Government Office for Science

Foresight

International Dimensions of Climate Change

R 6.1: The Implications on the UK of the Impacts of Climate Change and Sea-level Rise on Critical Coastal Infrastructure Overseas, 2010 to 2100

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Report Submitted to Foresight, Government Office for Science, July 2010

This Report has been commissioned as part of the UK Government's Foresight Project on the International Dimensions of Climate Change. The views expressed are not those of the UK Government and do not represent its policies.

Acknowledgments

We thank the Met Office Hadley Centre for permission to use their unpublished report on airports and sea-level rise titled: ‘Sea-Level Rise and Top 50 Global Coastal Airports’.

Contents

Executive Summary

There is a growing literature on the direct impacts of sea-level rise and climate change on the world's coastal areas, comprising local to global assessments. What is less developed is a consideration of the indirect effects or the international dimensions of these climate changes on individual countries such as the UK. The objective of this study is to address this deficiency and assess the potential implications on the UK of the physical and socio-economic impacts of climate change on coastal infrastructure around the world with an emphasis on sea-level rise. Using a synthesis of the existing scientific literature and policy-related documents, the study explores the physical environment and associated critical infrastructure in the coastal sector worldwide; the potential changes to coastal environments and the potential demand for new infrastructure; societal impacts and potential implications of sea-level rise on infrastructure elsewhere in the world, and the current and predicted potential threats and opportunities of these on the UK's citizens, government, and businesses. The report also discusses the potential implications on UK's future adaptation policy.

Global climate is changing, and sea levels are rising, possibly at an accelerating pace. Sea-level rise projections for the 21st Century vary widely from several centimetres to more than a meter depending on the source consulted. This will pose significant direct consequences on the Low Elevation Coastal Zones (LECZ)[1] around the world. Rising sea level can inundate low-lying areas, increase rates of shoreline erosion, cause loss of coastal wetlands, and saltwater intrusion, raise water tables and increase the probability of coastal flooding. The combined effects of sea-level rise and other climate-related factors such as storm surges could lead to rapid and significant coastal changes. In addition, coasts are changing significantly for a range of other reasons such as sediment starvation and human-induced subsidence driven by the rapidly growing population, developmental activities and urbanisation in coastal areas. One of the major issues in most coastal countries is the continuing development pressures on coastal areas despite the existing and growing risk of flooding and damage from storm surges and wave action associated with the

[1] In this study, the Low Elevation Coastal Zone or LECZ is considered as the land within 10m of mean sea level.

accelerating rising sea levels. All these changes will potentially have significant damages and costs on coastal communities and infrastructure around the world.

Due to the growing international interdependence such as economic, social, and cultural integration (e.g., increasing seaborne trade and people's movement), potential impacts in one country or region could be transferred to, and felt by other countries or regions worldwide, including the UK. These could potentially present negative (or perhaps positive) effects to other countries in different ways. However, prior to this study, the international dimensions of climate change on coastal areas on a developed nation such as the UK have been relatively unstudied.

This analysis shows that the LECZ concentrates people, economic activity and resulting infrastructure, so the impacts of climate change and sea-level rise could be large, especially if the magnitude of change is large. This will be exacerbated by coastal development, which is a profound trend that is likely to continue through the century, but effective adaptation could minimise the impacts. Hence, assessing the future depends on several distinct dimensions including the magnitude of sea-level rise and climate change, socio-economic change, and the success or failure of adaptation. In this study, a more qualitative approach was adopted for the assessment, which identifies both threats and opportunities for the UK. The report presents a summary of anticipated issues of the international dimensions of climate change, and qualitative interpretations of the potential direct and indirect implications on the UK, based on the current understanding of climate change phenomena and its potential impacts on natural and human systems. The study provides appropriate information to account for this international dimension of climate change for future adaptation plans. However, it is recognised that the issue remains complex, and actual quantification of the potential consequences will depend on various factors, including the potential additional factors due to non-climatic changes, necessitating detailed further study.

Some of the major potential threats on, and opportunities for, the UK include:

Potential impacts/threats:

- Disruption of supply chains by more frequent coastal disasters such as occurred to the oil global supply after Hurricane Katrina in 2005;

- Security threats due to forced population movements possibly leading to significant numbers of refugees and migrants and broader security issues in important parts of the world;
- A decline in UK prestige, as the UK and the wider developed world is erroneously blamed for all coastal disasters which are increasingly seen as a product of human-induced climate change rather than climate variability;
- Direct and indirect impacts on the UK finance, business and insurance industry;
- Potential impacts on the UK's small island overseas territories.

Potential benefits/opportunities:

- Export of world-leading UK coastal engineering and management expertise and to a lesser extent, UK coastal hazard modelling and assessment expertise in the insurance industry;
- Benefits to national prestige if the UK can gain credit for its strong position on responding to climate change, including strengthening the adaptation dimension which is critical for coastal areas;
- Possible benefits to UK coastal tourism due to rising temperatures.

Although, it is poorly understood, the major control that we have on these threats and opportunities is the success or failure of adaptation. Decisions taken today, for example protection/relocation of existing infrastructure or planning for development of new infrastructure or other related assets in coastal areas will affect how well the system adapts to climate change far into the future. Hence, today's decision makers need to make sure that those decisions are robust enough to cope with, or adapt to the changing climatic conditions in the future – including the international dimensions of climate change. The UK government can certainly promote adaptation both to potentially minimise the threats identified and to fully exploit the opportunities.

1 Introduction

Increasing scientific evidence over the last two decades suggests that human-induced emissions of heat-trapping greenhouse gases, including carbon dioxide, methane and nitrous oxide are influencing global climate (e.g., BINDOFF *et al*., 2007), and these trends are expected to intensify through the 21st Century (MEEHL *et al*., 2007). For coastal areas, these drivers and changes to the global climate system include more acidic ocean waters, accelerating sea-level rise, warmer sea-surface temperatures, and with less certainty, more severe hurricanes and possible other extreme events. Collectively, these will have adverse impacts and costs on coastal communities worldwide through this century (IPCC, 2007; NICHOLLS *et al*., 2007; 2009). Moreover, coastal areas are a focus of a growing population and economy, generally focussed on expanding urban areas with growing infrastructure demands and needs.

With the world experiencing growing inter-dependence in the form of economic, social and cultural integration, it is inevitable that impacts in one country or region could be transferred to, and felt by other countries or regions across the globe. This includes the UK with its open economy, mobile population, and high dependence on imported resources (e.g., energy) (HUNT *et al*., 2009). While Europe is in broad terms expected to cope with climate change, significant damages are expected elsewhere (PARRY *et al*., 2007), suggesting the need to evaluate indirect effects, including on the UK. However, despite the significant potential implications, most national assessments of the potential impacts of climate change and sea-level rise have so far focussed on the direct impacts within their geographic boundaries; and the international dimensions and the potential secondary impacts are poorly understood (HUNT *et al*., 2009; DEFRA, 2010). Coastal areas are of particular concern due to their large population, significant economy and importance in terms of trade.

The coastal zone typically has higher population densities than inland areas (SMALL and NICHOLLS, 2003; MCGRANAHAN *et al*., 2007). Most recently, LITCHER *et al*. (2010) shows the current population ranges between 67 to 153 million people within 1-m of sea level, and 557 and 709 million people within 10-m of sea level: the stated range reflects the uncertainty between the different global elevation and population models that are analysed. These areas also contain significant economic assets and activities including all seaborne trade (BIJLSMA *et al*., 1996; SACHS *et al*., 2001;

NICHOLLS *et al*., 2008a; DASGUPTA *et al*., 2007; 2009). The potential direct physical impacts of sea-level rise include inundation of low-lying areas, loss of coastal wetlands, increased rates of shoreline erosion, saltwater intrusion, higher water tables and higher extreme water levels that lead to coastal flooding (NICHOLLS, 2010). However, the coastal zone is also characterised by the presence of significant adaptation measures (often protection) and this already reduces risks due to climate variability. Significant additional adaptation efforts can be expected through this century due to sea-level rise and climate change, and important socio-economic trends such rising living standards and reducing tolerance of risk.

Coasts are also increasingly dominated by human activities (NORDSTORM, 2000; BUDDEMEIER *et al*., 2002; ERICSON *et al*., 2006). The rapid population growth in coastal areas has resulted in widespread conversion of natural coastal land areas to industrial and residential development uses, tourism agricultural land, and other socio-economic activities (VALIELA, 2006). Coastal urbanization is significant (SMALL and NICHOLLS, 2003) and sixty percent of the world's world's biggest cities with a population of over 5 million are located within 100km of the coast. In the last century, coastal degradation associated with a range of coastal change drivers has been widely reported around the world (CROSSLAND *et al*., 2005; VALIELA, 2006; NICHOLLS *et al*., 2009). Hence, climate change and sea-level rise can only exacerbate these existing problems, and climate change should not be seen as an issue in isolation, which impact and adaptation assessment should address

The primary objective of this report is to investigate the international aspects of climate change on infrastructure in the Low Elevation Coastal Zone[2] (or LECZ) and to assess how these impacts may affect the UK's citizens, government, and business. The main focus is sea-level rise. The study is mainly a qualitative and interpretative-based assessment based on literature review synthesis of existing research work, and limited new analysis of the distribution of coastal infrastructure using GIS[3]. It addresses in particular the following two key research questions:

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[2] The Low Elevation Coastal Zone (LECZ) is the area below 10-m elevation following MCGRANAHAN *et al*. (2007).
[3] Geographic Information Systems

- What are the long-term global trends that have potential implications on 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, with a focus on the implications of sea-level rise on coastal infrastructure and the implications of these on the UK (e.g., what are the dependencies for the UK).

The remainder of the report is structured as follows: Sections 2 reviews infrastructure, with a particular focus on coastal infrastructure and its distribution and global trends. Section 3 highlights the drivers for new coastal infrastructure. Section 4 considers the potential implications of climate variability on coastal infrastructure. Section 5 examines the potential implications of climate change coastal infrastructure by sector through this century. Section 6 considers coastal adaptation to climate change, especially protection. Section 7 assesses the potential implications (impacts/threats and benefits/opportunities) for the UK, and Section 8 draws conclusions.

2 Infrastructure and Coastal Infrastructure

2.1 Infrastructure and Cross-Sectoral Interdependence

Infrastructure represents the basic built structures, networks, and services and facilities that support the essential elements of a community. The term typically refers to the technical structures that form the basis for regional, national, and to a larger extent international socio-economic growth and societal wellbeing. Depending on the role they play, infrastructure is mainly classified into two categories:

- Lifeline/primary infrastructure – infrastructure that directly contributes to the survival of a community and its ability to respond and recover at the time of extreme events; and,
- Secondary infrastructure – infrastructure which contributes to the day-to-day development of a community.

Collectively, these include a range of sectors including: energy (e.g., nuclear power stations, oil refineries, hydroelectric power generation facilities, and oil and natural gas pipelines), transportation facilities (e.g., roads, railways, airports, etc.), communication structures, buildings, hospitals, schools, emergency facilities (e.g., police and fire stations), water utilities and waste water treatment plants, waste disposal facilities, etc.

The high cross-sectoral interdependence between infrastructure in our day-to-day life by implication demonstrates that, if one sector is damaged, the potential implications of these for the whole system could be significant. The degree of interdependence depends on the importance of the component infrastructure. Some infrastructure are considered as critical due to the significance of the role they play for the wellbeing of a society and socio-economic development (national and/or international level), and their replacement could be a prolonged and costly operation. Figure 1 demonstrates the network of infrastructure across a range of sectors.

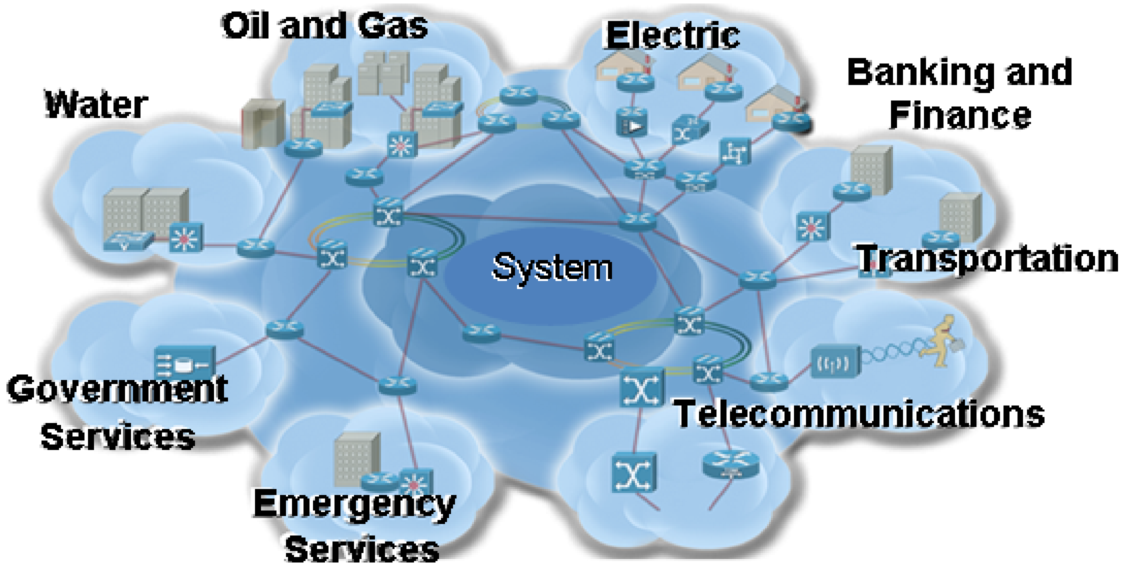

Figure 1: Illustrative diagram of a cross-sectoral network of infrastructure (Source: WATSON, 2003).

The world represents a network of networks, and any geographic area, network and functional area, could also represent a place of vulnerability if the global network fails in some way.

2.2 What is Coastal Infrastructure?

Coastal infrastructure refers to infrastructure located within the coastal zone. In this study, infrastructure within 10m of mean sea level (the Low Elevation Coastal Zone or LECZ) is considered as coastal following MCGRANAHAN *et al*. (2007). In this report, the main focus is on: (1) coastal cities, (2) ports and harbours, (3) critical infrastructure (e.g., oil refineries, nuclear power stations, and oil and natural gas terminals and pipelines), and (4) other infrastructure such as transportation infrastructure (e.g., airports). There is considerable overlap between these categories. In this analysis, infrastructure related to agricultural and fishery activities are excluded, assuming the impacts and their international dimension is relatively small. There is also extensive adaptation infrastructure in some coastal zones, such as the dike systems in the Netherlands. These are considered as adaptation measures in Section 6.

Table 1 shows the global percentage of infrastructure located within the coastal zone based on GIS analysis for this report (Note: the method used and its limitations are detailed in Appendix A).

Table 1: Global infrastructure distribution within the LECZ.

Infrastructure	Global Total+	LECZ Total	Percentage (%)
Cities (with population > 100,000)	1113	170	15
Airports	9915	1083	11
Nuclear power stations	249	30	12
Oil refineries	505	177	35
Ports	2658*	---	---
+Note: these numbers represent the total number included in the dataset sources used for this analysis. *Refers all sea/coastal ports (excluding river ports) – and all ports potentially are threatened by sea-level rise.			

Sections 2.2.1 to 2.2.4 briefly discusses the global distribution of infrastructure within the LECZ, and the potential implications of climate change and sea-level rise.

2.2.1 Coastal Cities

Due to the high concentration of human settlement and associated infrastructure assets, most coastal cities around the world are especially vulnerable to the potential impacts of climate change and sea-level rise. The LECZ represents a small fraction of the world's land area, but is inhabited by roughly 10 percent of the world's population, or about 600 million people, and an even higher fraction of its total urban population. The potential implications of climate change on cities are varied (WILBY, 2007). The particular concern associated with coastal cities and sea-level rise is inundation and increased frequency of coastal flooding. As discussed later, this will disrupt the city, but could also have important external effects.

Moreover, most of these cities are already threatened by extreme events and further are largely unprepared to respond and adapt to climate change and other important trends such as urbanization. Future sea-level rise is of particular concern as coastal cities built of thick Holocene deposits are also prone to subsidence, which is often greatly aggravated by human actions, such as drainage of susceptible soils and unsustainable extraction of groundwater (NICHOLLS, 2010). Many coastal cities have subsided a maximum of several metres during the 20th Century, although have all been protected to varying degrees of success.

In this analysis, about 1440 cities with population criteria of more than 50,000 people have been identified globally, of which more than 15% (about 218) cities (based on their centroid) are located within the LECZ. Table 2 demonstrates the global population concentration within the coastal zone.

Table 2: Number of cities within the LECZ by population class based on an analysis of the city centre.[4]

Population	Number of LECZ cities
> 5,000,000	7
1,000,000 - 5,000,000	35
500,000 - 1,000,000	24
250,000 - 500,000	38
100,000 - 250,000	66
50,000 - 100,000	48
TOTAL	218

Figure 2 illustrates the geographic distribution of world's major coastal cities based on this analysis. Most of these densely populated coastal cities are concentrated in south and south-east Asia. For instance, the seven largest coastal cities (with population of more than 5 million people) are distributed as: Rio de Janeiro (Brazil), Shanghai and Tianjin (China), Mumbai (India), Tokyo (Japan), Karachi (Pakistan), and Bangkok (Thailand). Other major coastal megacities that are missing are New York, Los Angeles, Jakarta, Metro Manila and Osaka to name just five megacities. This highlights the limitations of the method used and the need for a more detailed polygon-based analysis (e.g., NICHOLLS *et al*., 2008a) rather than considering as a point (see Appendix A). Many more coastal cities are emerging due to population growth, particularly in developing countries.

[4] Data Source: ESRI Data & Maps 9.3 [DVD], (2008). Redlands, CA: Environmental Systems Research Institute. The analysis shown here treats the cities as points not polygons.

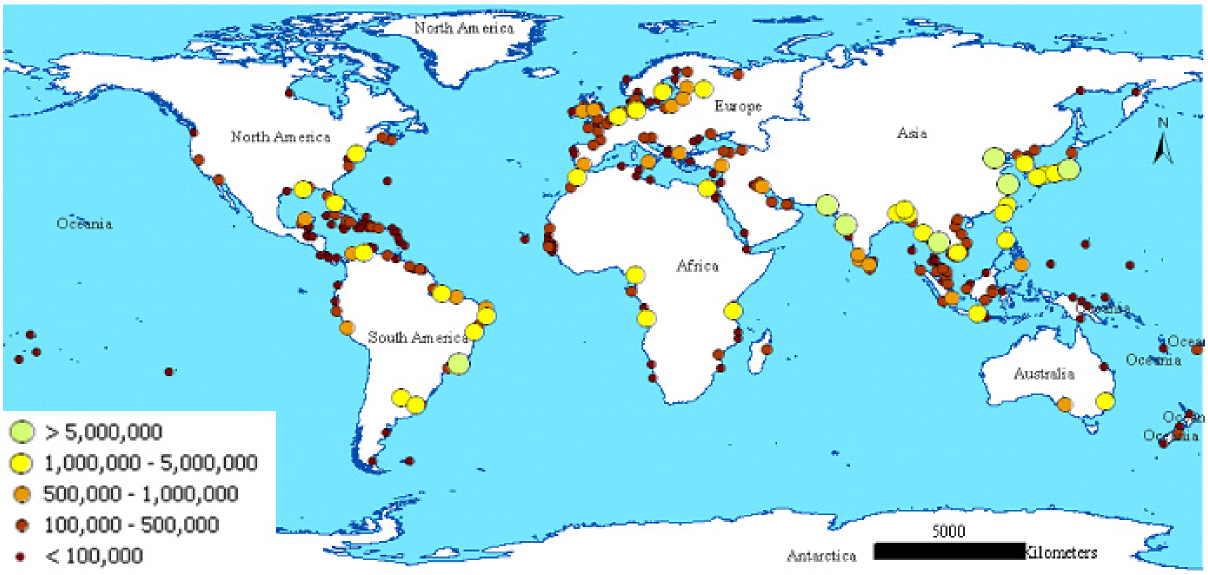

Figure 2: Geographic distribution of world's cities within the LECZ.[5]

Globally, around 42 coastal cities with a population of over 1,000,000 are located within the LECZ. However, NICHOLLS *et al*. (2008a) and HANSON *et al*. (2010) identified 136 cities with a population of more than one million people in 2005 that had major ports and harbours (Figure 2), and hence must be at least partially in the LECZ. The difference reflects the different methodologies, as these studies were based on city extent rather than the city centre (a point).

Figure 3 shows the distribution of the largest 136 port cities around the word, with the majority (119 port cities) classified as with seaports/harbours (including 16 deepwater ports and 2 oil terminals), and 17 with river ports influenced by coastal water levels (e.g., Philadelphia and New Orleans in USA, Ho Chi Minh City in Vietnam, and Guangdong in China). Globally they are concentrated in Asia with more than 38% (about 52 port cities), of which 27% (or 14 port cities) are located in China. The USA as a country contains the highest number of port cities (with 17 port cities).

[5] Source: ESRI Data & Maps 9.3 [DVD], (2008). Redlands, CA: Environmental Systems Research Institute.

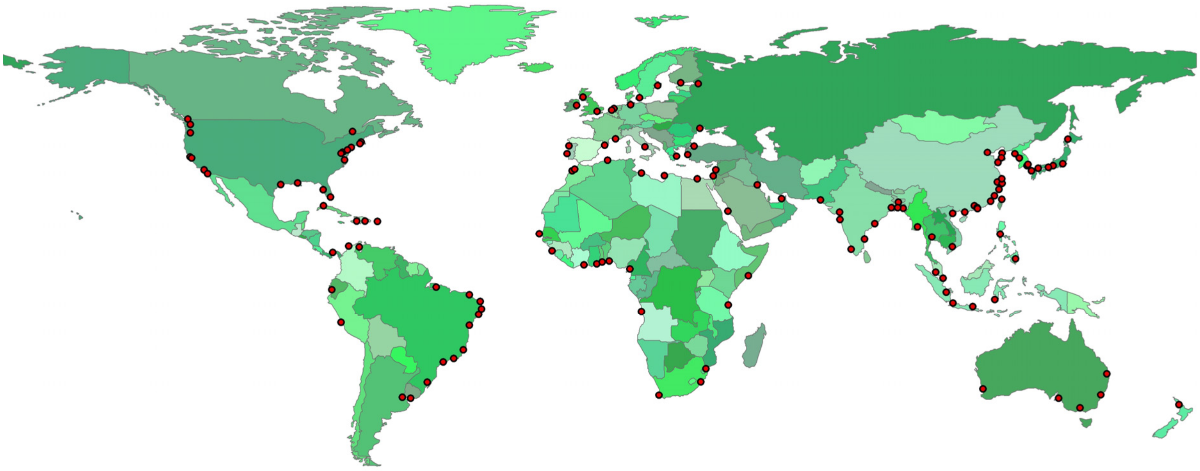

Figure 3: Location of the world's largest 136 port cities (NICHOLLS *et al*., 2008a; HANSON *et al*., 2010).

These port cities are wholly or partly located in low coastal areas with elevations that are potentially affected by today's storm surges, and hence will be affected by sea-level rise in the future (cf. HANSON *et al*., 2010). More than 27% (about 37 ports) of these port cities are located either partially or entirely in deltaic locations.

2.2.2 Port and Harbour Infrastructure

Most of the world's large coastal cities also include port and harbour infrastructure – and a rapidly growing seaborne international trade flow (which tripled over the past three decades (UNCTAD, 2008)). Ports and harbours are of significant socio-economic importance across the globe, particularly in developing countries. However, due to their high exposure and vulnerability to climate change and sea-level rise, the potential implications of possible impacts will inevitably be high. The case of Hurricane Katrina and the temporary disruptions and direct physical damages caused in New Orleans (in 2005) demonstrated the potential socio-economic impacts, not only at the local and regional scale but also its national to global implications in terms of factors such as oil prices and costs to the insurance industry (GROSSI and MUIR-WOOD, 2006; HALLEGATTE, 2008).

The world's seaborne trade flow has been expanding at an unprecedented rate, and ports are experiencing overwhelming demand for expansion. According to LLOYD'S LIST Ports of the World (2009), about 2,900 ports (including river ports) were identified worldwide. It is projected that the total TEUs[6] of containers handled globally will increase 2.5 times larger from 230 million (in 2000) to 600 million (in 2015). While this may not be reached due to the recent economic downturn, the global demand trend for expansion and implementation of port is expected to continue through this century. Figure 4 shows a global ranking based on the number of port calls in 2007: Europe and Asia are dominant globally.

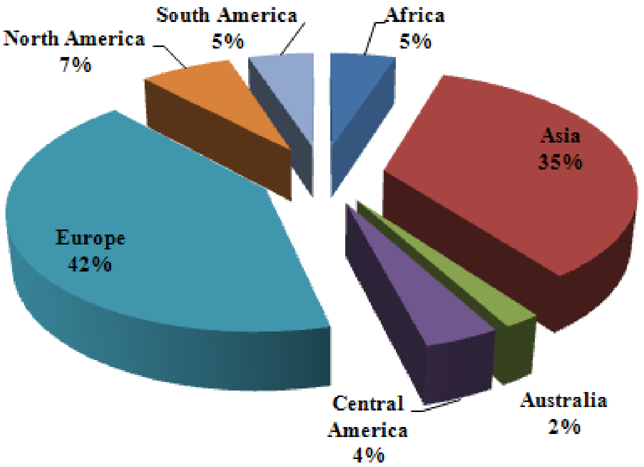

Figure 4: Regions ranked by number of port calls (in 2007) (Source: LLOYD'S LIST Ports of the World 2009).

Figure 5 illustrates the global distribution of sea/coastal ports, which are potentially threatened by sea-level rise. As these infrastructure play a significant role from local to global scale-networked seaborne trade flow, the potential implications of the impacts of climate change and sea-level rise will undoubtedly be very high, and will potentially have a significant international dimension that could potentially be felt by many nations across the globe.

[6] Twenty-Foot Equivalent Units

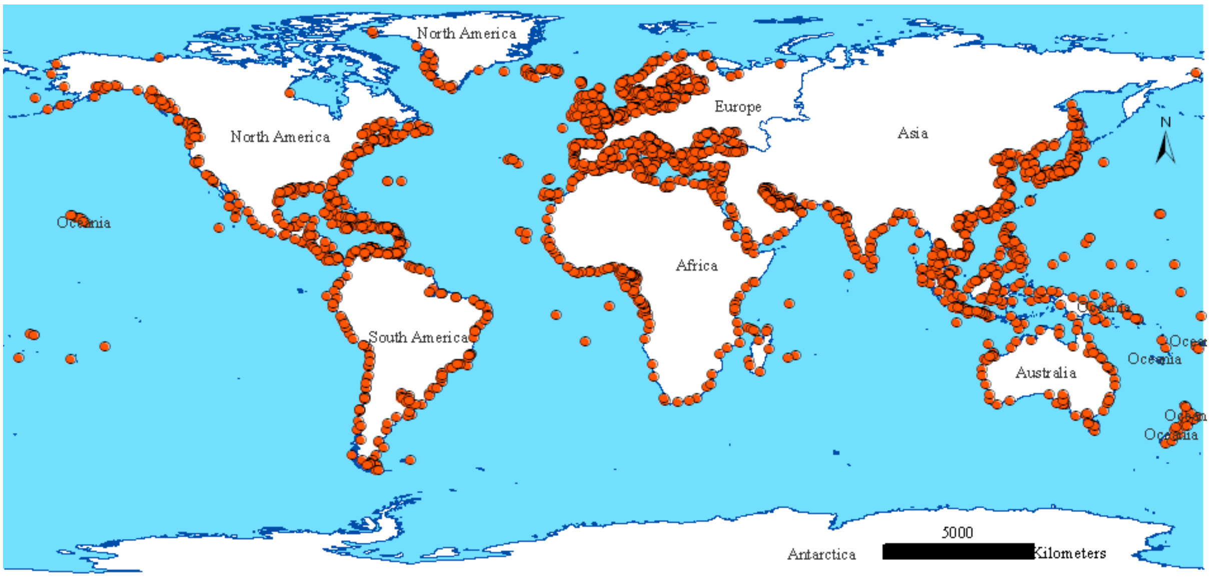

Figure 5: Geographic location and distribution of world's ports (excluding river ports) (Lloyd's List Ports of the World 2009).

According to LLOYD'S LIST Ports of the World 2009, of the ports with reported data worldwide, Table 3 and 4 illustrates the world's top 20 ports ranked based on tonnage and TEU, respectively. The list shows the dominant distribution of major ports in Asia.

Table 3: World's top 20 ports ranked based on tonnage.

Rank	Port Name	Country	Location		Tonnage (millions)
			Latitude	Longitude	
1	Shanghai	CHINA	31.25N	121.50E	560.0
2	Singapore	SINGAPORE	01.27N	103.83E	483.6
3	Rotterdam	NETHERLANDS	51.90N	004.48E	406.0
4	South Louisiana	USA	30.10N	090.48W	258.1
5	Xingang	CHINA	38.98N	117.75E	257.6
6	Hong Kong	HONG KONG	22.28N	114.15E	245.4
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	004.38E	182.9
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	009.98E	140.4
16	Incheon	SOUTH KOREA	37.45N	126.62E	138.1
17	Port Klang	MALAYSIA	03.00N	101.40E	135.5
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

Table 4: World's top 20 ports ranked based on TEU.

Rank	Port Name	Country	Location		Tonnage (millions)
			Latitude	Longitude	
1	Shanghai	CHINA	31.25N	121.50E	560.0
2	Singapore	SINGAPORE	01.27N	103.83E	483.6
3	Rotterdam	NETHERLANDS	51.90N	004.48E	406.0
4	South Louisiana	USA	30.10N	090.48W	258.1
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10	Dalian	CHINA	38.92N	121.65E	200.5
11	Antwerp	BELGIUM	51.25N	004.38E	182.9
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	009.98E	140.4
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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

2.2.3 Critical Coastal Infrastructure

Critical infrastructure consists of systems and assets that are vital to a society or a nation whose failure or damage would harm the physical and socio-economic security of the nation, and health and safety of its community. Energy infrastructure illustrates such a valuable infrastructure. Energy production processes often require a complex, interdependent, often expensive, and sometimes global infrastructure. However, most of the critical infrastructure worldwide is often geographically concentrated in areas that may become increasingly physically unstable to environmental changes, and distinctly vulnerable to events like natural disasters, such as flooding and extreme storms (PASKAL, 2009; PARFOMAK, 2008). As a consequence, any disruption of concentrated critical infrastructure could pose disproportionately significant effects (regional to global scale), with costs potentially running into billions of dollars. Hurricane Katrina (in 2005) demonstrated such geographic vulnerability and potential impact disrupting a substantial part of USA's energy and chemical infrastructure, and temporarily raising the global oil price.

In this study, three critical infrastructures are considered:

- Power stations especially nuclear power stations,
- Oil refineries, and
- Natural gas terminals

Nuclear Power Stations

Figure 6 shows the geographic distribution of the world's nuclear power station sites. Globally, about 249 nuclear power stations have been identified, 12% (30) of which are located within the LECZ (Figure 7). These are mainly concentrated in Europe – e.g., five and seven of these are located in Germany and the UK, respectively. Nuclear power generation is an important contributor to the world's electricity needs. In 1999, it supplied more that one sixth of global electricity and a substantial 30 percent of electricity in Western Europe alone.

The global energy demand is expected to continue to grow dramatically in this century, especially in developing countries due to the rapid population increase and economic growth. Nuclear power generation produces virtually no greenhouse gas (GHG) emissions, and have been considered by many countries (particularly by industrialised nations) as potential future strategies to reduce GHG emission and the risk of climate change. However, due to the need for an isolated location and high supply of cooling water, these stations will often continue to be sited in coastal areas. Hence, their numbers are likely to grow and climate change and sea-level rise will be an important consideration in their design.

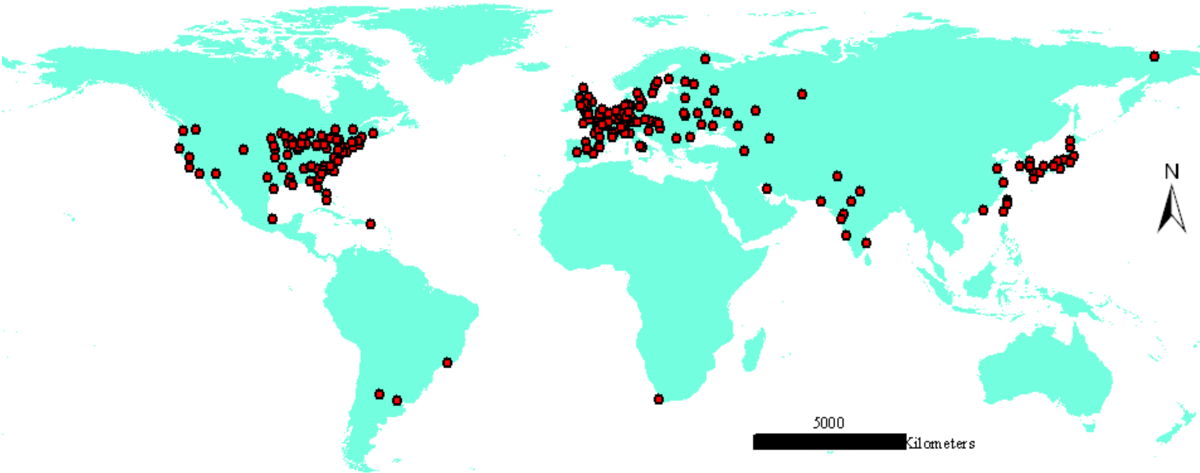

Figure 6: Nuclear power sites of the World (Status as of 31 December 1999).[7]

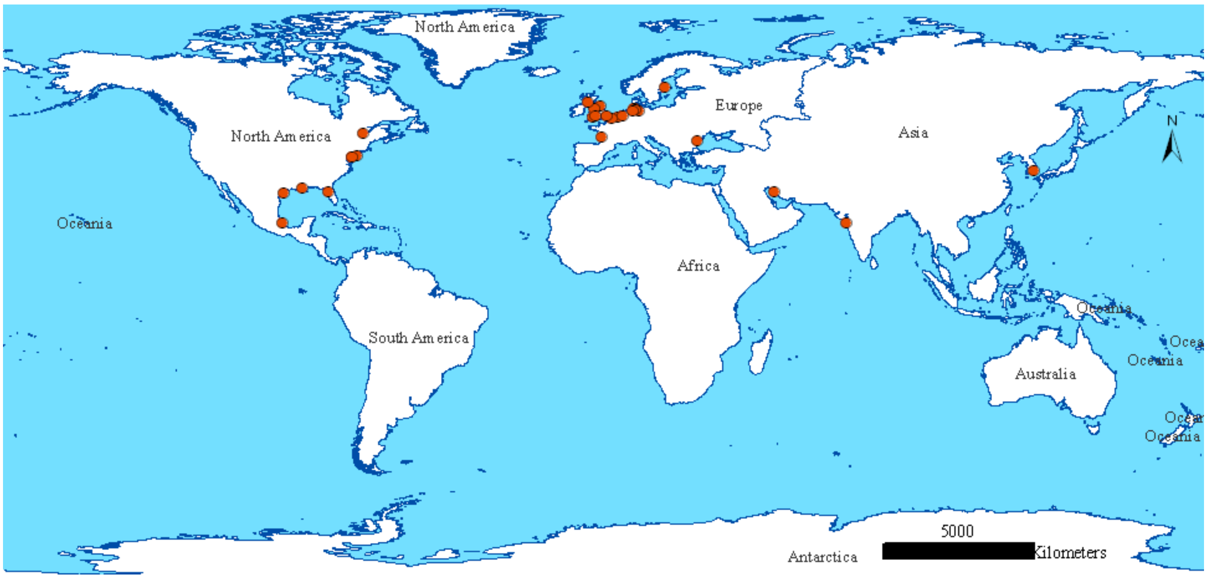

Figure 7: World's nuclear power stations located within the LECZ.

Oil Refineries

In 2008, global oil import/export amounted to 1970 (crude) and 728 (product) million tonnes (Figure 8). Europe (including the UK) represents the leading importer with approximately 28 percent (542 million tonnes of crude imports) and 19 percent (139 million tonnes of product imports). Table 5 shows one estimate of the lifetime of the potential oil reserves worldwide, although such projections are uncertain.

Table 5: Estimated lifetime of the regional and global oil reserves based on reserve-to-production ratio.[8]

[7] Source: Global Change Mater Directory: http://gcmd.nasa.gov/records/GCMD_GNV181.html (last accessed on 18 May 2010).

Regions	Lifetime (R/P^{+}) (in years)[9]
Asia Pacific	14.5
North America	14.8
Europe and Eurasia	22.1
Africa	33.4
South & Central America	50.3
Middle East	78.3
Total World	42.0
$^{+}$R/P=Reserves-to-Production ratio – shows the lifetime of the reserves.	

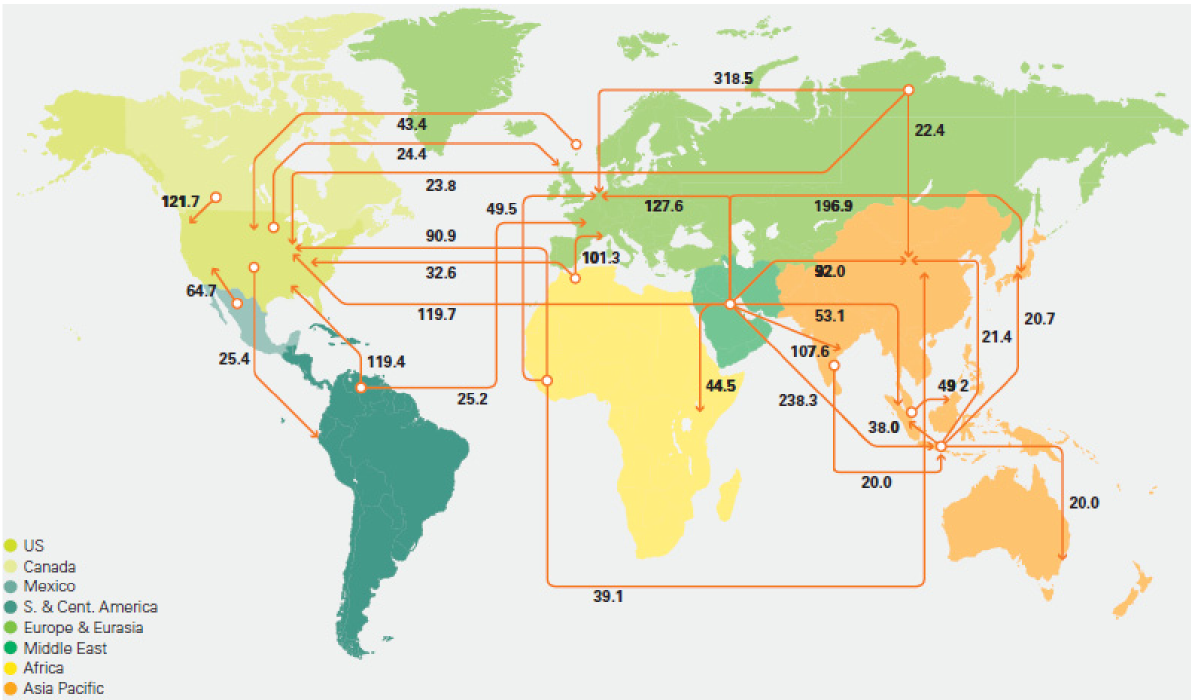

Figure 8: Global major oil trade flow networks in 2008 (in million tonnes).[10]

[8]Source: BP Statistical Review of World Energy, June 2009. Available at: http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2009_downloads/statistical_review_of_world_energy_full_report_2009.pdf (Last accessed on 20 May 2010).

[9] Assuming that the reserves remaining at the end of any year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate.

[10] Source: see footnote 8.

Globally, 505 oil refineries have been identified in this analysis (see Figure 9), with 177 refineries (35 percent) located within the LECZ (Figure 10). Oil refinery infrastructure is not expected to increase in the LECZ, and is likely to decline if oil production declines as is widely expected.

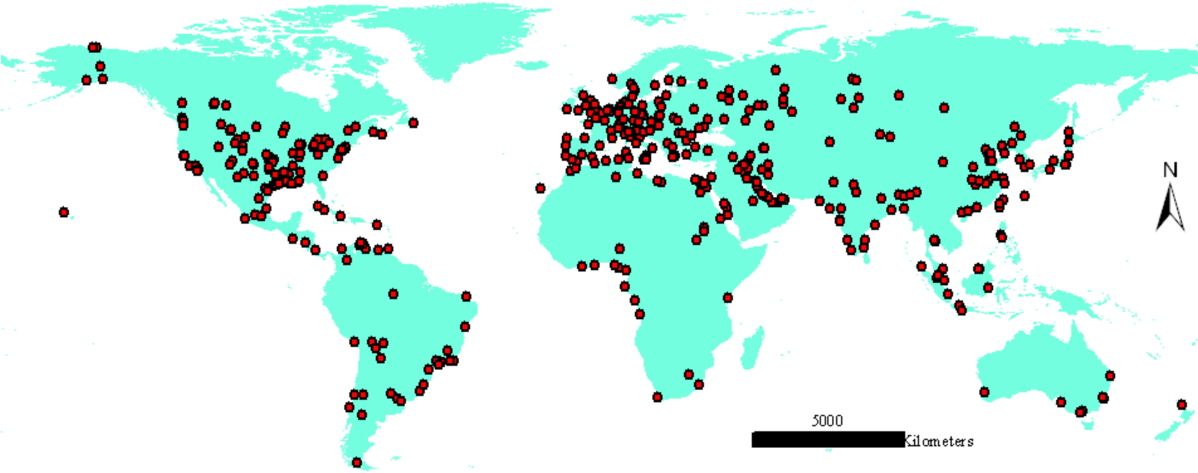

Figure 9: Geographic distribution of world's oil refineries (as of February 2004).[11]

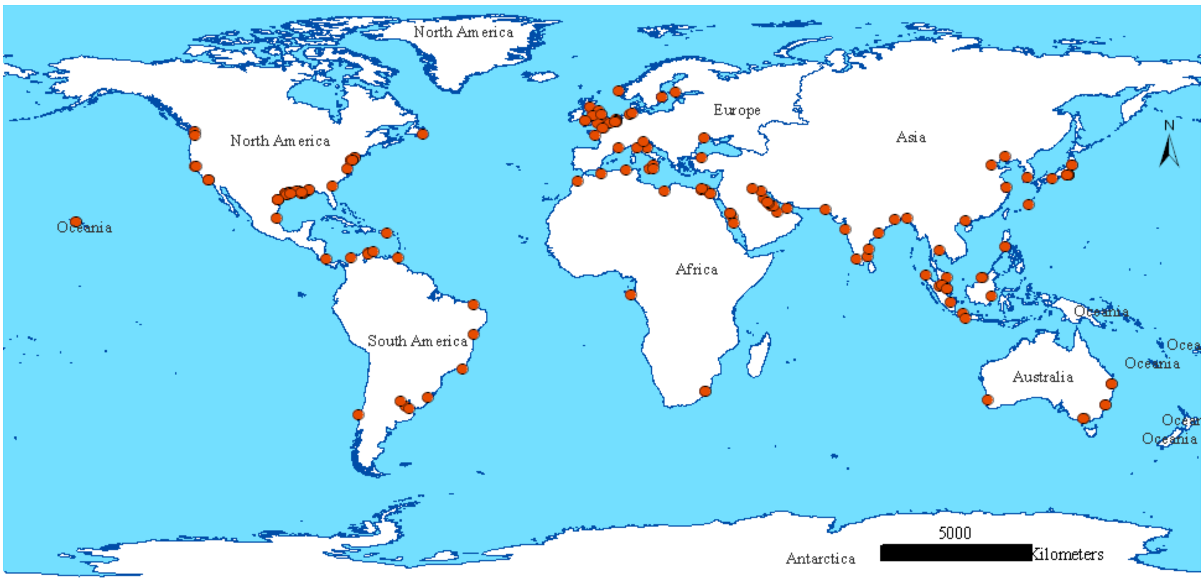

Figure 10: Global oil refineries located within the LECZ.

Natural Gas Terminals

[11] Source: http://finder.geocommons.com/ (Last accessed on 18 May 2010)

Natural gas is the fastest growing energy source, and is a key energy source for industrial sector uses and electricity generation worldwide. The global consumption is projected to rise by more than 48 percent from 2.9 trillion cubic metres (in 2006) to 4.3 trillion cubic metres (by 2030)[12]. Moreover, nations moving towards implementing strategies in reducing CO_2 emissions, the use of natural gas replacing other fossil fuels may get more and more attention worldwide; and hence the need for more infrastructure in the sector. This will include pipelines and specialised port and harbour facilities, which will inevitably have a coastal location, at least in part. For instance, Figure 11 shows the global natural gas (pipeline gas and LNG) trade flow network and the amount imported/exported in 2008. Figure 12 shows the geographic distribution of the world's LNG marine terminals.

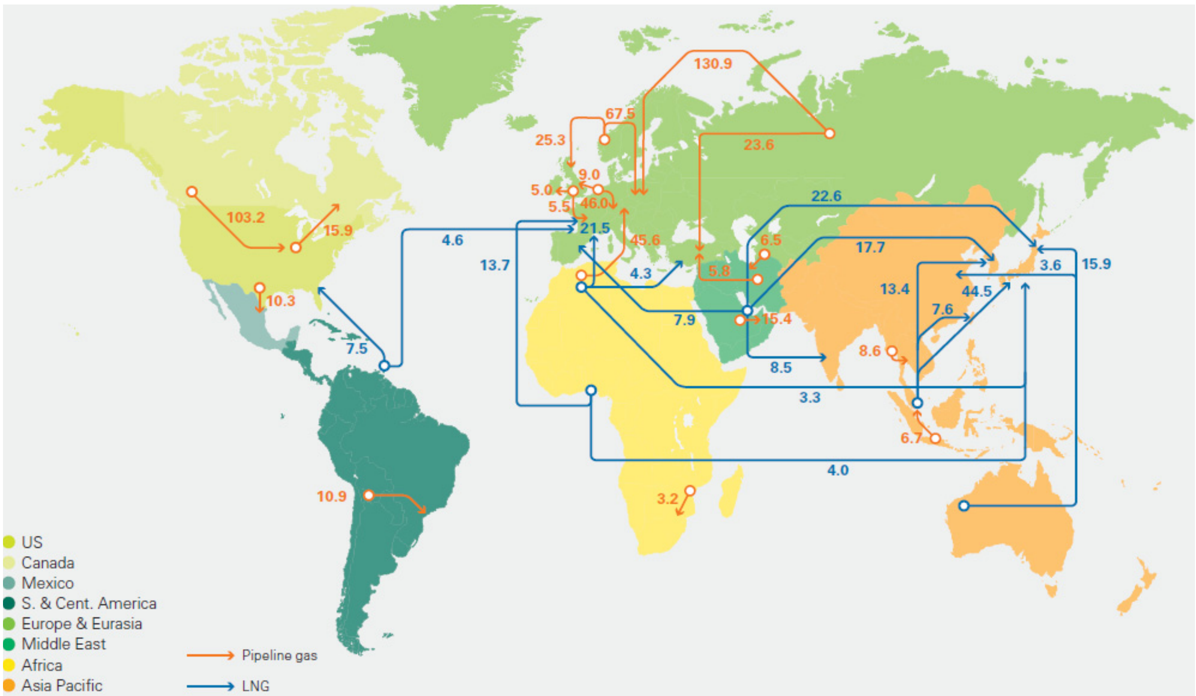

Figure 11: Global natural gas trade flow networks in 2008 (in billion cubic metres).[13]

[12] U.S. Energy Information Administration: Independent Statistics and Analysis – International Energy Outlook 2009: http://www.eia.doe.gov/oiaf/ieo/nat_gas.html (Last accessed on 21 May 2010)

[13] Source: see footnote 8.

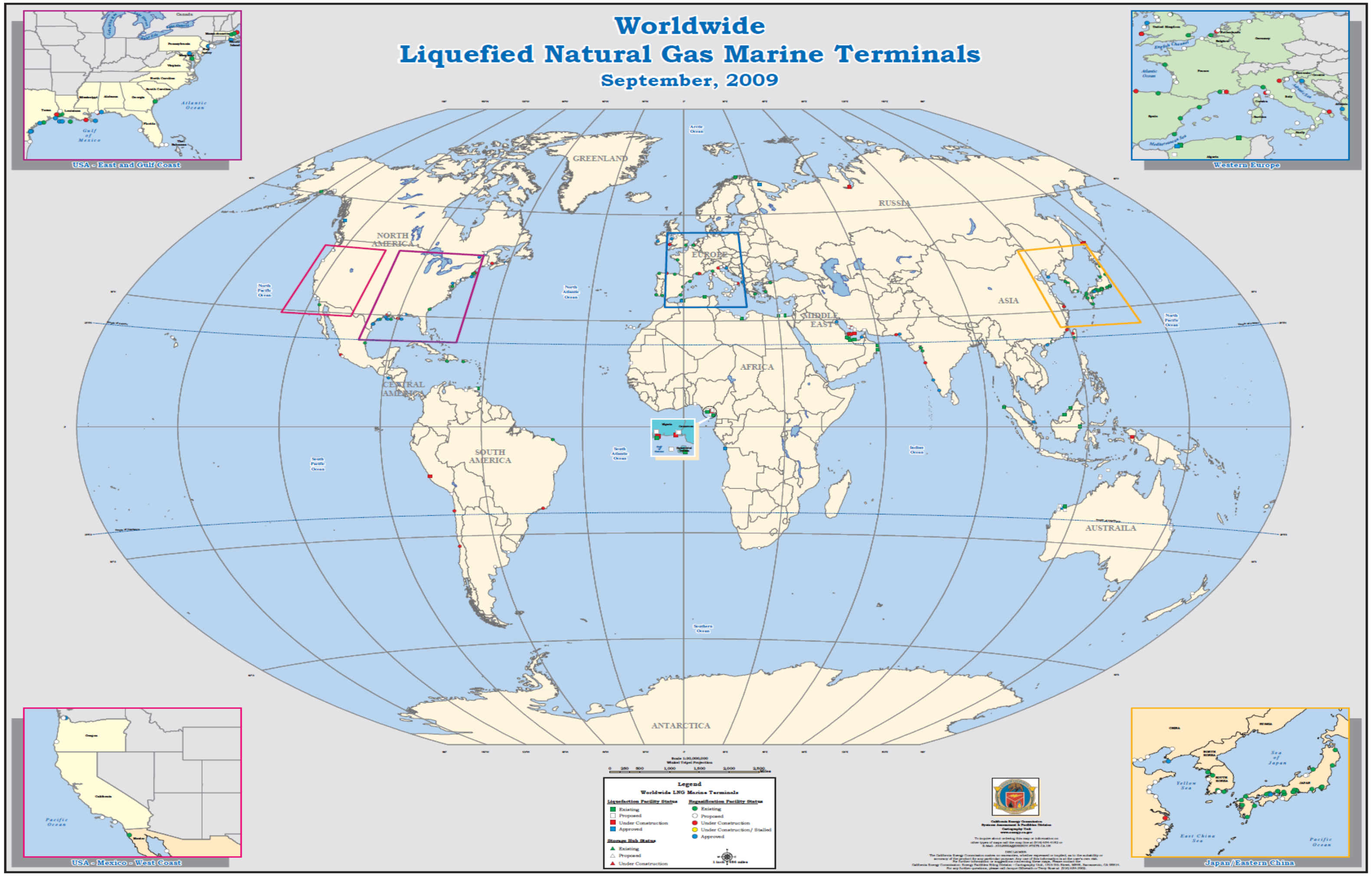

Figure 12: Global LNG (Liquefied Natural Gas) Terminals[14]

[14] The California Energy Commission: Worldwide Liquefied Natural Gas (LNG) Marine Terminals. Available at: http://www.energy.ca.gov/maps/Worldwide_LNG.pdf (Last accessed on 20 May 2010).

2.2.4 Other Coastal Infrastructure

Other coastal infrastructures include: transportation facilities (e.g., roads, railways), buildings, hospitals, schools, emergency facilities (e.g., police and fire stations), hydroelectric power generation facilities, water and wastewater treatment plants, waste disposal facilities, communication structures, facilities for tourism industry, etc. Most of these facilities are not especially coastal in location and they are not considered further.

Reflecting the concentration of coastal cities in Section 2.2.1, many airports are found in coastal areas. In this analysis, a total of 9915 airports have been identified worldwide, with 1083 airports (or 11%) located within the coastal zone (Figure 13).

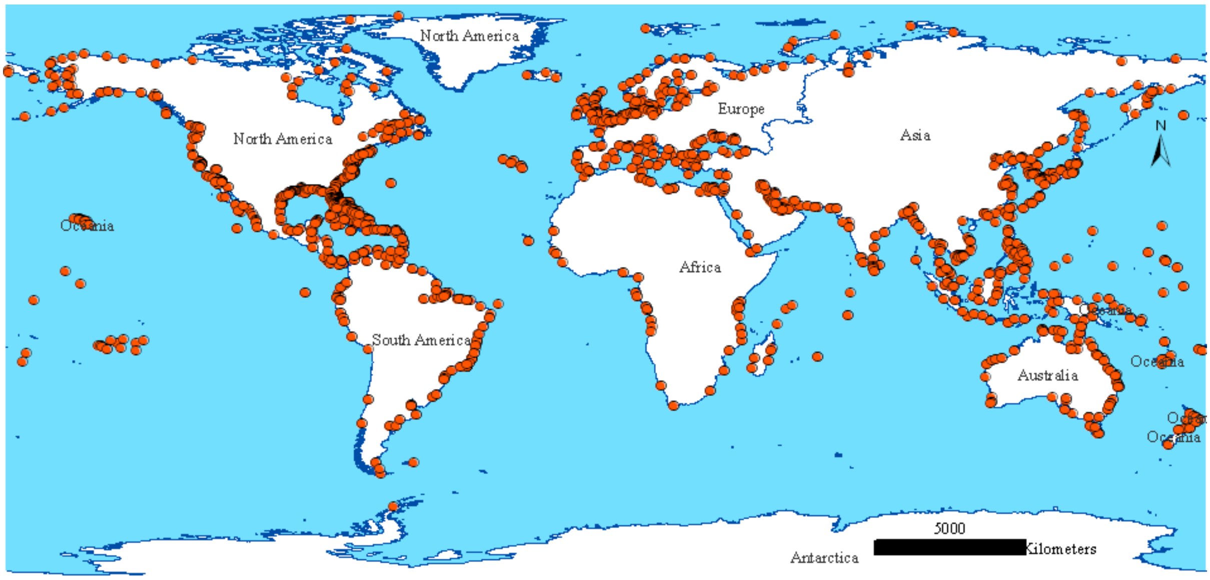

Figure 13: World's airports within the LECZ.[15]

Table 6 illustrates the world's top 10 airports ranked based on the total number of passengers (in 2009), that are located within the LECZ and are potentially threatened by rising sea levels.

[15] Source: Pacific Disaster Centre – Global Airports: http://www.pdc.org/mde/full_metadata.jsp?docId=%7B8454B00A-4A8C-4E2F-AD83-64F5051B022C%7D&loggedIn=false (Last accessed on 18 May 2010)

Table 6: World's top 10 busiest airports by passenger traffic (in 2009) located within the LECZ.

Rank+	Airport Name	Country	Total Number of Passengers
1 (5)	Tokyo International	JAPAN	61,903,656
2 (12)	John F. Kennedy International	UNITED STATES	45,912,430
3 (13)	Hong Kong International	CHINA	45,560,888
4 (14)	Schiphol, Amsterdam	NETHERLNDS	43,569,553
5 (15)	Dubai International	UNITED ARAB EMIRATES	40,901,752
6 (20)	San Francisco International	UNITED STATES	37,366,287
7 (21)	Singapore Changi	SINGAPORE	37,203,978
8 (22)	Guangzhou/Baiyun International	CHINA	37,048,550
9 (23)	Soekarno-Hatta International	INDONESIA	36,466,823
10 (25)	Miami International	UNITED STATES	33,886,025
+Values in brackets show the global top 30 ranking including inland airports.[16]			

GUSMÃO (2010) outlined the potential implications of sea-level rise on coastal airports worldwide, based on runway elevation. The study identifies the top 50 global coastal airports that are threatened by sea-level rise considering regional projections of relative sea-level rise. Table 7 shows the geographic location and elevation of the top 10 coastal runways by elevation.

[16] Source: Airports Council International's Data Centre: www.airports.org

Table 7: World's Top 10 runways threatened by relative sea-level rise+

Rank	Elevation (feet)	Country	(ICAO*) Runway	Latitude	Longitude
1	-15	Netherlands	(EHRD) ROTTERDAM	51.95209	4.42824
2	-13	Netherlands	(EHLE) LELYSTAD	52.45115	5.51102
3	-11	Netherlands	(EHAM) SCHIPHOL	52.30038	4.78348
4	-8	Netherlands	(EHNP) EMMELOORD	52.73024	5.74066
5	-7	France	(LFAK) DUNKERQUE GHYVELDE	51.04144	2.54886
6	-6	Egypt	(HEAX) ALEXANDRIA INTL	31.17466	29.93813
7	0	Australia	(YNSH) NOOSA	-26.42228	153.07190
8	0	Canada	(CYSZ) SQUIRREL COVE	49.12278	-66.53639
9	0	Canada	(CZAA) ALICE ARM	55.47816	-129.48496
10	0	Denmark	(EKSS) SAMSOE	55.88774	10.60398

*ICAO – International Civil Aviation Organisation

+ Source: Gusmão, 2010

3 Global Demand for New Coastal Infrastructure

Coastal areas are urbanising and experiencing major economic growth and expanding trade, as well as more general trends such as technological change and rising concern about technological issues. Independent of climate change, this will drive demand for new infrastructure and also shape the nature of this infrastructure, almost certainly causing significant changes to the world's coasts. These drivers are considered in turn.

Demography

Demographic variables (such as population size and urbanisation rate, population dynamics, age structure of the population, population density, extent of migration) are considered the most important drivers of new infrastructure. Key dimensions include:

- Population size: increases the demand for service infrastructure (e.g., energy demand, water and sanitation facilities, schools, hospitals, health facilities, etc.)
- Aging: more elderly-friendly infrastructure
- Population dynamics: stage of demographic transition influence appropriate composition of infrastructure investment
- Urbanisation: a general increase in demand for upgrading existing and/or for new infrastructure, e.g., in coastal areas, a need for coastal protection
- Migration: additional pressure on existing infrastructure and growing demand for new infrastructure

It is projected that the world's population will grow by about 47 percent (or an average growth of 0.77%) from 6.1 billion (in 2000) to 8.9 billion (in 2050) based on the medium UN scenario (Figure 14a). The major global demographic changes are taking place in densely populated developing countries. In many of the least developed countries, the 'population explosion' stage of the demographic transition is still active. Collectively, the less developed regions are projected to experience 58 percent growth over this half-century, as opposed to the more developed countries (with 2% projected growth). Africa and Europe represent the two extremes with the highest (i.e., 2.1% growth in 2010) and lowest (i.e., -0.14% growth in 2010) annual rate of population change, respectively (Figure 14b). However, although Europe, including the UK, has low fertility, rising life expectancy and associated shifts in the age distribution, combined with migration increased the growth rate by 0.1-0.2 points.

Coasts generally experience the highest population pressure and the increase in the LECZ is likely to exceed the global and regional trends, following observations over the last century. As shown in Section 2.2.1, many of the world's largest cities are located in coastal zones. A growing coastal population and rapid urbanisation will lead to higher demand for new coastal infrastructure. However, the type and emphasis of new infrastructure will depend on socio-economic dimensions (see Table 8).

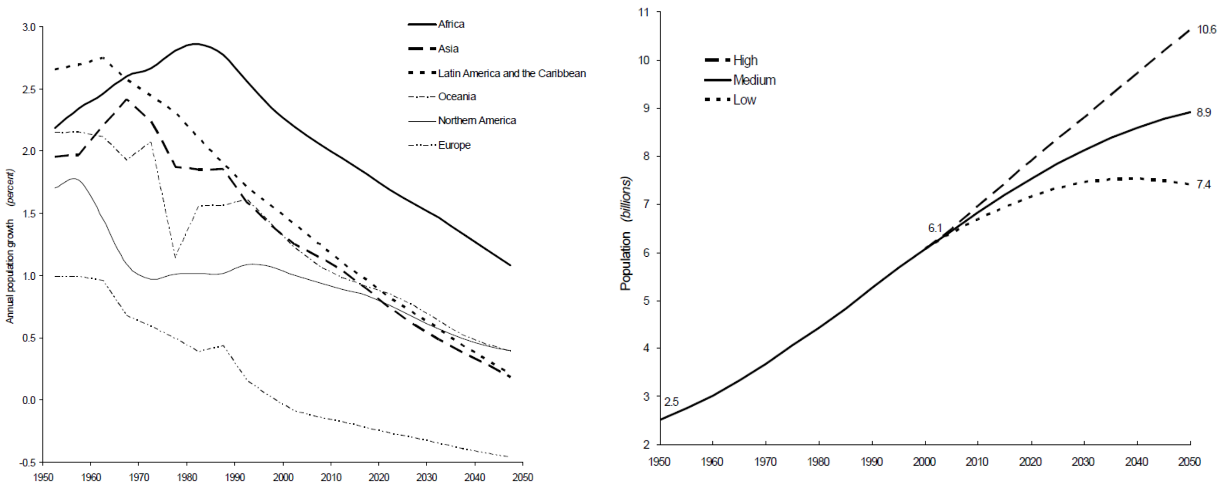

Figure 14: Global population and population change: observations and projections (to 2050): (a) total population and (b) annual rate of population change in major regions.[17]

Economic Change

Together with population growth, economic growth and the level of development play a key role on the potential need for new infrastructure across a range of sectors. For instance, infrastructure can facilitate/stimulate growth; a typical example would be the current practice in many countries on major stimulus investment on infrastructure as a response to the economic downturn. The additional growth and rising per capita income will further

[17] Source: United Nations Department of Economic and Social Affairs/Population Division (2004) - World Population to 2300. Available at: http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf (Last accessed on 15 May 2010).

initiate increased demand for infrastructure, such as a need to upgrade existing infrastructure to satisfy the added pressures and demands in range of sectors, e.g., energy, water, transport, etc., and stimulate a demand for high standards of infrastructure.

According to the OECD (2006) report titled 'Infrastructure to 2030', the global need for infrastructure investment is growing. For OECD countries, it is estimated that about US$50 trillion between 2005 and 2030 is required for investment in roads, water, electricity, telecommunications and rail, for building new infrastructure and to maintain and upgrade existing systems.

Technological Change

While its importance varies across sectors, technological change (for instance in major infrastructure such as energy, transportation, telecommunication), also plays a significant role on the development and demand of new/kinds of infrastructure, and can have potential impacts on future infrastructure. For instance, in the energy sector, the need/shift towards renewable energy resources drives technological change and a growth in marine renewables could have important implications for coastal areas (NICHOLLS *et al*., 2008b; 2010a) (see Table 8).

Environmental Issues

Environmental damage also plays a role on demand on infrastructure, and the challenges arisen could be substantial. For instance, rapid urbanisation and significant increase in economic activity and industrialisation, particularly in developing countries, is often associated with increased levels of pollution risk. Extensive utilisation and increased competition for resources also leads to environmental degradation. These could trigger an array of challenges and substantial associated costs.

Summary

Table 8 illustrates a summary of selected global non-climatic and environmental and socio-economic trends to coastal areas for the last century and this century. As the table exemplifies, most of these non-climatic drivers will potentially increase through this century. Although, substantial regional and local variations are expected, climate change and sea-level rise represent an additional driver of change and can only exacerbate these problems. The potential implications of these could be interpreted as potentially higher impacts, and possibly increase in demand for new infrastructure in the coastal sector worldwide.

Table 8: Examples of global non-climatic and environmental and socio-economic trends for coastal areas for the 20th and 21st Centuries based on the SRES Scenarios[+].

Environmental and socio-economic factors		**20th Century Trend[a]**	**21st Century trends (by SRES Future)**			
			A1 World[e]	A2 World	B1 World	B2 World
Global	Population in 2100 (billions)	↑	~7[b]	~15	~7[b]	~10
	GDP in 2100 (trillions 1990 US$)	↑	525-550	243	328	235
	Average GDP/capita in 2100 (thousands 1990 US$)	↑	75-79	16	47	24
Coastal Areas (the LECZ)	Net population influx (coastward migration)	↑	Most likely	Less likely	More likely	Least likely
	Infrastructure	↑	Largest increase	Large increase	Smaller increase	Smallest increase
	Human-induced subsidence[c]	↑ (L)	More likely		Less likely	
	Terrestrial freshwater/sediment supply[d]	↓	Greatest reduction	Large reduction	Smallest reduction	Smaller reduction
	Aquaculture	↑	Large increase		Smaller increase	
	Extractive industries	↑	Large increase		Smaller increase	
	Tourism	↑	Highest growth	High growth	High growth	Lowest growth
	Marine renewable energy[e]		Variable growth	Lowest growth	Highest growth	High growth
	Habitat destruction (direct and indirect)	↑	Continued loss		Reduced loss, stability or even recreation	

[+]Source: NICHOLLS *et al*. (2008b)
[a] ↑ increase; ↓ decrease; L Locally important
[b] In 2050, global population peaks 8.7 billion
[c] Subsidence due to sub-surface fluid withdrawal and drainage of organic soils in susceptible coastal lowlands
[d] Changes due to catchment management (as opposed to climate change)
[e] Depends on which A1 variant is considered – lowest under A1FI and highest under A1T

4 Coastal Infrastructure and Climate Variability

During the last four decades, natural hazards and weather-related events (e.g., river and coastal flooding, tsunamis[18], tropical cyclones and other severe storm events, etc) have caused major losses of human lives and livelihoods, destruction of social and economic infrastructure and environmental damages. For instance, the total direct economic damages associated with floods, storms, and other weather-related extreme events have increased from $3.9 billion per year (in the 1950s) by about ten times more to $40 billion per year (in the 1990s) (IPCC, 2001) – approximately one quarter of these damages (in the 1990s) are direct damages to infrastructure (FREEMAN and WARNER, 2001). According to MUNICH RE (2000), the total damage costs due to increase in surface temperature associated with the changing climate are estimated at over US$100 billion per year over the 21st Century.

Hurricanes/Tropical Cyclones

About 40 to 50 hurricanes and tropical storms occur globally per year. On average, ten tropical storms develop each year over the Atlantic Ocean, Caribbean Sea, or Gulf of Mexico – about 60 percent of these will strengthen enough to become hurricanes. For instance, in the U.S. Gulf or Atlantic coast, about five hurricanes make landfall and strike the coastline every three years and cause major damages (BLAKE *et al*., 2007) (see Box 1, a case study on the U.S. Gulf Coast). Table 9 lists the top ten costliest tropical cyclones ranked based on total damage costs, and Table 10 illustrates the top ten deadliest costal disasters during 1980-2008.[19] Storms which struck the USA dominate damage costs, while storms that struck Asia dominate the death toll, reflecting its higher population and greater vulnerability. Although recent natural disasters since 1980 are presented here, historically earlier severe natural disasters are recorded such as Hurricane Great Miami in 1926 in the

[18] 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.
[19] Note that, for consistency purposes, the data presented here are taken from a single source, as noted. But, other sources provide a much smaller damage cost estimates (e.g., PIELKE *et al.,* 2008). PIELKE et al. (2008) reported total damage costs of US$81 billion and US$20.6 billion (in 2005) due to Hurricanes Katrina and Wilma, respectively. The differences in dimensions could be associated with the differences in the methods used and the component damage costs considered by various studies.

USA with a total damage cost of US$140 billion (2005 estimate) (PIELKE *et al*., 2008), and the 13 November 1970 Bhola cyclone in East Pakistan (now Bangladesh) with a total death toll up to 500,000. When considering the severity of events and the death toll in Bangladesh, it has fallen dramatically since 1970/1991 due to the development of a warning system combined with shelters. This shows how people can adapt if there is sufficient knowledge, information and preparation (see also Section 6).

Table 9: The top ten costliest coastal disasters ranked based on damage costs (1980-2008). The damages costs are the total for each event and some may occur outside the LECZ.

Rank	Hurricane	Date	Severely Affected Areas	Damage, 2010 dollars (US$ billion)
1	Katrina	Aug. 2005	Louisiana, Mississippi, Alabama	142.0
2	Andrew	Aug. 1992	S. Florida, Louisiana, Bahamas	41.8
3	Ike	Sept. 2008	Texas, Louisiana, Cuba	39.3
4	Ivan	Sept. 2004	Caribbean Is., Alabama, Florida, Louisiana, Texas	26.8
5	Wilma	Oct. 2005	Cuba, Florida, Bahamas	25.0
6	Charlie	Aug. 2004	Florida, Cuba, Caribbean Is., N&S Carolina	21.0
7	Rita	Sept. 2005	Louisiana, Texas	18.2
8	Georges	Sept. 1998	Dominican Rep., Cuba, Florida, Louisiana, Mississippi, Alabama	17.4
9	Hugo	Sept. 1989	S. Carolina, Guadeloupe, Montserrat	17.4
10	Mireille+	Sept. 1991	Japan	16.4
+Typhoon				

Source: MUNICH RE NATCAT DATABASE

Table 10: The top ten most deadly coastal disasters (1980-2008). The death tolls are the total for each event and may occur outside the LECZ, especially where high terrain occurs near the coast such as Nicaragua and Honduras and Hurricane Mitch.

Rank	Disaster	Date	Severely Affected Areas	Total Death
1	Asian Tsunami+	Dec. 2004	Sri Lanka, Indonesia, Thailand, India	220,000
2	Cyclone Nargis	May 2008	Myanmar	140,000
3	Tropical Cyclone	Apr. 1991	Bangladesh	139,000
4	Tropical Cyclone	May 1985	Bangladesh	11,050
5	Tropical Cyclone	Oct. 1999	India, Bangladesh	10,000
6	Tropical Cyclone	June 1998	India	10,000
7	Hurricane Mitch	Nov. 1998	Honduras, Nicaragua, Florida	9,976
8	Cyclone Thelma	Nov. 1991	Philippines	6,000
9	Hurricane Georges	Sept. 1998	Domini. Rep., Cuba, Florida, Louisiana, Mississippi, Alabama	4,000
10	Cyclone Sidr	Nov. 2007	Bangladesh, India	3,360
+Included for reference – not a climate event.				

Source: MUNICH RE NATCAT DATABASE

Box 1: Case Study: The Implications of Climate Change on Coastal Infrastructure along the U.S. Gulf Coast

The U.S. Gulf Coast is one of the key economic and population centres (with more than 15 million people located in five states – Texas, Louisiana, Mississippi, Alabama, and Florida, and three major metropolitan areas) of the United States. It is home to major coastal cities, the nation's critical infrastructure including 7 of the 10 largest ports (by tons of traffic), the major oil and gas industries (which provide about 30% of the nation's crude oil production and 20% of its natural gas production), and other important transport and other infrastructure such as major international airports, railways, roads, etc. (NAS, 2008).

The geographic location and the very low-lying nature of the flat land along the Gulf coast, bordering the subtropical waters of the Gulf of Mexico, makes the region highly vulnerable to major hurricanes, more so than any other region in the USA. It is also a region where the potential impacts of sea-level rise will be exacerbated by significant subsidence due to natural (consolidation of deltaic sediments and, for example, movement of the Michoud fault in New Orleans) and human-induced (e.g., draining wetlands, diverting sediment-bearing floodwaters from the Mississippi River, and pumping of ground water) causes (e.g., BURDEAU, 2006; BURKETT *et al.*, 2003; DIXON *et al.*, 2006).

As demonstrated by Hurricanes Katrina and Rita in 2005, significant infrastructure (e.g., thousands of offshore drilling platforms, dozens of refineries, thousands of miles of pipelines, and other critical transport infrastructure such as major ports and harbours, airports, railways, roads, etc.) along the U.S. Gulf Coast is highly vulnerable to disruption and damages from storm surges and the high winds of tropical storms (NAS, 2008). Moreover, six of the U.S. top 10 freight gateway infrastructures are also at risk of sea-level rise (see Table1-Box1). The 2005 hurricanes caused significant damages to rail transport (e.g., one of the four major rail crossings of the Mississippi river, particularly the east-west traffic through the New Orleans interchange), disruption of major oil and gas production along the Gulf, disrupted about 20% of the nation's refinery capacity, and caused a closure of all oil and gas pipelines (CBO, 2006). Hurricane Katrina was the most destructive and costliest natural disaster in the U.S. history, claiming over 1,800 lifes and estimated damage cost of US$125 billion (2005), while hurricane Rita, exceeding Katrina both in intensity and maximum wind speed, claimed 120 lives and had a damage cost of US$16 billion (2005) (as reported in MUNICH RE NATCAT DATABASE). These disasters caused heavy damages on key coastal highway and railway bridges (causing rerouting of traffic which put increased strain on other routes), halted barge shipping (including export grain traffic out of the Port of New Orleans, the largest export grain port in USA), shut significant pipeline networks (which led to shortages of natural gas and petroleum products), and major damages and disruption to other infrastructure and services.

These damages illustrate the significant international dimension in addition to the local and regional consequences, as most of the international transport and other infrastructure in the region were affected and caused disruption of people's movement, import/exports, potential loss of imported raw materials, increase in prices of commodities, higher energy costs, higher costs to insurance industries, etc.

Table1-Box1: Top 10 U.S. Foreign Trade Freight Gateways by Value of Shipments, 2005 (Adapted from NAS, 2008).

Rank	Port	Mode	Shipment Value (US$ billions)
1	John F. Kennedy International Airport, New York	Air	134.9
2	Los Angeles, California	Vessel	134.3
3	Detroit, Michigan	Land	130.5
4	New York, New York, and New Jersey	Vessel	130.4
5	Long Beach, California	Vessel	124.6
6	Laredo, Texas	Land	93.7
7	Houston, Texas	Vessel	86.1
8	Chicago, Illinois	Air	73.4
9	Los Angeles International Airport, California	Air	72.9
10	Buffalo-Niagara Falls, New York	Land	70.5

Hurricane Katrina is by far one of the most devastating storms that took hundreds of lifes across the Gulf coast, and caused the largest relocation in U.S. history. Key statistics for Katrina are given by BURTON and HICKS (2005), and include:

- Duration: 23-31 August, 2005
- Highest winds: 280km/hr
- Maximum surge of 10 m and wave height of 10 m
- Number of fatalities: 1,800 people[20]
- About 300,000 homes and more than 1,000 historical and cultural sites damaged/destroyed
- Total damage costs:
  - Commercial structure damages – US$21 billion
  - Commercial equipment damages – US$36 billion
  - Residential structure and content damages – US$75 billion
  - Electricity utility damages – US$231 million
  - Highway infrastructure damages – US$3 billion
  - Sewer system damages – US$1.2 billion
  - Commercial revenue losses – US$4.6 billion
- Electrical system infrastructure: at peak 2.7 million people affected, and major disruption in communications and power
- Nuclear plants affected:
  - Mississippi: Grand Gulf (1231MW) – forced to run at reduced level during storm
  - Louisiana: River Bend (980MW), and Waterford 3 (1091MW)

[20] Source: GRAUMANN *et al*. (2005)

Indirect effects were also important and most importantly, the price of oil was raised by shortages due to Hurricane Katrina. Much of the insurance costs also fell on the London markets.

Extreme events can have other indirect effects. The 26 December 2004 Tsunami led to massive displacement of people and destruction of infrastructure around the Indian Ocean. This lead to an unprecedented international donor response and logistic challenges to international organisations and aid agencies worldwide. It also led to a relatively large loss of life of European holidaymakers. Large storms could have similar consequences.

Although it is impossible to prevent most natural disasters, adaptation measures which reduce the effects on human kind and its environment is often achievable. These require incorporating natural disaster mitigation measures into the planning, design and implementation of all sustainable 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, extreme climatic events are now attributed to climate change and hence western countries (including the UK) are blamed, even though extreme events have always occurred, and it is not established that climate change has made them worse.

5 Future Impacts of Climate Change and Sea-Level Rise on Coastal Infrastructure

This section presents a summary of the potential global impacts of climate change and sea-level rise and the possible implications on demand for infrastructure in the coastal sector based on the literature. In looking at trends through the 21st Century, three time slices (i.e., 2030, 2050, and 2100) are considered with reference to the base year (2010), and trends are reported as a snapshot at each of these time slices. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) estimated sea-level rise scenarios in the range 19 to 58 cm from 1990 to the 2090s (Table 11). It was also recognised that larger rises were possible in the IPCC report, but apart from an illustrative example, this was not quantified. Subsequently, there has been an extensive discussion about sea-level rise with many authors arguing for a range of possible change where the upper bound greatly exceeds the range in Table 11 (e.g., Pfeffer *et al*., 2008; Vermeer and Rahmstorf, 2009). Hence, here we consider scenarios of sea-level rise of 0.5 and 1.0, and 2.0 m (with a 2-m rise being a low probability H^{++} sea level range defined for vulnerability testing, as detailed in Lowe *et al*. (2009)) (see Table 12). This gives a range of impacts that samples the full range of possible changes. Although sea-level rise scenarios of ≥ 1m rise are considered unlikely during this century, the magnitudes of the potential impacts of such large scenarios are of major concern, and hence relevant in impact and vulnerability assessment.

Table 11: Projected global-mean climate parameters relevant to coastal areas at the end of the 21st Century for the six SRES marker scenarios (as reported by Meehl *et al.*, 2007). Note that sea-level rise may exceed the 95% bound due to contributions from the major ice sheets.

Climate Driver (Baseline refers to 1980-1999)			**SRES Marker Scenarios**					
			B1	**B2**	**A1B**	**A1T**	**A2**	**A1FI**
Surface ocean pH (Pre-industrial reference: 8.2) (Baseline: 8.1)			8.0	7.9	7.9	7.9	7.8	7.7
Sea Surface Temperature (SST) rise (^{o}C)			1.5	-	2.2	-	2.6	-
Sea-Level Rise	Best Estimate (m)		0.28	0.32	0.35	0.33	0.37	0.43
	Range (m)	5%	0.19	0.21	0.23	0.22	0.25	0.28
		95%	0.37	0.42	0.47	0.44	0.50	0.58

Table 12: Sea-level rise scenarios used in this assessment.

Scenarios	Time Slices			
	2010	2030	2050	2100
Low, L	0.05	0.11	0.20	0.5
High, H	0.06	0.18	0.35	1.0
High Plus Plus, H^{++}	0.10	0.31	0.64	2.0

5.1 Climatic Drivers of Change and Demand for Infrastructure

Climate change and sea-level rise pose significant additional pressures on the LECZ. Table 13 illustrates the ranges of potential drivers of impacts of climate change in coastal zones and their possible physical and ecosystem effects.

Table 13: 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 fertilisation; 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; flood and storm damage; erosion; 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)	Altered surges and storm waves and hence risk of storm damage and flooding.
Storm	Track (?, R)	
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.
Trend: ↑ – Increase; ? – Uncertain; and R – Regional Variability		

[+]Source: NICHOLLS *et al*. (2007)

These drivers of change could potentially lead to a range of negative socio-economic impacts. For instance, Table 14 exemplifies the potential climate-induced impacts on natural and human systems in the coastal zone. However, it is important to note that the potential implications and magnitudes of the impacts of sea-level rise will generally vary from place-to-place, and depend very much on various factors including the magnitude of sea-level rise (considering the regional variability) and other aspects of climate change, coastal morphology, human modifications, and population and socio-economic distribution in the coastal zone.

The LECZ contains a high and growing concentration of population and associated socio-economic activity leading to a major and expanding exposure of people and infrastructure to climate-induced coastal hazards. Hence, the potential impacts of climate change and sea-level rise could have significant implications on future development planning in the coastal sector, and this will influence the demand for infrastructure in the sector over the 21st Century.

Table 14: Summary of potential climate-related impacts on socio-economic sectors in coastal zones+.

Coastal Socio-Economic Sector	**Climate-related impacts (and their climate drivers)**						
	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	X	X	X	X	-	X	x
Agriculture & Forestry	X	X	X	X	-	X	x
Fisheries & aquaculture	X	X	x	-	x	X	X
Health	X	X	X	x	-	X	X
Recreation & tourism	X	X	x	-	X	-	X
Biodiversity	X	X	X	X	X	X	X
Settlement/ infrastructure	X	X	X	X	X	X	-
A&S-Air and Seawater, S-Storms, W-Waves, SL-Sea Level, R-Runoff, ACD-All Climate Drivers 'X' – strong, 'x' – weak, and '-' – negligible or not established.							

+Source: NICHOLLS *et al*. (2007)

5.2 Global Coastal Damages & Costs of Climate Change and Sea-Level Rise

Climate change and sea-level rise will have adverse impacts on coastal areas worldwide through the 21st Century (NICHOLLS *et al*., 2007). The magnitude of the potential damages and costs of such impacts will significantly depend, in addition to the magnitude of sea-level rise and climate change, on future socio-economic change (e.g., NICHOLLS, 2004). Socio-economic changes will almost certainly cause rapid growth in population and coastal infrastructure (Section 3); while human-induced subsidence has the potential to be significant in deltaic locations. To illustrate this point, NICHOLLS *et al*. (2008a) examined global exposure to flooding in large port cities[21] where coastal infrastructure is concentrated. They made high end assumptions about socio-economic changes, including urbanisation rates, climate change (sea-level rise and possible more intense storms) and subsidence. The population exposure to extreme water levels could increase by a factor of about 4 times from 40 million (in 2005) to 150 million (by the 2070s), and the assets exposed could increase by a factor of more that 10 times from US$3 to US$35 trillion. Roughly two-thirds of the increase in exposure are associated with socio-economic growth (population and economic growth, and urbanisation). Figure 15 exemplifies the global distribution of population and assets exposure, where Asia and North America contain the major exposed port cities.

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[21] Those port cities with more than one million people in 2005.

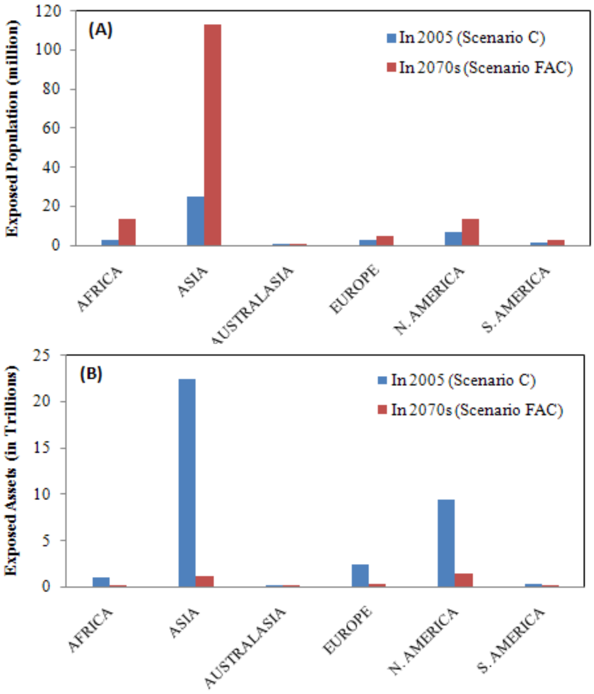

Figure 15: Global port city exposure – sea-level rise and extremes: (A) Exposed Population, and (B) Exposed Assets in 2005 (Scenario C) and by the 2070s (Scenario FAC).[22]

Building on this work, Figure 16 illustrates the regional changes in asset exposure to extreme water levels for smaller climate change scenarios (HANSON *et al*., 2010). These estimates demonstrate the growing exposure of assets in the top five regions over the 21st century. China and Europe are the two extremes with the highest and lowest growth in exposure, respectively, and the proportion of coastal infrastructure in port cities in Europe declines significantly compared to the other regions shown.

Figure 17 shows the global distribution of exposed assets in large port cities estimated for 2050 and 2070. It illustrates the major concentration of exposed population and associated infrastructure assets in Asia, especially on an axis from India to Japan, highlighting the fast growing economy in these rapidly developing countries in the region, plus the existing importance of Japan. Other regions with large concentrations of assets are Eastern USA and the southern North Sea. In 2070, the top ten cities in terms of asset exposure are estimated to be Miami, Shanghai, Guangdong, Tokyo, New York-Newark, Ho Chi Minh City, Osaka-Kobe, Bangkok, Amsterdam, and Rotterdam

[22] After NICHOLLS *et al*. (2008) [‘C’ refers Current City (as in 2005), and ‘FAC’ – Future City All Changes: Water Levels – due to climate (including sea-level rise and more intense storms) and human-induced subsidence].

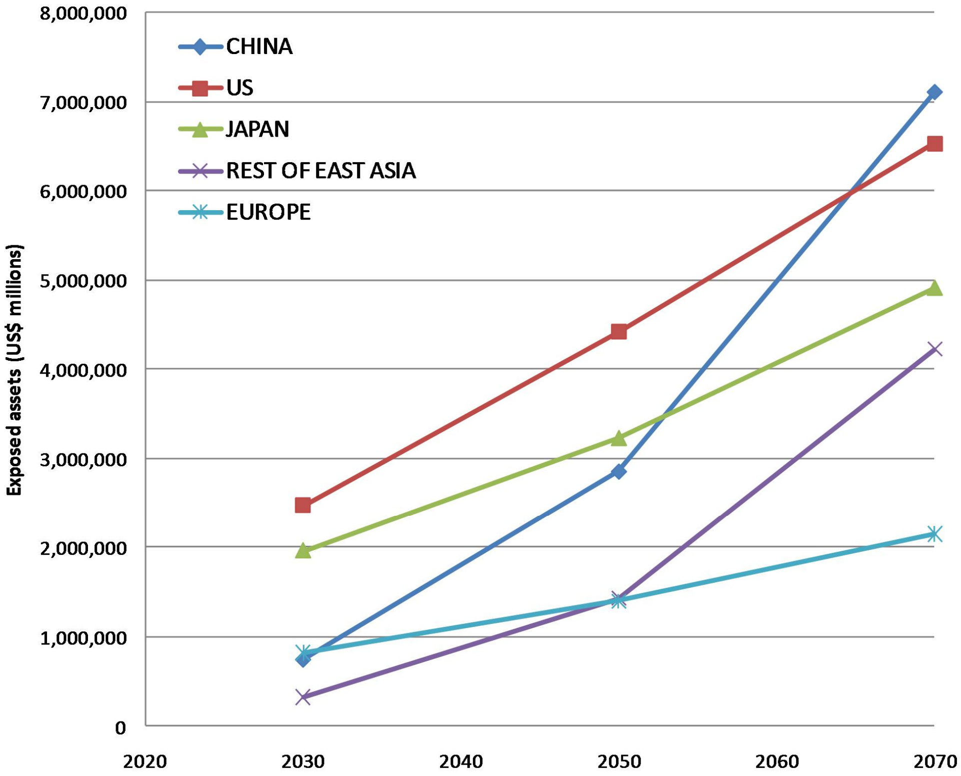

Figure 16: Regional changes in asset exposure for large port cities by 2070. The Top Five regions are shown under the Rapid Urbanisation, FAC water level and A1B climate scenarios[23]

[23] After HANSON *et al*. (2010) ['FAC' – Future City All Changes: Water Levels – due to climate (including sea-level rise and more intense storms) and human-induced subsidence]

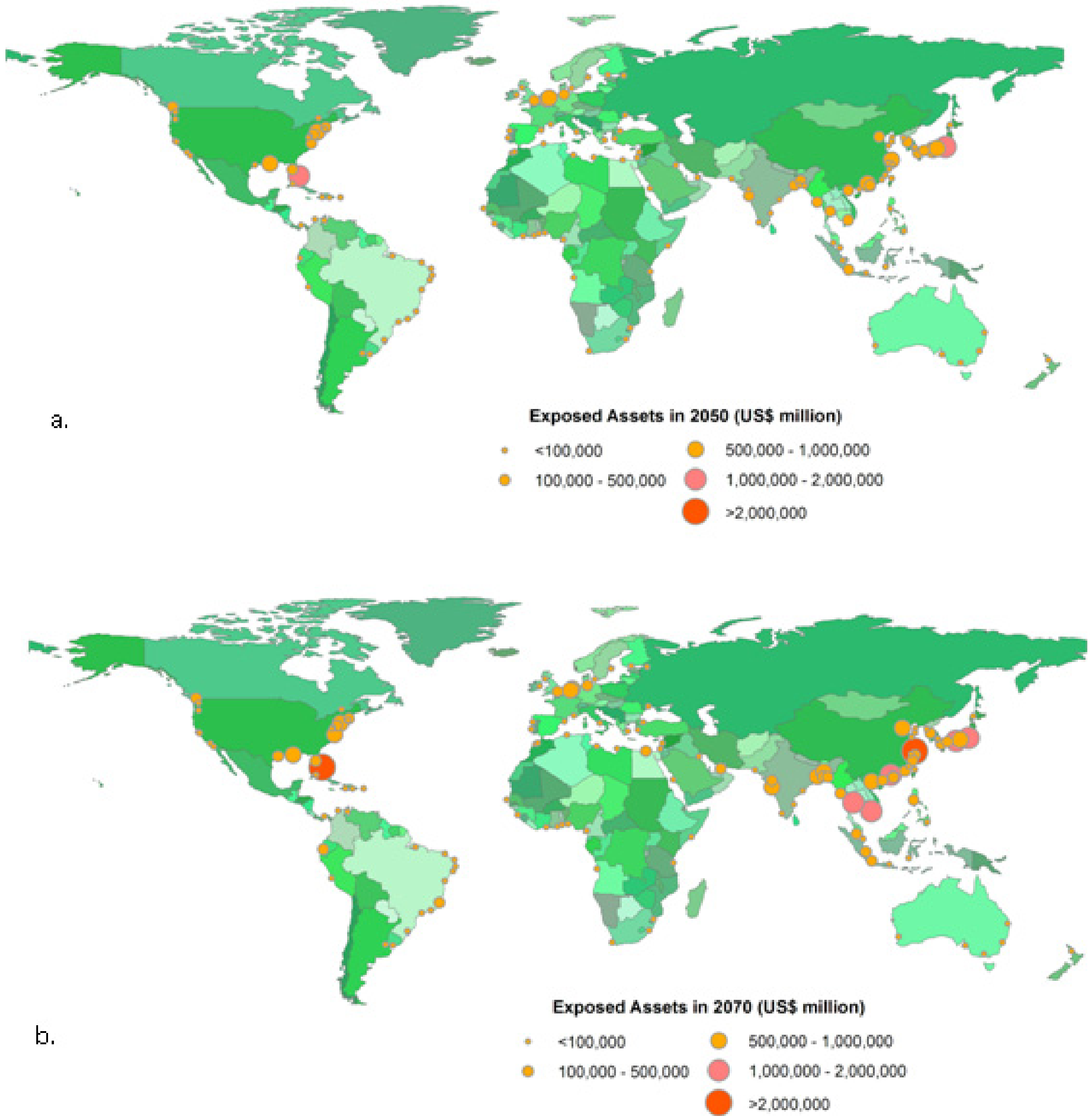

Figure 17: Global distribution of assets exposure in large port cities under the A1B (unmitigated) (50th sea level percentile) climate and FAC water level scenario: (a) by 2050, and (b) by 2070.[24]

In this analysis, selected sea-level rise scenarios have been considered and a simple comparison with the ground elevation of the coastal infrastructure was made to count the different infrastructure that are threatened under each scenario. There is significant uncertainty with such a procedure and the results should be taken as an indicative estimate. Table 15 presents some of the important coastal infrastructure that are identified in the analysis. Not surprisingly, a large proportion of the infrastructure in the LECZ appears threatened

[24] After HANSON *et al*. (2010), see footnote 22

Table 15: Global coastal infrastructure assets existing today that are exposed to sea-level rise; the numbers are estimated by comparing the ground elevation of the respective infrastructure to the sea-level rise scenarios considered, so these are indicative estimates (see Appendix A). (See also Table 12). As the number/size of airports and nuclear power stations are expected to grow, these should be taken as minimum estimates. For oil refineries, the reverse may be true due to the decline in oil production.

Coastal Infrastructure	**Below MSL**	**Sea-Level Rise Scenarios for selected time slices**												**Within the LECZ**
		2010			**2030**			**2050**			**2100**			
		L	H	H++	L	H	H++	L	H	H++	L	H	H++	
		0.05	0.06	0.10	0.11	0.18	0.31	0.20	0.35	0.64	0.5	1.0	2.0	
Airports	27	27	27	27	27	28	29	28	29	68	29	253	368	1083
Nuclear Power Stations	1	1	1	1	1	1	1	1	1	4	1	10	14	31
Oil Refineries	3	3	3	3	3	3	4	3	4	16	4	29	61	177
Note: all sea/coastal ports and harbours are exposed to sea-level rise, today and through the 21st Century.														

The threat of more intense tropical storms is also of widespread concern including to the insurance industry in the UK. However, while more costly disasters would result, the limited available literature suggests that in an average annual sense, the increase in changes is much less than the potential damage of sea-level rise (MENDELSOHN *et al.*, 2009; NARITA *et al.*, 2008; NORDHAUS, 2006). This is an important topic for further research.

5.3 Implications: Sectoral Assessment – Qualitative Interpretation

The following discussion considers a list of major sectors in the coastal zone, in which damages and costs in one country or region could be felt by, and influence the adaptation need of, other countries and regions worldwide.

Critical energy infrastructure

Although, there is a global move towards renewable energy source options (Table 12), fossil fuels are likely to be remain an important component of energy supply through the 21st Century. Hence, the UK will depend on importing large amounts of energy, with natural gas and maybe coal, being important components of our energy demand. It seems that these infrastructure systems are unlikely to be permanently disrupted by climate change and sea-level rise as we will likely adapt to these long-term changes (Section 6). However, temporary disruption to the infrastructure systems that provides these energy supplies is of concern and sea-level rise and climate change increase the consequences of extreme events. The evidence from Hurricane Katrina shows that major events in certain regions can have global consequences, and hence the UK can be directly impacted, via the disruption of supply from a specific area, and indirectly via rising prices triggered by a temporary decline in supply. (These issues may be raised with other traded commodities and goods as discussed below under Transport Infrastructure).

Coastal tourism industry

Tourism is one of the major cultural and socio-economic activities around the world. The coastal zone represents the main destination of tourists and a dominant sector in the industry worldwide. While tourism is expected to continue to grow substantially (Table 12), the spatial and temporal distributions of tourism demand and tourist movements will be influenced by climate change (HAMILTON *et al.*, 2005). From a UK perspective, changes in international tourism just represent changes in individual preferences and international tourists will simply be going to different locations. However, as the UK warms, it may well attract both a larger share of the domestic tourism market, and possibly international tourists who may choose the UK over locations to the south in Europe. Hence, climate change could represent an additional economic opportunity for the UK in terms of growing coastal-based tourism, and a pressure based on the infrastructure that this will demand (HAMILTON and TOL, 2007). The size of this effect is unclear it will be driven by the magnitude of temperature change in the UK. This issue could be investigated further at the UK and EU scale.

Transportation infrastructure

As with critical energy infrastructure, the damage during extreme events is of concern, as we will adapt to longer-term changes. Disruption of port infrastructure, especially 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 (e.g., new computer superchips are mainly made in one region in China near Hong Kong, raising the question of the effect of a super typhoon on global supply). Further analysis is beyond the scope of this chapter, but contingency planning for transport disruption is certainly an issue that requires more analysis.

Global security and migration

Global security and migration have raised significant global concern over the last two or three decades (DEFRA, 2010). In a coastal context, energy supply has already been mentioned, but this would probably be a temporary phenomenon which could be managed in a security sense. Of more concern are 'environmental refugees/migrants' who might be displaced by sea-level rise, as the threatened populations are large – as already extensively discussed (e.g., MYERS, 2002; DAGSPUTA *et al*., 2007; 2009). However, many analyses of sea-level rise ignore the possibility of protection and simply assume that the entire exposed population is displaced, which is not credible based on historic observations of human response to significant subsidence in low-lying coastal cities (NICHOLLS, 2010). As shown in Section 6, benefit-cost analysis shows that protection is the economically ration response in most developed areas and a protection response would be expected to be widespread, especially in coastal areas. Hence, the numbers of environmental refugees/migrants due to sea-level is unclear. The likely major 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. An ongoing Foresight project on Global Environmental Migration investigates in more detail how future environmental change could trigger and affect the pattern of long-term human migration worldwide.[25]

Business and finance sector

Additional impacts in the UK to those outlined above is less clear. Coastal disasters have important implications for the insurance industry (e.g., GROSSI and MUIR WOOD, 2006), but they recognise this and their research and development in this area to manage risks is significant. In many ways, their expertise in this area is something that the rest of the UK could try and benefit from, as the insights from this research are generally not in the public domain.

[25] For more detail, see: http://www.foresight.gov.uk/OurWork/ActiveProjects/EnvironmentalMigration/Migration.asp

6 Adapting Coastal Infrastructure to Climate Change and Sea-Level Rise

As outlined in the previous sections, the impacts of climate change and sea-level rise could be serious for coastal areas, unless there is significant coastal adaptation. Importantly, sea level is relatively unresponsive to climate mitigation compared to 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). While the science basis of this commitment is well understood, the coastal policy implications are as yet not widely appreciated.

Historically, adaptation has a long history in coastal areas worldwide. Although it has often been focussed 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 (IPCC CZMS, 1990; BIJLSMA *et al.*, 1996; KLEIN *et al.*, 2001):

(a) **Protection** – decreasing the probability of occurrence to reduce the risk of an event via hard or soft engineering;

(b) **Accommodation –** increasing the ability of a society to cope with the effects of an event (e.g., insurance, early warning and evacuation systems, floodwise buildings);

(c) (Planned) **Retreat –** limiting the potential effects to reduce the risk of an event (i.e., moving people/infrastructure back from vulnerable coastal areas through development control, land use planning, and set-back zones).

Table 16 gives a list of potential physical impacts of sea-level rise and some examples of adaptation responses illustrating these three generic strategies.

Table 16: Major physical impacts and some examples of potential adaptation responses to sea-level rise, illustrating the Protect, Accommodate, and Retreat strategies.

Physical Impact of Sea-Level Rise		**Some Examples of Potential Adaptation Responses**
Direct inundation, flooding and storm damage	Strom Surge (sea)	▪ Dikes/surge barriers (P) ▪ Building codes/flood-wise buildings (A) ▪ Land use planning/hazard delineation (A/R)
	Back water effects (river)	
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/hazard delineation (A/R)
Note: Adaptation Responses are coded: (P) – Protection; (A) – Accommodation; and (R) – Retreat		

Source: NICHOLLS and TOL (2006); NICHOLLS (2007)

Given that we are considering developed areas with the LECZ, it is important to note that benefit-cost analyses suggest that it is economically rational to protect these areas against sea-level rise, even against a ‘worst-case’ sea-level of 2-m during the 21st Century (NICHOLLS *et al.*, 2008c; ANTHOFF *et al.*, 2010). While these analyses suggests widespread protection of developed areas, there are several factors which suggest the need to remain cautious about the amount and success of protection we might expect.

- Protection is underpinned by socio-economic scenarios which show significant economic growth: lower growth may reduce the capacity to protect.

- The benefit-cost approach implies perfect knowledge and a proactive approach to the protection. Historical experience shows that most protection has been a reaction to actual or near disaster. Hence, high rates of sea-level rise may cause more frequent coastal disasters, even if the ultimate response is better protection.

- Even if it is economically rational to protect, there are questions of who pays and who benefits? The diversion of investment from other uses could overwhelm the capacity of some coastal societies to protect (cf. FANKHAUSER and TOL, 2005). Hence, this suggests an urgency for international assistance to these countries.

- Coastal societies are often poorly adapted to today's climate and overcoming this adaptation deficit will require substantial additional investment (PARRY *et al*., 2009).

- The analyses assume that the pattern of coastal development persists and attracts future development. However, major disasters such as the landfall of hurricanes could trigger coastal abandonment, and hence have a profound influence on future choices concerning coastal protection as the pattern of coastal occupancy might change radically. A cycle of decline in some coastal areas is not inconceivable, especially in future worlds where capital is highly mobile and collective action is weaker. As the issue of sea-level rise is so widely known, disinvestment from coastal areas may even be triggered without disasters: for example, small islands may not attaract investment due to sea-level rise (cf. BARNETT and ADGER, 2003).

Hence, success or failure of protection remains one of the major uncertainties about the effects of sea-level rise, both in terms of direct and indirect effects (NICHOLLS and CAZENAVE, 2010). Estimates of the costs of adaptation are extremely limited. Several studies are available that have tried to estimate the cost of protection in coastal areas: most recently and comprehensively the World Bank assessment on the Economics of Adaptation to Climate Change (NICHOLLS *et al*., 2010b). A global protection cost of between US$28 and US$90 billion per year up to 2050 was estimated across a range of sea-level rise scenarios up to a 1.26m rise by 2100 (Figure 18). Table 17 illustrates the component costs of coastal adaptation that are considered and the regional distributions. The method considers port upgrade, beach nourishment, and sea and river dikes in coastal lowlands. Sea dikes dominate the costs under the assumptions used. The possible effect of increased tropical cyclones was considered via a sensitivity analysis assuming a 10% increase in extreme events, the effect on costs is relatively small compared to the high sea-level rise scenario (Table 18). Hence, more intense storms are may be less important than widely thought in an average annual sense.

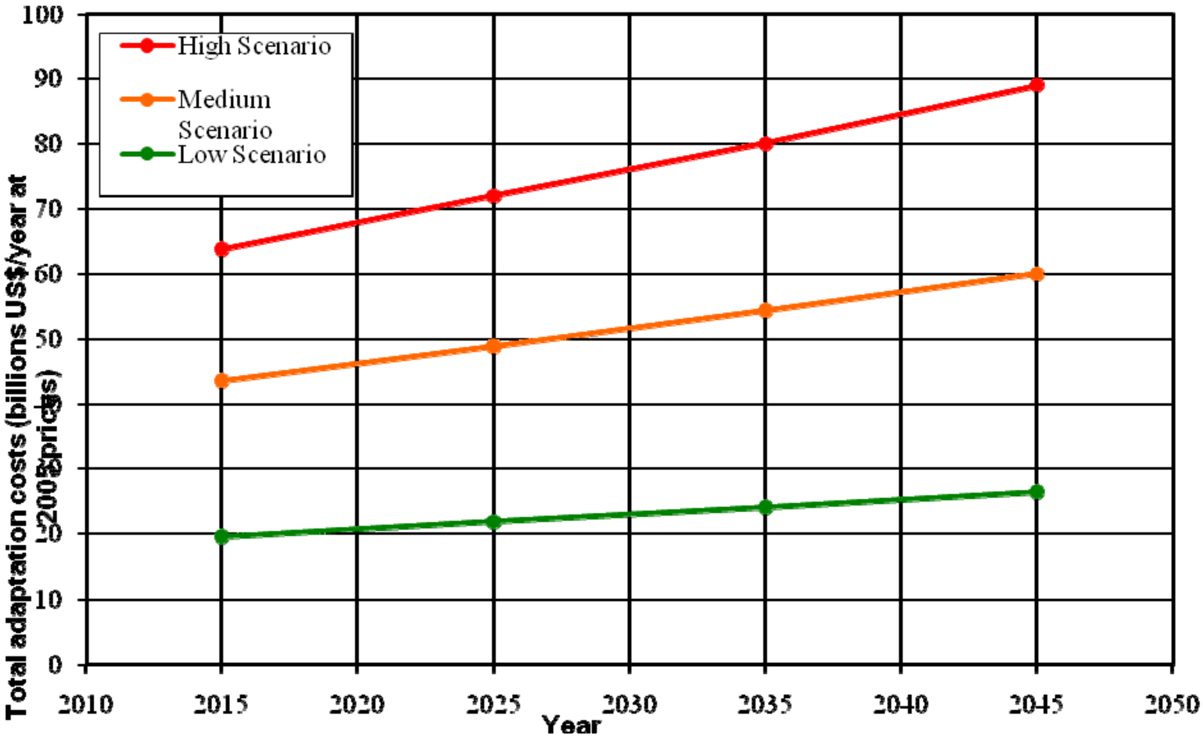

Figure 18: Global incremental adaptation costs for the high, medium and low sea-level rise scenarios corresponding to 126cm, 87cm, and 40cm rise by 2100 (NICHOLLS *et al*., 2010b).

Table 17: Incremental annual costs of adaptation for coastal protection by region and decade for the High SLR scenario (126cm rise by 2100) (US$ billion at 2005 prices, no discounting). High income countries are excluded.

		World Bank Regions												Total
		EAP		ECA		LAC		MNA		SA		SSA		
TOTAL ADAPTATION COSTS:														
Beach Nourishment	2010s	0.58		0.16		0.84		0.13		0.25		0.78		2.34
	2020s	0.77		0.25		1.17		0.19		0.33		1.07		3.28
	2030s	1.00		0.36		1.55		0.24		0.43		1.40		4.36
	2040s	1.34		0.50		2.09		0.31		0.58		1.87		5.89
Port Upgrades	2010s	0.24		0.08		0.05		0.05		0.03		0.03		0.49
	2020s	0.24		0.08		0.05		0.05		0.03		0.03		0.49
	2030s	0.24		0.08		0.05		0.05		0.03		0.03		0.49
	2040s	0.24		0.08		0.05		0.05		0.03		0.03		0.49
		CC	**MC**	**CC**	**MC**	**CC**	**MC**	**CC**	**MC**	**CC**	**MC**	**CC**	**MC**	
River Dikes	2010s	0.10	0.00	0.01	0.00	0.37	0.02	0.00	0.00	0.02	0.00	0.02	0.00	0.54
	2020s	0.10	0.01	0.01	0.00	0.38	0.04	0.00	0.00	0.02	0.00	0.03	0.00	0.59
	2030s	0.11	0.02	0.01	0.00	0.39	0.05	0.00	0.00	0.02	0.00	0.03	0.00	0.63
	2040s	0.11	0.02	0.01	0.00	0.40	0.07	0.00	0.00	0.02	0.00	0.03	0.01	0.67
Sea Dikes	2010s	9.52	0.86	3.06	0.28	10.4	0.94	1.17	0.11	1.83	0.17	3.58	0.32	32.2
	2020s	9.55	1.82	2.96	0.58	10.6	1.99	1.29	0.23	1.84	0.35	3.65	0.69	35.6
	2030s	9.58	2.78	2.94	0.87	10.7	3.06	1.25	0.36	1.85	0.53	3.73	1.06	38.7
	2040s	9.59	3.73	2.95	1.17	10.7	4.13	1.25	0.48	1.85	0.72	3.83	1.44	41.8
Note: 2010s=2010-19, 2120s=2020-29, 2030s=2030-39, and 2040s=2040-49; CC=Capital Cost, and MC=Maintenance Cost EAP-East Asia and Pacific, ECA-Europe and Central Asia, LAC-Latin America and Caribbean, MNA-Middle East and North Africa, SA-South Asia, SSA-Sub-Saharan Africa.														

Source: NICHOLLS *et al.*, 2010b.

Table 18: Increamental annual costs of adaptation for coastal zone protection and residual damage for the high sea-level rise scenario (i.e., 126cm rise by 2100) without and with cyclones (in US$ billion at 2005 prices, no discounting).

Coastal zone adaptation costs	High sea-level rise	High sea-level rise with cyclones[1]
Beach nourishment	4.5	4.5
River dikes	0.6	0.6
Sea dikes	36.7	39.1
Port upgrades	0.5	0.5
Residual damages[2]	2.0	2.0
Total	44.3	46.7

[1] A 10% increase in tropical cyclones over the 21st century is considered.
[2] Includes impacts remaining after adaptation, such as land loss, coastal flooding, and number of people flooded.

Source: EACC (2009) ; NICHOLLS *et al.* (2010b)

However, these costs assume a good existing infrastructure to upgrade, i.e. they are only incremental costs. 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). For coasts the ‘adaptation deficit’ has not been costed to date due to the lack of appropriate data. Hence, further assessments of coastal adaptation costs should receive priority.

This implies the need for more investments to meet the adaptation needs of today’s climate, before starting to think about future challenges. It is likely that for adaptation responses to be successful, the developed world, including the UK, will need to support these efforts with development aid.

7 Implications for the UK

This assessment has carried out an extensive analysis and review on the climatic and non-climatic stressors on the coastal zone over this century. This section synthesises the potential implications of the international dimensions of these drivers of change and their associated direct and indirect impacts on the UK. It is recognised that the indirect effects are poorly characterised, and yet these effects have the potential for key impacts and 'surprises'. Also, while negative threats dominate, opportunities are also apparent and considered later.

It is apparent that the question posed is multi-dimensional and impacts will be a function of the magnitude of climate change and sea-level rise, coastal development trends, and how successfully or not we adapt to climate and other drivers of change. Mitigation of climate change will reduce the magnitude of sea-level rise and climate change, but sea-level rise has a stronger commitment, and this emphasises the importance of adaptation both in this century and beyond (NICHOLLS *et al*., 2007). From the perspective of this assessment, the ideal future world would be one were climate impacts are minimised by a combination of climate mitigation and adaptation. For us to achieve this goal, there are important responsibilities for the developed world, including the UK. Further climate impacts cannot be reduced to zero, and residual risk always remains – comprehensive adaptation recognises this constraint and should address responses to defence failure, for example. In discussing the implications for the UK, we use a quadratic diagram that considers the magnitude of climate change as one axis, and the success or failure of adaptation as the other axis (Figure 19). This captures the two significant factors. The third factor of the level of development is a scale factor for the potential impacts and to a lesser degree the adaptation demands. It also represents an appropriate synthesis tool that reflects the current level of understanding of this complex problem, without overemphasising quantitative results that suggest more confidence than really exists.

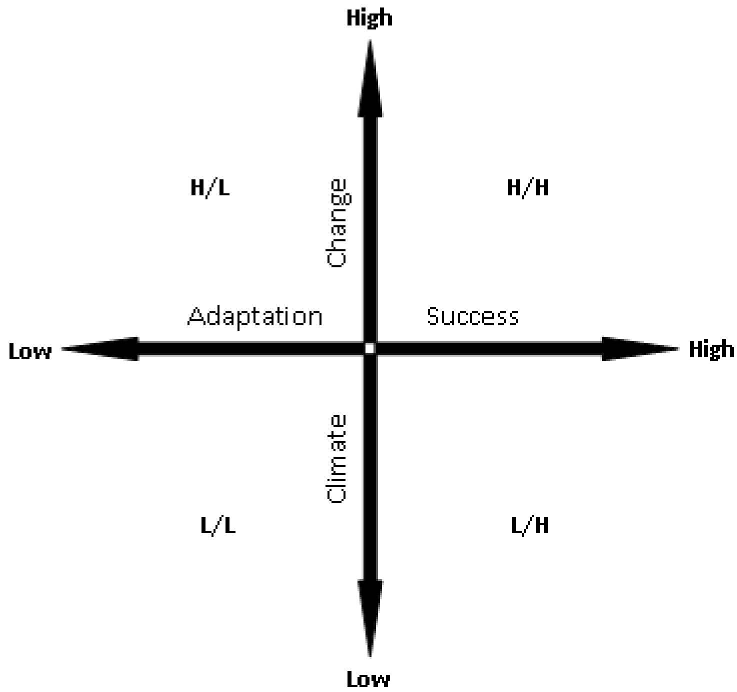

Figure 19: Synthesis of the potential impacts of climate change and benefits of adaptation over the 21st Century.

7.1 Potential Impacts/Threats

In terms of the effects of climate change, it is important to distinguish between temporary effects of ‘shocks’ and more permanent changes. More frequent coastal disasters is of concern due to both higher sea levels and possibly more intense storms and this is much more likely in the H/L and to a lesser degree in the L/L worlds (Figure 19). More disasters will lead to *repeated* temporary disruption to infrastructure delivery systems, e.g., disrupted imports, temporary increases in commodity prices, potential loss of imported raw materials, higher energy costs, etc. The case of Hurricane Katrina demonstrates a chain of impacts with cross-sectoral dimensions that caused major socio-economic damages in the coastal sector and beyond. While not a climate-based example, the effects of the recent volcanic ash cloud from Iceland in spring 2010 illustrates another example of unexpected disruption and economic costs. There are also potential direct impacts on foreign-coastal-based UK businesses and infrastructure, both from coastal disasters and more systematic changes. A scenario-based analysis of possible threats of this type to the UK would be a prudent ongoing government and business activity.

Failure of adaptation could trigger more long-term effects beyond temporary disruption and recovery. Scenarios of 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, could be expected. Wider security effects could emerge such as the undermining of governance in countries with significant coastal populations leading to conflict. This is most likely in the H/L world (Figure 19). The UK response would be to promote adaptation.

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 are seen as the cause of human-induced climate change. In many people's minds all disasters are now erroneously attributed to climate change. While this is scientifically flawed, perception is powerful and a succession of coastal disasters in the developing world could lead to serious implications. This again illustrates the benefits of the UK promoting adaptation to counter this perception. It would also link to the issue of the adaptation deficit which is essentially a development issue.

There are direct and indirect impacts on the UK finance, business and insurance industry. Coastal infrastructure will often be insured in the UK so coastal losses will fall on UK markets. This can be seen as a threat without appropriate research and development, but could be an opportunity if the risks are appropriately understood and costed (see Section 7.2). Again promoting adaptation and developing the H/H and L/H worlds would reduce the likelihood of these problems.

Potential impacts on the UK's overseas small island state territories is an important issue as small islands are repeatedly identified as highly vulnerable to sea-level rise and climate change (SEAR *et al*., 2001; MIMURA *et al*., 2007; NICHOLLS *et al*., 2007). The relevant territories are St Helena, Tristan da Cunha, Pitcairn Island, and Eastern Caribbean (which includes Montserrat, Turks and Caicos Islands and Anguilla) (see Box 2 for more detail). There is a need to explore the adaptation options as in some cases these islands may have limited options.

Box 2: Implications of Climate Change and Sea-Level Rise on Small Islands: UK's Overseas Small Island Territories.

The UK has fourteen Overseas Territories, of which eleven are small island territories[1] (see Figure below). Climate change means more than just a change in the weather for small islands everywhere. Many studies have outlined that, while the residents of small islands are not responsible for the causes of climate change, they are likely to be the first to experience the worst effects of climate change, most especially low-lying coral atolls (SEAR *et al*., 2001; TOMPKINS *et al*., 2005; MIMURA *et al*., 2007; NICHOLLS *et al*., 2007).

Small islands represent one of the key hotspots of societal and natural system vulnerability to climate change, and could potentially lose significant parts of their land area with a sea-level rise of 0.5 to 1m (BIJLSMA *et al*., 1996; MIMURA *et al*., 2007). Even on high islands, infrastructure is concentrated around the periphery, and hence they are disproportionately vulnerable to sea-level rise. Many small islands worldwide are already at risk from many environmental hazards. Sea-level rise and possible changes in the frequency and/or intensity of extreme weather events, such as extreme temperature and precipitation, tropical cyclones, storm surges, and coastal, river and rain-induced flooding constitute the components of climate change that are of most concern.

Hence, the UK small island territories represent a vulnerable collection of territories which could experience the potential threats of the changing climate. Sea-level rise will pose significant pressure on the important natural resource systems, coastal resources and environments, and water resources in most, if not all, of the UK's Overseas Territories. MCWILLIAMS (2009) details the potential implications of climate change on biodiversity. Coral reefs represent the most important coastal system components that are significantly threatened, which by implication could present severe adverse consequences as a result of the partial or total removal of coral protection and buffering that coral reefs provide (SEAR *et al*., 2001). The potential loss of protection to mangroves, sea grasses and other coastal ecosystems will lead to further loss of ecological habitats and coastal erosion problems. Additional stresses include sea surface temperature rise, ocean acidification, pollution, etc. Collectively, these would threaten the wellbeing of the natural and human systems on most of the small islands.

Moreover, due to their remoteness and high vulnerability – potential impacts of sea-level rise and more intense storms damages on infrastructure such as ports and harbours and airport structures and facilities could potentially result in certain islands being cut off communication completely. Further impact and adaptation studies building on earlier assessments such as SEAR *et al*., (2001) should be considered.

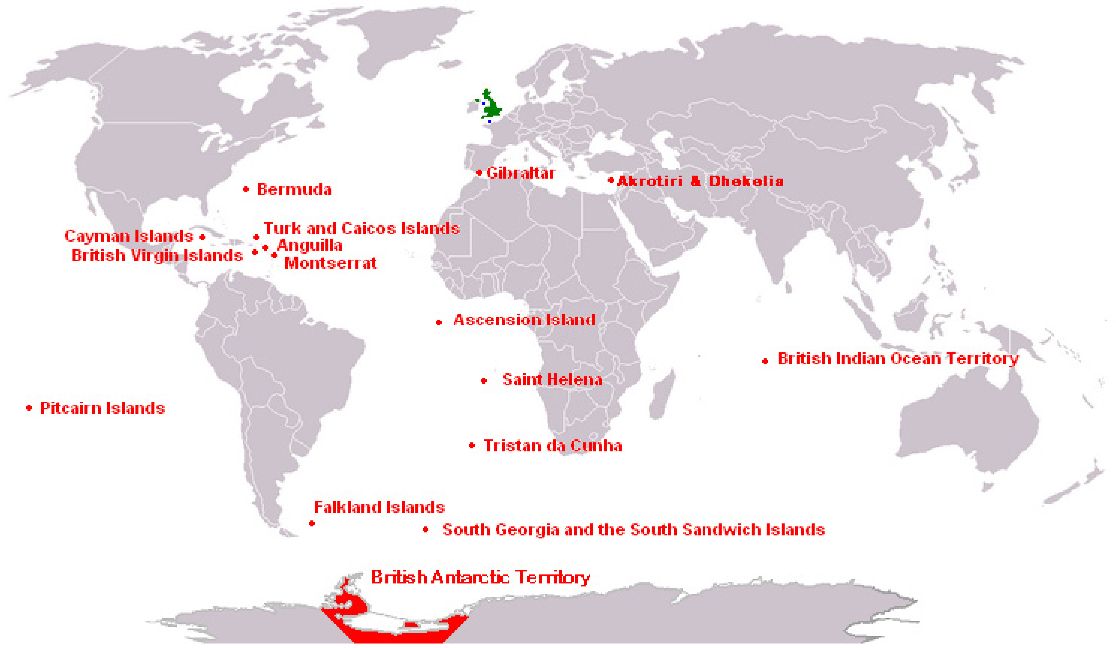

Figure1-Box2: The UK's Overseas Territories

[1] Ascension Island, Saint Helena, and Tristan da Cunha are treated as one group of islands.

7.2 Benefits/Opportunities

As well as threats, there are some potential benefits which have been touch on in Section 7.1. A major opportunity is for UK industry and commerce engaged in the coastal engineering and management imposed in the H/H and L/H worlds (Figure 19). The UK (together with the Netherlands) is world-leading in long-term strategic planning of coastal areas, as exemplified by the Shoreline Management Planning Approach which has been adopted more widely in initiatives such as EUROSION (2004) and the Thames Estuary 2100 Project (ENVIRONMENT AGENCY, 2009). As an example, Halcrow have been working on the coastal management and engineering in Louisiana since Hurricane Katrina. This is an opportunity that the UK government could strategically promote, working with the coastal engineering and management industry. It is noteworthy that the Dutch government have promoted Dutch expertise in coastal adaptation for the last 20 years or so, including hosting the World Coastal Conference (WCC'93, 1994), and most recently by the forthcoming ‘Deltas in Times of Climate Change’ in September 2010. The UK government could similarly promote UK expertise.

The hazard modelling and assessment community within the insurance sector is also well developed in the UK. This expertise will be important to maintain a sound insurance industry under a changing climate, and will also present opportunities in existing markets such as North America and emerging markets such as Asia.

National prestige was mentioned as a threat in Section 7.1. However, there is also an opportunity for Britain to gain from its strong stand on climate change. Efforts towards mitigation clearly show a country committed to respond to this issue. The commitment to sea-level rise means that for the LECZ, the benefits of this strategy are less than in other areas. This emphasises that complimentary efforts towards promoting adaptation could have substantial benefits for the UK, as well as globally.

Lastly, while it is unlikely to be a large effect in this century, tourist destinations could shift to the UK’s (and neighbouring European areas) benefit. This would mean less UK residents going overseas, and more international tourists visiting England with coastal tourism in mind. There may also be a threat, which would be the increasing demand for coastal infrastructure on the UK coast.

7.3 Summary

Table 19 summarises the potential direct and indirect impacts of the international dimensions of climate change on the UK.

Table 19: Summary of the potential physical impacts of sea-level rise, and the direct and indirect implications on the UK.

Physical Impacts of Sea-level Rise	Damages and Costs Elsewhere	Global Implications	Implications on the UK	
			Direct	Indirect
Direct inundation	Landward displacement of people; disruption of coastal services and infrastructures; impact on agriculture; declining coastal water quality; coastal morphological changes.	Impacts on coastal infrastructure; migration of people to urban areas; decline in agricultural production; temporary disruption in import/export--transportation; impact on tourism.	Disruptions on foreign-coastal-based UK infrastructure, business and services; migration pressure; higher prices on imported agricultural products; temporary lack of supply of resources and services; direct impact on UK overseas small island territories.	National economic impact and high living costs for UK citizens; pressure on resources and services; and associated health issues—such as transmitted diseases through migrants.
Flooding	Increasing flood risk; potential loss of life; population displacement; damage to infrastructure; loss of renewable and subsistence resources; impacts on tourism, recreation and	Damages to infrastructure (tourism, energy, transportation); loss of life; forced migration to urban areas and to wealthier countries; conflict over resources; global security issues and	Damages to foreign-coastal-based UK citizens, infrastructure and businesses; supply disruption and increased prices in imported resources (e.g., energy); Migration pressure; security	Impact on the UK business and finance sector; general impact on the economy; pressure on resources; global security issue also affecting the UK; cross-sectoral impacts (e.g., impacts on energy sector

Physical Impacts of Sea-level Rise	Damages and Costs Elsewhere	Global Implications	Implications on the UK	
			Direct	Indirect
	transportation functions; resource contamination.	increase in unstable states; impact on global economy; increase in global emergency and humanitarian aid; increased prices on goods and commodities; human health issues.	problems; direct impacts on British tourists/business travels; direct impact on UK overseas small island territories.	affecting other sectors); loss of investment in international development aid.
Storms and extreme water levels	Direct damages to coastal defence and protection works and other key coastal infrastructure; impacts on coastal morphology; more flooding risks and coastal erosion.	Flooding of people and infrastructure; more frequent disruptions of services; loss of life; coastal change impacts.	Direct impact on UK-owned foreign-coastal-based infrastructure and business; direct impact on UK overseas small island territories.	Political and cost implications of impacts on energy sector; international development aid.
Wetland loss (and changes)	Reduced CO_2 capture capacity; direct loss of ecological values; impact on fisheries; loss of recreational areas; loss of protection.	Contribution to climate change; impacts on communities' livelihood who depend on its resources; global change in fish prices; increased flood risk.	Migration; higher fish prices to UK consumers; direct impact on UK overseas small island territories.	Direct impact on UK citizens residing in those overseas states.
Coastal erosion	Land area loss (e.g.,	Pressure on tourism and	Need for international	Indirect impacts on

Physical Impacts of Sea-level Rise	Damages and Costs Elsewhere	Global Implications	Implications on the UK	
			Direct	Indirect
	beaches/dunes); increase vulnerability to flooding and storms; infrastructure damages; loss of non-monetary cultural values and resources; impact on tourism, recreation, and transportation functions.	leisure industry; energy sector; transportation sector; conflict over spaces.	development assistance; inland or back-to-UK displacement of foreign-coastal-based UK infrastructure and businesses; impacts on British tourists; direct impact on UK overseas small island territories.	the UK business and finance sector; general economic impact.
Saltwater intrusion	Direct food and water contamination; impact on fresh water resources; impacts on agriculture, forestry and aquaculture through decline in soil and water quality.	Public health problems; conflict over resources (such as freshwater); migration.	Direct impact on UK-owned coastal infrastructure and assets; Migration pressure; need for international development assistance;	General impact on the UK economy; impact on finance and businesses sectors.
Rising water tables	Drainage problems and increased flood risks; freshwater contaminations.	Community and infrastructure flooding; pressure on coastal water supplies; pollution and human health problems.	Direct impacts on UK-owned infrastructure and business.	General impacts on UK economy.

8 Conclusions

Climate change and sea-level rise will pose significant direct consequences on Low Elevation Coastal Zones (LECZ) around the world. Due to the growing international interdependence such as economic, social, and cultural integration (e.g., increasing seaborne trade and people's movement), potential impacts in one country or region could be transferred to, and felt by other countries or regions worldwide, including the UK. These could potentially present negative (or perhaps positive) effects to other countries in different ways. However, prior to this study, the international dimensions of climate change on coastal areas on a developed nation such as the UK have been relatively unstudied.

This analysis shows that the LECZ concentrates people, economic activity and resulting infrastructure, so the impacts of climate change and sea-level rise could be large, especially if the magnitude of these changes is large. This will be exacerbated by coastal development, which is a profound trend that is likely to continue through the century. However, effective coastal adaptation could minimise the impacts. Hence, assessing the future problems and opportunities depends on several distinct dimensions of change as outlined above. Hence a more qualitative approach was adopted for the assessment, which identifies both threats and opportunities for the UK.

The potential threats that were identified include:

- Disruption of supply chains by more frequent coastal disasters such as occurred to the global oil supply after Hurricane Katrina in 2005;
- Security threats due to forced population movements possibly leading to significant numbers of refugees and migrants and broader security issues in important parts of the world;
- A decline in UK prestige, as the UK and the wider developed world is erroneously blamed for all coastal disasters which are increasingly seen as a product of human-induced climate change rather than climate variability;

- Direct and indirect impacts on the UK finance, business and insurance industry;
- Potential impacts on the UK's small island overseas territories.

Potential opportunities that were identified include:

- Export of world-leading UK coastal engineering and management expertise and to a lesser extent UK coastal hazard modelling and assessment expertise within the insurance industry;
- Benefits to national prestige if the UK can gain credit for its strong position on responding to climate change, especially if we strengthen the adaptation dimension which is critical for coastal areas;
- Possible growth in UK coastal tourism.

The major control that we have on these threats and opportunities is the success or failure of adaptation. This is poorly understood with some taking an optimistic and bullish view that adaptation will make sea-level rise and climate change a non-problem and others being rather pessimistic about its prospects. The UK government can certainly promote coastal adaptation both to avoid the threats identified above and exploit the potential opportunities, and this could reinforce wider development and sustainability goals.

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Appendices

Appendix A: Material and Methods: Coastal Infrastructure

In this analysis, coastal infrastructure is considered as infrastructure located within the coastal zone. For the purpose of this study, infrastructure within 10m of mean sea level (the Low Elevation Coastal Zone, LECZ) is considered as coastal following McGranahan *et al*. (2007).

The following global coastal infrastructure are investigated: (1) coastal cities, (2) ports and harbours, (3) critical infrastructure (e.g., oil refineries, nuclear power stations), and (4) other infrastructure such as transportation (e.g., Airports).

A GIS-based analysis is performed using ArcMAP based on the geographic locations of the infrastructure and the GTOP30 Digital Elevation Model (30 Arc Seconds – approximately 1km resolution, developed by the U.S. Geologic Survey or USGS).

Steps:

1. GIS-compatible infrastructure data – including geographic locations and other information (such as associated population for cities) have been obtained from different available sources (see below).

2. Using ArcGIS and based on the DEM (i.e., GTOP30) – a shape file is extracted at selected elevation bands – including the 10m margin (the LECZ),

3. Overlaying the point feature shape files of the infrastructure on the LECZ shape file allows identifying the infrastructure distribution based on the elevation classes, and extracting those within the LECZ.

Limitations:

While there is a high uncertainty, this assessment is intended to highlight the global coastal infrastructure that are likely to experience the potential threats due to sea-level rise impacts in coastal areas, and could be of major concern.

Note that the dataset on the global coastal infrastructure considered in the analysis are based on possible publicly available sources, and inconsistencies of the dataset associated with the varying sources and their reliability raises uncertainty issues and are worth noting. For instance, as often the issues of critical energy infrastructure are rather sensitive national security in many countries the figures used here might not fully represent the actual global total, due to the lack of available information regarding some of these infrastructure.

Moreover, the scale, coarser resolution and the poor quality of the elevation data especially at the land-water boundary play a major role on the uncertainty of the results. Use of finer resolution and good quality dataset could give different and better results than reported here.

Data Sources:

The following list provides the data sources used in the analysis for each infrastructure considered:

Elevation Data and Cities:

ESRI Data & Maps 9.3 [DVD], (2008). Redlands, CA: Environmental Systems Research Institute.

World's Ports:

Lloyd's List Ports of the World (2009)

Nuclear Power Stations:

Global Change Mater Directory: *http://gcmd.nasa.gov/records/GCMD_GNV181.html* (last accessed on 18 May 2010)

Oil Refineries:

Source: *http://finder.geocommons.com/* (Last accessed on 18 May 2010)

Airports:

Pacific Disaster Centre – Global Airports: *http://www.pdc.org/mde/full_metadata.jsp?docId=%7B8454B00A-4A8C-4E2F-AD83-64F5051B022C%7D&loggedIn=false* (Last accessed on 18 May 2010)