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■ research article

Indirect impacts of coastal climate change and sea-level rise: the UK example

ROBERT J. NICHOLLS, ABIY S. KEBEDE*

Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton, SO17 1BJ, UK

Owing to globalization, the potential impacts of climate change/sea-level rise in one country/region are likely to affect and be felt elsewhere. Such indirect impacts could be significant but have received a limited analysis. This deficiency is addressed here using the indirect impacts on coastal infrastructure for the UK as an example. National opportunities and threats are identified. Potential indirect national threats include disruption of supply chains, security threats due to forced migration, a decline in national prestige, and impacts on the finance and insurance industries. Potential opportunities include export of world-leading coastal hazard and management expertise, and benefits to national prestige conferred by a strong response to climate change. Such opportunities and threats depend on several distinct dimensions of change, especially the magnitude of climate and socio-economic change, and the success/failure of appropriate responses. Promoting adaptation and climate mitigation is important to exploit the opportunities and address the threats. Adaptation should deal with more than the effects of climate change and link to the wider development agenda. These lessons are transferable to other developed countries and, indeed, many of the actions will be strengthened by collective action.

Policy relevance
National-level measures to address these indirect impacts will make a positive contribution to the global effort in addressing climate change (e.g. supporting emissions reductions). Countries should include the indirect effects of climate change in national assessments so that the national context and useful responses can be identified. Cooperation between nations is also important; countries must act together to more effectively address the direct and indirect effects of climate change (e.g. promoting a widespread adaptation response). International initiatives (such as the Belmont Forum initiative on Coastal Vulnerability) should be promoted and global environmental change research shared (e.g. within multilateral institutions).

Keywords: adaptation; climate change; coastal infrastructure; indirect impacts; international dimensions; sea-level rise

1. Introduction

Over the past two decades an increasing amount of scientific evidence has indicated that human-induced emissions of heat-trapping GHGs are influencing the global climate (e.g. Bindoff et al., 2007). These trends are expected to intensify throughout the 21st century (Meehl et al., 2007) and to cause a wide range of effects, including sea-level rise. Such effects will have adverse impacts and cost implications for coastal communities worldwide (IPCC, 2007; Nicholls et al., 2007).

Coastal areas are a focus for growing populations and economies, and provide important amenities that attract people, as well as the leisure and tourist industries. They typically have higher population densities than inland areas (McGranahan et al., 2007; Lichter et al., 2010), with up to 709 million people, worldwide, living within a 10-m elevation of sea level. Coasts also contain significant economic assets and are increasingly dominated by human activities (e.g. Nordstorm, 2000; Buddemeier et al.,

■ *Corresponding author. *E-mail*: ask2g08@soton.ac.uk

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2002; Ericson et al., 2006). Coastal urbanization is an important trend (e.g. Seto et al., 2011), and 60% of the world's cities with populations exceeding five million are located within 100 km of the coast (Nicholls et al., 2007). A massive investment in infrastructure is expected over the coming decades (OECD, 2006), with coastal zones inevitably being a major focus. The rapid population growth and urbanization in coastal areas has resulted in the widespread conversion of natural coastal land areas to industrial and residential uses, tourism, agriculture, and other socio-economic activities (Valiela, 2006). Over the last century, coastal degradation associated with a range of drivers of coastal change has been reported widely (Crossland et al., 2005; Valiela, 2006; Nicholls et al., 2009). Climate change and the associated rise in sea level can only exacerbate these existing problems, and thus should not be seen as an issue in isolation.

With growing global interdependence in the form of economic, social, and cultural integration, it is inevitable that impacts in one country or region will be transferred elsewhere across the globe, including to the UK (Darwin and Tol, 2001; Bosello et al., 2007, 2011; Hunt et al., 2009). Although Europe, in broad terms, is expected to cope with the direct effects of climate change, significant damages are expected elsewhere (Parry et al., 2007). This suggests that the indirect effects of climate change will be significant. However, most national assessments of climate change and sea-level rise have focused on direct impacts within the relevant national geographical boundaries, and the international dimensions and indirect impacts of sea-level rise as a result of climate change remain poorly understood (Hunt et al., 2009; DEFRA, 2010).

In this article, the effects of sea-level rise on coastal infrastructure, using sea-level rise in the low-elevation coastal zone[1] (or LECZ), and the potential indirect effects on the UK are used as a case study. Two specific research questions are addressed:

- What are the long-term global trends with implications for current and future (i.e. potential/planned) overseas coastal infrastructure that are critical to the UK?
- How will climate change and sea-level rise impact and modify these global trends, with a focus on the implications of sea-level rise on coastal infrastructure and the indirect implications for the UK?

In Section 2, the trends and distribution of coastal infrastructure are highlighted. In Section 3, the potential implications of climate variability on coastal infrastructure are considered. The potential implications of climate change and sea-level rise on coastal infrastructure are examined in Section 4. In Section 5, coastal adaptation to climate change (especially protection) is considered, and in Section 6 the potential implications for the UK, including transferable lessons, are discussed. Finally, some conclusions are offered in Section 7.

2. Coastal infrastructure trends and distribution

2.1. Overview

Throughout the world, existing and emerging urban areas by the coast are experiencing significant population and economic growth as well as major economic growth and expanding trade (see Table 1). This is driving substantial demand for new coastal infrastructure, and it is expected that there will continue to be major changes to the world's coasts.

Demographic change, including population growth and urbanization, is one of the most important drivers of new infrastructure. It is projected that the world's population will grow by about 47% by 2050 (equivalent to an average annual growth of 0.77%), from 6.1 billion people (in 2000) to 8.9 billion (in 2050), based on the medium UN scenario (see Figure 1a). Most demographic change is occurring in

TABLE 1 Non-climatic environmental and socio-economic trends for coastal areas for the 20th and 21st centuries

Environmental and socio-economic factors	20th century trend*	21st century trends (by SRES[a] future)				Broad trend
		A1 World	A2 World	B1 World	B2 World	
Net coastal migration (population)	↑	Most likely	Less likely	More likely	Least likely	Growth
Infrastructure (e.g. urban areas, industry, ports)	↑	Largest increase	Large increase	Smaller increase	Smallest increase	Growth
Human-induced subsidence	↑	More likely		Less likely		Local pressure[b]
Terrestrial freshwater/ sediment supply[c]	↓	Greatest reduction	Large reduction	Smallest reduction	Smaller reduction	Reduction
Desalination	↑	Largest increase	Large increase	Smaller increase		Growth
Aquaculture	↑	Large increase		Smaller increase		Growth
Extractive industries	↑	Large increase		Smaller increase		Growth
Tourism	↑	Highest growth	High growth	High growth	Lowest growth	Growth
Marine renewable energy	↑	Variable growth[d]	Lowest growth	Highest growth	High growth	Growth
Habitat destruction (direct and indirect)	↑	Continued loss		Reduced loss, stability or even recreation		Uncertain

Notes: *↑, increase; ↓, decrease; [a]Special Report on Emission Scenarios (SRES) (Nakićenović and Swart, 2002); [b]This is important in cities built on deltas (see Nicholls et al., 2008a; Jha et al., 2011); [c]Changes due to catchment management (as opposed to climate change *per se*). Most relevant for deltas, estuaries, and lagoons; [d]This depends on which A1 variant is considered. It is lowest under A1FI and highest under A1T.
Source: Adapted from Nicholls et al. (2011).

densely populated developing countries, particularly least developed countries, with Africa seeing the highest growth (see Figure 1b). Changes in the age structure are also important, with an aging population driving demand for coastal locations in many areas (e.g. Florida, Spain). As a result of net migration, coasts are generally under the highest population pressure, and the trends in the LECZ – if they continue to follow the historically observed pattern – are likely to exceed those for global and regional growth. A growing coastal population and rapid urbanization will invitably increase the demand for new coastal infrastructure (see Table 1).

Economic growth and the level of development play key roles in determining the potential need for new infrastructure across a range of sectors. Expected long-term growth and rising per capita income will increase the demand for new and improved infrastructure, including energy, water, and transport, and will stimulate demand for higher standards of infrastructure. It has been estimated that about US$50 trillion will be required between 2005 and 2030 for investment in new infrastructure and to maintain existing systems in Organisation for Economic Co-operation and Development (OECD) countries alone (OECD, 2006). Although this is not stated in the OECD study, a large proportion of this investment will be in coastal areas.

A number of different forms of infrastructure in the coastal zone are vulnerable to climate change and sea-level rise, including coastal cities, transport infrastructure (e.g. ports, harbours, and airports), and critical infrastructure (e.g. oil refineries, energy terminals, and nuclear power stations). Note that there is considerable overlap between these categories.

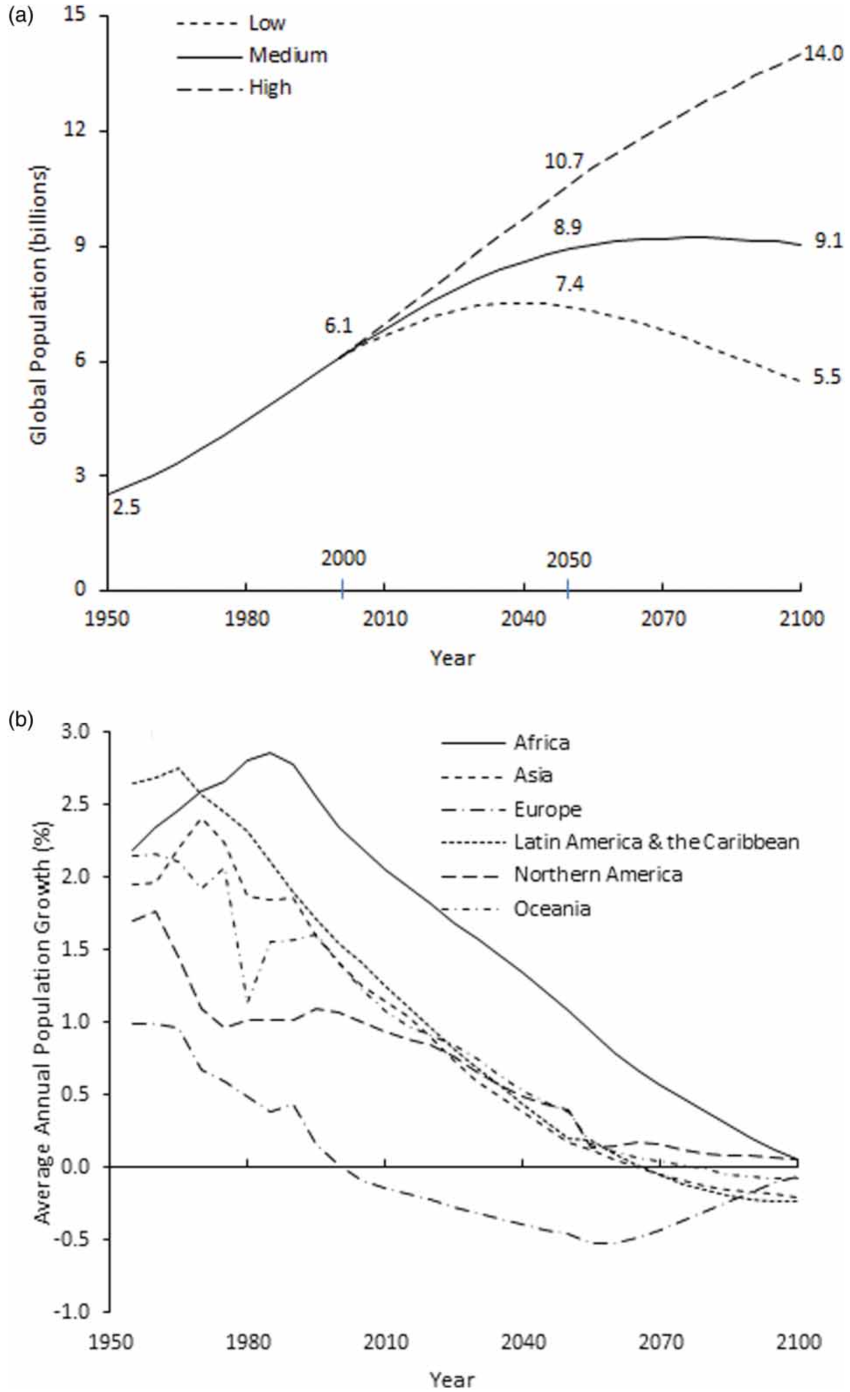

Figure 1 Global population and population change estimates: historic and future projections (to 2100). (a) Total population and (b) average annual rate of population change in major regions for the medium scenario
Source: Adapted from UN DESA (2004).

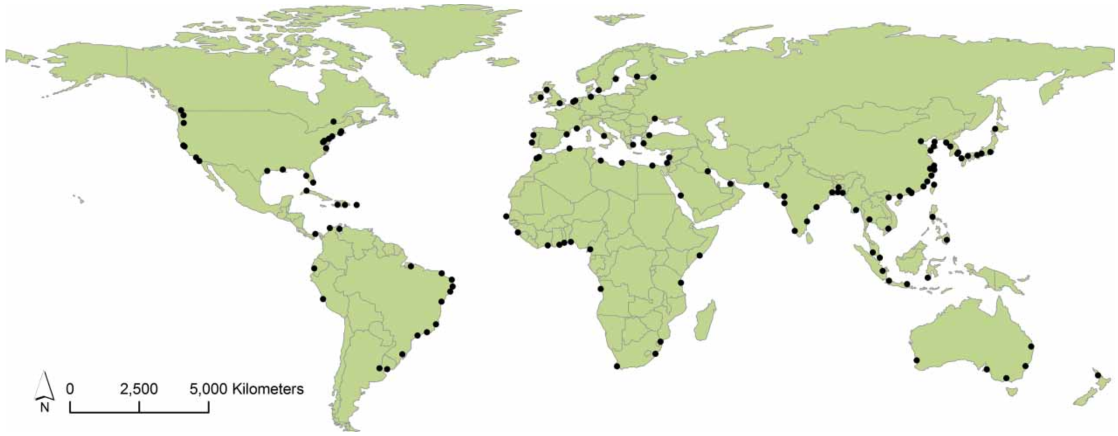

Figure 2 Location of the world's large port cities
Sources: Nicholls et al. (2008b), Hanson et al. (2010).

There is also an extensive defence infrastructure in some coastal zones, such as the dyke systems in the Netherlands and China (these are considered to be adaptation measures in Section 5).

2.2. Coastal cities

The potential implications of climate change for cities are varied (Wilby, 2007; Aerts et al., 2011). Of particular concern for coastal cities are inundation and the increased frequency of coastal flooding. Most of such cities are already threatened by extreme events (e.g. Kron, 2008, 2012) and, to a large extent, are not prepared to respond and adapt to climate change and other important trends such as urbanization. Many large coastal cities are built on thick Holocene deposits (usually in deltaic settings), which are prone to subsidence. Issues with these deposits can be aggravated by human actions, including drainage of susceptible soils and unsustainable extraction of groundwater (Nicholls, 2010; World Bank, 2010).

In this analysis, approximately 1113 cities, each with a population exceeding 100,000 (ESRI, 2008), were identified globally. About 418 cities (37.5%) are located wholly or partially within the LECZ. Nicholls et al. (2008b) and Hanson et al. (2010) identified 136 cities (about 33% of those located (wholly or partially) within the LECZ) globally, each with a population of more than one million (as of 2005), that also had major ports and harbours (see Figure 2). These cities are concentrated in Asia (52 port cities), including 14 port cities in China, and the US, which contains the highest number (17) of port cities. These are wholly or partly located in low coastal areas with elevations potentially affected by present-day storms, and hence will be affected by future sea-level rise (see Hanson et al., 2010). Thirty-seven port cities are located either partially or entirely in deltaic locations. Thus, for these cities, human-induced subsidence will be of additional concern.

2.3. Transport infrastructure

The socio-economic importance of ports and harbours in terms of international trade has increased significantly, with the global volume of seaborne trade flow tripling over the past three decades (UNCTAD, 2008). As a result of its high exposure and vulnerability to climate change and sea-level rise, the potential impacts of these factors on the transport infrastructure will be significant. The example of Hurricane Katrina and the subsequent temporary disruptions and direct physical damage caused in the Gulf ports around New Orleans in 2005 aptly demonstrate the potential

TABLE 2 World's top 20 ports (by tonnage)

			Location			
Rank	Port name	Country	Latitude	Longitude	Tonnage (millions)	Rank for containers (TEUs)*
1	Shanghai	China	31.25N	121.50E	560.0	2
2	Singapore	Singapore	1.27N	103.83E	483.6	1
3	Rotterdam	Netherlands	51.90N	4.48E	406.0	5
4	South Louisiana	USA	30.10N	90.48W	258.1	
5	Xingang	China	38.98N	117.75E	257.6	16
6	Hong Kong	Hong Kong	22.28N	114.15E	245.4	3
7	Nagoya	Japan	35.03N	136.87E	215.6	
8	Gwangyang	South Korea	34.90N	127.72E	202.4	
9	Qinhuangdao	China	39.92N	119.63E	201.9	
10	Dalian	China	38.92N	121.65E	200.5	
11	Antwerp	Belgium	51.25N	4.38E	182.9	13
12	Chiba	Japan	35.57N	140.12E	167.0	
13	Ulsan	South Korea	35.50N	129.38E	165.7	
14	Yokohama	Japan	35.43N	139.65E	141.8	
15	Hamburg	Germany	53.53N	9.98E	140.4	8
16	Incheon	South Korea	37.45N	126.62E	138.1	
17	Port Klang	Malaysia	3.00N	101.40E	135.5	15
18	Dampier	Australia	20.67S	116.70E	133.9	
19	Port Hedland	Australia	20.30S	116.57E	130.7	
20	Rizhao	China	35.48N	119.48E	110.1	

Note: *If port is in the top 20, ranked by containers, then this rank is given.
Source: Lloyd's List (2009).

socio-economic impacts of climate change, not only on local and regional scales, but also at the national and global level. For example, such events might lead to a temporary rise in global oil prices and costs to the insurance industry (Grossi and Muir-Wood, 2006; Hallegatte, 2008).

Lloyd's List (2009) identifies about 2658 sea/coastal ports worldwide and projects that the total TEUs[2] of containers handled globally will increase from 230 million (in 2000) to 600 million (in 2015) – a factor of over 2.5. Although, because of the recent economic downturn, this level may not be reached, the global demand trend for expansion and implementation of ports is expected to continue throughout this century. The global ranking based on the number of port calls in 2007 was Australia (2%), Central America (4%), Africa (5%), South America (5%), North America (7%), Asia (35%), and Europe (42%). Table 2 ranks the world's top 20 ports based on tonnage (14 of which are in Asia).

Finally, a total of 1083 (11%) global airports are located within the LECZ (Nicholls and Kebede, 2011).

2.4. Critical coastal infrastructure

Critical infrastructures are systems and assets for which failure or damage would harm the physical and socio-economic security of a country, or the health and safety of its community. Three examples are considered.

First, there are approximately 249 nuclear power stations throughout the world. Of these, 30% (i.e. 75) are located within 10 km of a coast.[3] Before the Japanese tsunami in 2011, nuclear power was expected to grow in volume and application, with coastal locations being favoured in order to meet cooling requirements (e.g. Greenpeace, 2007; Wilby et al., 2011). This is now less certain, but wherever such developments do proceed, climate change and potential sea-level rise will be important design considerations.

Second, globally, over 35% of oil refineries are located within the LECZ (Nicholls and Kebede, 2011). Europe (including the UK) is the leading importer of oil, with approximately 28% (542 million tonnes) of crude imports and 19% (139 million tonnes) of product imports in 2008. This use of energy may decline in time if global oil production peaks and/or there is a move to decarbonize energy use as is widely expected. However, it will certainly remain significant for the next few decades.

Third, natural gas is the fastest growing energy source worldwide. Global consumption is projected to increase significantly from 2.9 trillion cubic metres (in 2005) to 4.8 trillion cubic metres (in 2035) (US EIA, 2011). In addition, for those nations that implement strategies to reduce CO_2 emissions, the use of natural gas to replace other more carbon-intensive fossil fuels will provide additional benefits. There is therefore a need for more infrastructure in the natural gas sector, including pipelines and specialized port and harbour facilities. Such infrastructure will inevitably have a coastal location, at least in part, and hence will be vulnerable to climate change and sea-level rise.

3. Coastal infrastructure and climate variability

Over the last few decades, natural hazards and weather-related events (e.g. river and coastal flooding, tsunamis[4], tropical cyclones, and other severe storm events) have caused major losses of human lives and livelihoods, destruction of social and economic infrastructure, and environmental damage (Kron, 2008, 2012). For example, the annual direct economic damage associated with floods, storms, and other weather-related extreme events in the 1990s was estimated to be as much as $40 billion (IPCC, 2001). Approximately 25% of these damages were direct damages to infrastructure (Freeman and Warner, 2001). These losses have increased to over $200 billion per year (in 2010 terms), with the most damage occurring in 2005, the year of Hurricane Katrina (IPCC, 2012).[5] This growth in damage is largely due to an increase in exposure (Pielke et al., 2008).

On average, 80–90 tropical cyclones form globally per year. Tables 3 and 4 lists the top 10 costliest and deadliest tropical cyclones during the period from 1980 to 2010, ranked, respectively, according to total damage costs and deaths.[6] Storms striking the US dominate the damage costs, whereas storms striking Asia dominate in terms of the number of deaths, reflecting the higher coastal population and greater vulnerability in Asia. The death toll in Bangladesh has fallen dramatically since 1991 due to the development of warning systems combined with the use of shelters. This shows that people can adapt if there is sufficient knowledge, information, and preparation (see also Section 5).

The example of Hurricane Katrina in 2005 is highly significant. It was the most costly event and claimed about 1800 lives (Graumann et al., 2005) across the Gulf coast. It caused the largest relocation of people in US history (over one million). Approximately 300,000 homes, and more than 1000 historical and cultural sites, were damaged/destroyed (Burton and Hicks, 2005). Other direct damages included disruption of the electrical system infrastructure, which affected up to 2.7 million people. Three nuclear plants were also affected and were forced to run at a reduced level during the storm.

Extreme events can also have important indirect effects. During Hurricane Katrina, the price of oil was temporarily raised as a result of oil shortages, and much of the insurance costs fell on the London markets. Although not climate-induced, the 26 December 2004 tsunami killed 220,000

TABLE 3 Top 10 most costly climate-induced coastal disasters ranked based on damage costs (1980–2010)[a]

Rank	Hurricane	Date	Severely affected areas	Damage (US$$_{2010}$ billion)
1	Katrina	August 2005	Louisiana, Mississippi, Alabama	142.0
2	Andrew	August 1992	S. Florida, Louisiana, Bahamas	41.8
3	Ike	September 2008	Texas, Louisiana, Cuba	39.3
4	Ivan	September 2004	Caribbean Islands, Alabama, Florida, Louisiana, Texas	26.8
5	Wilma	October 2005	Cuba, Florida, Bahamas	25.0
6	Charlie	August 2004	Florida, Cuba, Caribbean Islands, N&S Carolina	21.0
7	Rita	September 2005	Louisiana, Texas	18.2
8	Georges	September 1998	Dominican Republic, Cuba, Florida, Louisiana, Mississippi, Alabama	17.4
9	Hugo	September 1989	S. Carolina, Guadeloupe, Montserrat	17.4
10	Mireille[b]	September 1991	Japan	16.4

Notes: [a]Damage costs are the total for each event. Some damage may have occurred outside the LECZ; [b]Mireille was a typhoon.
Source: Munich Re NatCatSERVICE, December 2011.

people and led to a massive amount of human displacement and destruction of infrastructure around the Indian Ocean. This led to an unprecedented international donor response and logistical challenges for international organizations and aid agencies worldwide. The 2011 Japanese tsunami killed more than 15,800 people, and also caused, for a developed country, unprecedented socio-economic and environmental damages. In addition to such direct effects, the indirect effects of these extreme events included the major Fukushima nuclear disaster and the interruption of global supply trends, both of which affected manufacturing around the world and, as noted, brought into question future plans for nuclear energy.

Although it is impossible to prevent most natural disasters, adaptation measures that reduce the effects on humankind and its environment are often achievable (see Section 5). These require

TABLE 4 Top 10 most deadly climate-induced coastal disasters (1980–2010)

Rank	Disaster	Date	Severely affected areas	Total deaths*
1	Cyclone Nargis	May 2008	Myanmar	140,000
2	Tropical cyclone	April 1991	Bangladesh	139,000
3	Tropical cyclone	May 1985	Bangladesh	11,050
4	Hurricane Mitch	November 1998	Honduras, Nicaragua, Florida	11,000
5	Tropical cyclone	October 1999	India, Bangladesh	10,000
6	Tropical cyclone	June 1998	India	10,000
7	Cyclone Thelma	November 1991	Philippines	6,000
8	Hurricane Georges	September 1998	Dominican Republic, Cuba, Florida, Louisiana, Mississippi, Alabama	4,000
9	Cyclone Sidr	Novembre 2007	Bangladesh, India	3,300
10	Tropical cyclone	November 1988	Bangladesh, India	2,500

Note: *Death tolls are totals for each event. Some deaths may have occurred outside the LECZ (e.g. Hurriance Mitch).
Source: Munich Re NatCatSERVICE, December 2011.

incorporating disaster mitigation measures into the planning, design, and implementation of development programmes in coastal areas. Warning systems will also be important, especially with regard to avoiding loss of life. However, some effects are based on perception as much as physical reality. For instance, the authors observe that across the media, extreme climatic events are now often (erroneously) attributed to or strongly linked to human-induced climate change. Accordingly, the historic emitters of GHGs are blamed, including the UK, even though extreme events have always occurred and it is not yet established that climate change has made them worse.

4. Coastal infrastructure, climate change, and sea-level rise

4.1. Overview

It was estimated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) that the sea level will rise by between 19 and 58 cm from 1990 to the 2090s (Meehl et al., 2007), although it was recognized that larger rises may be possible. There has been extensive debate about how much the sea level will rise, with some authors (e.g. Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009) claiming that the upper bound of sea-level rise greatly exceeds that reported in Meehl et al. (2007). Scenarios incorporating a sea-level rise of 0.5, 1.0, and 2.0 m (by 2100) were therefore considered here (see Table 5)[7], giving a range of impacts that samples the full range of possible changes. Although sea-level rise scenarios of $\geq$1 m are considered unlikely during this century, the magnitudes of the potential impacts of such rises are of major concern, and hence relevant in impact and vulnerability assessments.

4.2. Climatic drivers of change and impacts

Climate change and sea-level rise place significant additional pressures on the LECZ. A summary of the ranges of potential drivers of impacts of climate change in coastal zones and their possible physical and ecosystem effects is given in Table 6.

These drivers of change could potentially lead to a range of negative socio-economic impacts (Table 7). It is important to note that the impacts of climate change and sea-level rise will vary from place to place, and will depend on a range of factors including the magnitude of relative sea-level rise (including uplift/subsidence), other aspects of climate change, coastal morphology, human modifications, and population and socio-economic factors, all of which need to be considered in detailed assessments.

4.3. Coastal damages and the costs of climate change and sea-level rise

Nicholls et al. (2008b) examined global exposure to flooding in large port cities[8] where coastal infrastructure is concentrated and made high-end assumptions about socio-economic changes,

TABLE 5 Sea-level rise scenarios (in metres)

	Time slices			
Scenarios	2010	2030	2050	2100
I	0.05	0.11	0.20	0.5
II	0.06	0.18	0.35	1.0
III	0.10	0.31	0.64	2.0

TABLE 6 Main climate drivers for coastal systems, their trends due to climate change, and their major physical and ecosystem effects

Climate driver (trend)*	Main physical and ecosystem effects on coastal systems
CO_2 concentration (↑)	Increased CO_2 fertilization; decreased seawater pH (or 'ocean acidification') with negative impact on coral reefs and other pH sensitive organisms
Sea surface temperature (↑, R)	Increased stratification/changed circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality; pole-ward species migration; increased algal blooms
Sea level (↑, R)	Inundation; increased flood and storm damage; erosion (e.g. beaches); saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change)
Storm intensity (↑, R)	Increased extreme water levels and wave heights; increased episodic erosion, storm surge, risk of flooding, and defence failure
Storm frequency (?, R) Storm track (?, R)	Altered surges and storm waves and hence risk of storm damage and flooding
Wave climate (?, R)	Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach plan form
Run-off (R)	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply

Notes: *↑, increase; ?, uncertain; R, regional variability.
Source: Adapted from Nicholls et al. (2007).

including urbanization rates, climate change (sea-level rises and possibly more intense storms), and human-induced subsidence. The sea-level rise scenarios approximate scenario II in Table 5. Population exposure to extreme sea levels was estimated to increase by a factor of nearly 4 from about 40 million (in 2005) to about 150 million (in the 2070s), and the assets exposed to increase by a factor of nearly 12 from $3 trillion to $35 trillion (again by the 2070s). On a global scale, population growth, socio-economic growth, and urbanization are the most important drivers of the overall increase in both population and asset exposure. Figure 3a and 3b illustrates the global distribution of population and asset exposure, respectively, and emphasize their growing concentration in Asia, but with significant assets in North America as well. It is estimated that in 2070, the top 10 cities in terms of asset exposure will be Miami, Shanghai, Guangdong, Tokyo, New York–Newark, Ho Chi Minh City, Osaka-Kobe, Bangkok, Amsterdam, and Rotterdam (Hanson et al., 2010).

Similarly, Table 8 examines the exposure of coastal infrastructure based on the estimates of elevation and scenarios in Table 5. Although there are large uncertainties, a large proportion of the infrastructure in the LECZ appears threatened.

It is important to note that sea-level rise also raises extreme water levels (e.g. Menéndez and Woodworth, 2010). This mechanism is responsible for the majority of impacts of mean sea-level rise, even though the damages are often perceived as extreme events. The threat of more intense tropical storms is also of widespread concern as it will increase surges and extreme sea levels, as well as peak wind speeds. However, although this would generate more costly disasters, the available literature suggests that in an average annual sense, the increase in damages will be less than the potential damage of sea-level rise (Nordhaus, 2006; Narita et al., 2008; Mendelsohn et al., 2009). In part, this reflects that sea-level rise raises all events, rather than just a few more extreme ones. Nonetheless, this is an important dimension of climate change that deserves further research.

TABLE 7 Summary of potential climate-related impacts on socio-economic sectors in coastal zones

		Climate-related impacts (and their climate drivers)*						
Socio-economic sector	Examples of associated infrastructure	Temperature rise (A & S)	Extreme events (S, W)	Floods (SL, R)	Rising water tables (SL)	Erosion (SL, S, W)	Saltwater intrusion (SL, R)	Biological effects (ACD)
Freshwater resources	Dams, pipelines, wells	X	X	X	X	–	X	x
Agriculture and forestry	Drainage, irrigation	X	X	X	X	–	X	x
Fisheries and aquaculture	Ports and harbours, fish ponds	X	X	x	–	x	X	X
Health	Hospitals	X	X	X	x	–	X	X
Recreation and tourism	Coastal resorts	X	X	x	–	X	–	X
Biodiversity	Not appropriate	X	X	X	X	X	X	X
Settlements	Urban systems, including much of the above and others, e.g. roads, sewers	X	X	X	X	X	X	–

Notes: *A & S, air and seawater; S, storms; W, waves; SL, sea level; R, run-off; ACD, all climate drivers; X, strong; x, weak; –, negligible or not established.
Source: Adapted from Nicholls et al. (2007).

TABLE 8 Indicative estimates of existing global coastal infrastructure assets exposed to sea-level rise[a]

		Sea-level rise scenarios for 2050 and 2100						
		2050			2100			
		I	II	III	I	II	III	
Coastal infrastructure	Below MSL[b]	0.20	0.35	0.64	0.5	1.0	2.0	Within the LECZ
Airports	27	28	29	68	29	253	368	1083
NPS[c]	1	1	1	4	1	10	14	31[d]
Oil refineries	3	3	4	16	4	29	61	177

Notes: [a]All sea/coastal ports and harbours are exposed to sea-level rise. As the number of airports and nuclear power stations are expected to grow, these are minimum estimates. For oil refineries, the reverse may be true. However, these latter sites are likely to be reused for other infrastructure activities (e.g. ports or natural gas facilities); [b]Present MSL, mean sea level (1980–1999); [c]NPS, nuclear power stations; [d]75 NPSs are located within 10 km of a coast.

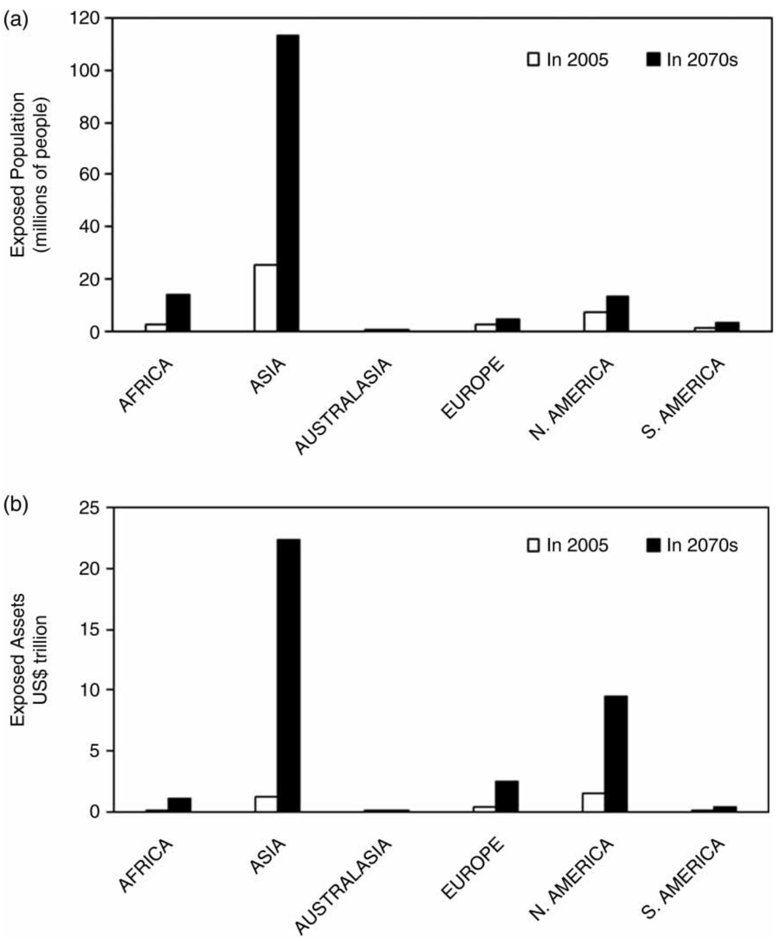

Figure 3 Global port city exposure to sea-level rise and extremes. (a) Exposed population and (b) exposed assets in 2005 and in the 2070s
Note: It is assumed that all socio-economic and climate changes (including sea level rise and more intense storms) and human-induced subsidence occurs.
Source: Adapted from Nicholls et al. (2008b).

4.4. Implications: sectoral assessments

4.4.1. Critical energy infrastructure and supply

Although there is increasing global interest in renewable energy (Table 1), fossil fuels are likely to remain an important component of energy supply throughout the 21st century. The UK will therefore continue to depend on importing large amounts of energy. Natural gas, and perhaps coal, will be important components of our energy demand. It is not likely that permanent disruption to these infrastructure systems will be caused by climate change and sea-level rise, because human beings will adapt to them (see Section 5). Of greater concern is the possibility of temporary disruption to these infrastructure systems caused by extreme events, events that will be exacerbated by climate change and sea-level rise. The case of Hurricane Katrina demonstrates that a major event in a certain region can have global consequences (and hence impact the UK) via the disruption of supply from a specific area, and indirectly via (temporary) rising prices triggered by a (temporary) decline in supply (see Section 4.4.2).

4.4.2. Transportation infrastructure

As above, it is expected that although there will be damage sustained during extreme events, humans will adapt to longer-term changes. Disruption of port infrastructure, especially during regional events such as Hurricane Katrina, are of particular concern, as the supply of key goods or resources to the UK could be disrupted, and prices affected. This will depend on the geographic distribution of supply. If most or all of the supply is from one region, the effect of extreme climate (and other) events is of concern. The global shortages of car parts caused by the Japanese tsunami in 2011 and of hard drives by the Thailand floods in 2011 demonstrate global reliance and the indirect implications of such events globally. Contingency planning for transport disruption to make supplies more robust is certainly an issue that requires more analysis.

4.4.3. Coastal tourism

Tourism is one of the major cultural and socio-economic activities around the world (Dabour, 2003; Neto, 2003). The coastal zone is the main destination of tourists and a dominant sector in the industry worldwide (Honey and Krantz, 2007; UNEP, 2009). Although expected generally to continue to grow substantially (Table 1), the spatial and temporal distributions of tourism demand and tourist movements will be influenced by climate change and variability (e.g. UN/WTO, 2008; Amelung and Moreno, 2009), especially if temperature rise is significant (Hamilton et al., 2005a, 2005b). From a UK perspective, changes in international tourism represent changes in individual preferences and international tourists will simply go to different locations. However, as the UK warms, it may attract both a larger share of the domestic tourism market, and possibly international tourists who may choose the UK over warming locations to the south (e.g. Agnew and Palutikof, 2006; Simpson, 2010). This is a potential economic opportunity for the UK in terms of growing coastal-based tourism, as well as a pressure based on the new infrastructure that this would demand (Hamilton and Tol, 2004). The size of this effect is unclear, as it will be driven by the magnitude of temperature change in the UK and elsewhere (Hamilton and Tol, 2007). Increases in travel costs, including the effects of climate mitigation policies, are also important for tourism and may refocus tourism on a more local activity.

4.4.4. Global security and migration

Global security and migration have raised significant global concerns over the last two or three decades (DEFRA, 2010). In a coastal context, supply disruption has already been mentioned, but this would probably be a temporary phenomenon that could be managed in a security sense. Of greater concern are the so-called ‘environmental refugees/migrants’ who might be displaced by sea-level rise, as the threatened populations are large (e.g. Myers, 2002; Dasgupta et al., 2009). However, many analyses of sea-level rise ignore the possibility of protection and simply assume that the entire exposed population is displaced. This is not credible based on observations of the human response to significant subsidence in low-lying coastal cities (Nicholls, 2010). Protection is an economically rational response in many cases and a widespread protection response would be expected, especially in areas that already have defences, such as Northern Europe and East Asia. It also belies the more complex processes of human migration, with a variety of push and pull factors likely to shape actual behaviour (e.g. Foresight, 2011a). Hence, the numbers of environmental refugees/migrants due to sea-level rise are uncertain. The main potential sources of such migrants are small islands, Africa, and parts of Asia. The likely importance of the UK as a destination for these potential migrants is unclear. Recent research has investigated in more detail how future environmental changes could trigger and affect the pattern of long-term human migration worldwide (see Black et al., 2011; Foresight, 2011a).

4.4.5. Business and finance sector

Additional impacts in the UK to those outlined so far are less clear. Benson and Clay (2004) have shown that the economic and financial impacts of and sensitivity to natural hazards are often determined by a complex and dynamic set of factors (e.g. a rapid shift in vulnerability, especially in a country experiencing economic transformation such as rapid growth, urbanization, and other social changes). Major coastal disasters can have important implications for the insurance industry (e.g. Grossi and Muir Wood, 2006; Kron, 2008, 2012), and it is an industry that recognizes this fact.[9] While new capital market instruments (such as catastrophe bonds, weather derivatives) that are used for dealing with risks of coastal and other weather- and disaster-related hazards are still in their infancy, the UK insurance industry (and the insurance sector in general) could benefit by promoting these instruments to other developing countries (e.g. Rasmussen, 2004). In many ways, the growing expertise in the insurance industry is something from which the rest of the UK could benefit, as the insights from this research are generally not in the public domain. This expertise in risk management is becoming more valuable and deserves further research (e.g. Skoufias, 2003).

5. Adaptation responses

The impacts of climate change and sea-level rise could be serious for coastal areas, unless significant coastal adaptation occurs. Importantly, sea level is relatively unresponsive to climate mitigation (e.g. emissions reductions) compared with other climate factors. Hence, there is a strong 'commitment to sea-level rise' and a corresponding 'commitment to adaptation' (Nicholls et al., 2007; Nicholls, 2010). Although the science basis of this commitment is well understood, the coastal policy implications are less appreciated.

Adaptation has a long history in coastal areas worldwide. Although it has often focused on protection, the available adaptation measures to climatic change and extremes can be put into a wider context as one of three generic adaptation strategies (see Table 9; see also Klein et al., 2001; Linham and Nicholls, 2010):

- *Protection*: decreasing the probability of occurrence to reduce the risk of an event via hard or soft engineering
- *Accommodation*: increasing the ability of a society to cope with the effects of an event (e.g. building codes and flood-wise buildings)
- (Planned) *Retreat*: limiting the potential effects to reduce the risk of an event (e.g. moving people/infrastructure back from vulnerable coastal areas through development control, land-use planning, and set-back zones)

Information measures such as disaster preparedness, hazard mapping, and flood warning/evacuation are also important and in many ways cross-cut and complement the three approaches listed above. Further adaptation is a process that needs to consider other development needs and must be ongoing in terms of monitoring and assessing adaptation responses, based on the aspirations of the adapting societies (Klein et al., 2001; Linham and Nicholls, 2010). Thinking of adaptation as a process is consistent with the 'commitment to adaptation', where appropriate portfolios of measures are identified and adaptation pathways are identified for implementation. The Thames Estuary 2100 project, for example, exemplifies this approach (e.g. Reeder and Ranger, 2010).

It is important to note that benefit–cost analyses suggest that it is economically rational to protect developed areas within the LECZ against present flooding and the impacts of sea-level rise, even against

TABLE 9 Major physical impacts of sea-level rise and examples of adaptation responses

Physical impact of sea-level rise		Potential adaptation responses*
Direct inundation, flooding, and storm damage	Storm surge (sea) Back-water effect (coastal rivers)	• Dykes/surge barriers (P)
		• Building codes/flood-wise buildings (A) • Land-use planning (A/R)
Loss of wetland area (and change)		• Land-use planning (A/R) • Managed realignment/forbid hard defences (R) • Nourishment/sediment management (P)
Erosion (both direct and indirect)		• Coastal defences (P) • Nourishment (P) • Building setbacks (R)
Saltwater intrusion	Surface waters	• Saltwater intrusion barriers (P) • Change water abstraction (A)
	Ground waters	• Freshwater injection (P) • Change water abstraction (A)
Rising water tables and impeded drainage		• Upgrade drainage systems (P) • Polders (P) • Change land use (A) • Land-use planning (A/R)

Note: *P, protection; A, accommodation; R, retreat.
Source: Adapted from Nicholls and Tol (2006).

a 'worst-case' rise of sea level of 2 m during the 21st century (Nicholls et al., 2008c; Anthoff et al., 2010). However, there are several additional factors to consider concerning adaptation and the decision to protect or not. First, protection responses are underpinned by socio-economic scenarios, all of which require significant economic growth. Lower growth may thus reduce the capacity to protect. Second, the benefit–cost approach implies perfect knowledge and a proactive approach to protection. Experience shows that most protection has been a reaction to actual or near disaster. Hence, high rates of sea-level rise may trigger more frequent coastal disasters, even if the ultimate response is better protection. Third, even if it is economically rational to protect, there are equity issues. The diversion of investment from other uses could overwhelm the capacity of some coastal societies to protect (cf. Fankhauser and Tol, 2005). This suggests an urgency to support the development of coastal management institutions, especially concerning the assessment of long-term adaptation choices pertinent to climate change and the potential need for international assistance in these countries. Fourth, the analyses assume that the current pattern of coastal development persists and is reinforced by future development. However, major coastal disasters could trigger a cycle of coastal decline or abandonment, and hence have a profound influence on future choices concerning coastal protection (cf. Barnett and Adger, 2003; Gibbons and Nicholls, 2006).

Hence, success or failure of protection remains one of the major uncertainties about the effects of sea-level rise, in terms of both direct and indirect effects (Nicholls and Cazenave, 2010). Estimates of the costs of adaptation are limited. There have been several studies that have tried to estimate the cost of protection in coastal areas (the most recent and comprehensive is the World Bank's assessment

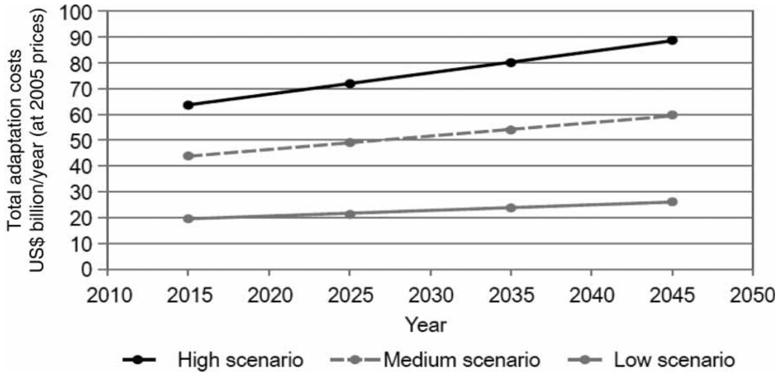

Figure 4 Global incremental adaptation costs for the high, medium, and low sea-level rise scenarios
Note: High scenario corresponds to 126 cm sea level rise by 2100; medium scenario to 87 cm sea level rise to 2100; and the low scenario to a 40 cm rise by 2100.
Source: Adapted from Nicholls et al. (2010).

on the economics of adaptation to climate change; see Nicholls et al., 2010). A global protection cost of between $28 billion and $90 billion per year up to 2050 was estimated across a range of sea-level rise scenarios up to a 1.26-m rise by 2100 (Figure 4).

Importantly, these costs assume that there is a good existing infrastructure to upgrade.[10] In most of the world this is not the case, and this 'adaptation deficit' must also be considered when evaluating adaptation costs (Parry et al., 2009; Hinkel et al., 2011). In effect, adapting to climate change involves adapting to climate variability and other coastal hazards (e.g. tsunamis). For coasts, the global 'adaptation deficit' has not yet been evaluated due to the lack of appropriate data. Hence, further, more comprehensive assessments of coastal adaptation costs and needs should be prioritized. This shows that climate change adaptation cannot be seen in isolation from wider development needs.

6. National implications of international changes

6.1. Overview

As shown in the recent Climate Change Risk Assessment (UK CCRA, 2012), climate change has many direct implications for the UK. Indeed, the potential risks of climate change in other parts of the world are much greater than those within the UK. These have significant potential indirect implications for the UK. Although these indirect effects are less well understood than the direct effects, they have the potential to produce key impacts and 'surprises'. Also, while threats dominate, opportunities are also apparent.

The threats and opportunities presented by climate change are a function of the magnitude of climate change and sea-level rise, coastal development trends, and how successfully society adapts to climate and other drivers of change.

From the perspective of this assessment, the ideal future world would be one where climate impacts are minimized by a combination of climate mitigation and adaptation (Nicholls et al., 2007). To achieve this goal, the developed world (including the UK) has important responsibilities. Figure 5 depicts four possible worlds defined according to the magnitude of climate change and the success/

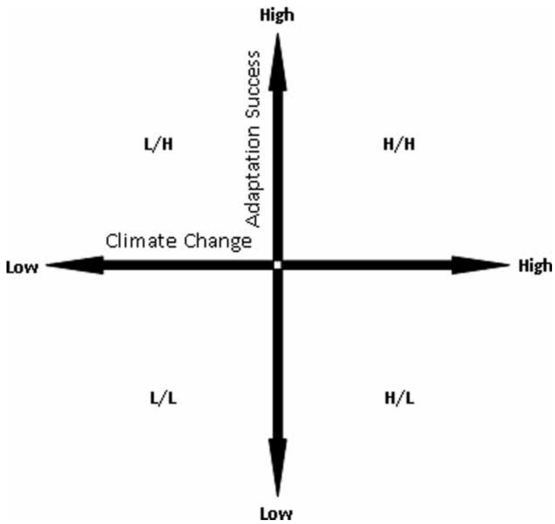

Figure 5 Synthesis of the potential impacts of climate change and benefits of adaptation over the 21st century

failure of adaptation. Level of development is a scale factor for the potential impacts (and to a lesser degree, the adaptation demands).[11]

6.2. Potential threats

It is important to distinguish between the temporary effects of 'shocks' and more permanent changes. More frequent coastal disasters are of greater concern due to both higher sea levels and the possibility of more intense storms. This is much more likely in the H/L world and to a lesser degree in the L/L world (Figure 5).[12] More disasters could lead to repeated temporary disruptions to infrastructure delivery systems (e.g. disrupted imports and exports, temporary increases in commodity prices, and higher energy costs). Events such as Hurricane Katrina demonstrated a chain of impacts that caused major damages via a spike in the oil price. Similarly, although they are not climate-based examples, the effects of the recent volcanic ash cloud from Iceland in 2010 and the disruption of global supply chains due to the Japanese 2011 tsunami constitute other examples of unexpected disruption and economic costs. The potential direct impacts on UK-owned foreign LECZ-based businesses and infrastructure, both from coastal disasters and more systematic changes, are also poorly understood.

Failure of adaptation could trigger more long-term effects beyond temporary disruption and recovery. Land loss and population displacement could trigger significant migration. The potential source countries are distant from the UK, but significant pressure on Europe in general, including the UK, may be expected. Wider security effects could emerge. For example, if the governance in source and host countries were undermined, this could lead to conflict and regional and wider consequences. This is most likely in the H/L world (Figure 5). The UK response would be to promote adaptation to minimize migration.

In the H/L and L/L worlds, a more indirect effect could be a decline in UK prestige, as the UK, with other developed countries, could be seen as the cause of human-induced climate change and hence responsible for climate-related disasters. As already discussed, many people erroneously attribute all disasters to climate change. While this is scientifically flawed, perception is powerful and a succession of coastal disasters could promote resentment and mistrust more widely than just in those directly affected. This issue is complicated, as several large developing countries are also becoming high emitters of GHGs and people's beliefs about climate change will inevitably evolve. Wide promotion of coastal adaptation to counter this perception could be of benefit to the UK and link to adaptation deficit issues (which is essentially a development issue).

There are direct and indirect impacts on the UK finance, business, and insurance industry. Coastal infrastructure is often insured in the UK, so coastal losses will fall on UK markets. This can be seen as a threat without appropriately understanding the risks, but there may be an opportunity if the risks are appropriately costed (see below). Again, promoting adaptation and any policies that make the H/H and L/H worlds more likely would reduce the likelihood of these problems.

Moreover, small islands have been repeatedly identified as highly vulnerable to sea-level rise and climate change (Sear et al., 2001; Nicholls et al., 2007). The potential implications of both indirect and direct impacts on the UK's overseas small island territories are therefore important and may pose a significant challenge.

6.3. Potential opportunities

There are also some potential opportunities for the UK. Coastal engineering and management is essential to developing the H/H and L/H worlds (Figure 5). The UK (together with the Netherlands) is a world leader in long-term strategic planning of coastal areas. This is exemplified by the Shoreline Management Planning Approach (DEFRA, 2006), which has been adopted more widely in initiatives such as Eurosion (2004), and the Thames Estuary 2100 Project (EA, 2009). For example, Halcrow (2011) have been working on coastal management and engineering in Louisiana since Hurricane Katrina. The UK Government could follow the Dutch Government and strategically promote this coastal engineering/management opportunity.[13]

The hazard modelling and assessment community is also well developed in the UK, with a focus on both national (e.g. ABI, 2006; RMS, 2007) and international risks (e.g. Grossi and Muir-Wood, 2006; RMS, 2009). This expertise is important for the maintenance of a sound insurance industry in the context of a changing climate and other drivers of change. It will also present opportunities in existing markets such as North America and emerging markets such as Asia.

Although national prestige may be affected (see Section 6.2), there is an opportunity for the UK to benefit from taking a strong stand on climate change. Current efforts towards mitigation (including the UK Climate Change Act) show that it is serious in addressing this issue. However, for the LECZ the benefits of a mitigation strategy are less significant than in other sectors due to the inevitability of there being some sea-level rise, irrespective of future levels of emissions. This emphasizes that complementary promotion of adaptation could thus have substantial benefits for the UK, as well as globally.

Finally, although it is unlikely to be experienced as a large effect during this century and is highly uncertain, the preferred coastal tourist destinations may shift northwards in a way that would benefit the UK (Simpson, 2010). Fewer UK residents would go overseas, and more international tourists would visit the UK with coastal tourism in mind. This would trigger an increasing demand for coastal infrastructure on the UK coast, which in turn would need careful management to minimize damage and maximize benefits.

6.4. How should the UK respond?

It has been highlighted in the previous two sections that the indirect implications of climate change and sea-level rise could be significant and need to be considered in national policy responses to address the challenges and maximize the opportunities. The UK already follows many of the recommended policies for other reasons, and the issues considered here provide further reasons to continue and strengthen these activities. A wide range of measures should be considered:

• The national coping capacity – in terms of improving resistance, resilience, and resource use – could be strengthened by considering current strategy (which mainly focuses on direct impacts; see Cabinet Office, 2012) and the temporary effects of 'shocks' and long-term changes elsewhere.

• The UK's soft power deployment at the global stage could be continued and improved to influence events by promoting climate mitigation and climate adaptation.

• Efficient and effective (coastal) transfer of coastal adaptation technologies (e.g. exporting coastal engineering and management expertise) that are consistent with the international mitigation and adaptation and development agendas could be promoted (e.g. Klein et al., 2000).

• Climate-proof investments in coastal areas (nationally and internationally) by the UK public and private sector could be promoted to help ensure the long-term success of these investments. This would include influencing multilateral organizations such as the World Bank.

• Disaster preparedness at home and overseas could be promoted. Disasters will inevitably continue to happen and it is important to be ready for them, both to respond to immediate issues and also to exploit the opportunities disasters afford to rebuild and restructure in new and improved ways.

• Finally, multidisciplinary and multinational research on coastal areas to reduce vulnerability could be encouraged (see below).

6.5. Lessons for other countries/institutions

The articles in this Special Issue, and the earlier Foresight (2011b) study, comprise a first step in improving the understanding of the indirect impacts of climate change at national scales. The findings also highlight the key issue that national-level measures to address these indirect impacts will make a positive contribution to the global effort in addressing climate change (e.g. supporting emissions reductions). As stated earlier, most countries will benefit from promoting policies that move society towards the L/H world of Figure 5. While the extent and nature of these indirect impacts depend on the socio-economic and political environment of the particular country, there are similar threats worldwide for both the developed and developing world.

Countries should include the indirect effects of climate change in national assessments so that the national context and useful responses can be identified. Cooperation between nations is also important–countries must act together to more effectively address the direct and indirect effects of climate change (e.g. promoting a widespread adaptation response).

The additional benefits that mitigation policies can bring in terms of avoiding the indirect and direct effects of climate change must also be recognized. Finally, international initiatives (such as the Belmont Forum initiative on Coastal Vulnerability) should be promoted and global environmental change research shared (e.g. within multilateral institutions).

7. Conclusions

Climate change and sea-level rise will have significant direct consequences for LECZs around the world throughout the 21st century and beyond. Because of globalization (e.g. increasing trade and human mobility), potential impacts in one country or region may be transferred to, and felt, elsewhere. These indirect effects may be positive or negative and have been relatively unstudied (however, see Hunt et al., 2009; DEFRA, 2010).

As people, economic activity, and infrastructure become concentrated around LECZs, so the impacts of climate change and sea-level rise will be significant. Coastal development will exacerbate these impacts, a profound trend that is likely to continue even if global populations stabilize. However, successful coastal adaptation to climate change and other drivers of change will minimize their direct and indirect impacts. Thus, there are several distinct dimensions of change to consider.

Among the potential threats to the UK are the following:

- The disruption of supply chains by more frequent coastal disasters (e.g. the global oil supply after Hurricane Katrina in 2005)
- Security threats due to forced population movements
- A decline in UK prestige, as the UK and the wider developed world is blamed for all coastal disasters
- Direct and indirect negative impacts on the UK finance, business, and insurance industries, all of which operate globally

There are also potential opportunities for the UK:

- The export of world-leading UK coastal engineering and management expertise (and to a lesser extent, UK coastal hazard and risk modelling and assessment expertise within the insurance sector)
- Benefits to national prestige if the UK can gain credit for its strong position on responding to climate change
- Possible growth in UK coastal tourism due to the rising temperatures

To adequately address the threats, a response to climate change, one that combines mitigation and adaptation, is required. To date, the focus has been on mitigation. The major control that the UK has for dealing with the identified threats and exploiting the relevant opportunities lies in the success or failure of adaptation. The promotion of adaptation could act synergistically with wider development and sustainability goals, e.g. by improving national coping capacity through consideration of the effects of both temporary shocks and long-term changes elsewhere or through efficient and effective technology transfer. Other countries and/or institutions could also learn from such national studies and initiatives. Importantly, international cooperation will be more effective in responding to these challenges than unilateral actions.

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Notes

1. The low elevation coastal zone (LECZ) is the area below an elevation of 10 m, following McGranahan et al. (2007). This is the land area that will be most affected by coastal processes and sea-level rise, directly and indirectly.
2. Twenty-foot equivalent units.
3. Many of these are outside the LECZ as they are built on elevated coastal locations.
4. Tsunamis are not related to climate variability, but tsunami events serve as an analogue for the problems of extreme events, including climatic-driven extreme events.

5. Note that these are lower bound estimates, as many other impacts including losses of human lives, ecosystem services, cultural heritages, etc. are often difficult to monetize, and are not reflected in economic damage loss estimates.
6. Note that, for consistency, the data presented here are taken from a common source.
7. A 2 m rise has a low probability H^{++} sea-level range defined for sensitivity analysis (see Lowe et al., 2009).
8. Port cities with more than one million people as of 2005.
9. In order to manage the associated risk, the insurance industry has exerted significant effort into research on major coastal disasters and coastal development (see www.williresearchnetwork.com).
10. Only adaptation 'incremental' costs for climate change, and not the adaptation deficit, are typically considered.
11. Figure 5 also represents an appropriate synthesis tool that reflects the current level of understanding of this complex problem, in a way that does not overemphasize the quantitative results.
12. 'H/L', 'L/L' etc. refer to the magnitudes of climate change or success of adaptation.
13. The Dutch have promoted national expertise in coastal adaptation for the last 20 years, for example by hosting the 1993 World Coast Conference (WCC, 1994) and establishing the Delta Alliance (see www.delta-alliance.org).

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