016). This leads to the question of is how future proof are these methods
453 especially given any time lag and inertia in the system? The impacts of climate change will continue
454 even if we were to stop all greenhouse emissions today due to inertia. The efficacy of management
455 measures aimed at tackling climate change impacts is determined by monitoring such as most other
456 measures are designed to monitor the impacts and effects within the estuary, such as changes to
457 salinity, species distribution or contamination. These are a means to inform management measures.
458 The Humber Estuary is managed through many legislative instruments, from international, to
459 European, national, and regional levels, including voluntary codes of conduct. In Section 2, we have
460 highlighted the international conventions which set out the requirement for countries to do
461 something, here we look at the specific requirements for managing a relatively small site in
462 comparison to the global treaties jurisdiction. At the international level, management of the Humber
463 must be considered according to the policies and guidance outlined in Section 4, whilst considering
464 national and local level regulations.

465 Nationally, The UK Climate Change Act (2008), amended in 2019, is the UK's response to reducing and
466 mitigating against climate change. It requires the UK to act to tackle climate change and reduce
467 greenhouse gas emissions by 100% of 1990 levels by 2050. This is important when considering ongoing
468 (e.g., shipping) or new (e.g., power stations) developments. The UK Marine Policy statement, as
469 required by the Marine and Coastal Access Act 2009, sets out guidelines for maintaining marine
470 environments in healthy, productive and resilient conditions, without compromising the ecosystem

Formatted: Not Highlight

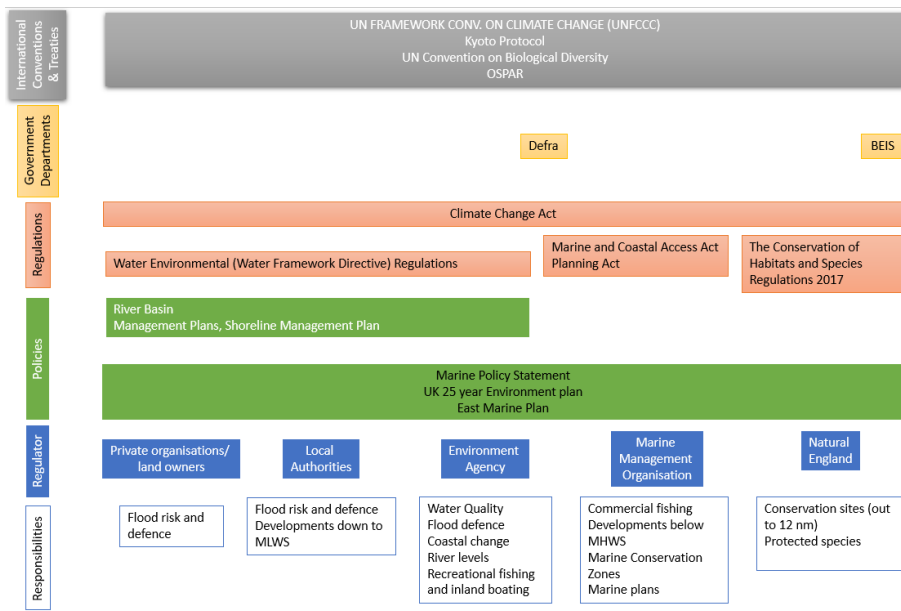
Formatted: Highlight

471 services and societal goods and benefits (Kelly et al., 2014; Turner and Schaafsma, 2015). The East
472 Marine Plan (within which the Humber Estuary sits) aims 'to facilitate action on climate change
473 adaptation and mitigation' by identifying areas for renewable energy generation (wave and tidal
474 energy) and carbon capture storage, in line with the European Renewable Energy Directive
475 (2009/28/EC) and the UK Climate Change Act, 2008. Local-level estuarine management is prominent
476 in the Humber Estuary in acknowledging that climate change increases the risk of flooding. The
477 Environment Agency has used a cost-benefit analysis to ~~implemented~~ the Humber Flood Risk
478 Management Strategy to manage flood risk, aiming to ensure that 99% of people who live close to the
479 Estuary have a good level of protection against tidal flooding for 25 years following the
480 implementation of the strategy (Environment Agency, 2008). The Humber Flood Risk Strategy
481 complements a range of regional plans, including Shoreline Management Plans (SMP) and Coastal
482 Habitat Management Plans (CHaMP). ~~It is of note that those not protected live at sites where the cost-~~
483 ~~benefit analysis would have indicated that protection is prohibitively expensive given the value of~~
484 ~~assets protected. See Figure 3 for a visualisation of the Humber relevant management measures.~~
485 To determine the sufficiency of the legislative framework and/or the organisations responsible, the
486 potential impacts highlighted in Section 2, were considered in terms of what (legislation) and who
487 (authorities) is responsible for managing these impacts (Table 1).

Formatted: Not Highlight

489 Many of the responsibilities for monitoring and managing the impacts of climate change within the
490 estuary appear to fall onto the Environment Agency, ~~an~~ the English environmental protection agency
491 (in the UK, Scotland, Wales and Northern Ireland have their own bodies as devolved agencies) ~~of water~~
492 ~~ways in the UK.~~ However, some specific responsibility falls to others, such as the Marine Management
493 Organisation (for assessing new development applications) or ~~private organisations or~~ Local
494 Authorities, and even private organisations, for the maintenance of some flood defences (see Figure
495 3). Vertical and horizontal integration between these legislative instruments and responsible
496 organisations is therefore imperative to ensure effective management that is compliant with
497 international, regional, and national legislation whilst taking into consideration specific challenges
498 within the Humber Estuary. How this can be achieved is not always clear or straightforward to achieve.

Formatted: Not Highlight



499
500 [Figure 3 Visualisation of the horizontal and vertical governance of the Humber Estuary specific to](#)
501 [estuarine waters management.](#)

502 ~~By analysing~~[A potential weakness in a](#)[Assessing](#) the potential impacts from climate change and the
503 legislative instruments, ~~what appears to be a weakness is the sheer~~ task of monitoring for the potential
504 [impacts of climate change which may be prohibitively expensive for many organisations. If for very few](#)
505 ~~organisations,~~ in most cases, it falls solely on the Environment Agency, although there is
506 [acknowledgement that other forms of monitoring, such as condition monitoring of the nature](#)
507 [conservation features and compliance monitoring for ongoing developments \(Elliott et al., 2022\) that](#)
508 ~~take place.~~ [Models can inform how an area may be impacted by climate change \(Falconer et al.,](#)
509 [2020REF\), but they have caveats and their spatial and temporal predictability, both from deterministic](#)
510 [and empirical modelling, gives them with their use and the results, therefore on a local level, they](#)
511 ~~have limited use in prioritising areas for monitoring.~~ [End-to-end models which link changes to the](#)
512 [natural environment with the socio-economic repercussions \(Peck et al., 2018\) have the potential for](#)
513 [use but require expensive parameterisation for individual areas. Hence, t](#)[To inform management](#)
514 [strategies, we need to have](#) ~~robust modelling in place~~ [to predict potential scenarios and determine](#)
515 [harmonised specific responses based on the site-specific information;](#) for instance, [the modelling](#)
516 [results and management responses for the south coast may not be appropriate or applicable to the](#)
517 [Humber Estuary. This would allow for a local policy to be developed, but by learning from local](#)

518 examples, national policy could be more aligned to the UK's responses (both environmental and
519 management) to climate change impacts.

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

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

533 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?	CommentsPotential 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 patterns 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 salinity 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 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 Framework Directive) Regulations	Environment Agency.	Funding and manpower 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 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?

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(WR)(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

567 [departmental strategies, which consider multiple targets, need to be sufficiently flexible to allow](#)
568 [targets and mitigation/adaptation methods to be updated according to site-specific conditions and](#)
569 [increasing knowledge.](#)

570 [It appears that the Humber Estuary, has good vertical integration of governance from the local to ~~link~~](#)
571 [from global thereby facilitating to local requirements to facilitate the implementation of suitable](#)
572 [management measures across all levels. However, ~~but~~ ideally, policies and legislative instruments,](#)
573 [including guidance, should include prescriptive guidance for what thresholds indicate an issue e.g.](#)
574 [approaching an action points \(a reference condition, threshold, trigger or -tipping point \(Elliott et al.,](#)
575 [2022REF\), or what actions can be taken can be done about it e.g. changes in pH?. To ensure successful](#)
576 [and sustainable development, the policies and strategies require to be tested rigourously, for example](#)
577 [against ~~would benefit from adhering to~~ the ten-tenets of sustainable management \(Elliott, 2013;](#)
578 [Barnard and Elliott, 2015\). These cover the ecological, economic, technological, societal,](#)
579 [administrative, legislative, political, ethical \(moral\), cultural and communication aspects of sustainable](#)
580 [solutions. Hence, ~~As indicated in the 10 tenets,~~ wider education, and engagement of stakeholders](#)
581 [\(e.g. CEDA, 2012; Newton and Elliott, 2016\) is required to address these issues and ensure adaptive](#)
582 [capacity is recognised and built into plans, policies, and existing developments. In line with the](#)
583 [coordination of climate change adaptation, this requires ensuring adaptive capacity is maintained](#)
584 [through all levels of the estuary stakeholders. The collation and dissemination of evidence and](#)
585 [monitoring data will become increasingly important to identify whether the effects and trends of](#)
586 [climate change are apparent. By ensuring the monitoring data and evidence are shared, the effects](#)
587 [and adaptive management strategies can be fed into marine plans to provide long-term resilience to](#)
588 [climate change and allow a greater integration, awareness and understanding of the effects of climate](#)
589 [change into policy and infrastructure changes. For example, this includes the need to consider all the](#)
590 [effects of individual managed realignment sites at the estuary level.](#)

591 **6.5 Concluding Remarks**

592 This paper details the potential challenges associated with managing vulnerable estuarine
593 environments in the face of climate change. There are efforts by stakeholders to address some of the
594 effects of climate change, but the ways in which estuaries are managed, [from the local to the global](#)
595 [scale globally to locally, needs to be improved improvement. Given the complexity of the system,](#)
596 [ranging from the natural to the societal, calls for a systems analysis approach \(Elliott et al. 2020\) and](#)
597 [hence r](#)Recently developed decision support systems (e.g. Lonsdale *et al.*, 2018) give progress towards
598 this end. The causes and effects of [exogenic pressures combined in](#) climate change are relevant from
599 the local to the global, and co-ordination is needed across all levels to encourage effective, suitable,

600 and sustainable management (Wolanski et al., 2019). In particular, while the causes need to be
601 addressed at the global level, the consequence need addressing at the local level. Hence, t
602 The link between the global and local needs to be considered within l~~egislation~~ to facilitate the
603 implementation of suitable management measures across all levels. This would enable scientists,
604 managers and decision makers to address site-specific climate change effects, relevant to the areas
605 they manage whilst remaining within the boundaries of more global-based guidance (Elliott et al.,
606 2015; Robins et al., 2016; Wolanski et al., 2019).

607

608 Using a case study of the Humber Estuary, this study demonstrates ~~the importance of vertical and~~
609 ~~horizontal integration across management levels. It also shows the relevance of developing site-~~
610 ~~specific assessments, as each estuary and its component habitats and species will be impacted by~~
611 ~~climate change in different ways and to differing degrees. This is challenging due to the coarse~~
612 ~~coverage of data and so there is a need for enhanced monitoring and research but also the realisation~~
613 ~~that action must be taken in the light of inadequate knowledge and data. Numerical models are~~
614 ~~increasingly being used to understand the behaviour of these systems and the effect that climate~~
615 ~~change may have over decadal to centennial timescales. Despite this, the models often highlight the~~
616 ~~uncertainty both in our understanding and in the predictive capability. However, there is scope to~~
617 ~~utilise these tools further and improve their predictive capabilities, to inform sustainable~~
618 ~~management.~~the ~~bottlenecks~~impediments to effective and long term management against the
619 potential harmful effects of climate change on the marine environment. The main bottleneck being
620 the lack of resources, or rather the current inability to monitor all aspects of the estuarine waters and
621 coastline, and the inability to currently address some of the effects. Many of the effects are wide-
622 ranging and therefore it requires the culmination of mitigation measures on a scale larger than the
623 estuary level to effectively mitigate against the effects. To do this, requires- the use of frameworks to
624 assess the potential impacts of any effects, the use of tools such as models, although their use is
625 associated with limitations, and the integration of the governance structures, both vertically and
626 horizontally.

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

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

634

635 As shown here, there is an increasing understanding of how our climate is changing, how
636 environmental systems ~~such as estuaries~~ are affected, and the ways they can be managed to become
637 more resistant and resilient through informed decision frameworks. ~~Whilst the use of targets,~~
638 ~~ambitions and goals are useful tools to ensure issues relating to impacts from climate change are~~
639 ~~tackled, there is the risk that the focus is on meeting targets, will not address the ancillary issues, for~~
640 ~~example, at local or regional levels. Due to the global-reaching impacts of climate change, a national~~
641 ~~strategy for harmonising targets and combatting climate change impacts may be an effective solution,~~
642 ~~albeit, costly to coordinate, implement and monitor.~~

643

644 Acknowledgements

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

649 References

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

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

656 Andrews, J.E., Burgess, D., Cave, R.R., Coombes, E.G., Jickells, T.D., Parkes, D.J. and Turner, R.K. 2006.
657 Biogeochemical value of managed realignment, Humber estuary, UK. *Science of the total environment*,
658 371(1): 19-30.

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

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

664 Apitz, S.E., Elliott, M., Fountain, M., Galloway, T.S. 2006. European environmental management:
665 Moving to an ecosystem approach, *Integrated Environmental Assessment and Management*, 2(1): 80-
666 85.

667 Australian Government. 2017. 2017 Review of Climate Change Policies December 2017. 54pp.
668 (Available from: [https://publications.industry.gov.au/publications/climate-](https://publications.industry.gov.au/publications/climate-change/system/files/resources/186/2017-review-of-climate-change-policies.pdf)
669 [change/system/files/resources/186/2017-review-of-climate-change-policies.pdf](https://publications.industry.gov.au/publications/climate-change/system/files/resources/186/2017-review-of-climate-change-policies.pdf)) [viewed
670 13/05/2020].

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

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

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

678 Bentley, M.G. 2011. The Global Spread Of The Chinese Mitten Crab *Eriocheir Sinensis*. In in *The Wrong*
679 *Place - Alien Marine Crustaceans: Distribution, Biology And Impacts*. Dordrecht: Springer Netherlands,
680 107–127.

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

684 Boyes, S., Elliott, M. 2015. The excessive complexity of national marine governance systems- Has this
685 decreased in England since the introduction of the Marine and Coastal Access Act 2009? *Marine Policy*,
686 51: 57-65.

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

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

692 CEDA. 2012. Climate Change Adaptation As It Affects The Dredging Community. CEDA Position Paper.
693 Available from: [https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-](https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-05-ceda_positionpaper-climatechangeadaptation.pdf)
694 [05-ceda_positionpaper-climatechangeadaptation.pdf](https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-05-ceda_positionpaper-climatechangeadaptation.pdf) [viewed 21/05/2017].

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

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

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

704 Cook, E.J., Jenkins, S., Maggs, C., Minchin, D., Mineur, F., nall, C., Sewell, J. 2013. Impacts of climate
705 change on non-native species, *MCCIP Science Review 2013*, 155-166, doi:10.14465/2013.arc17.155-
706 166

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

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

713 Creighton, C., Hobday, A.J., Lockwood, M., Pecl, G.T., 2016. Adapting management of marine
714 environments to a changing climate: a checklist to guide reform and assess progress. *Ecosystems*,
715 19(2): 187-219.

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

718 Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Dauvin, J.C., De
719 Mesel, I., Derweduwén, J., Gill, A.B., Hutchison, Z.L. 2020. Benthic effects of offshore renewables:
720 identification of knowledge gaps and urgently needed research. *ICES Journal of Marine Science*, 77(3):
721 1092-1108.

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

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

728 Defra. 2010. Adapting to climate change: A guide for local councils. 26pp. (Available from:
729 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/218798/adapt-localcouncilguide.pdf)
730 [/218798/adapt-localcouncilguide.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/218798/adapt-localcouncilguide.pdf)) [viewed 13/05/2020].

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

733 Department for Transport. 2012. National Policy Statement for Ports. 76pp. (available from
734 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf)
735 [/3931/national-policy-statement-ports.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf)) [viewed 15/11/2018].

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

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

740 Ducrotoy, J.-P., Elliott, M., Cutts, N.D., Franco, A., Little, S., Mazik, K., Wilkinson, M. 2019. Temperate
741 Estuaries: their ecology under future environmental changes. In: Wolanski, E., Day, J.W., Elliott, M.,
742 Ramachandran, R. (Eds.), *Coasts and Estuaries: The Future*. Elsevier, Amsterdam, ISBN 978-0-12-
743 814003-1.

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

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

750 Edwards, M., Bresnan, E., Cook, K., Heath, M., Helaouet, P., Lynam, C., Raine, R. and Widdicombe, C.
751 2013. Impacts of climate change on plankton, *MCCIP Science Review 2013*, 98-112,
752 doi:10.14465/2013.arc12.098-112

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

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

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

761 Elliott, M., Quintino, V.M. 2019. The Estuarine Quality Paradox Concept. *Encyclopaedia of Ecology*,
762 2nd Edition, (Editor-in-Chief B Fath), Elsevier, Amsterdam, Volume 1, p78-85; ISBN: 978-0-444-63768-
763 0. <https://doi.org/10.1016/B978-0-12-409548-9.11054-1>

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

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

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

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

775 Elliott, M., Cutts, N.D., Trono, A. 2014. A typology of marine and estuarine hazards and risks as vectors
776 of change: a review for vulnerable coasts and their management. *Ocean & Coastal Management*, 93:
777 88-99.

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

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

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

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

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

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

791 Environment Agency. 2008. The Humber Flood Risk Management Strategy: Planning for the Rising
792 Tides. Available from:
793 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308281/Humber_Strategy_Summary.pdf)
794 [308281/Humber_Strategy_Summary.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308281/Humber_Strategy_Summary.pdf) [Viewed 17/07/2020].

795 European Commission. 2013. Guidelines on Climate Change and Natura 2000. 105pp. Available from:
796 <http://ec.europa.eu/environment/nature/climatechange/pdf/Guidance%20document.pdf> [Viewed
797 09/02/2018].

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

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

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

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

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

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

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

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

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

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

828 HM Government. 2018a. A Green Future: Our 25 Year Plan to Improve the Environment. 151pp.
829 (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].

830
831

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

834

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

837

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

839 Health Protection Agency. 2012. Health Effects of Climate Change in the UK 2012. Current evidence,
840 recommendations and research gaps. Pp. 242. (Available from:
841 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]

842

843 Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung,
844 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional*
845 *Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental*
846 *Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir,
847 M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R.
848 Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New
849 York, NY, USA, pp. 1655-1731.

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

852

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

855 IPCC. 2013. Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis.*
856 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on*
857 *Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y.
858 Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New
859 York, NY, USA.

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

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

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

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

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

870 Klemetsen, A., Amundsen, P-A., Dempson, J.B., Jonsson, N., O'Connell, M.F., Mortensen, E. 2003.
871 Atlantic salmon *Salmo salar* L., brown trout *Salmo trutta* L. and Arctic charr *Salvelinus alpinus* (L.): a
872 review of aspects of their life histories, *Ecology of Freshwater Fish*, Vol. 12:1, DOI: 10.1034/j.1600-
873 0633.2003.00010.x

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

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

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

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

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

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

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

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

898 Mansanet-Bataller, M. 2010. The Challenges of Adapting to Climate Change. Climate Report. No. 21.
899 Available from:
900 [http://www.cdclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate](http://www.cdclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate_change.pdf)
901 [_change.pdf](http://www.cdclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate_change.pdf) [Viewed 21/05/2017]

902 Masselink, G., Russell, P. 2013. Impacts of climate change on coastal erosion, *MCCIP Science Review*
903 *2013*, Psges 71-86, doi:10.14465/2013.arc09.071-086

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

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

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

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

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

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

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

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

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

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

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

933 Munday, P.L., Dixon, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V., Døving, K.B.
934 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish,
935 *Proceedings of the National Academy of Sciences of the United States of America*, 106(6): 1848-1852.

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

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

941 Olenin, S, Elliott, M, Bysveen, I, Culverhouse, P, Daunys, D, Dubelaar, GBJ, Gollasch, S, Gouletquer, P,
942 Jelmert, A, Kantor, Y, Mézeth, KB, Minchin, D, Occhipinti-Ambrogi, A, Olenina, I, Vandekerkhove, J.
943 2011. Recommendations on methods for the detection and control of biological pollution in marine
944 coastal waters. *Marine Pollution Bulletin*, 62(12): 2598-2604.

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

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

949 OSPAR. 2009. Eutrophication Status of the OSPAR Maritime Area: Second OSPAR Integrated Report.
950 108pp. Available from: www.ospar.org/documents?d=7107 [viewed 26/03/2017]

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

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

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

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

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

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

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

968 Rasmussen, E. 1973. Systematics and ecology of the Isefjord marine fauna (Denmark). *Ophelia*, 11(1):
969 1-507.

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

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

978 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey,
979 A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, Wang, F. 2013. Observations: Ocean. In: *Climate*
980 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment*
981 *Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M.
982 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University
983 Press, Cambridge, United Kingdom and New York, NY, USA

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

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

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

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

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

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

997 Secretariat of the Convention on Biological Diversity. 2004. The Ecosystem Approach, ISBN: 92-9225-
998 023-x (available online at: <https://www.cbd.int/doc/publications/ea-text-en.pdf>) [Viewed
999 09/07/2017]

1000 Sheahan, D., Maud, J., Wither, A., Moffat, C. and Engelke, C. 2013. Impacts of climate change on
1001 pollution (estuarine and coastal). *MCCIP Science Review 2013*, 244-251,
1002 doi:10.14465/2013.arc25.244-251

1003 Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., & Rutherford, M. 2000. Holocene
1004 isostasy and relative sea-level changes on the east coast of England. *Geological Society*, London,
1005 Special Publications, 166(1): 275–298.

1006 Simpson, M. 2013. Impacts of climate change on tourism (and marine recreation), *MCCIP Science
1007 Review 2013*, 271- 283, doi:10.14465/2013.arc29.271-283

1008 Skinner, C. J., T. J. Coulthard, D. R. Parsons, J. A. Ramirez, L. Mullen, Mason, S. 2015. Simulating tidal
1009 and storm surge hydraulics with a simple 2D inertia based model, in the Humber Estuary, UK, *Estuarine
1010 Coastal Shelf Science*, 155, 126–136, doi:10.1016/j.ecss.2015.01.019.

1011 Solomon, Susan, ed. Climate change 2007-the physical science basis: Working group I contribution to
1012 the fourth assessment report of the IPCC. Vol. 4. Cambridge University Press, 2007.

1013 Townsend, M., Thrush, S.F., Carbines, M.J. 2011 Simplifying the complex: an “Ecosystem Principles
1014 Approach” to goods and services management in marine coastal ecosystems, *Marine Ecology Progress
1015 Series, Volume 434*: 291-301.

1016 Tunstall, S., Tapsell, S., Green, C., Floyd, P., George, C. 2006. The health effects of flooding: social
1017 research results from England and Wales, *Journal of Water and Health*, 4(3):365-380.

1018 Turley, C, Findlay, HS, Mangi, S, Ridgwell, A and Schimdt, DN. 2009. CO2 and ocean acidification in
1019 Marine Climate Change Ecosystem Linkages Report Card 2009. (Eds. Baxter JM, Buckley PJ and Frost
1020 MT), Online science reviews, 25pp.

1021 Turner, R.K., Schaafsma, M. (Eds.) 2015. Coastal zones ecosystem services: from science to values
1022 and decision making. Springer Ecological Economic Series, Springer Internat. Publ. Switzerland, ISBN
1023 978-3-319-17213-2.

1024 UNCLOS. 1982. United Nations Convention on the Law of the Sea of 10 December 1982. Available
1025 from: https://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm

1026 United Nations. 2011. Framework Convention on Climate Change Decisions adopted by the
1027 Conference of the Parties. 31pp. (Available from:
1028 <https://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf>) [viewed 13/05/2020].

1029 United Nations. 1998. KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON
1030 CLIMATE CHANGE. 21pp. (Available from: <https://www.kyotoprotocol.com/resource/kpeng.pdf>)
1031 [viewed 13/05/2020].

1032 United Nations. 1992. UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE.
1033 (Available from:
1034 [https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/co](https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf)
1035 [nveng.pdf](https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf)) [viewed 13/05/2020].

1036 Vézina, A., Hoegh-Guldberg, O. 2008. Effects of ocean acidification on marine ecosystems. *Marine*
1037 *Ecology Progress Series*, 373: 199-201.

1038 Wadey, M.P., Roberts, H. and Harris, J. 2013. Impacts of climate change on built structures (onshore
1039 and coastal), *MCCIP Science Review 2013*, 284-294, doi:10.14465/2013. arc30.284-294

1040 Wadhams, P., Munk, W. 2004. Ocean freshening, sea level rising, sea ice melting, *Geophysical*
1041 *Research Letters*, Vol. 31:11. doi:10.1029/2004GL020039

1042 Waterkeyn, A., Vanschoenwinkel, B., Vercampt, H., Grillas, P., Brendonck, L. 2011. Long-term effects
1043 of salinity and disturbance regime on active and dormant crustacean communities, *Limnology and*
1044 *Oceanography*, Vol. 56:3, Pages 1008-1022

1045 Whitfield, A.K., Elliott, M., Basset, A., Blaber, S.J.M., West, R.J. 2012. Paradigms in estuarine ecology-
1046 A review of the Remane diagram with a suggested revised model for estuaries, *Estuarine, Coastal and*
1047 *Shelf Science*, 97: 78-90.

1048 Whitfield, A.K., Elliott, M. 2011. Chapter 1.07: Ecosystem and Biotic Classifications of Estuaries and
1049 Coasts. In: Volume 1, Classification of Estuarine and Nearshore Coastal Ecosystems, C Simenstad and
1050 T Yanagi (Eds), In: E Wolanski & McLusky, DS (Eds) *Treatise on Estuarine & Coastal Science*, Elsevier,
1051 Amsterdam, pp.99-124.

1052 Winn, P.J.S., Young, R.M., Edwards, A.M.C 2003. Planning for the rising tides: the Humber Estuary
1053 Shoreline Management Plan, *Science of The Total Environment*, 314-316: 13-30.

1054 Wittmann, A.C., Pörtner, H.O. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature*
1055 *Climate Change*, 3(11): 995.

1056 Wright P. Impacts of climate change on ports and shipping. *MCCIP Sci. Rev.* 2013:263-70.

1057 Woodward, S. (2010). The Economic Potential of Nature Tourism in Eastern Yorkshire. (retrieved
1058 04/10/17 from
1059 [https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiMq9TpxtbWAhUEaFAKHytPcPlQFggrMAA&url=http%3A%2F%2Fmediafiles.thedms.co.uk%2FPublication%2FYs-](https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiMq9TpxtbWAhUEaFAKHytPcPlQFggrMAA&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)
1060 [EY%2Fcms%2Fpdf%2FYNT%2520ICRT%2520Report%252C%2520Nature%2520Tourism%2520in%2520Eastern%2520Yorkshire.pdf&usg=AOvVaw1JJ8E-dXhv8qviO1xDfQAY](https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiMq9TpxtbWAhUEaFAKHytPcPlQFggrMAA&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)
1061 [Publication%2FYs-](https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiMq9TpxtbWAhUEaFAKHytPcPlQFggrMAA&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)
1062 [EY%2Fcms%2Fpdf%2FYNT%2520ICRT%2520Report%252C%2520Nature%2520Tourism%2520in%2520Eastern%2520Yorkshire.pdf&usg=AOvVaw1JJ8E-dXhv8qviO1xDfQAY](https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiMq9TpxtbWAhUEaFAKHytPcPlQFggrMAA&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)
1063 [0Eastern%2520Yorkshire.pdf&usg=AOvVaw1JJ8E-dXhv8qviO1xDfQAY](https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKewiMq9TpxtbWAhUEaFAKHytPcPlQFggrMAA&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)

- 1064 Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.) 2019. Coasts and Estuaries: The Future.
1065 Elsevier, Amsterdam, ISBN 978-0-12-814003-1.
- 1066 Wragg, S. 2014. Hull City Council Flood Investigation Report: December 2013 City Centre Tidal Surge
1067 Event. Report to the Environment & Transport Overview and Scrutiny Committee, Hull City Council,
1068 4th February 2014. (accessible from
1069 <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)
1070
- 1071 Wright, P. 2013. Impacts of climate change on ports and shipping, *MCCIP Science Review 2013*, 263-
1072

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 *et 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 defensible 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).

33 This study summarises the relevant impacts from climate change on estuarine systems and how the
34 effects of climate change are currently being managed and governed locally, regionally and globally
35 through legislative measures (Section 2). The sufficiency or appropriateness of the legislative
36 framework and regional rules for protecting an estuary, using the Humber Estuary as a case study,
37 against the effects of climate change are explored (Section 3) and, as a result, recommendations are
38 made as to how policies can, or should be modified or improved (Section 4).

39 2 Climate Change and Management and Governance: The Global Challenge

40 Understanding the impact that climate change has on transitional systems is crucial to developing
41 management strategies that will be sustainable over the long-term (Donovan *et al.*, 2013; Jones *et al.*,
42 2013; Mieszkowska *et al.*, 2013). There are many recognised impacts and similarities of climate change
43 worldwide which increase the vulnerability and decrease the resilience of estuaries (Wolanski *et al.*,
44 2019). Elliott *et al.* (2015) summarises a conceptual framework relating to all the coastal effects of
45 climate change and Robins *et al.*, (2015), Robins (2019) and Ducrotoy *et al.* (2019) focus on the natural
46 science aspects within estuaries. Some of the most prominent threats to estuarine environments
47 highlighted within this literature are related to: increased carbon dioxide and concomitant changes in
48 temperature, sea level rise, and increasing storminess (IPCC, 2013) (see Figure 1).

49 In addition to these threats, there is a threat to socio-economics (summarised in Figure 1): the urban
50 and industrialised coastal and estuarine areas will become increasingly exposed to the effects of
51 climate change. As sea levels rise, storm activity intensifies and the physiography and biology of these
52 environments change, the lives and livelihoods of people, properties and assets will be threatened
53 (Simpson, 2013; Wadey *et al.*, 2013). Other coastal structures, such as coastal protection measures
54 (e.g. sea walls), and infrastructure (notably energy and transport) are likely to be affected. The
55 increase in sea level and storm surges can increase the risk of coastal properties being affected and
56 damaged due to flooding (Raynor, 2014). However, there are also wellbeing impacts from flooding
57 (see Tunstall *et al.* 2006).

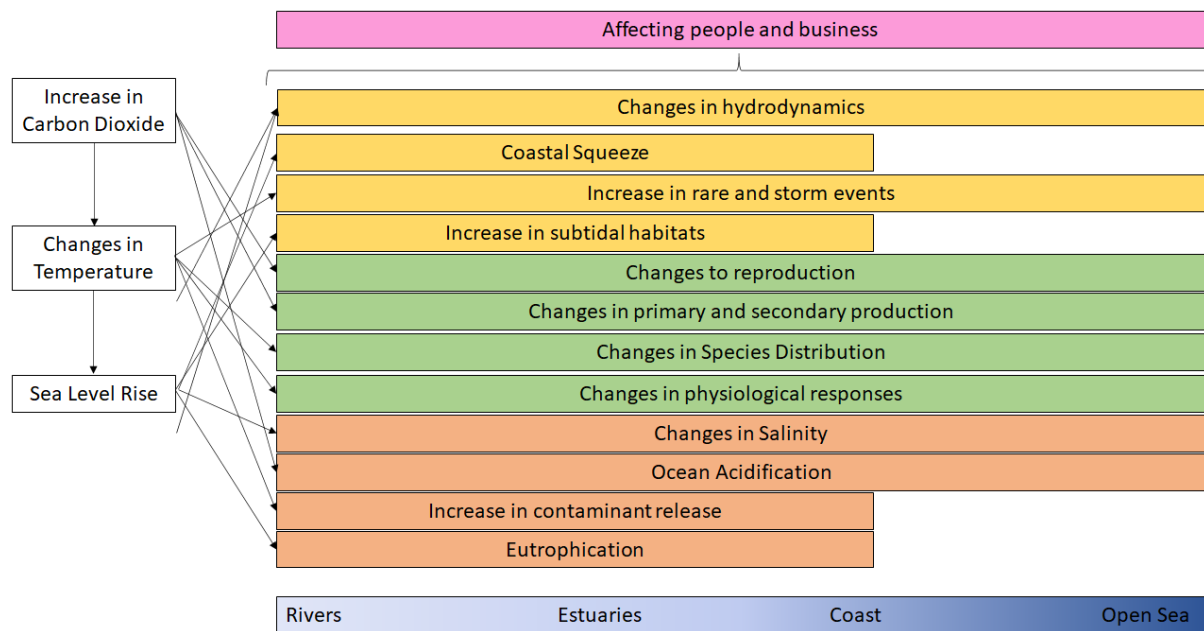
58 Wright (2013) noted that ports will be particularly affected by climate change associated impacts such
59 as enhanced storm surge activity, sea-level rise, temperature change, precipitation and high winds
60 (supported by Becker *et al.*, 2018; Hallegatte *et al.*, 2011). Most notably, changes to the physiography
61 and hydrodynamics could alter the system sediment budget and change the morphology of navigable
62 channels, thereby affecting shipping capabilities. If channels are deepened through increased erosion,
63 larger vessels could be accommodated but if channels infill, the size of ships could be restricted, and

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85

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).



86

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

90 Estuaries are managed through many legislative instruments at international, national and regional
 91 levels, including voluntary codes of conduct (Boyes and Elliott, 2014). Across all these levels, the
 92 legislation, policies, administration and management strategies are designed to safeguard ecosystems
 93 whilst allowing for sustainable development, and the management of ongoing and proposed activities.
 94 However, legislation does not tell us how to do something but rather permits what can and cannot be
 95 done (Cormier et al., 2019).

96 At a global level, there are international treaties and conventions, many of which are legally binding
 97 for countries that have formally ratified them e.g. the United Nations Convention on the Law of the
 98 Sea (UNCLOS, 1982). These international treaties set the minimum standard, for example, for
 99 environmental protection. Countries can implement higher standards of [marine] environmental
 100 protection, but not less. Here we briefly provide an overview of these overarching protection
 101 measures as they influence regional, national and local management measures.

102 In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development and the
 103 Sustainable Development Goals. There are 17 Sustainable Development Goals (SDGs) and associated
 104 targets, with SDG 14 focused on the oceans. The aim of SDG 14 'Life below water' is to "Conserve and
 105 sustainably use the oceans, seas and marine resources for sustainable development". Of its seven
 106 targets, Target 14.3 is to "Minimize and address the impacts of ocean acidification, including through
 107 enhanced scientific cooperation at all levels" is the most relevant when considering how estuaries are

108 responding to climate change and how these impacts can be managed. However, it is questioned
109 whether these targets are operationally satisfactory (Cormier & Elliott 2017).

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

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

122 Below this level, there are regional commissions, where multiple countries who share common seas
123 and/or coastline agree to management measures. For example, the European Commission sets out
124 Directives which, as with global treaties, set the minimum requirements. Under the European
125 Directive for Environmental Impact Assessments (2014/52/EC), developers have a duty to consider
126 the effects their development may have on the repercussions of climate change and vice versa
127 (Lonsdale et al., 2017). Comparable Legislation is found globally, such as the Canadian Impact
128 Assessment Act, 2019, which states that the assessment must consider “the extent to which the
129 effects of the designated project hinder or contribute to the Government of Canada’s ability to meet
130 its environmental obligations and its commitments in respect of climate change” (Government of
131 Canada, 2020).

132 Similarly, UNEP Regional Seas Conventions, such as the Convention for the Protection and
133 Development of the Marine Environment and Coastal Region of the Mediterranean Sea (Barcelona
134 Convention) and Convention for the Protection of the Marine Environment of the North-east Atlantic
135 (OSPAR Convention), are aimed at protecting marine areas used by multiple countries as a shared
136 resource. The OSPAR North-East Atlantic Environment Strategy 2020 states that “*first effects of
137 climate change and ocean acidification are apparent throughout the OSPAR Maritime Area and that
138 pressures on the marine environment from climate change and ocean acidification are set to grow*”
139 (OSPAR Commission, 2010). As such, and in accordance with this strategy, the OSPAR Secretariat has
140 committed to monitor and assess the nature, rate and extent of the effects of climate change and

141 ocean acidification on the marine environment and consider appropriate ways of responding to such
142 developments.

143 At the national level, there are three levels of marine and coastal governance:

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

151 The treaties set out what is expected, and the national legislation stipulates what can and cannot be
152 done legally to meet the international obligations. For example, in the UK, the Climate Change Act
153 2008 is an Act of Parliament under which the Secretary of State should ensure, amongst other
154 provisions, that the net UK carbon emissions (including from all six greenhouses gases targeted by the
155 Kyoto Protocol) by 2050 are at least 100% lower than the 1990 baseline. Additionally, an independent
156 UK Committee on Climate Change has been created under the Act to provide advice to UK Government
157 on these targets and related policies. The specific aspects relating to the Humber Estuary, eastern
158 England are explored in Section 3.

159 The above management measures generally consider geographic scope and scale, and it is only at the
160 local level where estuarine specific aspects are considered. At this local level, the administrators can
161 only enact current law and regulations, and the law may be more focussed on the repercussions of
162 not acting. Local management measures can be binding such as byelaws (which manage certain
163 activities in a certain area), or non-binding, such as codes of conduct or local policies related to,
164 amongst others, climate change adaptation (Defra, 2010).

165 Environmental management in estuaries, as with all other environments, needs to cover horizontal
166 integration, across all the stakeholders in an area, and vertical integration from the local , national and
167 regional to global level obligations. This requires that managers, regulators, and decision makers are
168 in place and that independent reviews of the governance are completed, i.e. a regulatory impact
169 assessment. However, governance structures, especially for the marine environment, are often
170 complex with overlapping roles and responsibilities (Lonsdale et al., 2015; Boyes & Elliott, 2015). There
171 are often perceived conflicts in this approach as the Government may set a policy e.g. increasing
172 reliance on renewable energy, but this requires renewable infrastructure to be built, and the

173 infrastructure may not be permitted to be built either for environmental (too large an impact) or
174 societal (objections based on impact to local amenities or economy) grounds. Therefore, it is
175 questioned what happens if targets are not met despite all departments acting lawfully.

176 The vertical integration from having international and regional agreements, conventions and
177 protocols which feed into the national and local governance as described above, is generally accepted
178 and well-implemented. However, there is also the need for horizontal integration which requires the
179 coordination of environmental goals and objectives with those of stakeholders across marine sectors
180 (Cormier et al., 2019). For example, constructing an offshore structure could only be permitted if the
181 goals/objectives of a marine protected area were not threatened. As demonstrated by Cormier et al.
182 (2019) and Lonsdale et al. (2015), this horizontal integration is complex: there are usually several
183 regulators (see Section 3 for those relevant to the Humber Estuary) that manage a marine area and
184 activities. Hence, cross-agency communication, with shared visions and agreements is key for effective
185 marine management.

186 3 What does this mean in reality? A Case Study of the Humber Estuary, UK

187 To explore the sufficiency or appropriateness of the legislative framework and regional rules for
188 protecting an estuary against the effects of climate change, we take the well-studied case study of the
189 Humber Estuary in the North East of England. It is one of the largest coastal plain estuaries in the EU,
190 extending approximately 62 km from Trent Falls to the open (North) sea (Figure 2). It is one of the
191 busiest and fastest growing areas for seaborne trade in Europe and provides an important
192 contribution to the UK economy (Ciavola, 1997; Jarvie, et al., 1997; Metcalfe et al., 2000). It supports
193 four major ports: Goole, Hull, Grimsby and Immingham, that import >20% of the UK's total inward
194 tonnage per year (Figure 2) and is rapidly growing as a national base for offshore wind installation and
195 operations in the North Sea. Many industries, cities and towns are clustered near these ports, with
196 much of the remaining land bordering the system used for agriculture.

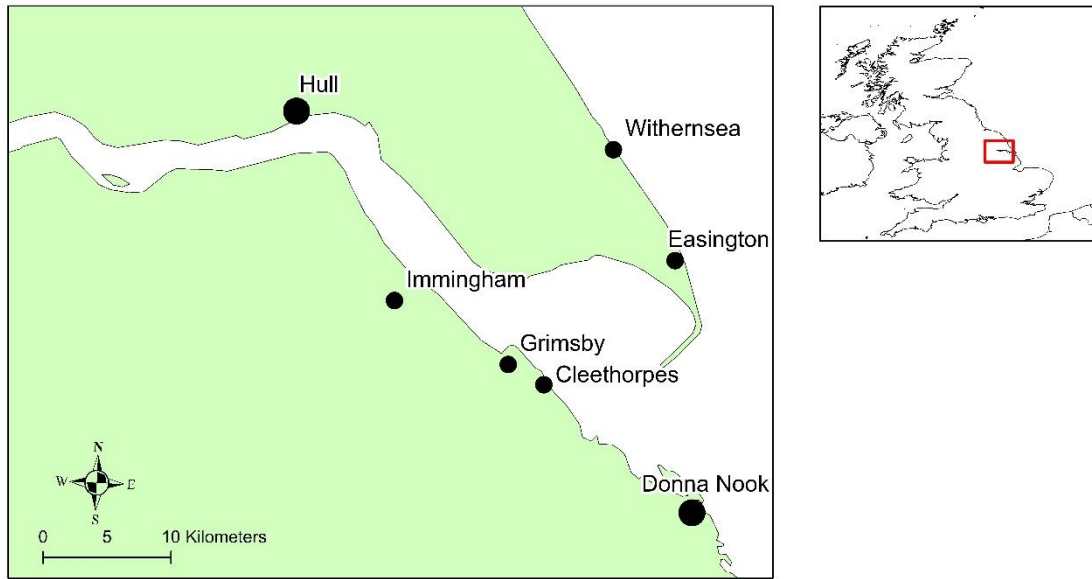


Figure 2 Case Study area

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

1 219 Estuary is managed through many legislative instruments, from international, to European, national,
2 220 and regional levels, including voluntary codes of conduct. Hence, management measures within the
3 221 Humber Estuary are designed to combat the effects of climate change, such as management
4 222 realignment sites or setting back or raising flood defences (Elliott et al., 2016). This leads to the
5 223 question of how future proof are these methods especially given any time lag and inertia in the system.
6
7 224 The efficacy of management measures aimed at tackling climate change impacts is determined by
8
9 225 monitoring such as salinity, species distribution or contamination.
10

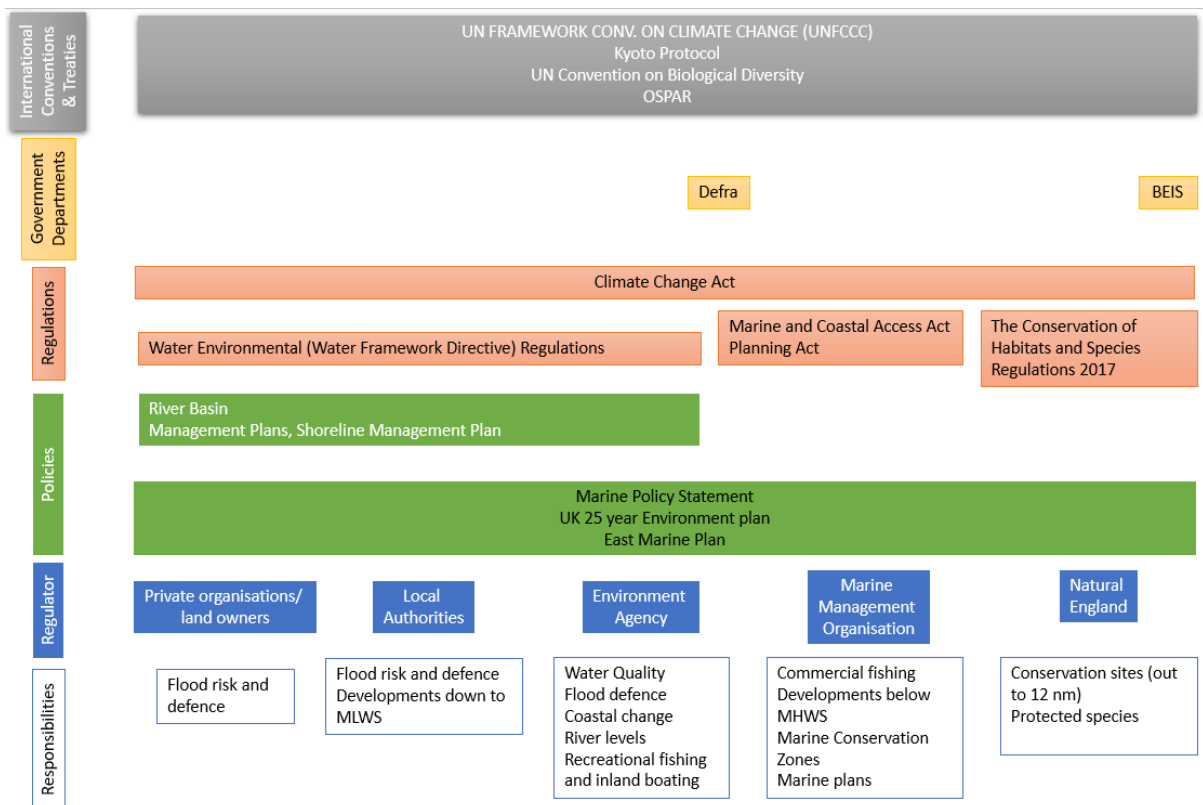
11
12
13 226 In Section 2, we highlighted the international conventions which set out the requirement for countries
14 227 to do something, here we look at the specific requirements for managing a relatively small site in
15 228 comparison to the global treaties jurisdiction.
16
17

18
19 229 Nationally, The UK Climate Change Act (2008), amended in 2019, is the UK's response to reducing and
20 230 mitigating against climate change. It requires the UK to act to tackle climate change and reduce
21 231 greenhouse gas emissions by 100% of 1990 levels by 2050- this is important when considering ongoing
22 232 (e.g., shipping) or new (e.g., power stations) developments. The UK Marine Policy statement, as
23 233 required by the Marine and Coastal Access Act 2009, sets out guidelines for maintaining marine
24 234 environments in healthy, productive and resilient conditions, without compromising the ecosystem
25 235 services and societal goods and benefits (Kelly et al., 2014; Turner and Schaafsma, 2015). The East
26 236 Marine Plan (within which the Humber Estuary sits) aims 'to facilitate action on climate change
27 237 adaptation and mitigation' by identifying areas for renewable energy generation (wave and tidal
28 238 energy) and carbon capture storage, in line with the European Renewable Energy Directive
29 239 (2009/28/EC) and the UK Climate Change Act, 2008. Local-level estuarine management is prominent
30 240 in the Humber Estuary in acknowledging that climate change increases the risk of flooding. The
31 241 Environment Agency has used a cost-benefit analysis to implement the Humber Flood Risk
32 242 Management Strategy to manage flood risk, aiming to ensure that 99% of people who live close to the
33 243 Estuary have a good level of protection against tidal flooding for 25 years following the
34 244 implementation of the strategy (Environment Agency, 2008). The Humber Flood Risk Strategy
35 245 complements a range of regional plans, including Shoreline Management Plans (SMP) and Coastal
36 246 Habitat Management Plans (CHaMP). It is of note that those not protected live at sites where the cost-
37 247 benefit analysis would have indicated that protection is prohibitively expensive given the value of
38 248 assets protected. See Figure 3 for a visualisation of the Humber relevant management measures.
39
40
41

42 249 To determine the sufficiency of the legislative framework and/or the organisations responsible, the
43 250 potential impacts highlighted in Section 2, were considered in terms of what (legislation) and who
44 251 (authorities) is responsible for managing these impacts (Table 1).
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

252

1
2
3 253 Many of the responsibilities for monitoring and managing the impacts of climate change within the
4
5 254 estuary appear to fall onto the Environment Agency, the English environmental protection agency (in
6
7 255 the UK, Scotland, Wales and Northern Ireland have their own bodies as devolved agencies). However,
8
9 256 some specific responsibility falls to others, such as the Marine Management Organisation (for
10
11 257 assessing new development applications) or Local Authorities, and even private organisations, for the
12
13 258 maintenance of some flood defences (see Figure 3). Vertical and horizontal integration between these
14
15 259 legislative instruments and responsible organisations is therefore imperative to ensure effective
16
17 260 management that is compliant with international, regional, and national legislation whilst taking into
18
19 261 consideration specific challenges within the Humber Estuary. How this can be achieved is not always
20
21 262 clear or straightforward to achieve.



263

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

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

1 271 (Elliott et al., 2022). Models can inform how an area may be impacted by climate change (Falconer et
2 272 al., 2020), but they have caveats and their spatial and temporal predictability, both from deterministic
3 273 and empirical modelling, gives them limited use in prioritising areas for monitoring. End-to-end
4 274 models which link changes to the natural environment with the socio-economic repercussions (Peck
5 275 et al., 2018) have the potential for use but require expensive parameterisation for individual areas.
6
7 276 Hence, to inform management strategies, we need robust modelling to predict potential scenarios
8
9 277 and determine harmonised specific responses based on the site-specific information; for instance, the
10 278 modelling results and management responses for the south coast may not be appropriate or
11
12 279 applicable to the Humber Estuary. This would allow for a local policy to be developed, but by learning
13
14 280 from local examples, national policy could be more aligned to the UK's responses (both environmental
15
16 281 and management) to climate change impacts.
17
18
19

20 282 The review in Table 1 also indicates that there is little in the way of preparatory or proactive mitigation
21
22 283 measures to combat when, and if, thresholds for biological impacts are reached for example, what is
23
24 284 to happen when there is a salinity shift? Is there anything that can be done to offset or mitigate the
25
26 285 changes?
27

28 286
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

287 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

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

		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 patterns 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 salinity 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

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

						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.

15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

288

		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

320 mitigation/adaptation methods to be updated according to site-specific conditions and increasing
321 knowledge.

322 It appears that the Humber Estuary, has good vertical integration of governance from the local to
323 global thereby facilitating suitable management measures across all levels. However, ideally, policies
324 and legislative instruments, should include prescriptive guidance for what thresholds indicate an issue
325 e.g. approaching an action points (a reference condition, threshold, trigger or tipping point (Elliott et
326 al., 2022), or what actions can be taken. To ensure successful and sustainable development, the
327 policies and strategies require to be tested rigourously, for example against the ten-tenets of
328 sustainable management (Elliott, 2013; Barnard and Elliott, 2015). These cover the ecological,
329 economic, technological, societal, administrative, legislative, political, ethical (moral), cultural and
330 communication aspects of sustainable solutions. Hence, wider education, and engagement of
331 stakeholders (e.g. CEDA, 2012; Newton and Elliott, 2016) is required to address these issues and
332 ensure adaptive capacity is recognised and built into plans, policies, and existing developments. In line
333 with the coordination of climate change adaptation, this requires ensuring adaptive capacity is
334 maintained through all levels of the estuary stakeholders. The collation and dissemination of evidence
335 and monitoring data will become increasingly important to identify whether the effects and trends of
336 climate change are apparent. By ensuring the monitoring data and evidence are shared, the effects
337 and adaptive management strategies can be fed into marine plans to provide long-term resilience to
338 climate change and allow a greater integration, awareness and understanding of the effects of climate
339 change into policy and infrastructure changes. For example, this includes the need to consider all the
340 effects of individual managed realignment sites at the estuary level.

341 5 Concluding Remarks

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

353 measures across all levels. This would enable scientists, managers and decision makers to address site-
1 354 specific climate change effects, relevant to the areas they manage whilst remaining within the
2
3 355 boundaries of more global-based guidance (Elliott *et al.*, 2015; Robins *et al.*, 2016; Wolanski *et al.*,
4
5 356 2019).
6

7
8 357
9

10 358 Using a case study of the Humber Estuary, this study demonstrates the impediments to effective and
11
12 359 long term management against the potential harmful effects of climate change on the marine
13
14 360 environment. The main bottleneck being the lack of resources, or rather the current inability to
15
16 361 monitor all aspects of the estuarine waters and coastline, and the inability to currently address some
17
18 362 of the effects. Many of the effects are wide-ranging and therefore it requires the culmination of
19
20 363 mitigation measures on a scale larger than the estuary level to effectively mitigate against the effects.
21
22 364 To do this, requires the use of frameworks to assess the potential impacts of any effects, the use of
23
24 365 tools such as models, although their use is associated with limitations, and the integration of the
25
26 366 governance structures, both vertically and horizontally.

27 367 There is extensive monitoring carried out on the Humber but monitoring is not a management
28
29 368 measure but rather the means of determining whether management measures have been effective
30
31 369 (Wolanski and Elliott, 2015; Elliott *et al.* 2022), and hence we need to understand the physical,
32
33 370 biological and chemical environment to inform management. A major gap is the availability of data to
34
35 371 understand the magnitude of the effects of climate change and what can be done about it.

36 372 As shown here, there is an increasing understanding of how our climate is changing, how
37
38 373 environmental systems such as estuaries are affected, and the ways they can be managed to become
39
40 374 more resistant and resilient through informed decision frameworks. Whilst targets, ambitions and
41
42 375 goals are useful tools to ensure issues relating to impacts from climate change are tackled, there is
43
44 376 the risk that the focus is on meeting targets, will not address the ancillary issues, for example, at local
45
46 377 or regional levels. Due to the global-reaching impacts of climate change, a national strategy for
47
48 378 harmonising targets and combatting climate change impacts may be an effective solution, albeit,
49
50 379 costly to coordinate, implement and monitor.
51

52 380 **Acknowledgements**

53
54 381 Centre for Environment, Fisheries and Aquaculture Science for their financial support of their doctoral
55
56 382 study of the first author and the Environment Agency and British Geological Survey for their financial
57
58 383 support of the doctoral study of the second author. Dr Tom Coulthard for his input into the research
59
60 384 development.
61
62
63
64
65

385 **References**

- 386 Agardy, T., Alder, J. 2005. Chapter 19 Coastal Systems IN: Sarukhan, J., Whyte, A. [Editors] 2005.
387 Millennium Ecosystem Assessment. ISLAND PRESS Washington, USA. (Available from:
388 <https://www.millenniumassessment.org/en/Condition.html#download>) [viewed 23/07/2021].
- 389 Andrello, M., Mouillot, D., Somot, S., Thuiller, W., Manel, S., 2015. Additive effects of climate change
390 on connectivity between marine protected areas and larval supply to fished areas. *Diversity and*
391 *Distributions*, 21(2):139-150.
- 392 Andrews, J.E., Burgess, D., Cave, R.R., Coombes, E.G., Jickells, T.D., Parkes, D.J. and Turner, R.K. 2006.
393 Biogeochemical value of managed realignment, Humber estuary, UK. *Science of the total environment*,
394 371(1): 19-30.
- 395 Antonov, J.I., Levitus, S., Boyer, T.P. 2002. Steric sea level variations during 1957–1994: Importance of
396 salinity, *Journal of Geophysical Research*, 107(C12): 14-1-14-8. DOI: 10.1029/2001JC000964
- 397 Antonson, H., Isaksson, K., Storbjörk, S., Hjerpe, M. 2016. Negotiating climate change responses:
398 Regional and local perspectives on transport and coastal zone planning in South Sweden, *Land Use*
399 *Policy*, 52: 297-305.
- 400 Apitz, S.E., Elliott, M., Fountain, M., Galloway, T.S. 2006. European environmental management:
401 Moving to an ecosystem approach, *Integrated Environmental Assessment and Management*, 2(1): 80-
402 85.
- 403 Australian Government. 2017. 2017 Review of Climate Change Policies December 2017. 54pp.
404 (Available from: [https://publications.industry.gov.au/publications/climate-](https://publications.industry.gov.au/publications/climate-change/system/files/resources/186/2017-review-of-climate-change-policies.pdf)
405 [change/system/files/resources/186/2017-review-of-climate-change-policies.pdf](https://publications.industry.gov.au/publications/climate-change/system/files/resources/186/2017-review-of-climate-change-policies.pdf)) [viewed
406 13/05/2020].
- 407 Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R. 2011. The value of
408 estuarine and coastal ecosystem services, *Ecological Monographs*, 81(2): 169-193.
- 409 Barnard, S., Elliott, M. 2015. The 10-tenets of adaptive management and sustainability: An holistic
410 framework for understanding and managing the socio-ecological system, *Environmental Science and*
411 *Policy*, 51: 181-191.
- 412 Becker, A., Ng, A.K., McEvoy, D. and Mullett, J., 2018. Implications of climate change for shipping: Ports
413 and supply chains. *Wiley Interdisciplinary Reviews: Climate Change*, 9(2), p.e508.
- 414 Bentley, M.G. 2011. The Global Spread Of The Chinese Mitten Crab *Eriocheir Sinensis*. In in *The Wrong*
415 *Place - Alien Marine Crustaceans: Distribution, Biology And Impacts*. Dordrecht: Springer Netherlands,
416 107–127.
- 417 Borja, Á, Elliott, M., Carstensen, J., Heiskanen, A-S., van de Bund, W. 2010. Marine management –
418 towards an integrated implementation of the European Marine Strategy Framework and the Water
419 Framework Directives. *Marine Pollution Bulletin* 60: 2175-2186.
- 420 Boyes, S., Elliott, M. 2015. The excessive complexity of national marine governance systems- Has this
421 decreased in England since the introduction of the Marine and Coastal Access Act 2009? *Marine Policy*,
422 51: 57-65.

- 423 Boyes, S., Elliott, M. 2006. Organic matter and nutrient inputs to the Humber Estuary, England. *Marine*
1 424 *Pollution Bulletin*, 53(1):136-143.
- 2
3 425 Brodie, J., Williamson, C.J., Smale, D.A., Kamenos, N.A., Mieszkowska, N., Santos, R., Cunliffe, M.,
4 426 Steinke, M., Yesson, C., Anderson, K.M., Asnaghi, V. 2014. The future of the northeast Atlantic benthic
5 427 flora in a high CO₂ world. *Ecology and Evolution*, 4(13): 2787-2798.
- 6
7 428 CEDA. 2012. Climate Change Adaptation As It Affects The Dredging Community. CEDA Position Paper.
8 429 Available from: [https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-](https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-05-ceda_positionpaper-climatechangeadaptation.pdf)
9 430 [05-ceda_positionpaper-climatechangeadaptation.pdf](https://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2012-05-ceda_positionpaper-climatechangeadaptation.pdf) [viewed 21/05/2017].
- 10
11
12 431 Ciavola, P. 1997. Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK),
13 432 *Catena*, Vol.30:4, Pages 369-389
- 14
15 433 Committee on Climate Change. 2019. Net Zero: The UK's contribution to stopping global warming.
16 434 (Available from: [https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-](https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf)
17 435 [contribution-to-stopping-global-warming.pdf](https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf)) [viewed 23/07/2019]
- 18
19
20 436 Committee on Climate Change. 2017. Progress in preparing for climate change. 2017 Report to
21 437 Parliament. Pp. 234. (Available from: [https://www.theccc.org.uk/wp-](https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf)
22 438 [content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf](https://www.theccc.org.uk/wp-content/uploads/2017/06/2017-Report-to-Parliament-Progress-in-preparing-for-climate-change.pdf))
23 439 [viewed 21/08/2017]
- 24
25
26 440 Cook, E.J., Jenkins, S., Maggs, C., Minchin, D., Mineur, F., nall, C., Sewell, J. 2013. Impacts of climate
27 441 change on non-native species, *MCCIP Science Review 2013*, 155-166, doi:10.14465/2013.arc17.155-
28 442 166
- 29
30 443 Cormier, R., Elliott, M., Rice, J. 2019. Putting on a Bow-tie to sort out who does what and why in the
31 444 complex arena of marine policy and management. *Science of the Total Environment*, 648: 293-305.
32 445 <https://doi.org/10.1016/j.scitotenv.2018.08.168>.
- 33
34
35 446 Cormier, R., Elliott, M. 2017. SMART marine goals, targets and management – is SDG 14 operational
36 447 or aspirational, is 'Life Below Water' sinking or swimming? *Marine Pollution Bulletin* 123: 28-33;
37 448 <https://doi.org/10.1016/j.marpolbul.2017.07.060>.
- 38
39 449 Creighton, C., Hobday, A.J., Lockwood, M., Pecl, G.T., 2016. Adapting management of marine
40 450 environments to a changing climate: a checklist to guide reform and assess progress. *Ecosystems*,
41 451 19(2): 187-219.
- 42
43
44 452 Cripps, I.L., Munday, P.L., McCormick, M.I. 2011. Ocean Acidification Affects Prey Detection by a
45 453 Predatory Reef Fish, *PLOSone*, doi: <http://dx.doi.org/10.1371/journal.pone.0022736>
- 46
47 454 Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Dauvin, J.C., De
48 455 Mesel, I., Derweduwen, J., Gill, A.B., Hutchison, Z.L. 2020. Benthic effects of offshore renewables:
49 456 identification of knowledge gaps and urgently needed research. *ICES Journal of Marine Science*, 77(3):
50 457 1092-1108.
- 51
52
53 458 Defeo, O, Elliott, M., (2021). Editorial - The 'Triple Whammy' of coasts under threat – why we should
54 459 be worried! *Marine Pollution Bulletin*, 163: 111832.
55 460 <https://doi.org/10.1016/j.marpolbul.2020.111832>
- 56
57 461 Defra. 2013. A Coastal Concordat for England. (Available from:
58 462 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256234/coastal-](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256234/coastal-concordat-20131111.pdf)
59 463 [concordat-20131111.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256234/coastal-concordat-20131111.pdf)). [Viewed 27/12/2017]
- 60
61
62
63
64
65

- 464 Defra. 2010. Adapting to climate change: A guide for local councils. 26pp. (Available from:
1 465 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/218798/adapt-localcouncilguide.pdf)
2 466 [/218798/adapt-localcouncilguide.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/218798/adapt-localcouncilguide.pdf)) [viewed 13/05/2020].
- 4 467 De Jonge, V.N., Elliott, M. 2001. Eutrophication. In: J Steele, S Thorpe & K Turekian (Eds.) *Encyclopaedia*
5 468 *of Ocean Sciences*. Vol. 2, Academic Press, London.p852-870.
- 7 469 Department for Transport. 2012. National Policy Statement for Ports. 76pp. (available from
8 470 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf)
9 471 [/3931/national-policy-statement-ports.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/3931/national-policy-statement-ports.pdf)) [viewed 15/11/2018].
- 12 472 Dixon, D.L., Munday, P.L., Jones, G.P. 2009. Ocean acidification disrupts the innate ability of fish to
13 473 detect predator olfactory cues, *Ecology Letters*, 13(1): 68-75.
- 15 474 Donovan, B., Horsburgh, K., Ball, T. and Westbrook, G. 2013. Impacts of climate change on coastal
16 475 flooding, *MCCIP Science Review 2013*, 211-218, doi:10.14465/2013. arc22.211-218
- 18 476 Ducrotoy, J.-P., Elliott, M., Cutts, N.D., Franco. A., Little. S., Mazik. K., Wilkinson. M. 2019. Temperate
19 477 Estuaries: their ecology under future environmental changes. In: Wolanski, E., Day, J.W., Elliott, M.,
20 478 Ramachandran, R. (Eds.), *Coasts and Estuaries: The Future*. Elsevier, Amsterdam, ISBN 978-0-12-
21 479 814003-1.
- 24 480 Durant, J.M., Hjermann, D.Ø., Ottersen, G., Stenseth, N.C. 2007 Climate and the match or mismatch
25 481 between predator requirements and resource availability, *Climate Research*, doi:
26 482 <http://dx.doi.org/doi:10.3354/cr033271>
- 29 483 Dürr, H. H., G. G. Laruelle, C. M. van Kempen, C. P. Slomp, M. Meybeck, Middelkoop, H. 2011.
30 484 Worldwide Typology of Nearshore Coastal Systems: Defining the Estuarine Filter of River Inputs to the
31 485 Oceans. *Estuaries and Coasts*, 34(3): 441-458, doi:10.1007/s12237-011-9381-y.
- 33 486 Edwards, M., Bresnan, E., Cook, K., Heath, M., Helaouet, P., Lynam, C., Raine, R. and Widdicombe, C.
34 487 2013. Impacts of climate change on plankton, *MCCIP Science Review 2013*, 98-112,
35 488 doi:10.14465/2013.arc12.098-112
- 38 489 Edwards, A.M.C., Winn, P.S.J. 2006. The Humber Estuary, Eastern England: Strategic planning of flood
39 490 defences and habitats, *Marine Pollution Bulletin*, 53(1-4): 165-174.
- 41 491 Elliott, M., Houde, E.D., Lamberth, S.J., Lonsdale, J.-A., Tweedley, J.R., 2022. Chapter 12, Management
42 492 of Fishes and Fisheries in Estuaries. In: *Fish and Fisheries in Estuaries – A Global Perspective* (ed.,
43 493 Whitfield, A.K., Able, K.W., Blaber, S.J.M. & Elliott, M.). John Wiley & Sons, Oxford, UK.
- 45 494 Elliott, M., Borja, A., Cormier, R. 2020. Managing marine resources sustainably: a proposed integrated
46 495 systems analysis approach. *Ocean & Coastal Management*, 197, 105315,
47 496 <https://doi.org/10.1016/j.ocecoaman.2020.105315>
- 50 497 Elliott, M., Quintino, V.M. 2019. The Estuarine Quality Paradox Concept. *Encyclopaedia of Ecology*,
51 498 2nd Edition, (Editor-in-Chief B Fath), Elsevier, Amsterdam, Volume 1, p78-85; ISBN: 978-0-444-63768-
52 499 0. <https://doi.org/10.1016/B978-0-12-409548-9.11054-1>
- 55 500 Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K. 2017. “And DPSIR
56 501 begat DAPSI(W)R(M)!” - a unifying framework for marine environmental management. *Marine*
57 502 *Pollution Bulletin*, 118 (1-2): 27-40. <http://dx.doi.org/10.1016/j.marpolbul.2017.03.049>.

503 Elliott, M., Mander, L., Mazik, K., Simenstad, C., Valesini, F., Whitfield, A., Wolanski, E. 2016.
1 504 Ecoengineering with Ecohydrology: Successes and failures in estuarine restoration, *Estuarine, Coastal*
2 505 *and Shelf Science*, 176: 12-35. doi: 10.1016/j.ecss.2016.04.003.

4 506 Elliott, M., Borja, Á., McWuatters-Gollop, A., Mazik, K., Birchenough, S., Anderson, J.H., Painting, S.,
5 507 Peck, M. 2015. *Force Majeure*: Will climate change affect our ability to attain Good Environmental
6 508 Status for marine biodiversity, *Marine Pollution Bulletin*, 95(1):7-27.

8
9 509 Elliott, M. 2014. Integrated marine science and management: wading through the morass. *Marine*
10 510 *Pollution Bulletin*, 86(1/2): 1-4. doi: 10.1016/j.marpolbul.2014.07.026

11
12 511 Elliott, M., Cutts, N.D., Trono, A. 2014. A typology of marine and estuarine hazards and risks as vectors
13 512 of change: a review for vulnerable coasts and their management. *Ocean & Coastal Management*, 93:
14 513 88-99.

16
17 514 Elliott, M. 2013. The 10-tenets for integrated, successful and sustainable marine management, *Marine*
18 515 *Pollution Bulletin*, 74: 1-5.

19
20 516 Elliott, M. 2011. Marine science and management means tackling exogenic unmanaged pressures and
21 517 endogenic managed pressures – a numbered guide. *Marine Pollution Bulletin*, 62: 651-655.

22
23 518 Elliott, M., Whitfield, A. 2011. Challenging paradigms in estuarine ecology and management,
24 519 *Estuarine, Coastal & Shelf Science*, 94:306-314.

26
27 520 Elliott, M., Underwood, G., Wilkinson, M., Mazik, K., de Jonge, V.N., Dodge, G. 2008. Statement by the
28 521 Expert Panel on the Eutrophic status of the Humber Estuary as Requested by the Environment Agency,
29 522 December 2008

30
31 523 Elliott, M., McLusky, D.S. 2002 The need for definitions in understanding estuaries. *Estuarine, Coastal*
32 524 *& Shelf Science*, 55(6) 815-827.

33
34 525 Environment Agency. 2005a. Humber Estuary Coastal Habitat Management Plan. Available from
35 526 <http://www.discoverysoftware.co.uk/FRaME/pdf/ChaMP.pdf> [Viewed 05/08/2020].

37
38 527 Environment Agency. 2008. The Humber Flood Risk Management Strategy: Planning for the Rising
39 528 Tides. Available from:
40 529 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308281/Humber_Strategy_Summary.pdf)
41 530 [/308281/Humber_Strategy_Summary.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/308281/Humber_Strategy_Summary.pdf) [Viewed 17/07/2020].

42
43 531 European Commission. 2013. Guidelines on Climate Change and Natura 2000. 105pp. Available from:
44 532 <http://ec.europa.eu/environment/nature/climatechange/pdf/Guidance%20document.pdf> [Viewed
45 533 09/02/2018].

47
48 534 Falconer, L., Hjøllø, S.S., Telfer, T.C., McAdam, B.J., Hermansen, Ø. and Ytteborg, E., 2020. The
49 535 importance of calibrating climate change projections to local conditions at aquaculture sites.
50 536 *Aquaculture*, 514, p.734487.

52
53 537 Feely, R.A., Alin, S.R., Newton, J., Sabine, C.L., Warner, M., Devol, A., Krembs, C., Maloy, C. 2010. The
54 538 combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an
55 539 urbanized estuary, *Estuarine, Coastal and Shelf Science*, 88(4): 442-449.

56
57 540 Freestone, D., Jones, N., North, J., Pethick, J., Symes, D. and Ward, R. 1987. The Humber Estuary,
58 541 Environmental Background, UK: Shell.

59
60
61
62
63
64
65

542 Garcia-de-Lomas, J., Dana, E.D., López-Santiago, J., González, R., Ceballos, G., Ortega, F., (2010)
1 543 Management of the Chinese mitten crab, *Eriocheir sinensis* (H. Milne Edwards, 1853) in the
2 544 Guadalquivir Estuary (Southern Spain), *Aquatic Invasions*, 5(3): 323-330.

4 545 Giffin, A.L., Brown, C.J., Nalau, J., Mackey, B.G. and Connolly, R.M., 2020. Marine and coastal
5 546 ecosystem-based adaptation in Asia and Oceania: review of approaches and integration with marine
6 547 spatial planning. *Pacific Conservation Biology*, 27(2), pp.104-117.

8
9 548 Gilbey, V., Attrill, M.J., Coleman, R.A. 2008. Juvenile Chinese mitten crabs (*Eriocheir sinensis*) in the
10 549 Thames estuary: distribution, movement and possible interactions with the native crab *Carcinus*
11 550 *maenas*, *Biological Invasions*, 10: 67-77.

13 551 Government of Canada. 2020. Policy Context: Considering Environmental Obligations and
14 552 Commitments in Respect of Climate Change under the Impact Assessment Act. (Available from:
15 553 [https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-](https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/considering-environmental-obligations.html)
16 554 [guide-impact-assessment-act/considering-environmental-obligations.html](https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/considering-environmental-obligations.html)) [viewed 13/05/2020].

18 555 Government of Canada. 2018. Adaptation and climate resilience. Strengthening our communities to
19 556 thrive in a changing climate.
20 557 [https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-](https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-actions-clean-growth-economy/adaptation-climate-resilience.html)
21 558 [actions-clean-growth-economy/adaptation-climate-resilience.html](https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-actions-clean-growth-economy/adaptation-climate-resilience.html)

23 559 Gross, J.E. 2003. Developing Conceptual Models for Monitoring Programs, (available from
24 560 http://science.nature.nps.gov/im/monitor/docs/Conceptual_modelling.pdf) [viewed 21/10/13].

26 561 Hallegatte S, Ranger N, Mestre O, Dumas P, Corfee-Morlot J, Herweijer C, Wood RM. Assessing climate
27 562 change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. *Climatic*
28 563 *change*. 2011 Jan;104(1):113-37.

30 564 HM Government. 2018a. A Green Future: Our 25 Year Plan to Improve the Environment. 151pp.
31 565 (Available from:
32 566 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf)
33 567 [/693158/25-year-environment-plan.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf)) [viewed 13/05/2020].

35 568 HM Government. 2018b. Strengthened Local Enterprise Partnerships. 30pp. (available from
36 569 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728058/Strengthened_Local_Enterprise_Partnerships.pdf)
37 570 [/728058/Strengthened_Local_Enterprise_Partnerships.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728058/Strengthened_Local_Enterprise_Partnerships.pdf)) [viewed 15/11/2018].

39 571 HM Government. 2014. East Inshore and East Offshore Marine Plans. (available from
40 572 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312496/east-](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312496/east-plan.pdf)
41 573 [plan.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312496/east-plan.pdf)) [viewed 27/11/16].

43 574 HM Government. 2011. UK Marine Policy Statement, London: The Stationary Office.

45 575 Health Protection Agency. 2012. Health Effects of Climate Change in the UK 2012. Current evidence,
46 576 recommendations and research gaps. Pp. 242. (Available from:
47 577 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/371103/Health_Ef](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)
48 578 [fects_of_Climate_Change_in_the_UK_2012_V13_with_cover_accessible.pdf](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]

50 579 Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung,
51 580 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional*
52 581 *Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental*
53 582 *Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir,

583 M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R.
1 584 Mastrandrea, and L.L.White (eds.)). Cambridge University Press, Cambridge, United Kingdom and New
2 585 York, NY, USA, pp. 1655-1731.

3
4 586 Humber Nature Partnership. 2017. Investing in Natural Capital. Creating the right environment for
5 587 economic investment. (Available from: [http://humburnature.co.uk/admin/resources/investing-in-](http://humburnature.co.uk/admin/resources/investing-in-natural-capital.pdf)
6 588 [natural-capital.pdf](http://humburnature.co.uk/admin/resources/investing-in-natural-capital.pdf)) [Viewed 21/08/2017]

7
8
9 589 IMO. 2020. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other
10 590 Matter. <http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx>

11
12 591 IPCC. 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis.
13 592 Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on
14 593 Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y.
15 594 Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New
16 595 York, NY, USA.

17
18
19 596 Jarvie, H.P., Neal, C., Robson, A.J. 1997. The geography of the Humber catchment, *Science of the Total*
20 597 *Environment*, 194: 87-100.

21
22 598 Johns, D., Smalls, M., Maslen, S. 2010. Coastal Schemes with Multiple Funders and Objectives FD2635.
23 599 Case Study Report 1 Alkborough Flats Tidal Defence Scheme. 10pp.

24
25 600 Jones, L., Garbutt, A., Hansom, J., Angus, S. 2013. Impacts of climate change on coastal habitats,
26 601 *Marine Climate Change Impacts Partnership: Science Review*, pp. 167-179.

27
28
29 602 Kelly, C., Gray, L., Shucksmith, R.J., Tweddle, J.F. 2014. Investigating options on how to address
30 603 cumulative impacts in marine spatial planning, *Ocean and Coastal Management*, 102: 139-148.

31
32 604 Klein, S.A., Soden, B.J. and Lau, N.C. 1999. Remote sea surface temperature variations during ENSO:
33 605 Evidence for a tropical atmospheric bridge. *Journal of Climate*, 12(4): 917-932.

34
35 606 Klemetsen, A., Amundsen, P-A., Dempson, J.B., Jonsson, N., O'Connell, M.F., Mortensen, E. 2003.
36 607 Atlantic salmon *Salmo salar* L., brown trout *Salmo trutta* L. and Arctic charr *Salvelinus alpinus* (L.): a
37 608 review of aspects of their life histories, *Ecology of Freshwater Fish*, Vol. 12:1, DOI: 10.1034/j.1600-
38 609 0633.2003.00010.x

39
40
41 610 Kroeger, K.D., Anderson, I., Baldwin, S., Brooks, W., Brush, M., Cai, W.J., Canuel, E., Casso, M., Chen,
42 611 R., Green, A. and McCallister, L., 2012. Fluxes in tidal wetlands. In *Report of The US East Coast Carbon*
43 612 *Cycle Synthesis Workshop* (pp. 5-7). Gloucester Point, VA: Virginia Institute of Marine Sciences.

44
45 613 Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M. and Gattuso,
46 614 J.P., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction
47 615 with warming. *Global change biology*, 19(6), pp.1884-1896. Little, S., Wood, P.J, Elliott, M. (in press).
48 616 Quantifying salinity-induced changes on estuarine benthic fauna: The potential implications of climate
49 617 change. *Estuarine, Coastal and Shelf Science*, in press.

50
51
52
53 618 Lonsdale, J., Nicholson, R., Weston, K., Elliott, M., Birchenough, A., Sühning, R., 2018. A user's guide to
54 619 coping with estuarine management bureaucracy: An Estuarine Planning Support System (EPSS) tool.
55 620 *Marine Pollution Bulletin*, 127: 463-477.

56
57 621 Lonsdale, J., Weston, K., Elliott, M., Blake, S., Edwards, R. 2017. The Amended European Environmental
58 622 Impact Assessment Directive: UK Marine Experience and Recommendations. *Ocean and Coastal*
59 623 *Management*, 148: 131-142.

60
61
62
63
64
65

- 624 Lonsdale, J-A., Weston, K., Barnard, S., Boyes, S., Elliott, M. 2015. Integrating Management Tools and
1 625 Concepts to Develop an Estuarine Planning Support System: A case study of the Humber Estuary,
2 626 Eastern England, *Marine Pollution Bulletin*, 100(1): 393-405.
- 4 627 Lonsdale, J. 2013. The Potential Uses of Dredged Material in the Humber Estuary, MSc Thesis,
5 628 University of Hull funded by TiDE (available from: [http://www.tide-](http://www.tide-project.eu/downloads/Pilot_project_Humber_estuary.pdf)
7 629 [project.eu/downloads/Pilot_project_Humber_estuary.pdf](http://www.tide-project.eu/downloads/Pilot_project_Humber_estuary.pdf)) [viewed 29/05/2015]
- 9 630 Maitland, P.S. 2003. Ecology of the River, Brook and Sea Lamprey. *Conserving Natura 2000 Rivers*
10 631 *Ecology Series No. 5*. English Nature, Peterborough.
- 12 632 Mander, L., Cutts, N.D., Allen, J., Mazik, K. 2007. Assessing the development of newly created habitat
13 633 for wintering estuarine birds, *Estuarine, Coastal and Shelf Science*, 75(1-2): 163-174.
- 15 634 Mansanet-Bataller, M. 2010. The Challenges of Adapting to Climate Change. *Climate Report*. No. 21.
16 635 Available from:
18 636 [http://www.cdcclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate](http://www.cdcclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate_change.pdf)
19 637 [_change.pdf](http://www.cdcclimat.com/IMG/pdf/21_Etude_Climat_EN_The_challenges_of_adapting_to_climate_change.pdf) [Viewed 21/05/2017]
- 21 638 Masselink, G., Russell, P. 2013. Impacts of climate change on coastal erosion, *MCCIP Science Review*
22 639 *2013*, Psges 71-86, doi:10.14465/2013.arc09.071-086
- 24 640 Mazik, K., Solyanko, E., Elliott, M. & De Jonge, V.N. 2009. Summary of microalgal species composition
25 641 and water quality in the Humber Estuary, Report to Environment Agency. Institute of Estuarine and
26 642 Coastal Studies, University of Hull, 26 March 2009, Report: YBB133-D1-2009.
- 29 643 Mazik, K., Thomson, S., Elliott, M., Solyanko, K., Phelps, A. 2008. CASI ground truth surveys — Humber
30 644 estuary 2008, Report to Environment Agency, Institute of Estuarine and Coastal Studies, University of
31 645 Hull, 8th December 2008.
- 33 646 MCCIP. 2017. Annual Report Card. (Available from: [http://www.mccip.org.uk/media/1770/mccip-](http://www.mccip.org.uk/media/1770/mccip-report-card-2017-final-artwork-spreads.pdf)
34 647 [report-card-2017-final-artwork-spreads.pdf](http://www.mccip.org.uk/media/1770/mccip-report-card-2017-final-artwork-spreads.pdf)) [viewed 21/08/2017].
- 37 648 MCCIP. 2013. Annual Report Card. Available from: [http://www.mccip.org.uk/annual-report-](http://www.mccip.org.uk/annual-report-card/2013/climate-of-the-marine-environment/)
38 649 [card/2013/climate-of-the-marine-environment/](http://www.mccip.org.uk/annual-report-card/2013/climate-of-the-marine-environment/) [Viewed 21/01/2017].
- 40 650 McCormick, S.D., Hanse, L.P., Quinn, T.P., Saunders, R.L. 1998. Movement, migration, and smelting of
41 651 Atlantic salmon (*Salmo salar*), Movement, migration, and smolting of Atlantic salmon (*Salmo salar*),
42 652 *Canadian Journal of Fisheries and Aquatic Sciences*, 55 (1): 77-92.
- 44 653 Mee, L.D., Jefferson, R.L., Laffoley, D., Elliott, M. 2008. How good is good? Human values and Europe's
45 654 proposed Marine Strategy Directive, *Marine Pollution Bulletin*, 56: 187-204.
- 47 655 Metcalfe, S.E., Ellis, S., Horton, B.P., Innes, J.B., McArthur, J., Mitlehner, A., Parkes, A., Pethick, J.S.,
48 656 Rees, J., Ridgway, J., Rutherford, M.M., Shennan, I., Tooley, M.J. 2000 The Holocene evolution of the
49 657 Humber Estuary: reconstructing change in a dynamic environment, *Geological Society, London, Special*
50 658 *Publications*, 175: 253-279
- 53 659 Mieszkowska, N., Firth, L., Bentley, M. 2013 Impacts of climate change on intertidal habitats, *MCCIP*
54 660 *Science Review 2013*, 180-192, doi:10.14465/2013.arc19.180-192
- 57 661 Miller, D.D., Ota, Y., Sumaila, U.R., Cisneros - Montemayor, A.M., Cheung, W.W.L. 2017. Adaptation
58 662 strategies to climate change in marine systems. *Global Change Biology*, 24 (1): e1-e14.
59 663 <https://doi.org/10.1111/gcb.13829>

664 MMO. 2016. Potential spatial effects of climate change in the South and East Marine Plan Area. MMO
1 665 Project Number 1077. 136pp.
2
3 666 Munday, P.L., Dixon, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O., Chivers, D.P. 2010.
4 667 Replenishment of fish populations is threatened by ocean acidification, *Proceedings of the National*
5 668 *Academy of Sciences of the United States of America*, 107(29): 12930-12934.
6
7 669 Munday, P.L., Dixon, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V., Døving, K.B.
8 670 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish,
9 671 *Proceedings of the National Academy of Sciences of the United States of America*, 106(6): 1848-1852.
10
11 672 Newton A and Elliott M (2016) A Typology of Stakeholders and Guidelines for Engagement in
12 673 Transdisciplinary, Participatory Processes. *Front. Mar. Sci.* 3:230. doi: 10.3389/fmars.2016.00230
13
14 674 Nunn, A.S., Harvey, J.P., Noble, R.A.A., Cowx, I.G. 2008. Condition assessment of lamprey populations
15 675 in the Yorkshire Ouse catchment, north-east England, and the potential influence of physical migration
16 676 barriers; *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18: 175-189.
17
18 677 Olenin, S, Elliott, M, Bysveen, I, Culverhouse, P, Daunys, D, Dubelaar, GBJ, Gollasch, S, Gouletquer, P,
19 678 Jelmert, A, Kantor, Y, Mézeth, KB, Minchin, D, Occhipinti-Ambrogi, A, Olenina, I, Vandekerkhove, J.
20 679 2011. Recommendations on methods for the detection and control of biological pollution in marine
21 680 coastal waters. *Marine Pollution Bulletin*, 62(12): 2598-2604.
22
23 681 OSPAR Commission. 2010. The North-East Atlantic Environment Strategy of the OSPAR Commission
24 682 for the Protection of the Marine Environment of the North-East Atlantic 2010–2020 (OSPAR
25 683 Agreement 2010-3). Pp27. (Available from:
26 684 https://www.ospar.org/site/assets/files/1200/ospar_strategy.pdf) [viewed 13/05/2020].
27
28 685 OSPAR. 2009. Eutrophication Status of the OSPAR Maritime Area: Second OSPAR Integrated Report.
29 686 108pp. Available from: www.ospar.org/documents?d=7107 [viewed 26/03/2017]
30
31 687 Painting, S., Foden, J., Forster, R., van der Molen, J. Aldridge, J., Best, M., Jonas, P., Walsham, P.,
32 688 Webster, L., Gubbins, M., *et al.* 2013 Impacts of climate change on nutrient enrichment, *MCCIP Science*
33 689 *Review 2013*, 219-235, doi:10.14465/2013. arc23.219-235
34
35 690 Pankhurst. N.W., Munday, P.L. 2011. Effects of climate change on fish reproduction and early life
36 691 history stages, *Marine and Freshwater Research*, 62: 1015-1026.
37
38 692 Passeri, D.L., Hagen, S.C., Medeiros, S.C., Bilskie, M.V., Alizad, K., Wang, D. 2015 The dynamic effects
39 693 of sea level rise on low-gradient coastal landscapes: A review, *Earth's Future*, 3(6):159-181.
40
41 694 Peck, M.A., Arvanitidis, C., Butenschon, M., *et al.* 2018. Projecting changes in the distribution and
42 695 productivity of living marine resources: a critical review of the suite of modelling approaches used in
43 696 the large European project VECTORS. *Estuarine, Coastal and Shelf Science* 201, 40–55.
44
45 697 Pinnegar, J.K., Cheung, W.W.L., Jones, M., Merino, G., Turrell, B., Reid, D. 2013 Impacts of climate
46 698 change on fisheries. *MCCIP Science Review 2013*, 302-317, doi:10.14465/2013. arc32.302-317
47
48 699 Potter, I.C., Chuwen, B.M., Hoeksema, S.D., Elliott, M. 2010. The concept of an estuary: a definition
49 700 that incorporates systems which can become closed to the ocean and hypersaline. *Estuarine, Coastal*
50 701 *& Shelf Science*, 87: 497–500.
51
52 702 Pörtner, H.O., Knust, R. 2007. Climate Change Affects Marine Fishes Through the Oxygen Limitation of
53 703 Thermal Tolerance, *Science*, 315(5808): 95-97.
54
55
56
57
58
59
60
61
62
63
64
65

- 704 Rasmussen, E. 1973. Systematics and ecology of the Isefjord marine fauna (Denmark). *Ophelia*, 11(1):
1 705 1-507.
2
- 3 706 Raynor, P. 2014. The Humber Estuary Flood Risk Management Strategy: Summary Strategy and
4 707 Business Case. 54pp. Available at:
5 708 <http://www2.eastriding.gov.uk/EasySiteWeb/GatewayLink.aspx?allId=592095>. [Viewed 26/01/2017]
6
- 7 709 Raynor, P., Chatterton, J. 2014. Flood Defences Cost Money, No Defences Cost More: an Economic
8 710 Case for the Humber and United Kingdom. Report Prepared on Behalf of the Humber Parliamentarians,
9 711 Local Authorities and the Humber Local Enterprise Partnership. Available at:
10 712 [http://www.floodcba.eu/main/wp-content/uploads/Flood-Risk-Management-Investing-in-the-future-](http://www.floodcba.eu/main/wp-content/uploads/Flood-Risk-Management-Investing-in-the-future-of-the-Humber-Estuary.pdf)
11 713 [of-the-Humber-Estuary.pdf](http://www.floodcba.eu/main/wp-content/uploads/Flood-Risk-Management-Investing-in-the-future-of-the-Humber-Estuary.pdf) [Accessed January 28, 2016].
12
- 14 714 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey,
15 715 A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, Wang. F. 2013. Observations: Ocean. In: Climate
16 716 Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment
17 717 Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M.
18 718 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University
19 719 Press, Cambridge, United Kingdom and New York, NY, USA
20
- 22 720 Roberts, D.A., Birchenough, S.N., Lewis, C., Sanders, M.B., Bolam, T., Sheahan, D. 2013. Ocean
23 721 acidification increases the toxicity of contaminated sediments. *Global change biology*, 19(2): 340-351.
24
- 26 722 Robins, P. 2019. Changing hydrology. In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.),
27 723 Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1.
28
- 29 724 Robins, P.E., Skov, M.W., Lewis, M.J., Giménez, L., Dacies, A.G., Malham, S.K., Neill, S.P., McDonald,
30 725 J.E., Whitton, T.A., Jackson, S.E., Jago, C.F. 2016. Impact of climate change on UK estuaries: A review
31 726 of past trends and potential projections, *Estuarine, Coastal and Shelf Science*, 169: 119-135.
32
- 34 727 Rosselló-Nadai, J. 2014. How to evaluate the effects of climate change on tourism, *Tourism*
35 728 *Management*, 42:334-340.
36
- 37 729 Santos, C.F., Ehler, C.N., Agardy, T., Andrade, F., Orbach, M.K. and Crowder, L.B., 2019. Marine spatial
38 730 planning. In World seas: an environmental evaluation (pp. 571-592). Academic Press.
39
- 40 731 Saul, R, Barnes, R, Elliott, M. 2016. Is climate change an unforeseen, irresistible and external factor –
41 732 a force majeure in marine environmental law? *Marine Pollution Bulletin*, 113: 25-35.
42
- 43 733 Secretariat of the Convention on Biological Diversity. 2004. The Ecosystem Approach, ISBN: 92-9225-
44 734 023-x (available online at: <https://www.cbd.int/doc/publications/ea-text-en.pdf>) [Viewed
45 735 09/07/2017]
46
- 48 736 Sheahan, D., Maud, J., Wither, A., Moffat, C. and Engelke, C. 2013. Impacts of climate change on
49 737 pollution (estuarine and coastal). *MCCIP Science Review 2013*, 244-251,
50 738 doi:10.14465/2013.arc25.244-251
51
- 53 739 Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., & Rutherford, M. 2000. Holocene
54 740 isostasy and relative sea-level changes on the east coast of England. *Geological Society*, London,
55 741 Special Publications, 166(1): 275–298.
56
- 57 742 Simpson, M. 2013. Impacts of climate change on tourism (and marine recreation), *MCCIP Science*
58 743 *Review 2013*, 271- 283, doi:10.14465/2013.arc29.271-283
59
- 60
61
62
63
64
65

744 Skinner, C. J., T. J. Coulthard, D. R. Parsons, J. A. Ramirez, L. Mullen, Mason, S. 2015. Simulating tidal
1 745 and storm surge hydraulics with a simple 2D inertia based model, in the Humber Estuary, UK, *Estuarine*
2 746 *Coastal Shelf Science.*, 155, 126–136, doi:10.1016/j.ecss.2015.01.019.

3
4 747 Solomon, Susan, ed. Climate change 2007-the physical science basis: Working group I contribution to
5 748 the fourth assessment report of the IPCC. Vol. 4. Cambridge University Press, 2007.

6
7 749 Townsend, M., Thrush, S.F., Carbines, M.J. 2011 Simplifying the complex: an “Ecosystem Principles
8 750 Approach” to goods and services management in marine coastal ecosystems, *Marine Ecology Progress*
9 751 *Series, Volume 434*: 291-301.

10
11
12 752 Tunstall, S., Tapsell, S., Green, C., Floyd, P., George, C. 2006. The health effects of flooding: social
13 753 research results from England and Wales, *Journal of Water and Health*, 4(3):365-380.

14
15 754 Turley, C, Findlay, HS, Mangi, S, Ridgwell, A and Schimdt, DN. 2009. CO2 and ocean acidification in
16 755 Marine Climate Change Ecosystem Linkages Report Card 2009. (Eds. Baxter JM, Buckley PJ and Frost
17 756 MT), Online science reviews, 25pp.

18
19
20 757 Turner, R.K., Schaafsma, M. (Eds.) 2015. Coastal zones ecosystem services: from science to values
21 758 and decision making. Springer Ecological Economic Series, Springer Internat. Publ. Switzerland, ISBN
22 759 978-3-319-17213-2.

23
24 760 UNCLOS. 1982. United Nations Convention on the Law of the Sea of 10 December 1982. Available
25 761 from: https://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm

26
27 762 United Nations. 2011. Framework Convention on Climate Change Decisions adopted by the
28 763 Conference of the Parties. 31pp. (Available from:
29 764 <https://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf>) [viewed 13/05/2020].

30
31
32 765 United Nations. 1998. KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON
33 766 CLIMATE CHANGE. 21pp. (Available from: <https://www.kyotoprotocol.com/resource/kpeng.pdf>)
34 767 [viewed 13/05/2020].

35
36
37 768 United Nations. 1992. UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE.
38 769 (Available from:
39 770 [https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/co](https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/coveng.pdf)
40 771 [nveng.pdf](https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/coveng.pdf)) [viewed 13/05/2020].

41
42
43 772 Vézina, A., Hoegh-Guldberg, O. 2008. Effects of ocean acidification on marine ecosystems. *Marine*
44 773 *Ecology Progress Series*, 373: 199-201.

45
46 774 Wadey, M.P., Roberts, H. and Harris, J. 2013. Impacts of climate change on built structures (onshore
47 775 and coastal), *MCCIP Science Review 2013*, 284-294, doi:10.14465/2013. arc30.284-294

48
49 776 Wadhams, P., Munk, W. 2004. Ocean freshening, sea level rising, sea ice melting, *Geophysical*
50 777 *Research Letters*, Vol. 31:11. doi:10.1029/2004GL020039

51
52
53 778 Waterkeyn, A., Vanschoenwinkel, B., Vercampt, H., Grillas, P., Brendonck, L. 2011. Long-term effects
54 779 of salinity and disturbance regime on active and dormant crustacean communities, *Limnology and*
55 780 *Oceanography*, Vol. 56:3, Pages 1008-1022

56
57 781 Whitfield, A.K., Elliott, M., Basset, A., Blaber, S.J.M., West, R.J. 2012. Paradigms in estuarine ecology-
58 782 A review of the Remane diagram with a suggested revised model for estuaries, *Estuarine, Coastal and*
59 783 *Shelf Science*, 97: 78-90.

60
61
62
63
64
65

784 Whitfield, A.K., Elliott, M. 2011. Chapter 1.07: Ecosystem and Biotic Classifications of Estuaries and
1 785 Coasts. In: Volume 1, Classification of Estuarine and Nearshore Coastal Ecosystems, C Simenstad and
2 786 T Yanagi (Eds), In: E Wolanski & McLusky, DS (Eds) *Treatise on Estuarine & Coastal Science*, Elsevier,
3 787 Amsterdam, pp.99-124.

5 788 Winn, P.J.S., Young, R.M., Edwards, A.M.C 2003. Planning for the rising tides: the Humber Estuary
6 789 Shoreline Management Plan, *Science of The Total Environment*, 314-316: 13-30.

8
9 790 Wittmann, A.C., Pörtner, H.O. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature*
10 791 *Climate Change*, 3(11): 995.

11
12 792 Wright P. Impacts of climate change on ports and shipping. *MCCIP Sci. Rev.* 2013:263-70.

13
14 793 Woodward, S. (2010). The Economic Potential of Nature Tourism in Eastern Yorkshire. (retrieved
15 794 04/10/17 from
16 795 <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>
17 795
18 796
19 797
20 798
21 799
22 799
23
24 800 Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.) 2019. Coasts and Estuaries: The Future.
25 801 Elsevier, Amsterdam, ISBN 978-0-12-814003-1.

26
27 802 Wragg, S. 2014. Hull City Council Flood Investigation Report: December 2013 City Centre Tidal Surge
28 803 Event. Report to the Environment & Transport Overview and Scrutiny Committee, Hull City Council,
29 804 4th February 2014. (accessible from
30 804
31 805 <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)
32 806
33
34 807 Wright, P. 2013. Impacts of climate change on ports and shipping, *MCCIP Science Review 2013*, 263-
35
36
37 808
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65