

CGE Training Materials  
for Vulnerability and Adaptation  
Assessment

Chapter 5  
Coastal Resources

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## 5.1. Introduction

Coastal areas concentrate people, economic activity and natural resources (Nicholls et al., 2007; Wong et al., 2014; USAID, 2015). More than 600 million people live below the 10-metre contour, there are 136 coastal cities with major ports, and there are major agricultural areas in deltas. With a net population movement towards coastal areas, coastal populations are growing more rapidly than global populations. Hence, the exposure to present coastal hazards is growing significantly, and this will be exacerbated by sea level rise and climate change. Assessing these growing risks provides a basis for preparing for them and for ensuring that coastal societies adapt in an appropriate manner.

A global sea level rise due to climate change will have a wide range of physical and ecological effects on coastal systems, including inundation, flood and storm damage, loss of wetlands, erosion, saltwater intrusion and rising water tables. Other effects of climate change, such as higher sea water temperatures, changes in precipitation patterns and changes in storm tracks, frequency and intensity, will also affect coastal systems, both directly and through interactions with sea level rise. Rising sea surface temperatures (SSTs) are likely to cause the migration of coastal species towards higher latitudes and increased coral bleaching. Changes in precipitation and storm patterns are less certain and will influence the risks of flooding and storm damage. The consequences of ocean acidification are adverse for many ecosystems, but more precise details remain uncertain.

Assessments of the vulnerability of coastal resources to the impacts of climate change can usefully distinguish between 'natural system vulnerability' and 'socioeconomic system vulnerability' (Klein and Nicholls, 1999). The analysis of socioeconomic vulnerability to sea level rise requires a prior understanding of how the natural system will be affected, and hence, assessments usually start with the natural system response. In existing studies, there is often a strong focus on sea level rise impacts. Although sea level rise is a major driver, other climatic and non-climatic stresses should be considered within a vulnerability and adaptation (V&A) assessment, as appropriate.

Adaptation to climate variability and other hazards is already widespread in coastal areas. Building on this, further adaptation to climate change and sea level rise will be essential for coastal areas during the twenty-first century and beyond, as appropriate. This will include consideration of rising mean sea level and extreme sea levels. Given the already large and rapidly growing population and economy within the coastal zone, autonomous adaptation alone will not be able to cope with the impacts of sea level rise (Moser, Williams and Boesch, 2012; Nicholls, 2014). Therefore, all levels of government have a fundamental role in developing and facilitating appropriate planned adaptation responses (Tribbia and Moser, 2008).

This chapter is structured as follows:

- Section 5.2 presents methods and approaches to assess these impacts, including a structured approach to V&A (vulnerability and adaptation) assessment based on (1) screening assessment, (2) more detailed impact assessment and (3) final assessment plan that links to wider coastal management;
- Sections 5.3 and 5.4 discuss tools and data, respectively;

- Section 5.5 discusses adaptation assessment and integration;
- References and recommended further reading are then provided with several appendices;
- Appendix 5-1 considers the drivers of coastal change, including climate and non-climate factors;
- Appendix 5-2 summarizes the biogeophysical and socioeconomic consequences of climate change on coastal resources;
- Appendix 5-3 describes different adaptations for coastal areas and resources.

Other chapters in the training materials contain important information for conducting assessments of climate change V&A. In particular:

- Chapter 2 discusses V&A frameworks;
- Chapter 3 addresses baseline socioeconomic changes. As noted in this chapter, coastal resources can change substantially over coming decades due to these causes;
- Chapter 4 reviews climate change scenarios. Climate change scenarios can drive estimated impacts and adaptations;
- Chapters 6, 7 and 8 consider water resources, agriculture and human health, respectively. There will be important interactions between coastal resources and all of these sectors;
- Chapter 9 discusses integration across sectors as well as adaptation, mainstreaming and monitoring and evaluation;
- Chapter 10 considers communication of V&A assessment in national communications.

## 5.2. Methods and approaches

### 5.2.1. General considerations

Given the wide range of possible impacts of climate change on coastal areas, there are numerous methods and expertise that can be employed, including three broad areas of knowledge that might be required (see Appendix 5.2): (1) coastal morphodynamics (i.e., understanding erosion/accretion); (2) coastal flood and inundation; and (3) groundwater hydrology (surface and groundwater salinization). Taking into consideration habitat and ecosystem changes may also be important, such as in reef or wetland environments. Various approaches to analyse the changes of coastlines due to climate change (and sea level rise in particular) are summarized by Klein and Nicholls (1999), Abuodha and Woodroffe (2006), Ramieri et al. (2011) and others. As climate change will impact the entire coastal area, the spatial scale of assessment should be broad (e.g., entire islands, sub cells and/or cells, large cities and environments and nations).

Three levels of assessment with different goals and levels of effort are distinguished, as shown in Table 5-1. Examples are given in Box 5-1.

Table 5-1  
**Levels of assessment for coastal vulnerability and adaptation assessments for sea level rise and climate change**

Level of assessment	Timescale required	Precision	Prior knowledge	Issues considered
Screening Assessment (initial issue scoping)	2–3 months	Lowest	Low	Define the key issues and directions of change in broad qualitative or semi-quantitative terms. Strong focus on sea level rise.
Impact Assessment (initial impact and adaptation assessment)	1–2 years	Medium	Medium	Building on the screening assessment, impacts are quantified, including the possible role of other climate change and non-climate drivers. Adaptive capacity should be considered.
Planning Assessment (linking to wider coastal management)	Ongoing (part of an adaptation process)	Highest	High	Building on the impact assessment, more comprehensive assessments are conducted, considering all relevant drivers (using multiple scenarios to explore uncertainty). Adaptation (see section 5.5) is an integral part of the assessment.

Source: Adapted from Klein and Nicholls, 1999.

Box 5-1

**Examples of coastal resource analysis in developing countries**

Appening Addo (2013) applied a screening assessment to Accra, Ghana, based on a coastal vulnerability approach and a major focus on erosion (Section 5.2.2). This study used a coastal vulnerability index (CVI) approach (Section 5.2.5 and Box 5.2). The coastline of Accra was divided into three distinct longshore sections based on the distinct geomorphology. The vulnerability index was estimated for each of these sections by analysing their relative risk factors to sea level rise and calculating the CVI. Overall, the analysis suggested that the risks are moderate. More insightfully, the relative spatial vulnerability within Accra was assessed, with the western section being most vulnerable to sea level rise, and the central section being least vulnerable. Threats to local populations and important wetlands were recognized in the western section. Important non-climate drivers were also apparent, such as beach mining (removal of beach materials for use in construction activities). This screening assessment provides a solid basis for further, more detailed analysis.

Box 5-1 (cont.)

**Examples of coastal resource analysis in developing countries**

A different approach to screening assessment has been applied in Mombasa and Dar es Salam, where global datasets were used to map and analyse each city and provide a first assessment of the issues raised by sea level rise (Kebede et al., 2010; Kebede and Nicholls, 2012). These studies used easily available, often global, datasets to conduct a first assessment of these two cities under sea level rise. Geographic information system (GIS) approaches were used to combine datasets and examine future issues, including elevation datasets with other information. On the other hand, existing defences were not considered to be effective, which appeared to be a reasonable assumption. A key feature in both cases was that the cities are expected to continue to experience rapid growth, so the future impacts of present extreme events can only increase. Sea level rise and changes to storm surges are components of climate change that have the potential to further increase the threats of flooding within both cities. In Mombasa, the exposure to a 1:100 year extreme water level is estimated to be 190,000 people and amounting to assets of 470 million United States Dollars (USD). More than half of this exposure is concentrated in the Mombasa Island division of the city, where about 117,000 people (2005 estimate) live below the 10-m elevation. By 2080, exposure could grow to over 380,000 people and 15 billion USD in assets, assuming the Special Report on Emissions Scenarios (SRES) A1B sea level and socioeconomic scenario (Nakicenovic et al., 2000). About 8% of Dar es Salaam is below the 10-m elevation. Over 30,000 people (2005 estimate) may be exposed to a 1:100 year event, rising to 200,000 people by 2070 under the same climate scenario. Assets that could be damaged resulting from such an event are also estimated to rise from 35 million USD (2005) to 9 billion USD (2070). In both cases, future exposure is more sensitive to socioeconomic than climate scenarios. Moreover, there is significant scope within the city limits in both cases to steer future development to areas that are not threatened by sea level rise. Hence, forward planning to focus population and asset growth in less-vulnerable areas could be an important part of a strategic response to sea level rise, if local governance can deliver on such policies. These screening assessments lay a foundation for future analysis.

Bangladesh has been recognized as highly vulnerable to sea level rise since the 1980s in a range of screening assessment studies (e.g., Milliman, Broadus and Gable, 1989; Warrick, Barrow and Wigley, 1993; Huq, Ali and Rahman, 1995). These studies identified that huge areas of land and large populations were threatened by sea level rise and raised the spectre of large numbers of environmental refugees due to sea level rise in Bangladesh and other populated deltas worldwide. In these studies, sea level rise, flooding and inundation were the main hazards considered. Subsequent impact assessments (Section 5.2.3) considered a wider range of possible climate change drivers and resulting hazards, including important issues such as salinization, and recognized the complexity of the region, such as the presence of a series of polders in coastal Bangladesh (e.g., Warrick and Ahmad, 1996; Ali, 1999; Karim and Mimura, 2008). These studies also increasingly addressed the issue of adaptation and a move to planning assessments (Section 5.2.4).



Box 5-1 (cont.)

**Examples of coastal resource analysis in developing countries**

There have been a number of studies linked to government or intergovernmental institutions such as the Government of Bangladesh (1994) and the World Bank (Dasgupta et al., 2014a, 2014b). There is an increased focus on national adaptation planning and the development of practical tools for coastal management that address climate change and other drivers in the context of development. A Bangladesh Delta Plan is being developed (see <<http://bangladeshembassy.nl/bangladesh-delta-plan-2100/>>) which is a Bangladesh version of the Dutch delta plan (Delta Commission, 2008), while other projects are developing integrated tools to support such management (e.g., Nicholls et al., 2013b; Lazar et al., 2015).

1. Who are the targeted end users of the results of the assessment (informing the level of technical detail required, the methods for the treatment of uncertainties, and the format for presenting results)?
2. What kind of output/information is expected from the assessment (i.e., public awareness materials such as climate scenarios and their potential impacts, key vulnerabilities such as risk/vulnerability maps, an adaptation strategy for a geographic area or sector)?
3. What resources are available to conduct the assessment (human and financial)?
4. How much time is available to conduct the assessment?

These questions set the basis for determining the type of assessment and consequently the tools and data requirements to perform the assessment.

It is important to design the assessment, including defining a scope and using precise questions. The methods used to answer these questions will need to be developed into a method that will require various tools and data. It is important to note that no single tool can answer all the questions/issues likely to be raised. Hence, users need to think how to link different tools and data to address their needs. Examination of earlier studies may be helpful in this regard.

The aim of screening assessments and impact assessments is to focus attention on critical issues concerning the coastal zone to assist with broad-scale prioritization of concerns and to target future studies, rather than to provide detailed predictions. These activities may link strongly to the development of material for the United Nations Framework Convention on Climate Change (UNFCCC) national communications.

Planning assessments seek to develop more detailed assessments of possible impacts and adaptation responses to sea level rise and climate change and initiate adaptation planning. Hence, such assessments are best embedded within operational or strategic coastal management and planning (IPCC, 1994; Kay and Alder, 2005; USAID, 2009). Planning assessments should be embedded within broader coastal management frameworks and activities which seek to integrate responses to all existing and potential problems of the coastal zone, including minimizing the vulnerability to long-term effects of climate change. While an individual assessment will be time delimited, the process within which planning assessment sits should be ongoing.

In determining the appropriate approach to use to assess the likely impacts of climate change on the coastal zone, a number of questions should be considered (see also Lu, 2008), including:

- What is the goal of the assessment and what issues should be assessed?
- What previous studies can inform the proposed assessment (these will include national communications and coastal management assessments, including assessments of present coastal hazards and issues)?

### 5.2.2. Screening assessment

A screening assessment can initially be qualitative and can be followed up by a semi-quantitative assessment. This level of assessment generally focuses on three major impacts of sea level rise on the coastal zone as a starting point: (1) inundation/flooding, (2) erosion and (3) salinization. However, other issues can be added based on local conditions/concerns as appropriate. The resulting socioeconomic issues and impacts in the study area can be assessed using the matrix shown in Table 5-2. The headings can be reviewed and defined, and then qualitative scores can be assigned to each cell on a scale from 1 to 10, or high/medium/low impact, and so on.

Table 5-2  
Screening assessment impact matrix

Biophysical impacts	Socioeconomic impacts								
	Tourism	Human settlements	Agriculture	Water supply	Fisheries	Financial services	Human health	Gender	Others
Inundation									
Erosion									
Flooding									

Biophysical impacts	Socioeconomic impacts								
	Tourism	Human settlements	Agriculture	Water supply	Fisheries	Financial services	Human health	Gender	Others
Salinization									
Other Impacts									

It should also be possible to identify any major contemporary non-climate problems and issues, such as beach mining and coastal development, or the effects of major interventions such as ports/harbours. Similarly, the role of other potential climate change factors can be reviewed and assessed, if appropriate. These can also be prioritized in a similar manner to sea level rise impacts. All this information will inform into a comprehensive assessments (see Table 5-1).

When considering sea level rise impacts in more detail, inundation and flooding can be assessed based on knowledge of land elevation versus mean and extreme sea level. Flood characteristics of a cliff coast versus a deltaic coast are clearly distinct. Similarly, for erosion, simple approaches can be used to get a feel for the scale of potential problems. A commonly applied rule to approximate the cross-shore erosion of sandy shorelines in response to sea level rise is the 'Bruun Rule' (Bruun, 1962). For a screening assessment, Nicholls (1998) showed that the Bruun Rule can be simplified as:

$$R = 100x S$$

Where:

R is the recession of the shoreline  
S is the rise in relative sea level

This is an approximate 'rule of thumb' for potential coastal erosion due to sea level rise in a rapid analysis. More comprehensive treatments of erosion are recommended for impact and planning assessments (see the discussion of erosion in Wong et al., 2014; Cooper and Pilkey, 2004; and Ranasinghe, Callaghan and Stive, 2012). Salinization is more difficult to assess and drawing on contemporary problems may be most useful. For example, areas that experience seasonal salinization today, such as coastal Bangladesh, will see enhanced salinization given relative sea level rise.

### 5.2.3. Impact assessment

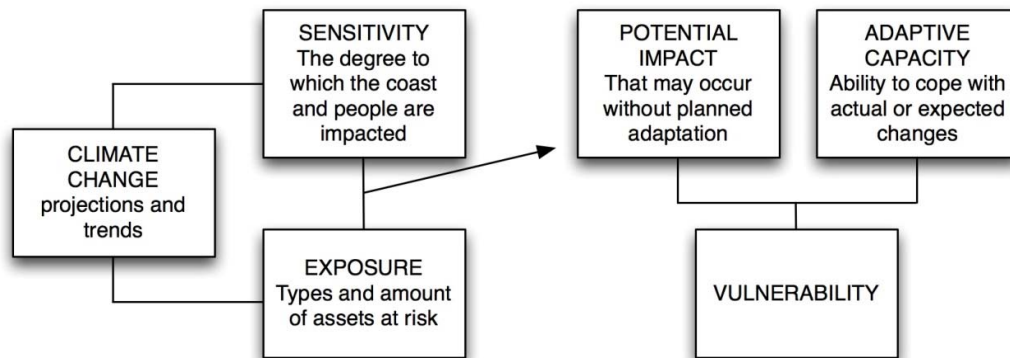
The results of the screening assessment identify the issues that require more detailed investigation, including the potential for impacts, the adaptive capacity and estimates of the resulting vulnerability. A report from the United States Agency for International Development (USAID) (USAID, 2009) outlines the following steps in a coastal vulnerability assessment, which are appropriate for an impact level of assessment, as defined in this guidance:

1. Assess climate change projections;

2. Assess exposure to climate change;
3. Assess sensitivity to climate change;
4. Assess health of coastal habitats and ecosystems;
5. Assess adaptive capacity.

Assessing a coastal area’s vulnerability to the impacts of climate change involves understanding: (1) the possible magnitude of climate change and sea level rise for a given region or locale; (2) what is at risk (climate change exposure and sensitivity); and (3) the capacity of society to cope with the expected or actual climate changes (adaptive capacity). Combined, these three factors define the vulnerability of people in a coastal location to climate change and sea level rise (see Figure 5-1). Note that all three components receive similar emphasis.

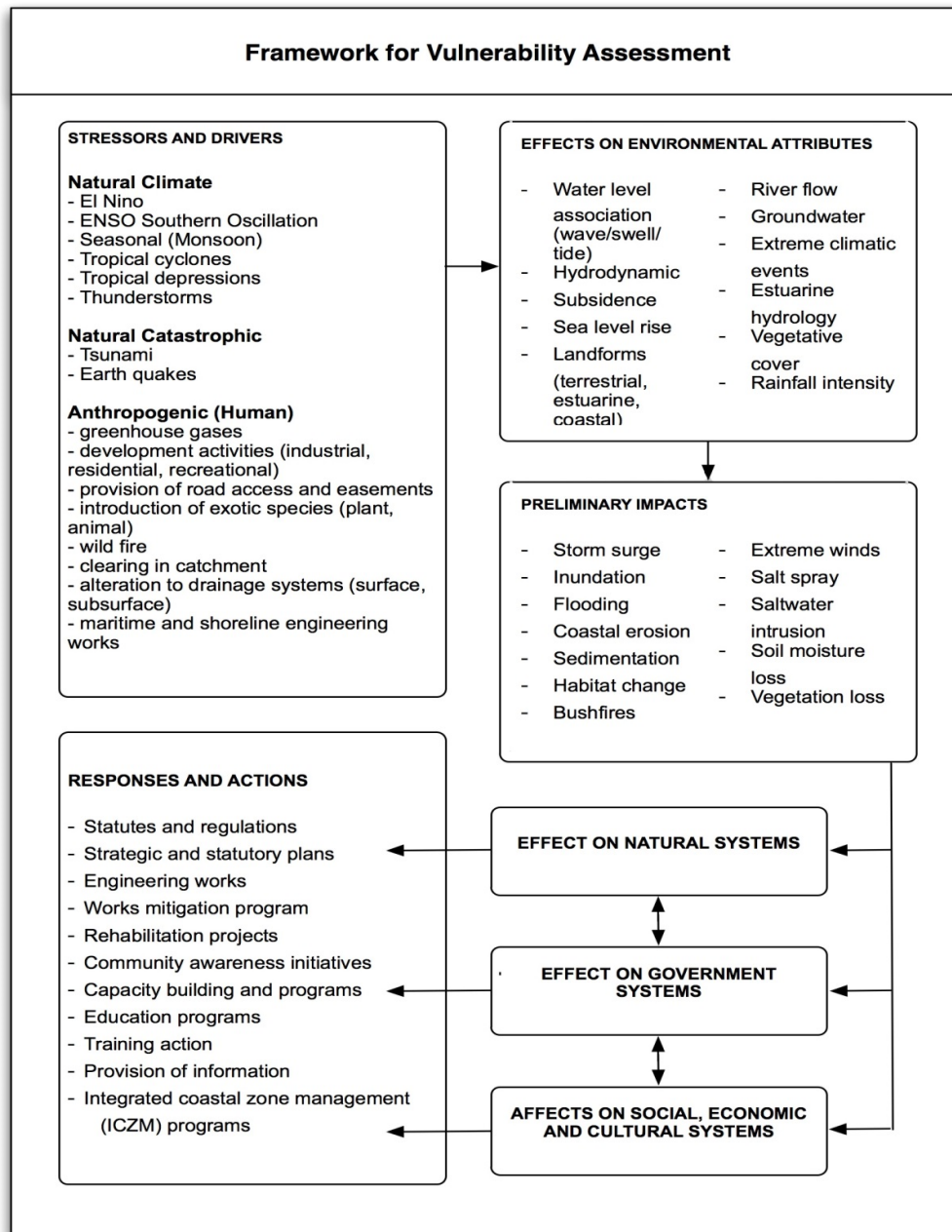
Figure 5-1  
**USAID coastal vulnerability assessment framework, which is appropriate for an impact assessment**



USAID: United States Agency for International Development.  
 Source: USAID, 2009.

Figure 5-2 shows how a vulnerability assessment can be put into action. First, the analysis distinguishes between the vulnerabilities to climate change of both the natural system and the socioeconomic system, even though they are clearly related and interdependent. Second, the analysis of socioeconomic vulnerability to sea level rise requires a prior understanding of how the natural system will be affected. Hence, the analysis of coastal vulnerability always starts with the natural system response. Note that other climatic and non-climatic stresses are acknowledged, indicating that climate change and sea level rise are not occurring independently from other processes and that the coastal system will evolve due to factors other than sea level rise and climate change. This helps to place climate change and sea level rise in an appropriate perspective, relative to non-climate drivers of change. Lastly, there is a preliminary consideration of responses and actions that will be necessary to adapt to climate change and sea level rise.

Figure 5-2  
 Example of a framework for impact assessment applied to a specific (Australian) setting



Note: This framework should be amended to reflect the study site conditions.

Source: Kay et al., 2006.

### 5.2.4. Planning assessment

Impact assessment identifies major potential impacts, challenges, vulnerabilities and preliminary ideas on responses, whereas planning assessment is required to explore

and understand what options are available to address these factors. The aim is to consider the realistic adaptation responses to sea level rise and other climate change drivers in the coastal zone to minimize future vulnerability and often to aid in formulating future policy or in determining detailed land use. A planning assessment is part of an ongoing investigation of a specific area. Assessing the future impacts of sea level rise and climate change on the coastal zone requires the understanding of major coastal processes in the study areas, such as the coastal sediment budget. The assessment must also consider other climate change impacts, such as changing storm frequency, intensity and direction, as well as non-climate drivers. These issues will be influenced by the scope of the planning assessment.

There are not many examples of planning assessments that address climate change, however the examples that do exist are mainly found in the developed world. At the regional scale, the Tyndall Coastal Simulator provides an important example for the northeast Norfolk coast of the United Kingdom of Great Britain and Northern Ireland. With this coast's long history of erosion and major coastal floods, there were important questions about how to manage the coast in the long term, including the issue of climate change. A detailed analysis of the linkages between erosion and flood risk on 50–60 km of the coast and its societal implications, assuming a wide range of climate and socioeconomic scenarios as well as exploring adaptation choices, was conducted (O'Riordan, Nicholson-Cole and Milligan, 2008; Dawson et al., 2009; Nicholls, Dawson and Day, 2015). Strong trade-offs between erosion management and flood risk management became apparent, and also provided a forum where relevant stakeholders engaged on these issues. The methods were applied in a subsequent Strategy Study of North Norfolk, directly informing management decisions for the coming decades.

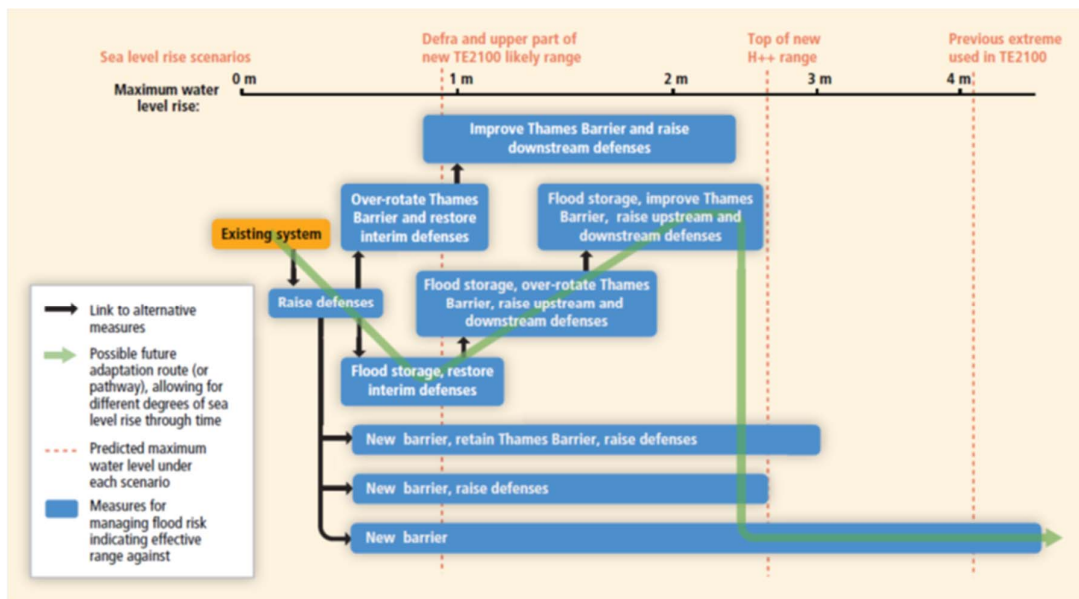
An example of a national integrated flood and erosion assessment undertaken on the coast of the United Kingdom is demonstrated by Evans et al. (2004a, 2004b) (see also Thorne, Evans and Penning-Rowsell, 2007). The assessment considered a comprehensive set of future socioeconomic scenarios of population, development and legislation, as well as sea level rise and climate change scenarios, beach and cliff evolution modelling and varying coastal protection and adaptation options. The aim was to quantify the likely future magnitude of flood and erosion risk in the United Kingdom and the potential to manage these risks to 2100. The study found a number of factors raised these risks, including the different coastal dimensions of climate change (sea level rise, storminess, waves and coastal erosion). Further, it found that these risks were manageable, especially if actions to address the issues were to be started immediately. Hence, national development pathways and planning for climate change are intimately linked. These analyses have continued to be developed by the national government as an ongoing process, most recently within the Climate Change Risk Assessment (DEFRA, 2012; Hames et al., 2012).

Similar processes are apparent in the Netherlands where the Delta Commission (2008) provided a long-term blueprint for the country, including climate change (see also Kabat et al., 2009; Stive et al., 2011). Rather than seeing this as a list of adaptation actions, it is better seen as establishing a flexible adaptation process for the Netherlands that is taking a long-term strategic view of what is required to keep the country 'safe' in a changing world. A delta plan has subsequently been developed for the Mekong Delta in Viet Nam, and a similar plan is under development for Bangladesh.

These examples show that planning assessments are integrated into wider coastal policy and ultimately merge into an adaptation and management process. Managing

uncertainty and maintaining flexibility are key issues, and ideas such as adaptation pathways have emerged from these analyses (Ranger, Reeder and Lowe, 2013; Haasnoot et al., 2013). Adaptation pathways recognize that there are often multiple ways (or pathways) to adapt to climate change. The best pathway may be difficult to identify because it will depend on multiple factors, including the rate of sea level rise and climate change. But identifying the different pathways today makes it possible to focus the analysis on improving our understanding of the choices ahead. Hence, it is possible to identify options if sea level rise is at the low or high end, minimizing the risks of over- or under-adapting and also ensuring that we maintain flexibility where appropriate. An example of adaptation pathways for responding to coastal flooding in the Thames Estuary (United Kingdom) is shown in Figure 5-3.

Figure 5-3  
Adaptation measures and pathways considered in the TE2100 project



TE2100: Thames Estuary 2100.

Sources: Wong et al., 2014; see also Lowe et al., 2009; Environment Agency, 2012.

The boxes in Figure 5-3 show the measures and the range of sea level rise (for extreme rather than mean sea level) over which the measures are effective. The black arrows link to alternative measures that may be applied once a measure is no longer effective. The red dashed lines show various twenty-first century sea level rise scenarios used in the analysis, including a conservative estimate of about 0.9 m by the United Kingdom Department for Environment Food and Rural Affairs (DEFRA) ('Upper part of new TE2100 likely range'), a high-level scenario ('Top of new H++ range') and an extreme scenario of over 4 m ('Previous extreme used in TE2100'). The thick green line shows one possible future adaptation route (or pathway), allowing for different degrees of sea level rise through time.

Adaptation is discussed further in Section 5.5.



### 5.2.5. Risk-based assessments: a blended approach

Risk-based approaches to V&A assessment have an explicit management-oriented approach that assesses risk to management organizations (which can be governments, communities, non-governmental organizations (NGOs), the private sector, etc.) due to climate change (see Chapter 2).

The application of risk-based approaches has evolved into a multi-scaled coastal risk assessment typically following an approach of ‘model scaling,’ whereby up-scaling (considering larger areas of assessment) is facilitated by progressively reducing the number of processes considered. This approach can be mapped to the sequence of screening assessments, impact assessments and planning assessments outlined above.

A ‘first-pass’ (screening) assessment approach can be conducted with a CVI approach (e.g., Gornitz et al., 1994; Thieler and Hammar-Klose, 2000), which can be used to assess erosion, flooding and salinization and can be applied at a broad national scale. This can provide initial ‘broad brush’ estimates of potential impacts.

The multi-scaled analysis approach using a landform hierarchy has been applied to analyse coastal erosion and flooding in England and Wales since the 1990s (Brampton and Motyka, 1993; Burgess et al., 2002; DEFRA, 2006; French et al., 2015). The availability of detailed aerial imagery, light detecting and ranging (LiDAR), and geomorphic knowledge bases have allowed the development of refined approaches elsewhere, including Australia (Gozzard, 2010; Eliot et al., 2011), and the approach is also widely transferable to coasts where erosion is important.

The fundamental benefit of this approach towards climate change impact assessment is improved consistency between models at different scales: the dominant land units when considered at lower scales determine the model type applied at each level. Although this does not prevent the application of invalid models to different landform types, it facilitates clear identification of the zones in which the selected model has reduced validity. The approach of multi-scaled landform assessment is commonly used for land use and hydrological studies (Schoknecht, Tille and Purdie, 2004; van Gool, Tille and Moore, 2005).

Developing these approaches may be useful for long-term management, including climate change issues (Box 5.2), although data constraints may prohibit the full application of this type of approach to coastal V&A assessment by Parties not included in Annex I of the Convention (non-Annex I Parties) without additional technical assistance. The core principles of a multi-scaled approach provide a pathway for the long-term application in subsequent studies, with a view to augmenting datasets when appropriate funding becomes available. Importantly, ‘scale thinking’ also provides a framework for considering the application of the specific impact assessment tools outlined in Section 5.3.



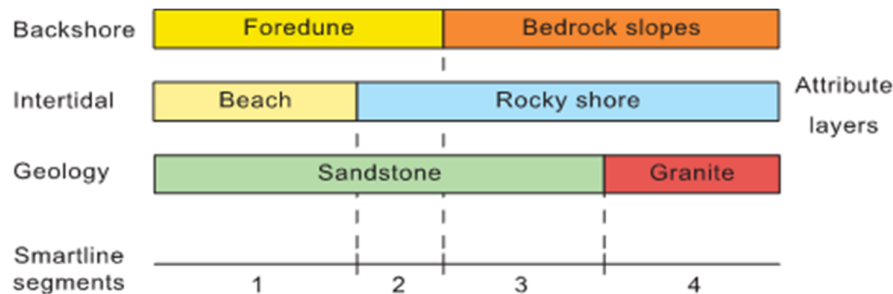
### 5.3. Tools

There is a range of tools available to support coastal V&A assessment across all three levels of assessment (Table 5-1). These include the following types of tools: (1) decision support; (2) modelling and analysis; (3) data collection, processing and management; (4) visualization; (5) stakeholder engagement and outreach; (6) conceptual modelling; (7) project management; and (8) monitoring and assessment. The user will need to assess which of these types are required.

Box 5-2

#### Vulnerability assessment using a one-dimensional (line) mapping approach

Coastal geomorphology datasets can be compiled in a line format with each of the different landform attribute fields displayed or analysed individually or as specific combinations of attributes. A line map is able to segment the coast at every point where any of the landform attributes change, as illustrated in the figure below.



Because of the essentially linear nature of coasts, a one-dimensional (line) map is a useful and efficient format for many descriptive and analytical purposes, but there are some applications for which polygon or topographic mapping is required. For example, while the coastal geomorphology mapping could indicate potentially flood-prone coastal segments, a contour map or digital elevation model (DEM) is necessary to delineate the actual areas likely to be inundated.

Along with geomorphic variability, coasts can be segmented based on other factors such as land use and population density. This approach is followed when applying CVI methods (e.g., Thieler and Hammar-Klose, 2000), shoreline management planning (DEFRA, 2006; Nicholls et al., 2013b) and also in the Dynamic and Interactive Vulnerability Assessment (DIVA) global assessment tool (McFadden et al., 2007).

A range of tools and methods (11 in total) applied globally to support V&A assessment of coastal resources are described in the UNFCCC Compendium (updated after the 2009 meeting on mainstreaming adaptation in Berlin; see also Kay and Travers, 2008; and Ramieri et al., 2011). Methods and tools are generally used to establish the current physical condition of the coast, to consider the variability of each condition in the face of ongoing natural environmental factors and to evaluate the likely response. A brief summary of a selection of these tools is shown in Table 5-3.

Table 5-3  
**Strengths and limitations of selected tools for vulnerability and adaptation assessment of coastal resources in the UNFCCC Compendium**

Method	Strengths	Limitations
Shoreline planning method	Widespread application around the world's coasts in coastal management based on a one-dimensional data model (see Box 5-2 above).	Requires customization to individual coastal zone management administrative systems.
Coastal vulnerability index (CVI)	Generally easily calculated and employed for rapid vulnerability assessment.	Requires customization of variables for case-by-case use.  (see Ramieri et al., 2011.)
Dynamic and interactive vulnerability assessment (DIVA)	Provides an overview of climatic and socioeconomic scenarios and adaptation policies on regional and global scales. Could be downscaled providing a useful database resource.	Provides coarse-scale resolution of potential coastal impacts at a national scale, some limited perspectives on vulnerability of the coast to climate change. Downscaling requires significant data collection and is not well documented.  (Not currently available for download.)
CoastClim and SimClim	Commercial decision-making aid for changed climate conditions.	Purchase necessary (not free to use).
Smartline	Cost-effective and rapid geomorphic mapping of coastal sensitivity; applicable at multiple scales.	Adaptation to local and site-specific scale will require testing and validation.

In coastal V&A, there has also been an increasing trend towards assessing the practical options for climate change adaptation by applying broad V&A frameworks (as discussed in Chapter 2), complemented with specific tools. This enhances the ability to mainstream the results of coastal V&A assessments into existing government systems aimed at managing coastal zones (see Chapter 9).

Two tools that are not in the UNFCCC Compendium that may have particular application as they provide generic methods for the assessment of coastal flooding are:

- Discover Coastal Inundation (available at <https://coast.noaa.gov/applyit/inundation/discover.html>).
- The EBM Tools Network (available at <http://www.ebmtools.org/?q=digital-coast-coastal-inundation-toolkit.html>).

Several important trends are apparent in the evolution of the assessment techniques and tools (Abuodha and Woodroffe, 2006; Ramieri et al., 2011) and include:

- More consideration of uncertainties involved in climate and impact projections and scenarios;
- Increased integration of climatic and non-climatic stressors and drivers;
- More realistic recognition of both the potential for and limitations to societal responses;
- Increased importance of stakeholder involvement;

- A purposeful shift from a science-driven to a policy-driven perspective.

Many of the tools are heavily dependent on the availability of input datasets (Section 5.4). Although it is likely that several of these tools and techniques could be adapted and updated for use by non-Annex I countries, this will require further focused investigation with specific attention to data availability and in-country capacity. Selected tools are given in Table 5-4, although users are encouraged to conduct their own searches, because new tools continue to be made available.

Table 5-4  
Selected tools categorized according to function

Tool function	Description	Example links
Process and management tools	Help when designing and conducting a planning process that incorporates the distinct elements that address the vulnerabilities, risks and uncertainties inherent in climate-related planning.	National Oceanic and Atmospheric Administration (NOAA) Using Flood Exposure Maps: < <a href="https://www.coast.noaa.gov/floodexposure/#-10575352,4439107,5z">https://www.coast.noaa.gov/floodexposure/#-10575352,4439107,5z</a> >  (See also Chapter 2 for community-based vulnerability and assessment tools)  European Union/Innovative Management for Europe's Changing Coastal Resource (IMCORE) coastal adaptation guidance: < <a href="http://www.coastaladaptation.eu/index.php/en/">http://www.coastaladaptation.eu/index.php/en/</a> >  Georgetown Climate Center Adaptation Tool Kit: Sea-level Rise and Coastal Land Use: < <a href="http://www.georgetownclimate.org/resources/adaptation-tool-kit-sea-level-rise-and-coastal-land-use">http://www.georgetownclimate.org/resources/adaptation-tool-kit-sea-level-rise-and-coastal-land-use</a> >
Visualization, stakeholder engagement and outreach tools	Generally simple to use but can include web-based geographic information system (GIS) visualization tools that require special software, hardware and expertise.	CanVis: < <a href="https://coast.noaa.gov/data/digitalcoast/pdf/canvis-guidance.pdf">https://coast.noaa.gov/data/digitalcoast/pdf/canvis-guidance.pdf</a> >  Sea Level Rise Explorer: < <a href="https://imex.psu.edu/project/sea-level-rise-explorer/">https://imex.psu.edu/project/sea-level-rise-explorer/</a> >  Google Mashups: < <a href="http://clear.uconn.edu/training/maps/mashup.htm">http://clear.uconn.edu/training/maps/mashup.htm</a> > and < <a href="http://www.google.com/earth/">http://www.google.com/earth/</a> >
Modelling and analysis tools (social impacts)	Can be used to analyse (and visualize) the social impacts that could result from future hazards and climate change.	CDC/ATSDR SVI (Social Vulnerability Index; USA data only): < <a href="https://www.atsdr.cdc.gov/placeandhealth/svi/index.htm">https://www.atsdr.cdc.gov/placeandhealth/svi/index.htm</a> >
Modelling and analysis tools (wetland impacts)	Can be used to investigate the effects of potential future conditions/scenarios to coastal wetlands and mangroves.	Sea Level Rise Affecting Marshes Model (SLAMM-Viewer; USA locations only): < <a href="https://coast.noaa.gov/digitalcoast/tools/slamm.html">https://coast.noaa.gov/digitalcoast/tools/slamm.html</a> >
Modelling and analysis tools (climate variability)	Defines the basics of El Niño and La Niña, and how specific 'El Niño Southern Oscillation (ENSO)' events are defined.	< <a href="http://iri.columbia.edu/climate/ENSO/background/pastevent.html">http://iri.columbia.edu/climate/ENSO/background/pastevent.html</a> > and < <a href="https://www.climate.gov/enso">https://www.climate.gov/enso</a> >

When choosing a tool to use in an assessment, the following factors should be considered:

- Make sure you understand the time, funding and expertise needed to collect the data needed to set-up, run, interpret and communicate the tool (or tools) results. One of the best ways to gather this information is by talking to people who have used the tool and the tool developer;
- Allow enough time for an iterative process. Tool use is most effective when stakeholders can explore a range of alternatives and make improvements to scenarios (and possibly the tools themselves) as they learn about the process, the trade-offs involved in meeting diverse objectives and the possible results of different decisions;
- Make sure you are using tools that provide the types of results that you need. Some tools provide general indices rather than quantitative results, while others provide detailed quantitative results, which may need to be generalized for management and communication purposes. In addition, some tools may not provide results at the temporal or spatial scales required for management decisions;
- Do not expect tools to provide all the answers. Tools are generally best used to assess strategic-level decisions with respect to climate change impacts rather than tactical decisions.

## 5.4. Data

Estimating possible future impacts of climate change on coastal zones must be based on an understanding of the current sensitivity and exposure of coastal areas to present-day natural hazards (e.g., storms, extreme waves). The selected issues and tools (Section 5.3) will define the data that are required. A wide range of data might be required, such as coastal erosion or inundation and local observational data on biophysical conditions, or socioeconomic data on the population and economy.

In most countries, various government departments (e.g., departments of environment, planning, etc.) and similar sources from coastal operators (e.g., port/harbour operators) can provide the local to national data needed for analysis. In addition, growing numbers of global-level datasets can be obtained online (see examples summarized in Table 5-5). These are useful, especially for screening and impact assessments (Table 5-1).

Table 5-5  
**Example online data sources for coastal vulnerability and adaptation assessment**

Category	Title	Description	Link
Sea-level data	Permanent Service for Mean Sea Level (PSMSL)	PSMSL is the global data bank for long-term sea level change information from tide gauges and bottom pressure recorders around the globe.	< <a href="http://www.psmsl.org/">http://www.psmsl.org/</a> > < <a href="http://ilikai.soest.hawaii.edu/uhsic/data.html">http://ilikai.soest.hawaii.edu/uhsic/data.html</a> >
Sea-level data	Global Sea Level Observing System (GLOSS)	GLOSS provides data from 290 sea-level stations worldwide for long-term climate change and oceanographic sea-level monitoring.	< <a href="http://www.gloss-sealevel.org/">http://www.gloss-sealevel.org/</a> >

Category	Title	Description	Link
Remotely sensed topography data	Land Process Distributed Active Archive Centre (LP DAAC)	LP DAAC is a component of NASA's Earth Observing System Data and Information System (EOSDIS) that processes, archives and distributes land data and products derived from Earth Observing System (EOS) sensors.	< <a href="https://lpdaac.usgs.gov/data_access/">https://lpdaac.usgs.gov/data_access/</a> >
Remotely sensed topography data	Shuttle Radar Topography Mission (SRTM)	SRTM is a NASA project providing high-resolution, digital topographic database of the Earth, excluding the high latitudes.	< <a href="http://www2.jpl.nasa.gov/srtm/">http://www2.jpl.nasa.gov/srtm/</a> >
Oceanographic drivers	NOAA National Oceanographic Data Center (NODC)	NODC provides global and regional data on a range of oceanic drivers and parameters.	< <a href="http://www.nodc.noaa.gov/">http://www.nodc.noaa.gov/</a> >
Oceanographic drivers	Global Oceanographic Data Center (GODAC)	Online data centre of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).	< <a href="http://www.godac.jp/top/en/index.html">http://www.godac.jp/top/en/index.html</a> >
Storminess (for the Pacific only)	Pacific Storms Climatology Products (PSCP)	PSCP is focused on improving our understanding of patterns and trends of storm frequency and intensity – 'storminess' – within the Pacific region.	< <a href="http://www.pacificstormsclimatology.org/">http://www.pacificstormsclimatology.org/</a> >
Storminess	SURGEDAT: The World's Storm Surge Data Center	SURGEDAT archives the location and height of more than 700 tropical surge events around the world since 1880.	< <a href="http://surge.srcc.lsu.edu/data.html">http://surge.srcc.lsu.edu/data.html</a> >
Socioeconomic data	Socioeconomic Data and Applications Center (SEDAC)	SEDAC hosts a range of relevant data, including two estimates of global population distribution: (1) Gridded Population of the World (GPW) and (2) Global Rural-Urban Mapping Project (GRUMP).	< <a href="http://sedac.ciesin.columbia.edu/">http://sedac.ciesin.columbia.edu/</a> >
Socioeconomic data	LandScan	LandScan provides estimates of ambient populations.	< <a href="http://web.ornl.gov/sci/landscan/">http://web.ornl.gov/sci/landscan/</a> >
Socioeconomic scenarios	SSP Database – International Institute for Applied Systems Analysis (IIASA)	Contains national scenarios consistent with the shared socioeconomic pathway (SSP) scenarios.	< <a href="https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&amp;page=about">https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&amp;page=about</a> >

Finally, it is important to consider a number of factors concerning the availability and use of data in coastal V&A assessments:

- Invest in the data management and documentation process up front by accounting for data management and documentation in the project design and budget. Well-managed and documented data are much more useful to a project because they can be used by multiple collaborators over a long time period. They are also

consistent with the tiered approach suggested here, where multiple assessments are expected;

- Recognize that poor data input into tools or models will result in poor output. There is no clear threshold for when data or analyses are too limited or flawed to be valid, but assessments should always be checking for this possibility, especially in the preliminary stages. A lower level of data precision is needed for regional and/or long-term decisions than local decisions for immediate needs or site-specific impact assessments. Similarly, as the level of assessment increases from screening to impact to planning assessments, data requirements will also increase (see Table 5-1);
- Be open and honest about data gaps and the uncertainty of existing data. Identifying and presenting data gaps up front will lend credibility to the process and help focus resources on gathering needed data. The data collection process can be beneficial to a project (and vice versa) if it is used as a time to build partnerships and a common body of information;
- Incorporate human knowledge into the assessment process. Subject matter experts can fill gaps in existing datasets, and local resource users are often one of the best sources of information about historical and current resource use and condition. Collection of human knowledge should use rigorous social science data collection techniques;
- Plan to support a long-term data acquisition process to ensure a steady improving set of coastal data and information.

## 5.5. Adaptation assessment and integration

### 5.5.1. Planning

In selecting adaptation measures, it is important to acknowledge differences among countries and regions. Different national or regional contexts drive the need to tailor adaptation measures to local conditions (e.g., what existing adaptation to coastal hazards exist, if any?). Adaptation measures need to be commensurate with the realities of time, funding, personnel and institutional capacity. Capacity to respond to climate change issues will grow with time, experience and the positive reinforcement that comes with success. Early successes of adaptation for climate change may begin with establishing building setbacks and buffer areas where development would be strongly controlled or not permitted at all (e.g., in currently undeveloped areas or areas proposed for future development that are exposed to flooding and erosion). Equally, considering sea level rise in the design of already-planned coastal engineering works may also be an initial success. More complex adaptation measures might emerge, including those that involve managing coastal systems, development and maintenance.

Population and infrastructure density are other key considerations in selecting measures. For example, in developed areas facing potential increases in erosion and/or flooding, the favoured adaptation option would be structural shore protection (to stabilize the shoreline) versus retreat. In underdeveloped areas, the opposite would be likely (i.e., a strategy of retreat would be favoured). Retreat refers to a series of measures that would remove the population and development by 'retreating' landward (i.e., away from the potential risk) – in this case not locating the population and development there in the first place.

The adaptation deficit should also be considered. Are coasts well adapted to today's conditions and what is needed to address these issues? Further, are measures to deal with climate change consistent with addressing the adaptation deficit?

Coastal managers, stakeholders and decision makers can use a range of criteria in deciding the best adaptation option within a given local context (Linham and Nicholls, 2010; USAID, 2015). Criteria include:

- **Technical effectiveness:** How effective will the adaptation option be in solving problems arising from climate change (i.e., might some measures be more beneficial than others)?
- **Costs:** What is the cost to implement the adaptation option? Is one approach both cheaper and more effective? Is the measure a 'no-regrets' measure; that is, would it be worthwhile regardless of climate change (e.g., increasing the safety of people who are already threatened during storms, enhancing coastal ecosystems that are already vulnerable or of urgent concern for other reasons)? Are there any indirect costs?
- **Benefits:** What are the direct climate change related benefits? Does taking action reduce risk to life and damage to human health, property or livelihoods? Or does it reduce insurance premiums? Are there any greenhouse gas reduction advantages that could be valued according to the market price for carbon credits? Other potential benefits include increased ecosystem goods and services and positive contributions to economic value chains.
- **Implementation considerations:** How easy is it to design and implement the option in terms of level of skill required, information needed, scale of implementation and other barriers?
- **Compatibility with existing coastal management approaches:** Is the adaptation option compatible, if not could an important barrier to application raise issues that reflect and review the current approach to coastal management and possibly contribute to changes in management philosophy?

Most adaptation measures can help in achieving multiple objectives and benefits. 'No-regrets' measures should be the priority. For example, wetlands protection and living shoreline strategies would be beneficial even in the absence of climate change (Royal Society, 2014). Living shorelines protect from erosion and simultaneously can enhance vegetated shoreline habitats today, and in the future, as wetlands migrate landward. This, in turn, can benefit natural resources-dependent livelihoods and increase community resilience. Compare this to the option of constructing a seawall – a strategy that also could protect against erosion in a specific location, but at the same time may cause problems in the future (e.g., erosion of adjacent shorelines or preventing wetland migration), and bring little benefit to the wider community and natural ecosystem. Measures that provide few benefits other than protection require a high degree of certainty about the impact from climate change at a particular site.

Each sector has implementation challenges and strategies for adaptation. The list below is sourced from the USAID guidebook for coastal development planners (USAID, 2009):

- Ensure adequate governance capacity;
- Strengthen legal frameworks;



- Strengthen personnel capabilities;
- Highlight the costs of 'doing nothing';
- Develop sustainable funding;
- Plan for externalities;
- Maintain a scientific basis for policy;
- Maintain an inclusive and participatory process;
- Select technically appropriate and effective measures.

While the focus is longer-term, this can also include storms and climate variability such as the El Niño Southern Oscillation (ENSO) (Box 5-3; see also Appendix 5-1).

Box 5-3

**Operational ENSO-based seasonal sea-level forecasts for Pacific Islands**

The Pacific ENSO Applications Climate Center (PEAC) developed and runs the operational ENSO-based canonical correlation analysis statistical model. PEAC started developing sea-level forecasts for the U.S.-affiliated Pacific Islands (USAPI) region with lead times of 3–6 months in advance. Due to the demand for longer lead-time (6–12 months) forecasts, PEAC has developed its forecast model to incorporate both SSTs and the zonal wind component of trade winds and has successfully forecast over longer time scales. This is supporting the development of a more efficient, long-term response plan for hazard management in the region. These services may be extended to the non-USAPI region in the South Pacific. (More information can be found at <http://www.weather.gov/peac/>; see also Chowdhury and Chu, 2014.)

### 5.5.2. Integration with other sectors

When assessing the impact of climate change on the coastal sector, it is important to consider how changes in other sectors may also contribute to impacts in the coastal sector. For example, increased water stress (reduced rainfall) could impact the coastal sector, destabilizing natural coastal barriers such as dunes or mangroves.

Although impact and adaptation planning are discussed at the sector-specific level, it is important to consider the interrelationships between sectors and how these may influence overall risk prioritization and adaptation planning. Such a cross-sector assessment is referred to as 'integration'. The aim of integration is to understand the interrelationships between sector-specific risks to set impact and adaptation priorities. This may be important for policymakers and other stakeholders to understand how a sector, community, region or nation could be affected in total by climate change and what the total economic impact may be. It may also be important to know how different sectors, regions or populations compare in terms of relative vulnerability to help set priorities for adaptation.

Chapter 9 of these training materials provides further details about integrating impact assessment and adaptation outcomes.



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**Websites: Computer-based decision tools**

- Adaptation Wizard: Risk-Based Analysis and Decision-Making, UK Climate Impacts Programme*. Available at <<http://www.ukcip.org.uk/wizard/#.VhhCtk2FPcs>>.
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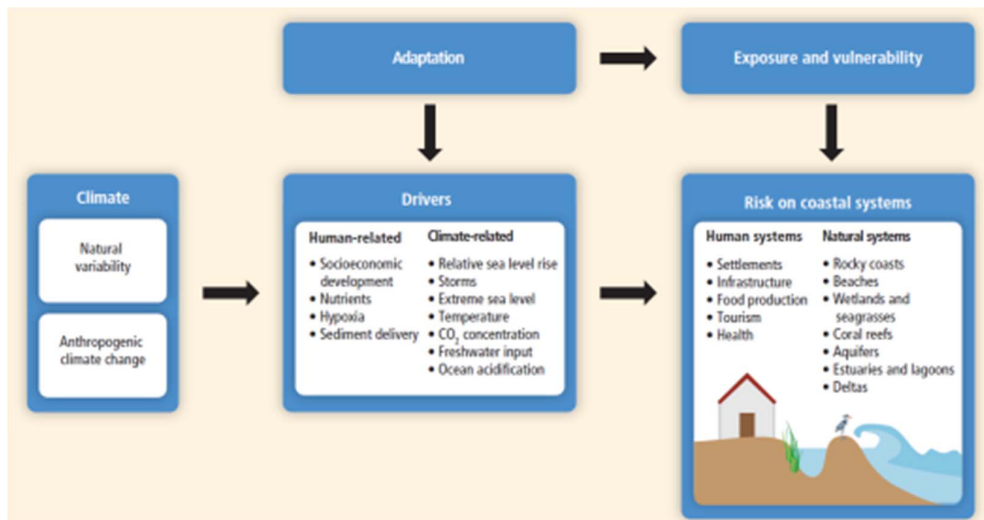
## Appendix 5-1: Drivers of climate change on coastal resources

### Drivers of change

Coasts are dynamic areas where complex interactions occur between climate and non-climate drivers of change, as summarized in Figure 5-4. A useful approach to consider key drivers of climate change in coastal zones and their impact on secondary coastal processes is shown in Table 5-6. This approach considers eight primary climate drivers and their respective impact on a set of secondary or process variables. The approach is useful in that it allows a user to establish an assessment matrix for a range of impact assessments. Table 5-7 defines four major impacts of sea level rise, how they might impact with other climate and non-climate factors and possible adaptations.

Figure 5-4

**Climate, both anthropogenic changes or natural variability, affects and interacts with climate- and human-related drivers**



*Note:* The risk on coastal systems is the outcome of integrating the drivers associated with hazards, exposure and vulnerability. Adaptation options can be implemented either to modify the hazards or the exposure and vulnerability, or both.

*Source:* Wong et al., 2014.

Table 5-6  
**Primary drivers of coastal climate change impacts, secondary drivers and process variables**

Primary driver	Secondary or process variable
<ul style="list-style-type: none"> <li>• Mean sea level</li> <li>• Sea surface temperature (SST)</li> <li>• Carbon dioxide (CO<sub>2</sub>) concentration (ocean acidification)</li> <li>• Wind climate</li> <li>• Wave climate</li> <li>• Rainfall/run-off</li> <li>• Ocean currents</li> <li>• Air temperature</li> </ul>	<ul style="list-style-type: none"> <li>• Local (relative) sea level (see Table 5-7)</li> <li>• Local currents</li> <li>• Local winds</li> <li>• Local waves</li> <li>• Groundwater</li> <li>• Coastal flooding</li> <li>• Coastal morphodynamics (erosion/accretion)</li> <li>• Estuarine and coastal hydrodynamics</li> <li>• Coastal water quality</li> <li>• Ecological status (examples below)                             <ul style="list-style-type: none"> <li>- Wetlands (saltmarsh/mangroves)</li> <li>- Coral reefs</li> <li>- Sea grass</li> </ul> </li> </ul>

Source: NCCOE, 2004.

Table 5-7  
**Main natural system effects of relative sea level rise and examples of adaptation options**

Natural system effect		Possible interacting factors		Possible adaptation options
		Climate	Non-climate	
1. Inundation/ flooding	a. Surge (flooding from the sea)	Wave/storm climate  Erosion  Sediment supply	Sediment supply  Flood management  Erosion  Land reclaim	Dikes/surge barriers/closure dams [P – hard]  Nourishment, including dune construction [P – soft]  Ecosystem-based barriers (e.g., mangrove afforestation) [P – soft]
	b. Backwater effect (flooding from rivers)	Run-off	Catchment management and land use	Building codes/flood-proof buildings [A]  Land use planning/hazard mapping [A/R]  Planned migration [R]
2. Wetland loss (and change)		CO <sub>2</sub> fertilization  Sediment supply  Migration space	Sediment supply  Migration space  Land reclaim (i.e., direct destruction)	Gabions/breakwaters [P – hard]  Nourishment/sediment management [P – soft]  Land-use planning [A/R]  Managed realignment/forbid hard defenses [R]

Natural system effect		Possible interacting factors		Possible adaptation options
		Climate	Non-climate	
3. Erosion (of 'soft' morphology)		Sediment supply Wave/storm climate	Sediment supply	Coastal defenses/seawalls/land claim [P – hard] Ecosystem-based barriers (e.g. mangroves) [P – soft] Nourishment [P – soft] Building setbacks/rolling easements [R]
4. Saltwater intrusion	a. Surface waters	Run-off	Catchment management (over-extraction) Land use	Saltwater intrusion barriers Desalination [A] Move water abstraction upstream [R]
	b. Groundwater	Rainfall	Land use Aquifer utilization	Insert impermeable barriers Freshwater injection Change water abstraction [A/R]

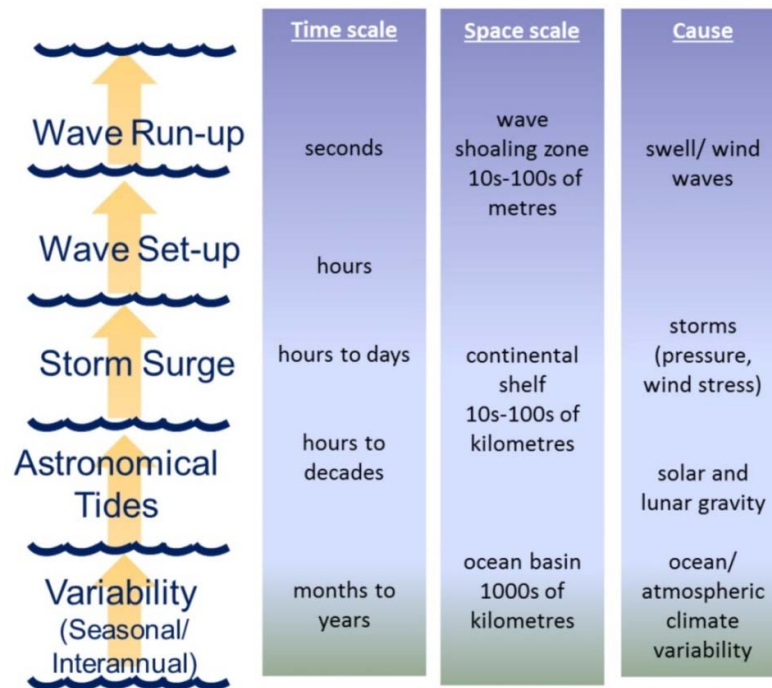
*Note:* Potential interacting factors that could offset or exacerbate these impacts are also shown. Some interacting factors (e.g., sediment supply) appear twice as they can be influenced both by climate and non-climate factors. Adaptation options are coded: P – Protection (hard or soft); A – Accommodation; R – Retreat. Sources: Adapted from Nicholls, 2014; see also Linham and Nicholls, 2010.

## Sea level

Sea level varies at many time scales for a range of reasons, including short-term oscillations such as wind waves and longer-term changes in the mean sea level. The components of extreme sea levels are shown in Figure 5-5.

Longer-term relative sea level rise (i.e., the rise of the sea relative to the land, which itself may be rising or falling) occurs as a result of global, regional and local changes in ocean and land levels (Church et al., 2010; Nicholls et al., 2011b, 2014). Global mean sea level (GMSL) change is a change in the global volume of the ocean. There are three main components: (1) thermal expansion of the ocean as it warms; (2) the melting of small glaciers and ice caps due to human-induced global warming; and (3) changes in the mass balance of the Greenland and Antarctic ice sheets. Regional and local spatial variations in sea level change have three main causes: (1) meteorological-oceanographic factors such as differences in the rates of oceanic thermal expansion, changes in long-term wind and atmospheric pressure and changes in ocean circulation; (2) changes in the regional gravity field of the Earth due to ice melting (caused by the redistribution of mass away from Greenland, Antarctica, as well as small glaciers); (3) vertical land movements (uplift and subsidence) due to natural and human-induced geological processes such as neotectonics, glacio-isostatic adjustment (GIA) and sediment compaction/consolidation. Importantly, human activity has often influenced rates of subsidence in susceptible coastal lowlands, such as deltas, by land reclamation and by lowering water tables through water extraction and improved drainage. Locally these changes can exceed the magnitude of changes in sea level expected due to climate change through the twenty-first century.

Figure 5-5  
Main contributions to extreme sea levels



## Mean Relative Sea Level

*Note:* These rise with relative mean sea level (with thanks to Kathy McInnes from the Commonwealth Scientific and Industrial Research Organisation, CSIRO).

As a result of climate change, it is likely that both mean conditions and extremes in sea-level conditions will change, and this needs to be considered when assessing the implications of sea level rise. The combined effect of rising sea levels and changes in extremes will probably produce much greater risks in the coastal zone than any single factor. Interaction with other factors, such as sedimentary and morphodynamic processes in coastal systems, also needs to be considered.

Relative sea level rise has a wide range of impacts on coastal processes. In addition to raising the ocean level, rising sea level also affects the coastal processes that operate around the mean sea level (e.g., tides, waves; refer to Table 5-6 and Figure 5-5). The immediate effects of a rise in sea level therefore include inundation, increased frequency and depth of flooding of coastal land and saltwater intrusion. Longer-term effects include morphodynamic changes, particularly beach erosion and salt marsh decline, as the coast adjusts to the new environmental conditions.

The main focus in these appendices is on changes over the next 80 years (to 2100). However, sea level rise is likely to continue for centuries even if the climate is stabilized as the ocean takes a very long time to reach equilibrium to a new climate. This has been termed the 'commitment to sea level rise' which, in turn, leads to a commitment to both coastal impacts and to adaptation if these impacts are to be managed. It means that we can expect that each generation of coastal managers will need to do more in response to sea level rise than the previous generation. Although the underlying science has been recognized since the 1980s, the policy implications are less



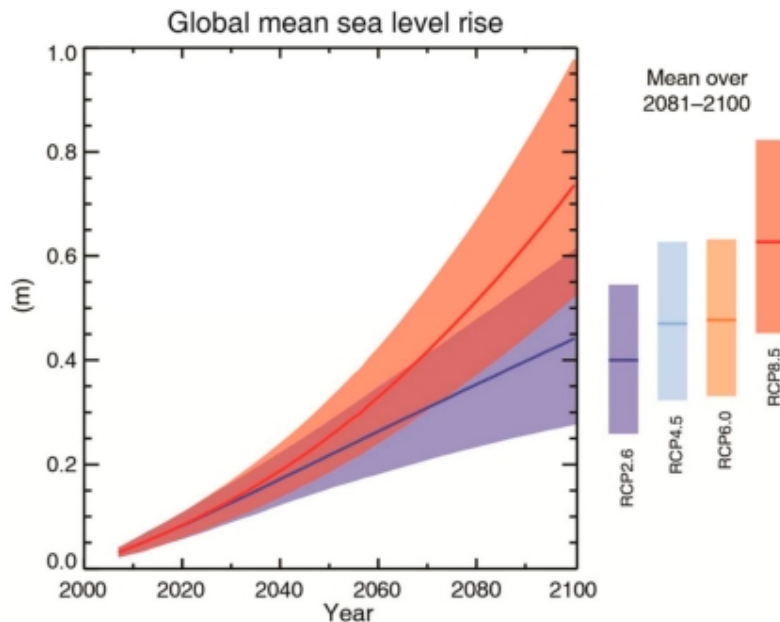
appreciated and it is important to consider this long-term issue when planning for sea level rise (Nicholls et al., 2007; Wong et al., 2014).

### Mean sea level scenarios

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) GMSL scenarios are shown in figure 5-6. GMSL rises of up to 1 m by 2100 are shown for the highest emissions scenario (RCP8.5). These results represent the likely range that encompasses 66% of the possible rise, meaning that changes outside this range are quite possible (e.g., Hinkel et al., 2015). Church et al. (2013) note that GMSL rise will not exceed the likely range by “several tenths of a metre of sea level rise during the twenty-first century”. It is important to note that there is strong interest from coastal stakeholders in this high-end range of GMSL rise, because this would produce the highest impacts and adaptation needs. A number of studies have estimated GMSL rises exceeding the IPCC range based on semi-empirical methods that correlate sea level rise to temperature rise, paleo-climate analogues and physical limits (Nicholls et al., 2014). To try and provide a pragmatic limit for impact and adaptation analysis, a high change range of scenarios which is termed the H++ range was proposed with an upper limit of a 2-m rise by 2100 (e.g., Lowe et al., 2009; Nicholls et al., 2014). The key concept is to promote analysis of impacts and adaptation that consider the wide range of uncertainty across a set of scenarios.

Figure 5-6

**Projections of global mean sea level rise over the twenty-first century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5**



*Note: The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean over the period 2081–2100 for all representative concentration pathway (RCP) scenarios are given as colored vertical bars, with the corresponding median value given as a horizontal line.*

*Abbreviation: CMIP: Coupled Model Intercomparison Project Phase 5.*

*Source: Church et al., 2013.*

The climate-induced GMSL rise needs to be downscaled to local (or relative) sea level. This requires consideration of the regional and local components of sea level (Nicholls et al., 2014). In some cases, guidance documents already exist for sea level rise scenarios, mainly in developed countries (e.g., Lowe et al., 2009). If this information is not available, information on possible regional sea level rise can be found in IPCC AR5. Land uplift/subsidence can be difficult to assess although useful information on total changes can be found in Oostanciaux et al. (2012), while estimates of GIA are available from Peltier (2004). The potential for large amounts of human-induced subsidence needs to be considered if appropriate. This is not a universal process but is potentially important in many susceptible coastal areas such as deltas (Ericson et al., 2006; Syvitski et al., 2009). Asian cities built on deltas and alluvial plains are especially vulnerable, as noted by the World Bank (2010).

### **Changes in storms and extreme water levels**

Major coastal storms lead to important impacts, as shown in hurricanes Katrina (2005) and Sandy (2012) in the United States, Xynthia (2010) in France, Sidr (2007) in Bangladesh, Nagris (2008) in Myanmar (Burma) and Haiyan (2013) in the Philippines. Hence it is vital to understand the likelihood of such events in terms of winds, extreme sea levels and wave conditions. In many places the historical variability of storm parameters is not well understood, and this is an important goal for improving this aspect of coastal management. There are a growing number of datasets on historical storms and extreme sea levels, which are useful in this regard (e.g., Needham and Keim, 2012; Haigh et al., 2015).

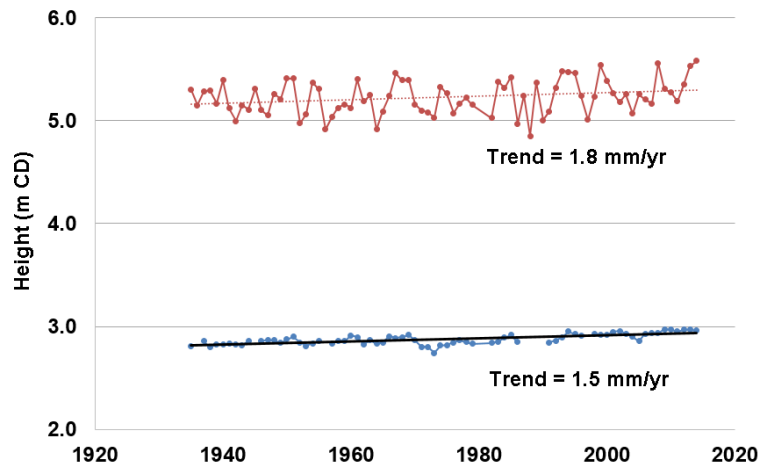
The issue of climate change and storms has often been confused because there are indirect effects of relative sea level rise, and possible direct effects of climate change. Indirectly, rising mean sea levels are causing a rise in extreme sea levels worldwide (Menéndez and Woodworth, 2010) and where waves are depth-limited, higher sea levels also increase local wave heights, even if offshore waves are constant (promoting erosion) (Townend, 1994; Townend and Burgess, 2005). The question of storm intensity and whether larger surges are resulting from climate change is much less certain. These factors vary on many timescales and hence a trend over the last three decades is not evidence of a systematic trend (WASA Group, 1998).

According to the IPCC special report on extremes and disasters (IPCC, 2012), it is likely that there has been a poleward shift in the main northern and southern storm tracks since the 1960s. There is strong agreement with respect to this change for a wide selection of cyclone parameters and cyclone identification methods, and European and Australian pressure-based storminess proxies are consistent with a poleward shift over this time period which indicates that the evidence is robust. Advances have been made in documenting the observed decadal and multi-decadal variability of extratropical cyclones using proxies for storminess. Therefore, the recent poleward shift should be seen in the light of new studies with longer timespans which indicate that the period 1960-2010 coincides with relatively low cyclonic activity in northern coastal Europe in the beginning of the period. Several studies suggest an intensification of high-latitude cyclones, but there is still insufficient knowledge of how changes in observational systems are influencing the cyclone intensification. So even in cases of high agreement among studies, the evidence cannot be considered to be robust. Thus, we have only low confidence in these changes.

According to IPCC (2012) and Church et al. (2013), rising trends in extreme coastal high water across the globe reflect increases in mean sea level, suggesting that mean

sea level rises, rather than changes in storms, are largely contributing to this increase (although data are sparse in many regions and this lowers the confidence in this assessment). For example, trends in the mean and the annual highest sea levels are shown for Southampton, United Kingdom, in Figure 5-7. It is therefore considered likely that sea level rise has led to a change in extreme coastal high water levels. It is also likely that there has been an anthropogenic influence on increasing extreme coastal high water levels via mean sea-level contributions. Hence, it is very likely that mean sea level rise will contribute to upward trends in the future.

**Figure 5-7**  
Rise in mean and annual extreme sea level at Southampton, United Kingdom, since 1935 (see Haigh, Nicholls and Wells, 2010)



Source: Ivan Haigh, University of Southampton.

Given the large uncertainties in storm parameters, changes in waves and surges might be analysed using a sensitivity analysis approach (e.g., if waves get bigger or change their direction of approach, as explored by Dawson et al., 2009).

### Other oceanic drivers

Other oceanic drivers include wave climate, ocean currents, ocean acidification and SST (Nicholls et al., 2007; Wong et al., 2014).

The magnitude, frequency and approach direction of waves impacting the coast are significant drivers of shoreline change. As discussed for storms in the section preceding this one, the systematic change in offshore waves during storms and wave climate in general is less certain, although the methods to develop this understanding are developing (e.g., Hemer et al., 2013; Wolf, Lowe and Howard, 2015). Global observations are also becoming available, which may provide useful statistics on historical conditions.

Increased atmospheric carbon dioxide (CO<sub>2</sub>) dissolving in the oceans has lowered ocean surface pH by 0.1 unit since 1750 (termed 'ocean acidification'). This is almost certain to continue as it is linked directly to greenhouse emissions. Ocean acidification will likely have significant spatially and temporally variable impacts on marine biodiversity.

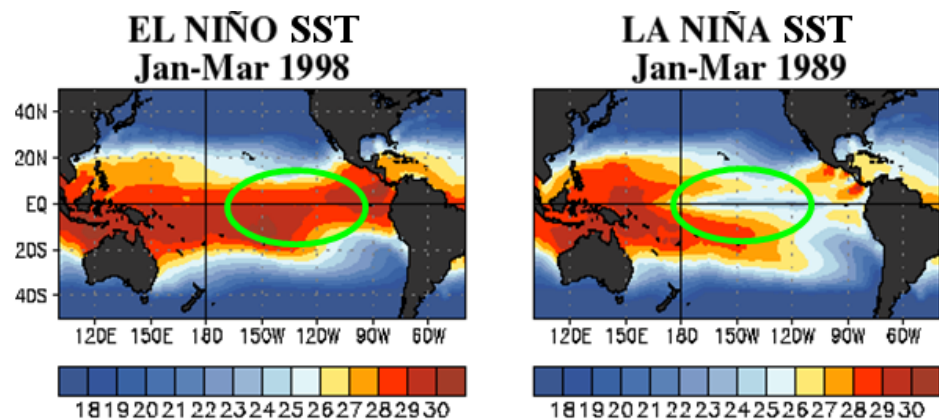
Projected changes in SST are likely to drive changes in stratification/circulation, reduced incidence of sea ice at higher latitudes, increased coral bleaching and mortality, poleward species migration and increased algal blooms. Changes in global and regional SST particularly influence significant natural climate fluctuations, which have important coastal implications, as discussed below.

### Relevant natural climate fluctuations

There are several natural climate fluctuations that influence extreme sea levels (Figure 5-5) and hence, need to be considered. Most importantly, the El Niño/La Niña Southern Oscillation climate cycle is influenced by changes in global and regional SST. This in turn causes regional sea-level variability and changes on seasonal time scales, especially in the Pacific Box 5-2). Other significant natural climate fluctuations with important coastal implications that might be considered include the North Atlantic Oscillation. However, they are smaller than El Niño, which is considered here as the most important climatic fluctuation.

El Niño is caused by the major warming of equatorial waters in the Pacific Ocean. In this case, the anomaly of the SSTs in the tropical Pacific increases by 0.5°C to +1.5°C in the NINO 3.4 Region<sup>1</sup> from its long-term average (Figure 5-8). On the other hand, La Niña is caused by major cooling of the same equatorial waters, in which case the anomaly of the SSTs in the tropical Pacific decreases (by 0.5°C to -0.5°C in the NINO 3.4 Region) from its long-term average (Figure 5-8).

Figure 5-8  
Sea surface temperatures in the typical El Niño (left panel) and La Niña (right panel) events



Source: NOAA NWS, 2010.

The Southern Oscillation represents the atmospheric component of the cycle in which lower (higher) than normal sea level pressure occurs near Tahiti, and higher (lower) sea-level pressure occurs in Australia during El Niño/La Niña conditions.<sup>2</sup> El Niño events occur every three to seven years and may last for many months, causing significant economic and atmospheric consequences worldwide. During the past 40 years, 10 El Niño (La Niña) events occurred, the worst being 1997–1998 (1998–

<sup>1</sup> The NINO 3.4 Region is bounded by 120°W–170°W and 5°S–5°N.

<sup>2</sup> See <[http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/ensocycle/enso\\_cycle.shtml](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/enso_cycle.shtml)>.

1999). Previous to this, the El Niño event in 1982–1983 was the strongest. Some of the El Niño events have persisted for more than one year. These El Niño/La Niña events are associated with consistent climate anomalies (i.e., shifts in temperature, precipitation and sea-level patterns) across the globe and high SST anomalies can lead to coral bleaching (Nicholls et al., 2007). These events are therefore treated as an important component of the climate system as they impact weather on a global scale (see Clarke, 2008, and references therein for the dynamics of ENSO). This is a large science base and there is a large literature base available on this issue<sup>3</sup>.

The tropical climate variability has been found to be heavily influenced by the ENSO climate cycle (Bjerknes, 1966; Ropelewski and Halpert, 1987; Chu, 1995). Low sea level during the El Niño events and high sea level during the La Niña events are the results of this influence (Chowdhury, Chu and Schroeder, 2007). Rainfall and tropical cyclone activities in the Pacific and Caribbean are also influenced by ENSO. Hence, the uncertainties induced by ENSO conditions should be considered in analyses in the Pacific, the Caribbean and South America (e.g., Losada et al., 2013).

### **Non-climate drivers**

There has been extensive human modification of coastal systems that have served to significantly influence the exposure and sensitivity of the coast to climate change (see Table 5-7 see at the beginning of this appendix). These modifications include changes to sediment supply and pathways through a range of mechanisms, including port/harbour construction, coastal protection works and upstream damming for freshwater supply/hydroelectric power and deforestation. Coastal subsidence due to groundwater abstraction is also locally significant, particularly in delta coasts. These influences must be carefully considered in the assessment of future coastal impacts (outlined in Appendix 5-2). In addition, careful consideration of future socioeconomic scenarios of changes in coastal regions (e.g., urbanization) should also be considered in impact assessments (see Chapter 3). Land subsidence to groundwater withdrawal and drainage might be relevant to consider here, although this needs to be considered with the relative sea level rise scenarios (see Section 5.2.2).

For other issues, examples can be drawn from Vermaat et al. (2005); Nicholls et al. (2008, 2011a); and Lloyd's Register, QinetiQ and Strathclyde University (2013).

In addition, the impacts of geological natural hazards, in particular earthquakes (which can both substantially change relative sea level in a matter of minutes and trigger devastating tsunamis), should also be considered.

Tables 5-6 and 5-7 above summarize some of the main biogeophysical and socioeconomic impacts of climate change and sea level rise, and their interactions. These biogeophysical effects in turn will have direct and indirect socioeconomic impacts on human settlements, agriculture, freshwater supply and quality, fisheries, tourism, financial services and human health in the coastal zone (Nicholls et al., 2007; Wong et al., 2014).

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<sup>3</sup> See the following links and references therein:

<<http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml>>;  
<<http://iri.columbia.edu/our-expertise/climate/forecasts/enso/current/>>;  
<<https://www.climate.gov/enso>>.

## Appendix 5-2: Impacts of climate change on coastal resources

### Potential impacts

The impacts of sea level rise and climate change can be broadly grouped into two main categories: biogeophysical impacts such as erosion and inundation (Table 5-7, Appendix 5-1), and socioeconomic impacts associated with biogeophysical impacts such as the loss of land and impacts on livelihoods. The key biophysical effects of sea level rise and climate change on coastal systems from a societal perspective include:

1. Inundation and increased flood-frequency probabilities;
2. Erosion;
3. Saltwater intrusion;
4. Rising water tables;
5. Biological effects.

The potential socioeconomic effects of climate change are:

1. Direct loss of economic, ecological, cultural and subsistence values through loss of land, infrastructure and coastal habitats;
2. Increased flood risk to people, land and infrastructure and the values stated above;
3. Other effects relating to changes in water management, salinity and biological activity, such as loss of tourism, loss of coastal habitats and effects on agriculture and aquaculture.

The impacts of climate change on coastal zones are well documented in the contribution of Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), specifically in the chapter on coastal systems and low-lying areas (Wong et al., 2014). Table 5-8 summarizes the links between both types of climate change impacts as well as their effects on the coastal environment.

Irrespective of climate change, coastal areas face a wide range of issues associated with population growth, water pollution, changes in freshwater flows, resource exploitation and degradation and widespread habitat change. These existing stresses are likely to be exacerbated by climate change, making it imperative to include coastal adaptation as part of effective coastal management and a priority for immediate action for coastal areas (USAID, 2009; Wong et al., 2014).

Table 5-8  
Examples of primary and secondary effects of climate change on the coastal zone

Effect category	Example effects on the coastal environment
Primary biogeophysical impacts (see table 5-2)	<ul style="list-style-type: none"> <li>• Displacement of coastal lowlands and wetlands</li> <li>• Increased coastal erosion</li> <li>• Increased flooding</li> <li>• Salinization of surface and groundwater</li> </ul>
Primary socioeconomic impacts	<ul style="list-style-type: none"> <li>• Loss of property and land</li> <li>• Increased flood risk/loss of life</li> <li>• Damage to coastal protection works and other infrastructure</li> <li>• Loss of renewable and subsistence resources</li> <li>• Loss of tourism, recreation and coastal habitats</li> <li>• Impacts on agriculture and aquaculture through decline in soil and water quality</li> </ul>
Secondary socioeconomic impacts	<ul style="list-style-type: none"> <li>• Impact on livelihoods</li> <li>• Impact on human well-being</li> <li>• Impact on human health</li> <li>• Political effects of primary impacts</li> <li>• Threats to particular cultures and ways of life</li> </ul>
Infrastructure and economic activity	<ul style="list-style-type: none"> <li>• Diversion of resources to adaptation/increasing protection costs</li> <li>• Increasing insurance premiums</li> </ul>

Source: Adapted from Abuodha and Woodroffe, 2006.

### Biophysical impacts

The key future impacts and vulnerabilities on coastal ecosystems are well documented in the relevant IPCC assessments (Nicholls et al., 2007; Wong et al., 2014). Table 5-9 outlines the main climate drivers for coastal ecosystems, their trends due to climate change and their main physical and ecosystem effects. Further detail on the impacts can be found in Wong et al. (2014, Section 5.4.2).

Table 5-9  
Main climate drivers for coastal systems, their trends due to climate change and their main physical and ecosystem effects

Climate driver (trend)	Main physical and ecosystem effects on coastal ecosystems
CO <sub>2</sub> concentration (I)	Increased CO <sub>2</sub> fertilization; decreases seawater pH (or 'ocean acidification'), which negatively impacts coral reefs and other pH-sensitive organisms
Sea surface temperature (SST) (I, R)	Increased stratification/changes circulation, reduced incidence of sea ice at higher latitudes, increased coral bleaching and mortality, poleward species migration, increased algal blooms
Sea level (I, R)	Inundation, flood and storm damage; erosion; saltwater intrusion; rising water tables/impaired drainage; wetland loss (and change)
Storm intensity (I, R)	Increased extreme water levels and wave heights; increased episodic erosion, storm damage, risk of flooding and failure of flood defenses



Climate driver (trend)	Main physical and ecosystem effects on coastal ecosystems
Storm frequency (? , R), storm track (? , R)	Altered surges and storm waves and, hence, risk of storm damage and flooding
Wave climate (? , R)	Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach platform
Run-off (R)	Altered flood risk in coastal lowlands, altered water quality/salinity, altered fluvial sediment supply, altered circulation and nutrient supply

Key: (I) = Increasing; (?) = uncertain; (R) = regional variability.

Source: Nicholls, 2010.

## Socioeconomic impacts

Socioeconomic impacts of climate change are generally built on the biogeophysical changes summarized in Tables 5-8 and 5-9. The socioeconomic impacts of climate change will be cross-cutting in nature; the key climate-related impacts on the various socioeconomic sectors within the coastal zone are presented in Table 5-10. These impacts were seen by Nicholls et al. (2007) and Wong et al. (2014) to be overwhelmingly negative. Additional detail on the impacts on each individual sector can be found in Wong et al. (2014) (see also Section 5.4.3).

Table 5-10

Summary of climate-related impacts on socioeconomic sectors in coastal zones

Coastal socioeconomic sector	Temperature rise (air and seawater)	Extreme events (storms, waves)	Floods (sea level, run-off)	Rising water tables (sea level)	Erosion (sea level, storms, waves)	Saltwater intrusion (sea level, run-off)	Biological effects (all climate drivers)
Freshwater resources	X	X	X	X	–	X	X
Agriculture and forestry	X	X	X	X	–	X	X
Fisheries and aquaculture	X	X	X	–	X	X	X
Health	X	X	X	X	–	X	X
Recreation and tourism	X	X	X	–	X	–	X
Biodiversity	X	X	X	X	X	X	X
Settlements/ infrastructure	X	X	X	X	X	X	–
Gender	X	X	X	X	X	X	–

Key: X = strong; x = weak; – = negligible or not established.

Source: Nicholls, 2010.

## Appendix 5-3: Coastal adaptation

Given that sea level rise is very likely to occur for centuries (see Section 5.2.1), the need for adaptation in coastal areas will also continue for centuries. Against this backdrop, a 'commitment to coastal adaptation' needs to be built into long-term coastal management policy (Nicholls et al., 2007; Wong et al., 2014).

Natural systems have a capacity to respond autonomously to external pressures, such as climate change, and this can be described as the natural ability of coastal systems to respond. For example, a healthy, unobstructed wetland would respond by depositing more sediment and growing vertically (and laterally), keeping pace with sea level rise, and this would be an example of autonomous adaptation. Therefore, although the wetland would change, it is likely to survive. In many places, however, human activities – such as development (physical obstruction), reduced sediment inputs or pollution in the coastal zone – have reduced the natural system's ability to adapt. Planned adaptation to sea level rise should therefore include consideration of options to reverse these trends of 'maladaptation' so as to increase the natural resilience of the coast and increase the capacity for autonomous adaptation.

Socioeconomic systems in coastal zones also have the capacity to respond autonomously to climate change. Farmers may switch to more salt-tolerant crops and people may move out of areas increasingly susceptible to flooding.

Because impacts are likely to be significant, even taking into account autonomous adaptation, there is a further need for planned adaptation. Examples of initiatives that embrace planned adaptation for climate change are the adoption of strengthened and improved physical planning and development control regulations. This could also include those relating to integrated coastal zone management (ICZM) and shoreline management planning (see Box 5-4). They could also include implementation of an environmental impact assessment process and coastal disaster management.

Planned and therefore proactive adaptation is aimed at reducing a system's vulnerability by either minimizing risk or maximizing adaptive capacity. Five generic objectives of proactive adaptation relevant to coastal zones can be identified:

1. **Increasing robustness of infrastructural designs and long-term investments:** Infrastructure would be designed to withstand more intense and frequent extreme events;
2. **Increasing flexibility of vulnerable managed systems:** Systems would be designed and operated to cope with a wide variety of climate conditions. Flexibility can include improving a system's resilience (i.e., its capacity to recover from extreme events);
3. **Enhancing adaptability of vulnerable natural systems:** Natural systems can be made more adaptable by reducing stresses they currently face, such as degradation of habitat, and enabling them to adapt through such means as removing barriers to migration (e.g., removing hard coastal structures that can block inland migration of wetlands);
4. **Reversing maladaptive trends:** Many current trends increase vulnerability to climate change (e.g., subsidizing development in flood plains can increase the number of people and amount of property in low-lying coastal areas vulnerable to sea level rise and increased coastal storms);

5. **Improving societal awareness, preparedness and warnings:** Education about risks from climate change and how to reduce or respond to them can help reduce vulnerability.

Box 5-4

**Shoreline management planning for adaptation**

The most recent shoreline management guidelines used in England and Wales are applied at a national level (DEFRA, 2004, 2006; Nicholls et al., 2013a) and can be adapted for use elsewhere. They are a set of proactive strategies for shoreline management that will be implemented within shoreline management plans. The coast is divided into process units based on geomorphic criteria, and further divided into management units, reflecting coastal land use. For each management unit, one of four strategic responses are selected for three epochs in time, such as protect (termed 'hold the line') for developed areas, or allow natural processes to occur (termed 'no active intervention'), where human impacts might be minor. Although these approaches have not been applied in developing countries, this type of approach is widely transferable and similar approaches are expected to be developed widely in the coming few decades.

For coastal zones, another classification of three basic adaptation strategies is often used (e.g., Dronkers et al., 1990; Linham and Nicholls, 2010):

1. **Protect:** to reduce the risk of an event by decreasing the probability of its occurrence;
2. **Accommodate:** to increase society's ability to cope with the effects of the event;
3. **Retreat:** to reduce the risk of the event by limiting its potential effects.

Each of these strategies is designed to protect human use of the coastal zone and, if applied appropriately, each has different consequences for coastal ecosystems.

**Retreat** involves giving up land to the sea by strategic retreat from or prevention of future major developments in coastal areas that may be affected by future sea level rise. **Accommodate** involves altered use of the land, including adaptive responses, such as elevating buildings above flood levels and modifying drainage systems. Retreat and accommodation help to maintain the dynamic nature of the coastline and allow coastal ecosystems to migrate inland unhindered, and therefore to adapt more naturally. In contrast, **protection** can often lead to 'coastal squeeze' and loss of habitats, although this can be minimized by using soft approaches to defence, such as beach nourishment. This strategy involves defending areas of the coast, by building or maintaining defensive structures or by artificially maintaining beaches and dunes. It is generally used to protect settlements and productive agricultural land, but often involves the degradation and loss of the natural functions of the coast. Retreat and accommodation are best implemented proactively, whereas protection can be either reactive or proactive.

Information measures are also important for disaster risk reduction and compatible with protection, accommodation and (less so) retreat. For example, flood warning systems can forecast extreme sea levels and waves and be linked to disaster

preparedness approaches. Innovation and improvement in such systems have been rapid and this is likely to continue.

Options for adaptation to saltwater intrusion in groundwater are not explicitly covered by the three generic options of retreat, accommodate and protect. There are, however, a number of options:

- Reclaiming land in front of the coast to allow new freshwater lenses to develop;
- Extracting saline groundwater to reduce inflow and seepage;
- Infiltrating fresh surface water;
- Inundating low-lying areas with freshwater;
- Widening existing dune areas where natural groundwater recharge occurs;
- Creating physical barriers.