

This Primer has been prepared by Johan Hinkel from the Global Climate Forum, Robert Arthur from the American University of Ras Al Khaimah, Ze Edson from the Oceanography Institute at the University of Sao Paulo, and Bill Dougherty from the Climate Change Research Group

Suggested Citation:

AGEDI. 2017. Sea level Rise Primer. LNRCCP. CCRG/GCF/AURAK/IO

This report was prepared as an account of work sponsored by the Abu Dhabi Global Environmental Data Initiative (AGEDI). AGEDI neither makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, nor usefulness of the information provided. The views and opinions of authors expressed herein do not necessarily state or reflect those of the EAD or AGEDI.

Acknowledgments

Many individuals provided invaluable support, guidance, and input to the National Coastal Vulnerability Index (CVI) project. The authors would like to express their sincere and heartfelt expressions of gratitude for their review by providing comments, feedback and /or data towards the multiple deliverables within the project process including:

Mr. David Robinson, Department of Municipal Affairs and Transport
Dr. Fahed Alhammadi, Ministry of Climate Change and Environment (MOCCA)
Dr. Frederic Launay, Environment Agency, Abu Dhabi (EAD)
Dr. John Burt, New York University (NYU)
Ms. Maria Cordeiro, Environment Agency – Abu Dhabi (EAD)
Ms. Naoko Kubo, Ministry of Climate Change and Environment (MOCCA)
Mr. Peter Brian Fippingger, Environment Agency – Abu Dhabi (EAD)
Dr. Richard Perry, Environment Agency – Abu Dhabi (EAD)
Dr. Simon Pearson, Environment Agency – Abu Dhabi (EAD)

We are additionally thankful for the participation, time and effort that the EAD team and the EWS-WWF team who participated in the multitude of meetings and dialogue.

About this Sea Level Rise Primer

In October 2013, the Abu Dhabi Global Environmental Data Initiative (AGEDI) launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder-driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research sub-projects across 5 strategic themes.¹ The "Sea Level Rise Primer" sub-project within this Programme aims to identify and discuss the key policy issues and challenges associated with adapting to rising sea levels from climate change.

The purpose of this Primer is to offer a comprehensive discussion of what has been learned in carrying out the research activities involved in the study. In short, this report seeks to provide the reader with a comprehensive overview of the risks associated with sea level rise induced by climate change, supported by a discussion of available methods and frameworks to assist coastal planners in the assessment of suitable adaptation responses in the face of uncertainty.

¹ For more information on the LNRCC programme, please contact Jane Glavan (Inrclimatechange@ead.ae).

Table of Contents

	<u>page</u>
<u>ABOUT THIS SEA LEVEL RISE PRIMER</u>	I
<u>LIST OF FIGURES</u>	VI
<u>LIST OF TABLES</u>	VI
<u>LIST OF BOXES</u>	VII
<u>LIST OF ACRONYMS</u>	VIII
<u>SELECTED GLOSSARY</u>	IX
<u>1. INTRODUCTION</u>	1
<u>2. UNDERSTANDING SEA LEVEL RISE</u>	2
2.1. CURRENT SEA LEVEL RISE	2
2.1.1. THERMAL EFFECTS	3
2.1.2. DEGLACIATION EFFECTS	4
2.1.3. GRAVITY EFFECTS	6
2.1.4. OTHER EFFECTS	7
2.1.5. SUMMARY	7
2.2. FUTURE SEA LEVEL RISE	8
2.2.1. PROGRESS AND KEY LIMITATIONS OF PAST SEA LEVEL RISE MODELING	8
2.2.2. KEY MODELING CHALLENGES	9
2.2.3. ADVANCES IN COUPLED ICE-OCEAN-ATMOSPHERE MODELS	10
<u>3. SEA LEVEL RISE AND COASTAL ZONES</u>	12
3.1. REGIONAL COASTAL ENVIRONMENT CONTEXT	12
3.2. NATIONAL COASTAL ENVIRONMENT CONTEXT FOR THE UAE	14
3.2.1. ABU DHABI	16
3.2.2. DUBAI	17
3.2.3. SHARJAH	17
3.2.4. AJMAN	18
3.2.5. UMM AL QAWAIN	18
3.2.6. RAS AL KHAIMAH	19
3.2.7. FUJAIRAH	19
<u>4. FRAMEWORK FOR DECISION-MAKING</u>	20
4.1. COASTAL ADAPTATION MEASURES	20
4.1.1. PROTECTION MEASURES	21
4.1.2. ACCOMMODATION MEASURES	22
4.1.3. RETREAT MEASURES	23
4.2. ADAPTATION FRAMEWORKS	24
4.2.1. UKCIP RISK, UNCERTAINTY AND DECISION MAKING FRAMEWORK	25

4.2.2.	THE ADAPTATION SUPPORT TOOL OF THE EUROPEAN CLIMATE ADAPTATION PLATFORM	25
4.2.3.	IRGC RISK GOVERNANCE FRAMEWORK	26
4.3.	RISK MANAGEMENT APPROACHES	27
4.3.1.	TYPES OF COASTAL DECISIONS	28
4.3.2.	DECISION MAKING FRAMEWORKS	28
4.3.3.	CHOOSING A SUITABLE DECISION MAKING FRAMEWORK	30
4.3.4.	CHOOSING SUITABLE SEA-LEVEL RISE SCENARIOS	31
5.	<u>NEXT STEPS</u>	32
6.	<u>LIST OF REFERENCES</u>	34

List of Figures

	<u>page</u>
Figure 2-1: Causes underlying sea level change (IPCC, 2007) [Red annotations ours]	3
Figure 2-2: Sea level rise due to global thermal expansion (top: Indian Ocean: bottom: World oceans) for the period 1955-2010. Linear trend line and percent variance shown in red (adapted from Levitus, et al., 2012).....	4
Figure 2-3: Illustration of the self-gravitation effect (adapted from Kirshen and Wake, 2014)6	6
Figure 2-4: Range in the IPCC’s global mean sea level rise projections in 2100 under the high emission scenarios (Jevrejeva et al., 2014).....	9
Figure 3-1: Observed and modeled ice flow velocity fields in the Greenland glaciers (Price et al., 2011).....	13
Figure 3-2: Tropical Cyclone Gonu churns off the coast of Oman. (Source: NASA Earth Observatory)	13
Figure 3-3: Area of stronger than normal northwesterly winds (Shamal) and higher wind-induced waves (Fencil and Klein, 2009)	14
Figure 3-4: Map of UAE Arabian Gulf and Gulf	15
Figure 4-1: Possible adaptation measures to address sea-level rise. Source: (Brown et al., 2013)	20
Figure 4-2: Examples of shoreline protection measures	21
Figure 4-3: The risk governance process. Source: IRGC (2005)	25
Figure 4-4: The 8 Steps of the UKCIP adaptation framework (Source: Willows and Connell, 2003)	26
Figure 4-5: Different kind of coastal adaptation decisions in terms of risk aversion and decision horizon).....	28
Figure 4-6: Applicability of decision-making framework in terms of two characteristics of the adaptation decisions	30

List of Tables

	<u>Page</u>
Table 2-1: Contributions to global mean sea-level rise over 1993-2010 (adapted from Church et al., 2013; Table 13.1).	7

List of Boxes

	<u>Page</u>
Box 2-1: Deglaciation dynamics (adapted from National Snow and Ice Data Center).....	5
Box 4-1: Thames Estuary 2100 Project	32

List of Acronyms

ACE	Antarctic Climate & Ecosystems
AGEDI	Abu Dhabi Global Environmental Data Initiative
AR	Assessment Report
CBA	cost-benefit analysis
CCRG	Climate Change Research Group
CEA	cost-effectiveness analysis
CESM	Community Earth System Model
CISM	Community Ice Sheet Model
CMIP	Coupled Model Intercomparison Project
DSL	dynamic sea level
EAD	Environment Agency of Abu Dhabi
EEA	European Environment Agency
EU	European Union
GCC	Gulf Cooperation Council
GCM	General Circulation Model
GTE	Global Thermal Expansion
IRGC	International Risk Governance Council
IPCC	Intergovernmental Panel on Climate Change
Km	kilometer
LNRCCP	Local, National, and Regional Climate Change Programme
mm	millimeter
RCP	Representative Concentration Pathway
SIMIP	Sea-Ice Model Intercomparison Project
SLR	Sea Level Rise
UAE	United Arab Emirates
UKCIP	United Kingdom Climate Impacts Programme
VLM	Vertical land movement

Selected Glossary

Ablation	Snow and ice removed from an ice mass via meltwater runoff, sublimation, wind scour, or glacial calving (mechanical fracturing and separation).
Accretion	Increase in ice mass by basal growth in the case of floating ice, the compression of snow into ice, or freezing of water that has pooled on the ice or percolated into snow from rain, meltwater, or flooding of sea/lake/river water.
Accumulation	Snow and ice added to an ice mass via snowfall, frost deposition, rainfall that freezes on/in the ice mass, refrozen meltwater, wind-blown snow deposition, and avalanching.
Cryosphere	The term “cryosphere” comes from the Greek word, “krios,” which means cold. It refers to the frozen water part of the Earth system. One part of the cryosphere is ice that is found on land. Including the continental ice sheets found in Greenland and Antarctica, as well as ice caps, glaciers, and areas of snow and permafrost. The other part of the cryosphere is ice that is found in water, including frozen parts of the ocean, such as waters surrounding Antarctica and the Arctic.
Flood-proofing	Any combination of structural or non-structural additions, changes, or adjustments to a building that reduces or prevents flood damage to the structure and/or its contents.
Glacier	A perennial terrestrial ice mass that shows evidence of motion/deformation under gravity.
Grounding Line	The transition zone between grounded and floating ice.
Ice Sheet	A large (i.e., continental-scale) dome of glacier ice that overwhelms the local bedrock topography, with the ice flow direction governed by the shape of the ice cap itself.
Ice Shelf	Glacier ice that has flowed into an ocean or lake and is floating, no longer supported by the bed.
Icefield	A sheet of glacier ice in an alpine environment in which the ice is not thick enough to overwhelm the local bedrock topography, but is draped over and around it; glacier flow directions in an icefield are dictated by the bed topography.
Sea Ice	Floating ice from frozen seawater.
Snow	Ice-crystal precipitation that accumulates on the surface.
Soil Ice	Ice in permafrost.

1. Introduction

With rising sea levels will come new challenges for planners and decision-makers in the UAE. Sea level rise will mean that tides, waves and storm surges can reach further inland than before, resulting in flooding, erosion, receding shorelines and the deterioration of groundwater quality (Dasgupta et al, 2007; Kirshen and Wake, 2014). The vulnerability of coastal areas to rising seas depends on many factors including shoreline elevation, the topography of the land and the seabed, the presence of natural barriers, and other local characteristics. Other impacts of climate change, such as changing wind and rainfall patterns, will also come into play, such as more intense rainfall coinciding with storm surges, amplifying the impacts of rising seas.

As with all other countries that have an extensive coastline, the UAE is confronted with the need to prepare for sea level rise. The task of planning for sea level rise is challenging on many levels. On the one hand, it is a scientifically complex with current general circulation models unable to integrate the ice-air-ocean interactions under increasing concentrations of greenhouse gases (GHGs) in the atmosphere. On the other hand, the magnitude and timing of impacts are uncertain. Hence, different stances on addressing risks from sea level rise will be appropriate for different areas in the UAE.

This Sea Level Rise Primer seeks to support decision-making pertinent to sea level rise. The Primer aims to be a helpful interface between sea level rise, a topic that is highly technical and multi-faceted, and decision-makers and other stakeholders in the UAE and the Arabian Gulf region who are interested in coastal development and protection. The focus is on three (3) key areas:

- Increasing the scientific understanding of what sea level rise is, how it is predicted, and the status of international research efforts to improve General Circulation models to adequately reflect atmosphere-ocean-ice dynamics;
- Identifying how sea level rise will impact vulnerable infrastructure in the Arabian Peninsula generally and the UAE specifically, on an emirate-by-emirate basis; and
- Laying out a range of planning tools and options (i.e., a planning toolkit) to assist planners in the efforts to integrate sea level rise considerations into maritime plans.

In sum, this Primer can be considered a toolkit for action for confronting sea level rise. It is also important to note what this Primer does not cover – *it does not predict the increase in sea level in the Arabian Gulf nor does it include any analysis of the magnitude of the impacts of sea level rise scenarios for coastal areas in the UAE.*

The remainder of this Primer is organized in three parts. The next section offers scientific background on sea level rise, including a review of the causes of current sea level rise, and an overview of the status and challenges associated with international efforts to model sea level rise. Section 3 provides an overview of the Gulf region generally - and the UAE's specifically - regarding vulnerable infrastructure from sea level rise along the Arabian Gulf and Gulf of Oman. It aims to primarily characterize the types of infrastructure (e.g. power,

transport and other infrastructure) that would be vulnerable to sea level rise and secondarily the natural habitats at risk (e.g. mangroves, conservation land). Finally, Section 4 focuses on a toolkit for decision-makers, with part devoted to a review of the basic adaptation framework as used in several regional settings and the remainder a discussion of risk management approaches available for planning in the UAE context.

2. Understanding sea level rise

Over many millennia, the Earth's climate has cycled between ice ages and warm interglacial periods (Church et al., 2013; Cazenave, 2014; Church, et al., 2010). While the earth's climate has been relatively stable over the last several thousand years, this is now rapidly changing. Increasing concentrations of carbon dioxide and other greenhouse gases in the atmosphere are trapping heat and there is strong evidence that the climate has begun to respond. One of the major and certain consequences of climate change is rising sea level. This section of the Primer provides an overview of the current understanding of the various mechanisms contributing to sea level rise under climate change, together with an assessment of the capability of the current suite of models to capture these mechanisms adequately enough for having confidence in future sea level rise projections. The subsections below describe the most crucial factors for the UAE to be aware of regarding sea level rise from climate change.

2.1. Current sea level rise

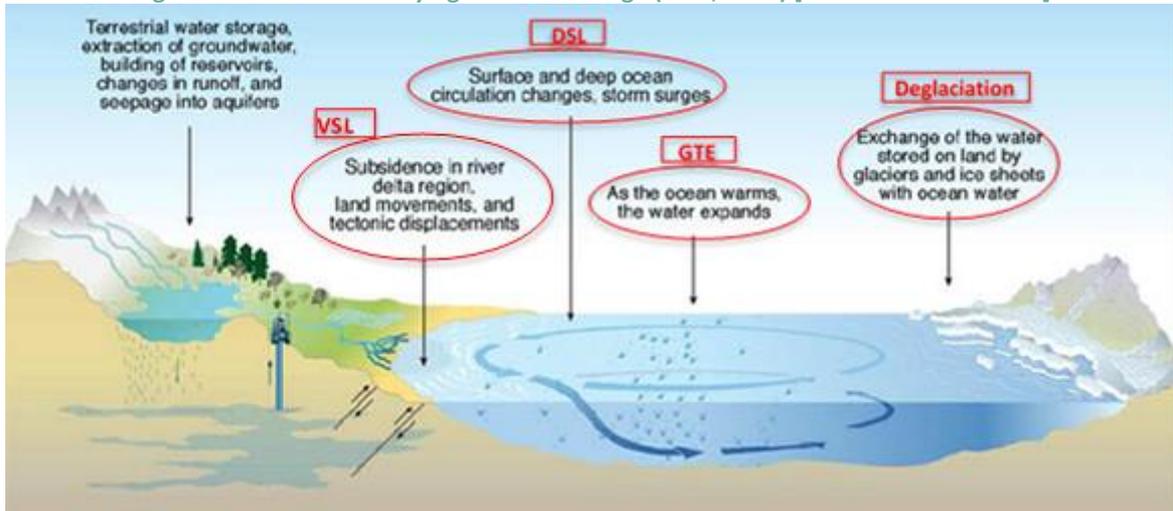
Increasing concentrations of carbon dioxide and other greenhouse gases in the atmosphere are trapping heat and the climate has begun to respond. One of the major and certain consequences is rising sea level, a process that has already begun. Prior to the 1990s, sea level was largely recorded by tide gauges fixed to coastal structures grounded in the solid Earth, showing over the last 2 centuries a rise of just over 1 millimeter per year. Beginning in the 1990s, satellites have provided near-global altimetry coverage of the ocean. Since then, both satellites and tide gauges have indicated a rise of about 3.2 millimeters per year (Church et al., 2013). Taking into consideration all sea level observations, the seas are not only rising, but accelerating (IPCC, 2007; ACE CRC, 2009).

Understanding the underlying causes of sea level rise that has been observed over the past decades is an important point of departure. There are a wide variety of processes that cause sea level to change on time scales ranging from hours to millennia, and spatial scales ranging from regional to global (Church et al., 2013; Kirshen and Wake, 2014). These are outlined in the bullets below, illustrated in Figure 2-1, and discussed in the subsections that follow.

- *Thermal effects:* The ocean warms or cools (because the density of water is closely related to its temperature),
- *Deglaciation effects:* Water is transferred between the ocean and glaciers/ice sheets, known as ablation

- *Gravity effects:* Shifts in Earth’s gravity field are induced by changes in the mass distribution on land (self-gravitation or static effect), and ocean and atmosphere dynamics (the dynamics effect).

Figure 2-1: Causes underlying sea level change (IPCC, 2007) [Red annotations ours]



- *Other effects:* These include vertical land movement effects that are associated with glacial isostatic adjustment, tectonic activity, groundwater mining, or hydrocarbon extraction; as well as terrestrial water storage.

2.1.1. Thermal effects

Thermal effects influence sea levels as water expands with increasing temperature (Church et al., 2013; IPCC, 2007; Yin, 2012; Antonov et al, 2005; Lombard et al, 2005). Simply put, with rising atmospheric temperatures due to increasing concentrations of greenhouse gases, oceans function as heat sinks that absorb this excess heat and mean sea levels rise to maintain atmosphere-ocean equilibrium. In other words, as ocean water heats up, it expands and takes up more space.

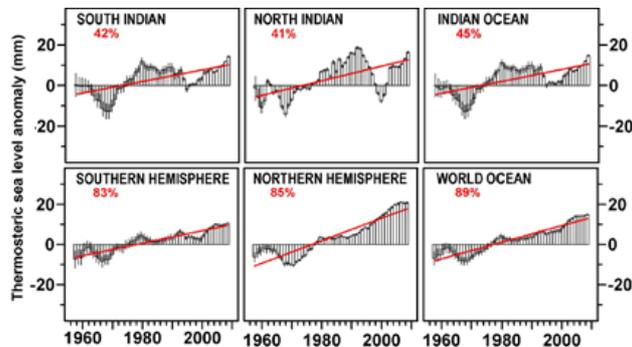
There is a time lag between the change in sea surface temperatures and the rise in sea level. That is, the heat capacity of the ocean is so large there will be a delay before thermal equilibrium is reached and thus before the full effects of warming are evident on sea levels (Pugh, 2004; IPCC, 2007; Church et al., 2013; Hassanzadeh et al., 2007). Warming atmospheric temperatures will continue to cause sea levels to rise far after any global greenhouse gas emissions and subsequent temperature stabilization scheme are reached. And, since the ocean stores a considerable amount of heat of the past climate, its response to global warming will be generally nonlinear (de Vries, et al., 2014). Termed “Global Thermal Expansion (GTE), it is a complex theoretical problem from a modeling perspective and an ongoing research issue that is trying to address diverse density effects within the ocean (Griffies and Adcroft, 2008; Griffies & Greatbatch, 2012).

There are good current estimates of the amount of sea level rise that can be attributed to global thermal expansion.

Levitus et al (2012) provided an update of previous estimates by Antonov et al (2005) regarding sea level change due to global thermal expansion. They conducted a detailed analysis of historical ocean temperature data from 1955-2010 using tide gauge and satellite data and concluded that thermal expansion of the ocean has led to an average rate of sea level rise of about 0.41 ± 0.04 mm per year for the upper 700-meter layer of the world's oceans.

This represents about a 25% increase over the earlier estimates by Antonov et al (2005) and reflects the use of additional satellite data available. As shown in Figure 2-2, comparing trends in the Indian Ocean and the World Oceans shows that there is significant spatial variation of the global rate of sea level rise rate, as well as the uncertainty associated with the estimated rate of seal level rise. Currently, it is estimated that somewhere between a third and one half of the past century's rise in sea levels can be directly linked to warmer oceans simply occupying more space (Griffies & Greatbatch, 2012; Levitus et al., 2012; Yin, 2012).

Figure 2-2: Sea level rise due to global thermal expansion (top: Indian Ocean: bottom: World oceans) for the period 1955-2010. Linear trend line and percent variance shown in red (adapted from Levitus, et al., 2012)



2.1.2. Deglaciation effects

Sea levels are also rising due to a process known as deglaciation (Church & Clark, 2013). This refers to a large number of melting and calving² processes (Church & Clark, 2013b) and roughly can be associated with ice melting processes associated with glaciers, Antarctic ice shelves, and Greenland ice sheets. As temperatures warm, glaciers retreat unless snow precipitation increases to make up for the additional melt. The decline in Arctic sea ice over the last several decades, both in extent and thickness, has been cited as evidence for rapid climate change (Church & Clark, 2013; Church & Clark, 2013b).

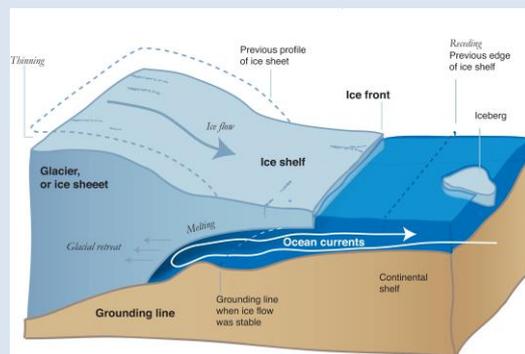
Melting and calving of land-based ice results in a major transfer of water and ice from the land into the oceans. This transfer of water to the oceans is a major contributor to global mean sea-level rise and has exceeded the contribution from thermal expansion over the past two decades (NRC, 2012; Church et al., 2013). The process of melting and calving is complex, and is briefly described in Box 2-1. Observations of rapid mass loss associated with dynamic change in the ice sheets have been brought to the public's perception through various dramatic episodes of ice calving reported in the press (see for example, <http://www.businessinsider.com/largest-ice-glacier-calving-filmed-2015-1>).

² "Calving" refers to the sudden release and breaking away of a mass of ice from a glacier, iceberg, ice front, or ice shelf.

Deglaciation processes can also be counterintuitive, as recent research into ice sheet dynamics has shown (Strzelecki et al., 2015; Robel and Tziperman, 2016). For example, as an ice shelf grows in area and thickness, it can buttress the inland ice, stemming its outflow. If this happens, the grounding line³ can stabilize or advance, thereby slowing sea level rise. On the other hand, if the grounding line retreats, sending inland ice further afloat, the shelf may begin a runaway collapse. As the grounded surface area of the outflowing glacier decreases, so does its friction against the bedrock, allowing it to flow with greater ease. It may also shorten as icebergs begin to calve off, possibly leading to complete shelf disintegration. This allows the inland ice to accelerate its flow into the ocean—and accelerate sea level rise. Indeed, when Antarctica’s Larsen B Ice Shelf collapsed in the early 2000s, the inland ice flow sped up nearly tenfold (Lindsay, 2002). Rapid retreat of the grounding lines of Pine Island, Thwaites, Haynes, Smith, and Kohler glaciers of West Antarctica has been documented since the early 1990s, showing rapid thinning and marine ice sheet instability that will significantly contribute to sea level rise in decades to come (Rignot et al., 2014).

Box 2-1: Deglaciation dynamics (adapted from National Snow and Ice Data Center)

A marine *ice sheet* is grounded on bedrock, below the surface of the sea. An ice sheet grows by receiving more snowfall at its surface than it loses by melting and outflow. As it grows in bulk, gravity begins to pull it downslope and into the ocean. Eventually, the leading edge forms a cantilevered *ice shelf* that floats on the water but remains attached to the anchored part of the ice sheet (Hanna et al., 2013; Holland and Holland, 2015). The transition from grounded ice sheet to a floating ice shelf is the so-called “grounding line” (see Figure below). Inland ice and meltwater that flows seaward past from the grounding line on the ice sheet makes a direct contribution to sea level rise. Ice that melts or calves from the ice shelf makes effectively no contribution to sea level rise because the ice is already floating.



Of greatest concern are contributions from the Greenland and Antarctic ice sheets because of the very large quantities of freshwater stored. Combined, these ice sheets contain the equivalent of about 64 meters of sea level rise; 58 meters for the Antarctic ice sheet and 4 meters for the Greenland ice sheet (Bamber et al., 2001; NSIDC, 2014). Since 1992, the melting of other glaciers (i.e., not including the Greenland and Antarctic ice sheets) have been responsible for about 30% of the observed sea-level rise, and the Greenland and Antarctic ice sheets are responsible for about 10% each (Church, et al., 2013). For these reasons, regional climate change now occurring in West Antarctica is a pressing concern for sea level rise. A West Antarctic meltdown would transform coastlines, affecting infrastructure and livelihoods in densely populated areas around the world. The deluge would also threaten fragile ecosystems such as mangroves, coral reefs, sea

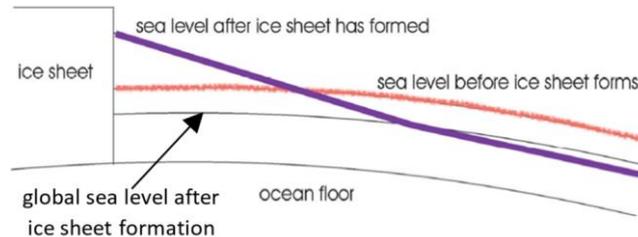
³ The “grounding line” is the point at which glaciers start to float (see Box 1).

grass meadows, and salt marshes—all of which provide the livelihood of many coastal communities (Barnes and Kaiser, 2009; Belchier, 2009).

2.1.3. Gravity effects

There are two important gravity effects that influence sea levels. First, the self-gravitation or static effect accounts for local land, ice, and water characteristics. Since ice and water have mass, ice and water on land will attract ocean water, literally pulling the ocean toward, for example, an ice sheet when it is formed. Consequently, sea level will be higher near an ice sheet rather than further away from it, all else being equal. This is illustrated in Figure 2-3.

Figure 2-3: Illustration of the self-gravitation effect (adapted from Kirshen and Wake, 2014)



On the other hand, when land ice melts and water mass is added to the ocean, it raises sea level by a small amount averaged over the whole globe. However, close to the ice mass itself (within about 3,000 km) it may cause a sea level fall by a reduction in the self-gravitation effect illustrated in Figure 2-3. The impact of self-gravitation on future sea level projections was ignored in early Intergovernmental Panel on Climate Change (IPCC) assessment reports (Kirshen and Wake, 2014; Kuo, 2006). Subsequent research has led to an increased understanding of how this component can help to explaining some of the vexing spatial differences in past sea level records, as well as working out the details of its impact in the future (Mitrovica et al., 2001). Incorporating these patterns, called ‘fingerprints’ into interpretations of paleo-sea level records has been essential in for understanding records that were previously difficult to reconcile (Kirshen and Wake, 2014).

The other gravity effect is associated with ocean dynamics (Howard et al., 2014; Levermann, et al., 2005). These dynamic effects account for mean sea levels rise that can differ from location to location at local spatial scales. This happens because the addition of freshwater from glaciers and ice sheets to the ocean leads to an instantaneous increase in global mean sea level, but because it is communicated around the ocean basins via a dynamical adjustment, it is not instantaneously globally uniform (Kawase, 1987; Cane, 1989). This change in spatial variation is potentially influenced by the interplay of changes in ocean dynamics and spatial variations in the seawater density due to its warming (Howard, et al., 2014), known as the change in dynamic sea level (DSL). For any given location, DSL is comprised of a global component associated with average sea level rise and a component associated with changes in the spatial variation of sea level relative to the global average (e.g. Milne et al., 2009; Pardaens et al., 2011). DSL changes are associated with the fluid dynamic state of the ocean as currents, density, boundary fluxes of mass and buoyancy (Griffies & Greatbatch, 2012) and account for a small portion of sea level rise, typically less than 15% of regional sea level rise (Yin, 2012).

2.1.4. Other effects

There are two other minor contributors to mean sea level rise. Local and regional vertical land movements result in regional changes in relative sea level (Church et al., 2013; Aubrey and Emery, 2013). Vertical land movement (VLM) is a generic term for all processes that impact the elevation at a given location (tectonic movements, subsidence, groundwater extraction), causing land to move up or down. This is typically a slow process with magnitudes commonly between -10 (sinking) and +10 (rising) mm/year (CLIMsystems, 2016). Local vertical land movement becomes relevant when looking at the local effects of sea level rise. VLM can either exacerbate or dampen the sea level rise experienced at a particular coastal location. In a place where VLM is upward like Norway (Weng, 2014), sea level rise is smaller. When VLM is downward like in the city of Manila (Aubrey and Emery, 2013), locally experienced sea level rise is stronger.⁴

Table 2-1: Contributions to global mean sea-level rise over 1993-2010 (adapted from Church et al., 2013; Table 13.1).

Contributor to sea level rise	Sea level rise (mm/year)	Share (%)
Thermal effects	1.1	34%
Deglaciation effects (Antarctica, Greenland)	0.6	19%
Deglaciation effects (other glaciers)	0.9	27%
Gravity and other effects	0.6	12%
“Unexplained”	0.3	8%
Observed global mean sea level rise	3.2	100%

Changes in terrestrial water storage can also affect sea levels (Kirshen and Wake, 2014; Gornitz, 2000). Large scale changes to Earth's surface by manmade activities during the past decades have impacted river runoff at continental-scales. This is important because a decrease in the amount of water stored on continents results in more water being stored in the oceans. Decreasing amounts of water stored on land is associated with groundwater extraction, draining of wetlands, or other changes in land cover that reduce soil moisture (e.g., deforestation) eventually results in additional water flowing into the ocean and causing sea levels to rise. On the other hand, an increase in the storage of water in reservoirs and artificial lakes diminishes the outflow of water to the sea. While the construction of dams during the 20th century significantly increased terrestrial storage of water, groundwater extraction is now equivalent to or larger than expanded surface water storage, resulting in a net zero or small positive contribution to sea-level rise in recent years from changes in terrestrial water storage (NRC, 2012; Church et al., 2013).

2.1.5. Summary

As the previous sub sections have shown, there are three main ways in which increasing concentrations of GHG in the atmosphere are causing sea level to rise. As air temperatures rise, water in the sea is also becoming warmer and expanding (i.e., thermal effects); mountain glaciers are retreating while polar ice sheets on Greenland and Antarctica are shrinking (i.e., deglaciation effects); and shifts in the mass distribution on land and oceans (i.e., gravity effects). The relative contribution of each of these effects is summarized in Table

⁴ See Section 3.2 for a review of VLM for the Arabian Peninsula.

2-1. Notably, the sum of the estimated contributions to sea level rise do not adequately explain the observed rise, leading to the “unexplained” category in Table 2-1. Possible reasons for this discrepancy include the inadequate ocean database, particularly for the deep and Southern Hemisphere oceans, leading to an underestimate of ocean thermal expansion, and inadequate measurements of the cryosphere (Kirshen and Wake, 2014; Holland and Holland, 2015).

2.2.Future sea level rise

Predicting future sea-level rise is an important issue related to the continuing buildup of atmospheric greenhouse gas concentrations. The Greenland and Antarctic ice sheets, with the potential to raise sea level nearly 70 meters if completely melted, dominate uncertainties in projected sea-level change (Alley, et al., 2005; Kopp et al., 2014; Church et al., 2013). Interpreting past changes in sea and projecting future changes requires sophisticated numerical modeling using coupled ice-atmosphere-ocean general circulation models. While substantial advances have been made, these models are widely known to poorly represent the complex interactions between the atmosphere, the cryosphere, and the ocean environment (Alley et al., 2005; Church, et al, 2013; Holland and Holland, 2015). This section reviews the progress and key limitations of past modeling approaches, some the key challenges ahead, and an update of the current status of coupled ice-ocean-atmosphere models.

2.2.1. Progress and key limitations of past sea level rise modeling

Projecting future changes in mean sea level has been based on coupled atmosphere-ocean general circulation models. Such models allow the simulated climate to adjust to changes in climate forcing, such as increasing atmospheric carbon dioxide. Until the early 1990’s, climate models did not consider ice dynamics and treated ice sheets as shallow snow fields with prescribed representative topography, and ignored soil ice altogether (Bitz and Marshall, 2013). Cryosphere modeling (i.e., frozen water found on land and in water) evolved in parallel with, but independent of the global climate models to predict sea level rise.

Philippe Huybrechts was the first to develop an operational three-dimensional thermomechanical ice sheet model in the late 1980s (Huybrechts, P & Oerlemans, 1988; Huybrechts, 1990). The Huybrechts model has been used to study and characterize the Greenland and Antarctic Ice Sheets and underpins the projections of ice sheet response to climate change in the IPCC reports (Bitz and Marshall, 2013). Similar models have now been developed in several research groups, and sea-ice intercomparison experiments have been carried out to evaluate model strengths and weaknesses (Payne, et al, 2000).

The five IPCC Assessment Reports have synthesized results of modeling efforts from the CMIP process. In all five IPCC reports, sea level projections have been assembled using conventional methods of estimating sea level rise – that is by simulating contributions from individual sea level components, such as thermal expansion, and melting ice from glaciers and ice sheets (Jevrejeva et al., 2014). As shown in Figure 2-4, each of the IPCC reports has produced a wide range of projections for sea level by 2100. In AR4, there were four main

physical processes that the models used did not adequately treat, namely the response of floating ice shelves to climate change; the connection between floating ice shelves and flow in the ice sheets; the nature of rapid flow in ice streams and outlet glaciers; and the effect of water at the base of the ice sheet on ice flow (ACE, 2009).

In AR5, the difficulties in modeling ice mass loss from the Greenland and Antarctica ice sheets have persisted.

This has led to an explicit acknowledgement with the report itself that: “. . . the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause sea level to rise substantially above the likely range during the 21st century. This potential additional contribution cannot be precisely quantified but there is medium confidence that it would not exceed several tenths of a metre of sea level rise” (Church et al., 2013).

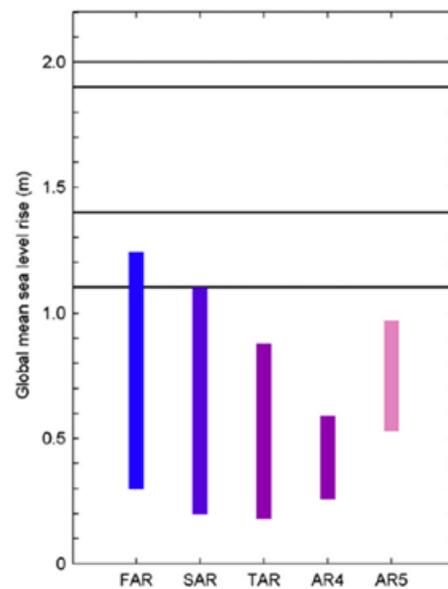
The situation today is that there is still no robust, credible model for the interaction of melting ice sheets with the ocean to improve sea level rise estimates (Holland and Holland, 2015; Bitz and Marshall, 2013).

The low-order glacier models implemented in global climate models to date are based on a simplified representation for ice sheet flow, which is not well-suited to ice shelves, ice streams, and ice sheet margins. This is why the IPCC’s sea level rise projections are reported as being of “medium confidence” only, implying a 33% probability that future sea level rise will lie outside the stated range. As noted above, this is largely due to difficulties in projecting ice mass loss from the Greenland and Antarctica ice sheets but is also due to the difficulty of adequately representing contributions from the over 120,000 glaciers around the world. While there has been significant progress in sea level change research in general since AR5, numerical modeling of the glacier-ocean interactions remains at an early stage and will require further study (Holland and Holland, 2015; Little et al., 2014; Liu et al., 2013).

2.2.2. Key modeling challenges

Recent ice-ocean modeling development efforts are focusing on higher-order solutions of ice dynamics and glacier stress and strain regimes (Pattyn et al., 2008; Price et al., 2008; Jaroush, 2008). In parallel, as will be described in the next subsection, there are community-scale programs that are seeking to couple more sophisticated, high-resolution ice sheet models into global climate models building off the Glimmer ice sheet model developed at the University of Bristol and elsewhere (Rutt et al., 2009). It is important to note, however, that fully-coupled global climate models continue are still in their infancy due to the complex modeling challenges involved (Bitz and Marshall, 2013).

Figure 2-4: Range in the IPCC’s global mean sea level rise projections in 2100 under the high emission scenarios (Jevrejeva et al., 2014)



Specifically, there are three main challenges regarding the coupled ice-ocean modeling of melting of the Greenland and Antarctica ice sheets (Richardson et al., 2011; Holland and Holland, 2015; Church et al., 2010). First, the kinds of observational data needed for building which ice-ocean coupled models is currently incomplete. While satellite remote sensing has greatly facilitated the monitoring of glacier surfaces, data on the nature of the bed upon which the ice sheet rests has proven more difficult to obtain. This is important because it defines the forces affecting the migration of the grounding line and subsequent marine ice sheet instability (Payne et al., 2000; Calov et al., 2010). Moreover, observations of the ocean waters at the periphery and beneath glaciers have been difficult to acquire (Vaughan, 2013; Holland, 2013).

Second, there is a gap in knowledge about the physics of deglaciation. While there seems to be a reasonably good understanding of the way that outlet glaciers reaching the ocean disintegrate by melting (Luthi et al., 2013), there is far less known about the physics of calving (Batholomaeus and Bassis, 2014; Murray et al., 2015). There is ongoing debate about the share of Antarctic mass loss is due to calving (as opposed to melting where the glaciers meet the ocean). However, there is ample evidence and broad consensus that it is substantial (e.g., Jakobshavn glacier in Greenland which removed 12 square kilometers of ice in one day). With rapid glacier retreat, it is likely that a large fraction of the loss would be due to calving. With the process of calving poorly understood, modeling of that process remains challenging leading to uncertain sea level projections (Holland and Holland, 2015).

The third major challenge is simply the computational burden of modeling ice-ocean interactions. Computational limitations mean that coarser grid resolution (i.e., around 100 km) have needed to be used, which have had the effect of misrepresenting flowing ice streams (Holland, 2000). That is, because slower flowing ice cannot contribute as rapidly to sea-level change, coarse grid spacing can cause models to respond more slowly than actual ice sheets. Furthermore, actual ice sheets transmit longitudinal stress perturbations (i.e., along the long axis) almost instantaneously, but inland-ice models do not incorporate this effect well. Accordingly, such ice-sheet models may underestimate actual rates of change. Finally, to adequately simulate ice sheet retreat and calving, simulated oceans must change their vertical and horizontal extents as the ocean invades the space occupied by the ice sheet and receives meltwater from the glacier (Charbit et al., 2002). This requires extensive reengineering of existing global climate models (Holland and Holland, 2015) as well as the need for much greater computing power (Cornford et al., 2012).

2.2.3. Advances in coupled ice-ocean-atmosphere models

The Coupled Model Intercomparison Project (CMIP) began in 1995 to coordinate atmosphere-ocean general circulation modeling efforts and has evolved over time. In its Fifth Assessment Report (AR5), the IPCC's CMIP-5 protocols and related publications describe a rather complex research status on modeling mean sea level rise indicating the use of a combination of hydrodynamic approaches for modeling some variables and a combination of semi-empirical and statistical approaches for modeling other variables (Church & Clark, 2013b; Griffies & Greatbatch, 2012; Yin, 2012). Previously, ice sheets were not explicitly

included in the CMIP process and separate modeling studies had to be used to make projections of their future contributions to sea level, leading to mismatches between the climate data used to force these models and the contemporary version of the CMIP projections (Nowicki, 2016).

Widely reported rapid mass loss of ice sheets have sharpened the need to couple ice sheets with the rest of the climate system. A better understanding of the role of sea ice for the changing climate of the planet is one of the central aims of the ongoing phase of this process – the diagnostic Coupled Model Intercomparison Project 6 (CMIP6). Within CMIP6, there is an endorsed working group that is focused exclusively on ice and ocean interactions called the Sea-Ice Model Intercomparison Project (SIMIP). SIMIP aims to better understand how sea ice works and evolves in the coupled climate system of the planet (Notz et al., 2016; Nowicki et al., 2016).⁵

SIMIP is currently underway and is seeking to combine model simulations with observations in order to advance the understanding of interactions between ice, air, and ocean in the models. The plan is to compare modeling results with the observational record. This would then enable data-based conclusions of whether model simulations are capturing behavior observed in the real world and when they are not, identifying ways by which agreement can be improved. Ultimately, the results of the SIMIP process are intended to allow for more realistic simulations of the sea-ice cover, including more robust projections of its future evolution and relationship to sea level rise. During 2016, the work of SIMIP has focused on convening a series of workshops to bring sea-ice modeling and observing expertise together. It is important to note that the process is essentially just getting underway. It is anticipated that the results of the SIMIP process will be incorporated into the next IPCC Assessment Report, AR6, which is expected to be released in three working group contributions during the 2020-2021 time period (IPCC, 2016), with the Summary for Policymakers report published sometime in 2022.

Preliminary findings emerging from the various modeling activities currently underway within the SIMIP process suggest that some models are getting better at modeling ice-ocean interactions. For example, the Community Ice Sheet Model (CISM) is a next-generation ice sheet model used for predicting ice sheet evolution and sea level rise in a changing climate (Price et al., 2015). Developed at the Fluid Dynamics and Solid Mechanics division at the Los Alamos National Laboratory, the model is freely available to the glaciology and climate modeling communities and serves as the ice dynamics component of the Community Earth System Model (CESM), one of the General Circulation Models included in the CMIP process. CISM builds off the earlier Glimmer ice sheet model developed by Rutt et al (2009). The model has been used in experiments to mimic the dynamic changes observed on Greenland's three largest outlet glaciers, Jakobshavn Isbræ, Helheim Glacier, and Kangerdlugssuaq Glacier during the 2000s. As shown in figure 2-5, there is reasonably good agreement regarding the ice flow velocity as observed (left) and modeled (right).

⁵ Additional details are available at <http://www.climate-cryosphere.org/activities/targeted/simip>

3. Sea level rise and coastal zones

Future sea level rise represents a major threat to infrastructure including roads, telecommunication systems, buildings, and industrial facilities, all of which are important elements of the current and planned built environment. The UAE and Gulf states may be more vulnerable to sea level rise than most regions of the world due to particularly high concentrations of population and economic activity in coastal zones. This section of the Primer provides an overview of the regional coastal environment, focused on the Arabian Gulf, plus a brief overview of the major infrastructural elements of each emirate in the UAE.

3.1. Regional coastal environment context

The physical impacts consequences of sea level rise can be broadly classified into three categories: erosion, flooding, and saltwater intrusion (Nicholls, and Cazenave, 2010; Titus and Barth, 2001; Nicholls et al., 2011; Hussain and Javad, 2016). The most obvious consequence of a rise in sea level would be permanent flooding (inundation) of low-lying areas. Coastal areas with sufficient elevation to avoid inundation would be threatened by erosion or shoreline retreat. A rise in sea level alters the relationship of the shore profile to the water level. When combined with storm surge, sea level rise it has the capability of sharply eroding unprotected shorelines. Gradual and instantaneous sea level rise will also lead to seawater intrusion processes in coastal aquifer systems with different levels of land-surface inundation.

An overwhelming majority of the Arabian Gulf region's inhabitants are coastal dwellers and a dominant share of economic activity occurs in inundation-vulnerable, urban centers that are at risk from these impacts. Many coastal residents and economic activities can be found in areas that are backfilled or reclaimed from the sea for development projects. These areas are valuable commercial property and are particularly vulnerable to SLR impacts because of their low elevation above sea level. Moreover, coastal population growth and tourism patterns, already expanding rapidly, are likely to continue, further exacerbating coastal zone vulnerability to climate change.

Historically, sea levels in the shallow Arabian Gulf have been rising at rates that exceed the global average. Based on tide gauge data analyzed in the IPCC's Fourth Assessment Report, the average rate of global average sea level rise during the period 1961-2003 was about 1.8 mm/yr (IPCC, 2007). While comprehensive assessments are not available for the entire Arabian Gulf, an analysis of tidal gauge data in the western part of Arabian Gulf near Bahrain shows average sea level rise rate to be about 2.27 mm/yr over the 1989-2008 period (Ayhan and Alothman, 2009). One outstanding feature of the coastline along the western and southern coast of the Gulf is its extremely low relief, only about 35 cm per km, which amplifies the effect of even small increases in sea level. This is evidenced by the presence of extensive intertidal areas and coastal salt flats (sabkha), often several kilometers in width and many kilometers long.

Recent extreme storm events in the Arabian Peninsula region may be harbingers of future climate change. In 2007, the Gulf experienced the strongest cyclone on record for the Arabian Sea. Cyclone Gonu (see Figure 3-1). At category 5, Gonu had wind speeds that peaked around 240 km/hour, produced heavy rainfall near Oman’s eastern coastline, reaching up to 610 mm, and caused flooding and heavy damages (NASA 2007). With climate change, the intensity, frequency, and geographic scope of regional cyclone generation and subsequent storm surges may pose new systematic risks to coastal areas in the Arabian Peninsula. The development of new disaster risk management strategies, as discussed in the next section of this Primer, may be necessary to cope with such emerging threats.

In AR4, the IPCC was cautious concerning the potential change in frequency of cyclonic activity under climate change (IPCC, 2013).

This was attributed to the some of the same data availability and other issues discussed in the previous section of this Primer. That is, “... there is low confidence in attribution of changes in tropical cyclone activity to human influence. This is due to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity, and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings.” (IPCC, 2013). However, the IPCC goes on to indicate that “... the frequency of the most intense storms will more likely than not increase substantially in some basins ...” including the west Asia region in where the GCC countries are located. However, while it is currently inconclusive regarding the likely changes in *frequency* of cyclones in the region, it is almost certain that an increase in sea surface temperature will be accompanied by a corresponding increase in cyclone *intensity*, due to the additional heat accumulated in the air-ocean system.

Increasing sea surface temperature can lead to higher peaks of storm surges and a greater risk of coastal disasters. Changes in both the moist static stability of the atmosphere and the underlying sea surface temperature may be the critical determinants of the possible

Figure 3-2: Observed and modeled ice flow velocity fields in the Greenland glaciers (Price et al., 2011)

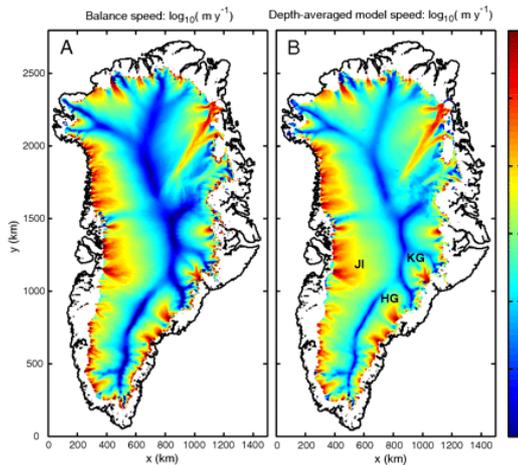


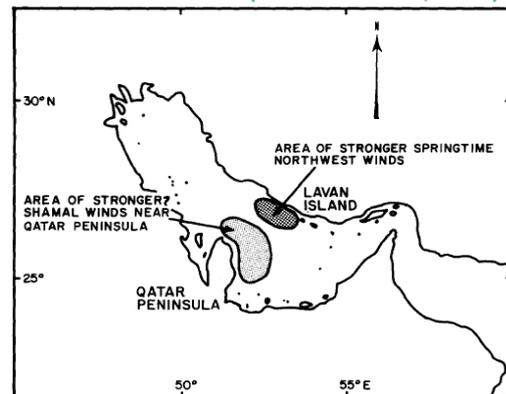
Figure 3-1: Tropical Cyclone Gonu churns off the coast of Oman. (Source: NASA Earth Observatory)



variations of the maximum potential intensity of stronger than normal northwesterly winds known as “Shamals”. Shamal cyclogenesis, the generation of high-velocity winds and even cyclones from strong Shamal winds, is another factor in storm surges that could be experienced in greater magnitude in Qatar under climate change (see Figure 3-1). During one well-defined winter shamal event in the past, sea levels increased by 10-20 cm in the eastern half of the Arabian Gulf, with sea levels increasing by 20-30 cm in the coastal shallows of the UAE (Thoppil and Hogan, 2010). Shamal systems, in combination with climatic changes in atmospheric pressure, sea-surface temperature, coastal topography, and tidal effects, could result in higher peaks of storm surges and a greater risk of coastal disasters. Hazards from storm surges will only get worse as sea levels rise and coastal populations expand.

Throughout the Arabian Gulf region, there are a variety of types of coastal protection measures in place. Some of the “hard” coastal protection measures and options are identified and discussed in Section 4 of this Primer. However, there are numerous types of natural habitats, typically described as “soft” measures, which provide important coastal protection services under current and future seal level rise. The extent and capability of natural habitats to protect the coastline are discussed and documented in a separate sub-project of the LNRCCP and are available in the online Coastal Vulnerability Inspector.⁶

Figure 3-3: Area of stronger than normal northwesterly winds (Shamal) and higher wind-induced waves (Fencel and Klein, 2009)



3.2. National coastal environment context for the UAE

The United Arab Emirates adjoins both the Arabian Gulf and the Gulf of Oman (see Figure 3-4). The UAE’s western coast is aligned with the south-eastern end of the Arabian Gulf, and on the eastern side of the UAE is a smaller coast along the Gulf of Oman. The entire coastline of the UAE, along both the Arabian Gulf and the Gulf of Oman is approximately 1,318 km. This does not include the coastline of the many offshore islands, nor does it include the additional length of coast resulting from the many developments consisting of land reclaimed from the ocean.

⁶ For more information about the Coastal Vulnerability Index sub-project and its links with sea level rise, please contact the AGEDI Climate Change team at lnrclimatechange@ead.ae.

The characteristics of the Arabian Gulf coastline differ significantly from those in the Gulf of Oman (Hellyer and Aspinall, 2005). The coastline along the Arabian Gulf is much longer and is typically characterized by sandy low-lying coastal sabkhas and islands whereas the coast along the Gulf of Oman is rockier. Moreover, there has been strong socioeconomic growth since the UAE's founding 1971, with most of this development concentrated along the Arabian Gulf coastline.

The Arabian Gulf itself is an inland body of water connected by the narrow Strait of Hormuz to the Gulf of Oman which is open to the Indian Ocean. Under climate change the Arabian Gulf is expected experience large increases in sea surface temperatures well as changes in salinity and circulation patterns. The extent of these changes has been modeled as part of a separate sub-project of the LNRCCP and are available in the online Regional Ocean Modeling Inspector. In addition, the impact of desalination on Arabian Gulf waters has been modeled as part of another sub-project of the LNRCCP and is available in the online Desalination and Climate Change Inspector.⁷

In the future, deglaciation and global thermal expansion are the components of sea level rise that will most affect the waters around the UAE. Gravity effects (i.e., shifts in Earth's gravity field induced by land mass redistribution and ocean/atmosphere dynamics) are projected to be negligible, as learned through the LNRCCP's regional ocean modeling sub-project. Vertical land motion (VLM) is also projected to be negligible, as reported by the limited observations in the region from the Système d'Observation du Niveau des Eaux Littorales (SONEL) initiative available at <http://www.sonel.org>. SONEL aims at providing high-quality continuous measurements of sea- and land levels at the coast from tide gauges (relative sea levels) and from modern geodetic techniques (vertical land motion and absolute sea levels) for studies on long-term sea level trends, but also the calibration of satellite altimeters.⁸

Figure 3-4: Map of UAE Arabian Gulf and Gulf of Oman coastal zones (source: www.zu.ac.ae/)



The potential exposure of the UAE to the impacts of sea-level rise, given the current socioeconomic conditions and projected population increases in coastal areas, is significant. Sea level rise will potentially impact the entire extent of the UAE's natural and built environment along the coast. Current shoreline

⁷ For more information about the Regional Ocean Modeling and Desalination and Climate Change sub-projects and its links with changing physical properties of the Gulf, including dynamic sea level rise, please contact the AGEDI Climate Change team at lnrclimatechange@ead.ae.

⁸ The two closest gauges to the UAE are in Bahrain and Oman. Both show that vertical land motion trends between -0.5 mm/yr and 0.5 mm/year; essentially inconclusive.

protection measures to protect vital infrastructure will likely be inadequate under future sea level rise since such measures have been designed under conditions of a stable climate. Natural habitats (e.g., seagrasses, mangroves) are also likely to be adversely affected. Low-lying and shallow grade shores along the Arabian Gulf coastline imply high inundation risk to the natural and built environment. Moreover, sea level rise coupled with higher magnitude storm surges along the Gulf of Oman coastline threaten the built environment. Taken together, sea level rise poses important nationwide policy questions regarding current and future development plans and investment decisions for each emirate. The extent of coastal infrastructure at risk from sea level rise is briefly discussed in the subsections below for each emirate. Except for Abu Dhabi, the red-shaded areas in the orientation maps at the beginning of each subsection focus on the coastal extent that is considered to have the highest concentration of population and infrastructure at risk within the individual emirates. In the subsections below, individual emirates are being addressed since there are no emirate-specific policies in place regarding sea level rise.

3.2.1. Abu Dhabi



Abu Dhabi is the largest emirate thus it has the longest coastline of any emirate. It lies to south and west, starting at the UAE-Saudi Arabian border and extends to just south of Jebel Ali in Dubai. The Abu Dhabi has many off shore islands and natural habitats that can protect the coast from storm surges and extreme wave events. Many of these islands host coral reefs that also protect coastline by dissipating wave energy. There are several offshore reefs along the

western end of the coast. A few mangrove stands exist on the leeward side of these islands, with large stands of mangroves around the city of Abu Dhabi. Sea grass also exist in the calmer waters between the islands and the coastline.

A large concentration of important infrastructure exists along the Abu Dhabi emirate coastline that is exposed to future sea level rise. The E 11 Coastal Highway runs along the coast from the border with Saudi Arabia, through Abu Dhabi and on to Dubai. Most of this highway system is in near proximity to the shoreline of the Gulf (i.e., within 3 km). In the Western Region, there is the refinery complex of Ruwais, one of the larger refinery complexes in the world, situated directly on the coast. The city of Abu Dhabi itself is situated on a low-lying island which is about 7 meters above sea level. Numerous islands (for example Yas Island, Saadiyat Island) have experienced rapid development in recent years, as has the coastline behind Abu Dhabi and north eastward along the coast. Building infrastructure at risk from climate change includes office and residential high-rises, schools, desalination and electrical generation plants, shopping malls and hospitals.

3.2.2. Dubai



The coastline of Dubai is shorter than that of Abu Dhabi. The total Dubai coastline is about 60 km, although new offshore projects are expected to add significantly more coastline that would be exposed to sea level rise impacts (e.g., the Dubai waterfront project, Palm Jebel Ali). Much of Dubai's coastline has been developed, the port of Jebel Ali in the south, to the city of Dubai in the north. The southernmost coast of Dubai south of Jebel Ali is undeveloped with the Dubai Marine Sanctuary located at the Dubai – Abu Dhabi border. The Palm Jumeirah is an artificial archipelago jutting out into the Arabian Gulf whose construction began in 2001, with dense concentration of residential and tourist infrastructure. The level of the island is four meters above mean high tide, with sea level rise of 50 cm incorporated into its design, plus an additional buffer to protect against tides, storm surges and high seas, with (Morris, 2010).

Much of Dubai's infrastructure and buildings are located either on the coastline or into the Gulf and will be exposed to future sea level rise. Port Rashid and Port Jebel Ali, Dubai Drydocks, the iconic Burj Al Arab Hotel, Dubai Federal Hospital and numerous hotels/resorts are located directly on the waterfront. The Dubai International Airport is located about 3 km away from the coastline. Nevertheless, this and other infrastructure along the coast is surrounded by hard coastal protection structures (i.e., breakwaters) that rise from 3 to 4.25 meters above mean sea level. Nevertheless, property and infrastructure valued at hundreds of millions of dirhams is in place that is at risk given the uncertainties in sea level rise projections.

3.2.3. Sharjah



Sharjah is the only emirate to front both the Arabian Gulf and the Gulf of Oman. It also surrounds the emirate of Ajman, resulting in two separate coastlines along the Arabian Gulf. The southern coastline, between Ajman and Dubai is completely developed. The northern coast, between Ajman and Umm Al Qawain, contains less infrastructure, although the town of Al Hamriya lies in this region. Like most of the UAE Arabian Gulf coast, Sharjah is located on a coastal sabkha plain around the inlet, Khor Khail which terminates in a coastal lagoon. Two other lagoons are at the southern end of Sharjah, Al Khan Lagoon and Al Mamzar Lagoon.

The northern coast of Sharjah is sand beach and sabkha, with a large inland waterway project spanning the Sharjah - Umm Al Qawain border. Numerous resorts and hotels line the shores of Sharjah as well as important cultural sites. These include the Central Souq, Sharjah Art Museum and Heritage Area, the Islamic Arts and Culture building and Crystal Plaza. Port Khalid and the Dubai – Sharjah Highway are both at risk as the highway runs within proximity of the three lagoons. During a recent storm event,

Sharjah's Corniche was flooded from the impact of 3-meter high waves forcing the closure of the road (Arthur & Garland 2016). Al Hamriyah to the north has its port, power station and free zone authority which are at risk from sea level rise induced flooding events. The main inlet is fringed with marinas and surrounded by warehousing, shipyards, and industrial facilities. Just north of this inlet is Al Hamriya's Khor that is surrounded by residential and retail properties.

3.2.4. Ajman



The smallest of all the emirates, Ajman's capital city, Ajman, is built around the Khor Ajman and extends along its entire coastline. Benefitting from its proximity to Dubai and Sharjah, Ajman has also seen rapid development having many high-rise buildings and touristic infrastructure. At the northern end of Khor Ajman are large mangrove stands with minimal infrastructural development surrounding it. This area is ringed by major transport routes that are set back less than 200 meters away. To the south lie currently undeveloped lands, while on the other side lies the southern arm of the Khor comprising port facilities and ancillary industries, including warehousing areas such as the Ajman drydocks, and Ajman Free Trade Zone. The southern shore of Ajman has several large resorts and has been extensively developed with residential, office and retail buildings in the immediate vicinity of the shoreline.

3.2.5. Umm Al Qawain



Umm Al Qawain is situated on a small low-lying peninsula that extends northward into the Arabian Gulf and lies just north of the border with Sharjah. Beyond the capital district, there are approximately 25 km of mostly open coastline that consist of sabkah areas, tidal flats and salt marshes. As the currents flow north and east along the coast, sediments have been deposited behind this peninsula creating many near shore sandy barrier islands, such as the barrier island of Sinaiya, which protects an extensive intertidal zone that has been recognized as being of international importance to migratory waterfowl (UAE Interact).

The barrier islands protect most of Umm Al Qawain's shoreline from the large waves that are generated during shamal wind events during the winter season. Residential, commercial and tourist properties cover the peninsula while the E-11 highway passes within a kilometer of the shoreline in several places. New bridges allow the E-11 highway to pass over the tidal flats easing natural water flows in support of the health of tidal flats in the area. A small port facility has been built within the protection of mangroves and barrier islands is subject to sea level rise risks.

3.2.6. Ras Al Khaimah



The Ras Al Khaimah emirate has the most geologically complex coast resulting from the proximity of the Hajar mountains which add sediments and alluvial fans to the coastal plain. The wider southern portion of the plain is covered by sand dunes, the plain narrows to north where the Hajar mountains eventually meet the Gulf (Goudie et al. 2000). Land reclamation projects in the south attached a small island, in which the town of Jazirat was located, to the mainland. A land reclamation project of Marjan Island is similar to some of the large urban development zones elsewhere in the UAE. Several barrier islands protect mangroves and a portion of Ras Al Khaimah

city.

The old city of Ras Al Khaimah is built on a low-lying extension of sand that is backed by Khor Ras Al Khaimah. This inlet terminates in a large coastal lagoon that contains a large mangrove forest. The Saraya islands are long near-shore barrier islands extending north for approximately 7 km and protect northern neighborhoods of Ras Al Khaimah from storm surge during Shamal events. The Ras Al Khaimah Maritime city surrounds an artificial inlet with Saqr port, which is the largest bulk port facility in the region. The coastal plain narrows from the port to the border with Oman. There are mangrove stands that are ringed by transport and building infrastructure. The coast of Ras Al Khaimah is heavily developed putting government buildings, schools, residences, commercial developments and resorts that will be at risk from future sea level rise.

3.2.7. Fujairah



Fujairah is located along the eastern shore of the UAE. Facing the Gulf of Oman, landforms are characterized by sedimentary deposits from the Hajar Mountains with more rocky soils and with less sand. This coastline is open to the Arabian Sea. The Hajar Mountains descend to the coast with just narrow strips of coastal plain utilized for development. The city of Fujairah is the only large city along this coast, it has port facilities that can accommodate cruise ships, container ships and oil tankers. A pipeline from Abu Dhabi to Fujairah resulted in expansion of this important facility. Built on the

west coast, ships can avoid the narrow Straits of Hormuz that is already one of the busiest shipping lanes in the world.

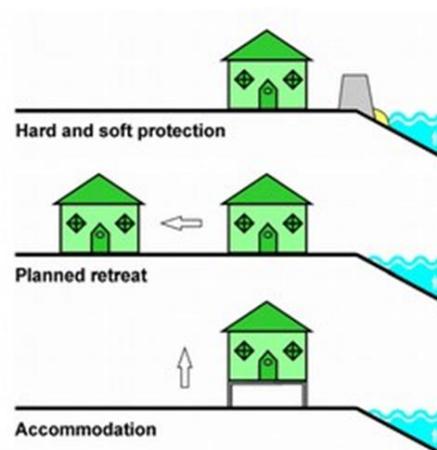
The narrow coastal plain has seen much development; several large-scale resorts are on the northern coast close to the town of Dibba. In addition to the port, the city of Fujairah contains several important facilities that may be at risk from sea level rise in the Gulf of Oman. These facilities include large oil storage and exporting facilities, warehousing and industrial developments built around the port. The large Fujairah integrated electrical and desalination plant is situated on the coast at the northern end of Fujairah which is the largest desalination hybrid plant in the world. This coast was greatly affected by tropical cyclone Gonu that travelled along the Gulf of Oman in 2007 causing severe flooding once it reached Fujairah.

The road from Fujairah to Kalba was closed to flooding, waves were reported to be as high as 10 meters. With sea level rise, these type of storm surges will pose higher risks for flooding and other storm-associated damages.

4. Framework for decision-making

This section of the Primer offers a tool-kit for coastal decision-makers charged with making future plans under the threat of sea level rise. The tool-kit is structured into three subsections. The first subsection presents an overview of commonly employed adaptation measures and policies. The second subsection presents an overview of the adaptation process and illustrates this with a couple of adaptation frameworks as used in several regional settings. The third subsection then zooms into one step of the adaptation process, the adaptation options appraisal, and presents decision making frameworks relevant for the appraisal of coastal adaptation options.

Figure 4-1: Possible adaptation measures to address sea-level rise.
Source: (Brown et al., 2013)



4.1.Coastal adaptation measures

A diverse variety of coastal adaptation measures is available. On a basic level, three types of adaptation measures are available, as illustrated in Figure 4-1 and described in the bullets below (Klein et al., 2001; Nicholls et al., 2007):

- *Protection measures*, which are defensive measures and other activities that physically protect areas against inundation, tidal flooding, the effects of waves on infrastructure, shore erosion, salinity intrusion and the loss of natural resources. Protection measures may be ‘hard’ or ‘soft’ structural solutions (see Section 4.1.1.).
- *Accommodation measures*, which are measures involving the continued occupancy and use of coastal zones and do not prevent the land from being flooded. Instead, accommodation measures increase people's ability to cope with the effects of extreme events. Accommodation measures include erecting emergency flood shelters, elevating buildings on piles, converting agriculture to fish farming, or growing flood- or salt-tolerant crops. The majority of farms in the UAE are not adjacent to UAE shorelines.
- *Retreat measures*, which are measures involving a withdrawal from the coast. This can be either proactive and planned, or reactive and unplanned in the form of a forced retreat. Retreat measures reduce potential effects of erosion or flooding by limiting coastal exposure (i.e. population, assets, infrastructure, etc in the floodplain). This may involve preventing development in coastal areas, or allowing development to take place on the condition that it will be abandoned if necessary.

Adaptation strategies adapted in a location generally combine different adaptation measures. Protection measures can, for instance, be installed inland including a retreat measure in the overall adaptation strategy. Further, there are measures that cannot be assigned exclusively to one category. For example, land reclamation could be implemented as a protection measure as well as an accommodation measure.

4.1.1. Protection measures

Protection measures aim to physically protect areas vulnerable to coastal flooding and erosion. While protection measures in general must be implemented proactively, provisional measures (dams made from sand-bags etc.) might be implemented in a reactive way. Hard structural measures and soft structural measures are distinguished. Hard structural measures utilize structures that provide a solid barrier between the land and sea and resist the energy of the tides and waves, thus preventing land-sea interaction from taking place (French, 2001). These measures are illustrated in Figure 4-2 and briefly described in the bullets below.

Figure 4-2: Examples of shoreline protection measures



- *All forms of sea dikes or levees:* The primary function of sea dikes is to protect low-lying, coastal areas from either temporary inundation through extreme sea-level events (storm surges, tropical cyclones, etc.) or permanent inundation due to sea-level rise.
- *Seawalls, revetments, bulkheads:* In contrast to dikes, the primary function of seawalls is to prevent further erosion of the shoreline. Nevertheless, they have a secondary function as coastal flood defences.
- *Groynes:* Groynes protect against coastal erosion. While seawalls are built parallel to the shoreline, groynes are built orthogonal. In contrast to seawalls, they do not provide the additional benefit of flood defence.
- *Detached breakwaters:* Detached breakwaters are defence structures built parallel to the shoreline. In contrast to seawalls they are built in the sea. Breakwaters have the primary function of breaking waves and thus prevent erosion and protect fragile coastal infrastructures (e.g. marinas). Off-shore breakwaters, coastal breakwaters and beach breakwaters are distinguished by their distance to the shoreline which can vary from 10 to 1,000 meters.
- *Tide- and flood-gates:* Gates are adjustable flood defences used to control water flow. Gates can be closed on demand to stop water flow during extreme events.

- *Saltwater intrusion barriers:* flow barriers to control seawater intrusion on coastal groundwater systems. These barriers may be built below surface.

While hard defenses prevent natural forces from interaction with the protected area, soft engineering technologies are integrated into natural processes to avoid the negative impacts of hard defenses. While hard measures are often an ad-hoc reaction to coastal hazards, soft measures are a shift towards a more holistic and proactive approach. Some of the key soft measures are described in the following bullets:

- *Beach nourishment:* Beach nourishment is the artificial addition of sediment of suitable quality to a beach area that has a sediment deficit. As an adaptation measure, it is primarily used to fight shoreline erosion. Nevertheless, flood reduction may be an additional benefit of beach nourishment.
- *Dune restoration and/or creation:* Dune restoration and/or creation refers to the restoration of natural or artificial dunes into a better state of overall function, in order to maximise coastal protection. Artificial dune construction and dune rehabilitation are technologies aimed at reducing both coastal erosion and flooding in adjacent coastal lowlands.
- *Wetland restoration and/or creation:* Wetland restoration and/or creation for coastal protection is most commonly applied to salt marshes and mangroves. As with dune restoration, wetland restoration aims at both reducing both coastal erosion and flooding.

The economics of the soft versus hard alternatives depend upon several factors. These include the historic erosion rate; relative grain size of the material from where the fill comes from, and the cross-sectional volume and length of beach fill. Soft alternatives aim to maintain a flexible shoreline location and natural beach conditions even at the end of the design life, thereby maintaining many of their environmental and recreational services.

4.1.2. Accommodation measures

Accommodation measures involve the continued occupancy and use of low-lying zones by increasing communities' ability to cope with extreme events. Accommodation measures must be implemented proactively as they require advanced planning. As with protection measures, we can distinguish between hard and soft accommodation measures. Hard measures include all technologies which involve physical changes to accommodate increased flooding and erosion. These are briefly described in the bullets below.

- *Land raising:* Land raising or land reclamation has the primary objective of creating flood-proof areas, usually by filling low-lying areas with, for example, sand or soils.
- *Flood-proofing of buildings and infrastructure:* The primary objective of flood-proofing is to reduce or even avoid impacts of coastal flooding on buildings or infrastructure. Flood proofing measures include elevating buildings/structures, employing designs and building materials which make them more resilient to flood impacts and waterproofing buildings. Flood-proofing is often combined with insurance, which can be designed to provide incentives for households or businesses to take flood-proofing measures.

- *Improved drainage systems.* Introducing or improving drainage systems has the objective of creating flood-proof areas by reducing flooding due to water-logging. Improved drainage systems are integral to any accommodation strategy. See for example: <http://www.ucsusa.org/global-warming/global-warming-impacts/tidal-flooding-sea-level-rise-miami-dade-county-florida#.WH5u8xsrKUK>

Soft accommodation measures include all measures which enhance understanding and awareness of coastal risks and enable coastal populations to undertake appropriate responses to extreme events. This section of the primer seeks to highlight the range of options; the next section of the primer seeks to provide a framework for choosing among them, given national circumstances. Some of the most notable soft measures are described in the following bullets.

- *Flood hazard mapping:* Flood hazard mapping defines those areas which are at risk of flooding under extreme conditions. Its primary objective is to reduce the impact of coastal flooding, although mapping of erosion risk areas is also possible. Flood hazard mapping enhances understanding of flood risk and informs further accommodation measures in high risk areas.
- *Flood warning systems:* Flood warning systems are a means of detecting flood events in advance. The public is thus warned so that appropriate actions can be taken to reduce exposure to coastal flooding.
- *Insurance systems:* Insurance systems are an accommodation measure that aim at enabling population of vulnerable areas to cope with the economic impacts of flood events. Insurance systems can be combined with other accommodation measures. For example, a home-owner may receive a reduction of insurance costs, if they implement flood-proofing measures on their properties. Insurance can however also be used as a retreat measure. For instance, risk-based insurance increases the insurance cost for property owners with greater flood risk exposure, thus, providing incentives to locate properties out of the flood-plain.
- *Emergency planning:* emergency planning aims at coping with flood events once they occur. It is usually combined with flood warning systems. While the flood warning system informs about an upcoming event, the emergency plan implements the reduction of exposure to the event.

4.1.3. Retreat measures

Retreat measures include all forms of withdrawal from the coast and thus reduce exposure to flooding and erosion. Retreat measures limit the potential effects of erosion or flood events. Retreat may be carried out reactively as a response to existing threats as well as proactively as an adaptation to future conditions. Reactive retreat measures involve:

- *Unplanned retreat in response to an extreme event:* Unplanned retreat is a response to an extreme event. Inundated areas are left by inhabitants and not repopulated again.

- *Managed realignment:* Managed realignment is the deliberate process of altering flood defenses to allow flooding of a previously defended area. This often involves the relocation of houses and infrastructure as well as the installation of new defenses. The land that is abandoned is often transformed into wetland (salt marshes), thus managed realignment usually also reduces flood risk by enhancing coastal protection.

In contrast, proactive retreat measures try to steer development away from the coastal zone to avoid creation of exposure in areas which will be at risk of flooding or erosion under future sea-level rise (SLR). These measures involve the following:

- *Setback zones:* Coastal setbacks define a prescribed distance to a coastal feature (for instance the highest shoreline during spring tides), within which development is limited or prohibited by regulation (Cambers, 1998; Rochette et al., 2010). Setback zones can be defined in terms of horizontal distance (to reduce erosion risk) or elevation (to reduce flood risk).
- *Land use plans:* retreat measures can take the form of changes in land use plans. If coastal land that was formerly planned for settlements is reclassified as agricultural land, further development is avoided and thus exposure to coastal events is minimized.

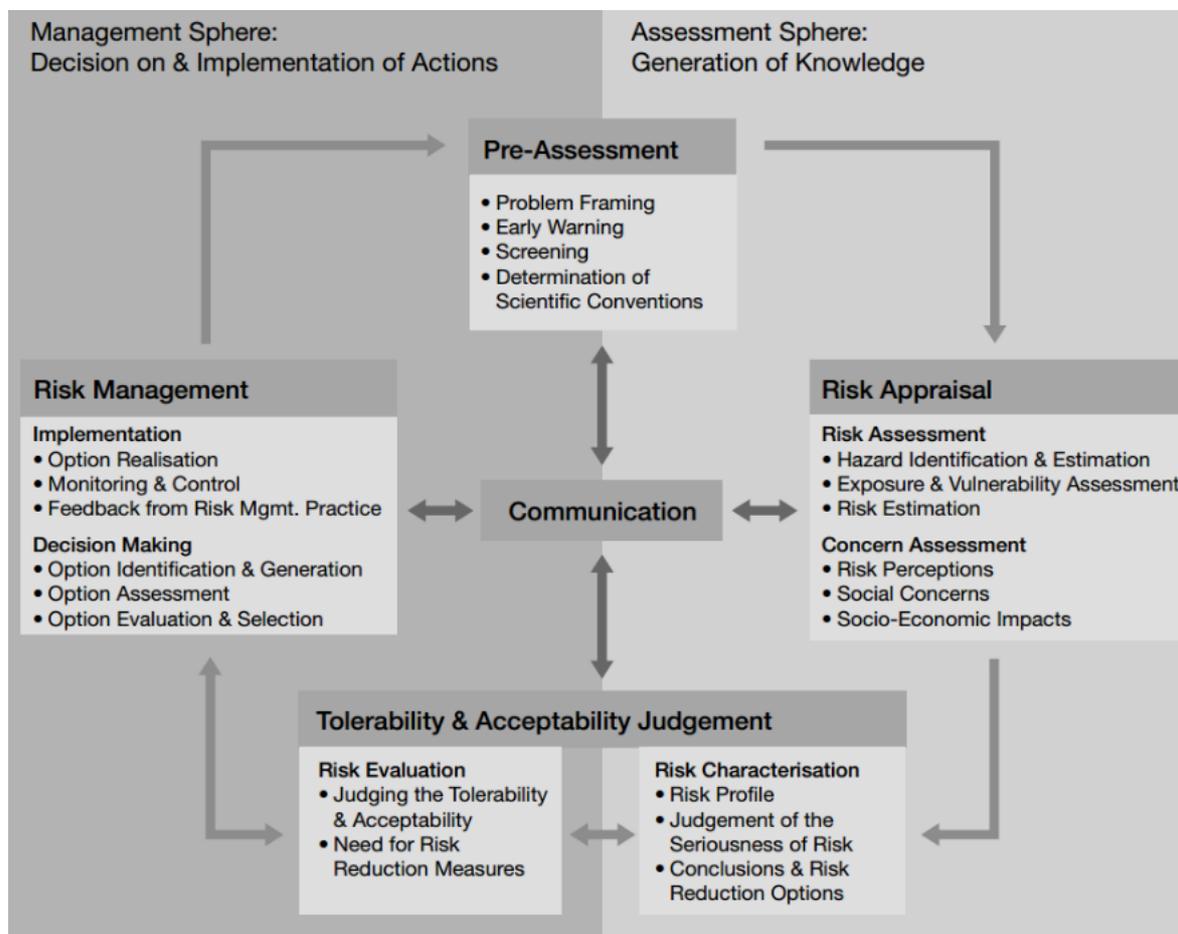
4.2. Adaptation frameworks

A wide variety of frameworks for the adaptation process have been developed and applied in diverse regional settings. Despite this variety, there is wide agreement that this process in an iterative learning process involving several generic stages that can be summarized as follows (PROVIA, 2013):

- *Identifying adaptation needs* (vulnerability, potential impacts and adaptive capacity). The goal at this stage is to gain more knowledge about the risks and opportunities faced with in given context. Which impacts may be expected under climate change? Are the vulnerable actors aware of the threat? What are the major decisions that need to be addressed?
- *Identifying adaptation measures.* The goal of this stage is to identify adaptation measures that could potentially be applied.
- *Appraising adaptation options.* The goal of this stage is to decide between alternative adaptation options or strategies (i.e., combinations of measures).
- *Planning and implementing adaptation options.* The goal of this stage is to implement the options.
- *Monitoring and evaluation.* The goal at this stage is to monitor the implementation process and the outcomes achieved, to evaluate what was done and to learn from the experiences gained.

Below we illustrate these broad stages with the help of three prominent adaptation frameworks and highlight some of their specific features and emphasis.

Figure 4-3: The risk governance process. Source: IRGC (2005)



4.2.1. UKCIP Risk, Uncertainty and Decision making Framework

The UKCIP Risk, Uncertainty and Decision making Framework (UKCIP, 2003) is one of the most prominent frameworks specifically dedicated at climate change adaptation (see Figure 4-3). There are several important characteristics of the framework. It is circular, and suggests the assessment should be repeated as new information becomes available. Feedback and iteration are encouraged, thus the problem, objective and decision-making criteria can be refined. Stages 3, 4, and 5 are intended to allow the decision-maker to differentiate between climate and non-climate factors and decide whether a more detailed analysis is necessary.

4.2.2. The Adaptation Support Tool of the European Climate Adaptation Platform

The European Commission and the European Environment Agency (EEA) have partnered to produce a European Climate Adaptation Platform (Climate-ADAPT). The platform contains an Adaptation Support Tool which aims to “assist users in developing climate change adaptation policies by providing guidance, links to relevant sources and dedicated tools.” (European Environment Agency, 2013). The support tool is based on the stages model of the

policy cycle, and emphasises that adaptation is an iterative process meaning that users are encouraged to re-consider different steps as necessary. This is done “. . . in order to ensure that adaptation decisions are based on up-to-date data, knowledge and policies [...] and will also allow monitoring and timely assessment of successes and failures and encourage adaptive learning.” (European Environment Agency, 2013).

The tool builds on and borrows from the UKCIP Adaptation Wizard and various risk assessment frameworks. The steps in the Adaptation Support Tool are as follows: 1) Getting started; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 5) Implementation; and 6) Monitoring & Evaluation.

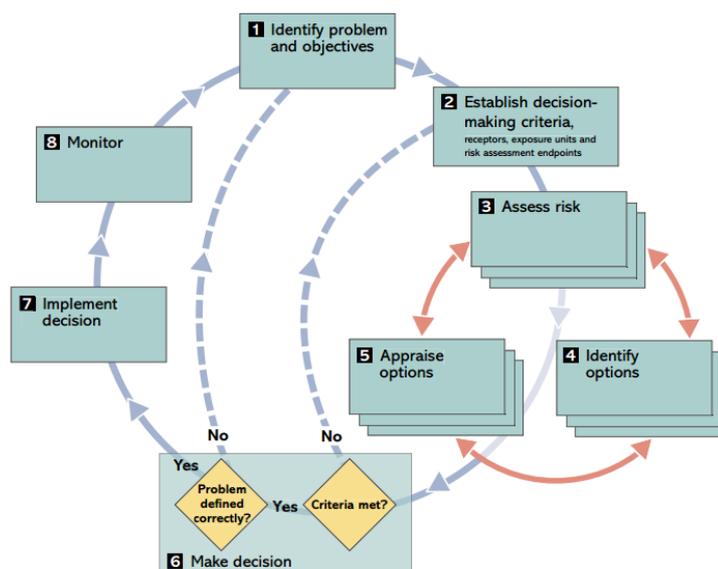
4.2.3. IRGC risk governance framework

Risk governance extends beyond the classical framing of risk management and climate change adaptation in that it also includes the wider societal, institutional and cultural context in which the risk and adaptation occur. It applies the principles of good governance (such as transparency, effectiveness, efficiency, and acceptability) to the domain of risk management (Jaeger et al., 2001) and emphasizes how diverse people think about and respond to risks (Slovic, 1987). Hence, a prerequisite for “good” risk governance means understanding “the complex web of actors, rules, conventions, processes and mechanisms concerned with how relevant risk information is collected, analyzed and communicated, and how management decisions are taken.” (Renn, 2008 p.9).

Concerns about the lack of capacity to cope with these major disasters has led to foundation of the International Risk Governance Council (IRGC) and the development of the IRGC risk governance framework (IRGC, 2005). This framework draws upon the literature and experiences of decades of risk research and risk management practice and is as response to the increasingly interconnected and complex challenges associated with major risks societies are facing. The IRGC conceptualizes risk governance in the following four iterative phases (see Figure 4-4):

- The *pre-assessment* phase aims to capture the variety of issues associated with a risk and to establish a common understanding of

Figure 4-4: The 8 Steps of the UKCIP adaptation framework (Source: Willows and Connell, 2003)



these amongst all relevant actors, with a particular emphasis placed on diverse framing of the issues. This step also includes an analysis of the risk governance institutions and arrangement currently in place such as monitoring networks, early warning systems, emergency response teams, contingency plans, compensation and insurance schemes, etc.

- The **risk appraisal** phase aims at providing the knowledge base for the societal decision on how to deal with the risk. This comprises both a scientific assessment of the physical attributes of risk (hazard, vulnerability and risk quantification) as well as an assessment of the social concern and questions associated with the risk.
- The **risk characterization and evaluation** (called “Tolerability and Acceptability Judgement” in Figure 3 phase aims at judging whether the risk is acceptable or tolerable. Risk characterization refers to the relevant scientific evidence and risk evaluation to the value-judgement of relevant stakeholders.
- Finally, the **risk management phase** aims at deciding and implementing appropriate risk management options. Risk management options are assessed against a wide variety of criteria such as effectiveness, efficiency, external side effects, sustainability, fairness, ethical acceptability and public acceptance.

Risk communication is relevant throughout all of the four phases aiming at fostering mutual understanding amongst all actors involved as well as tolerance for conflicting views. It is important to note that the IRGC framework is not a one-size fits all prescription but a collection of strategies, methods and tools whose applicability depends on the context, because the risk governance process must be flexible and open to adaptation for the specific context of each risk (Renn, 2008).

4.3. Risk management approaches

The previous subsection presented frameworks that cover the whole adaptation process. This current subsection now focuses on so-called risk management or decision making frameworks which may be appropriate for the step of appraising coastal adaptation options in the UAE planning context. All of the 4 subsections included in this section address an important aspect of risk management. Their treatment is presented at a foundational level (i.e., informative but non-exhaustive).

Generally, adaptation options should be assessed against all available knowledge. This includes all uncertainties and ambiguities amongst expert opinions and their distinct approaches, because considering uncertainty and ambiguity only partially may misguide the choice of adaptation options, which in turn may lead to maladaptation (Jones et al., 2014; Renn, 2008). In the case of long-term coastal decision making that accounts for future sea level rise, two main uncertainty dimensions need to be considered:

- Uncertainty in mean and extreme sea-level changes, including global and regional climate-induced mean sea-level rise, local vertical land movement (due to glacial-isostatic adjustment, tectonics, land subsidence), changes in tides, surges and waves.

- Uncertainty in socio-economic development, including population development, economic growth, price of capital for investments, etc.

4.3.1. Types of coastal decisions

No general recipe can be given on which decision analytical framework to use for coastal adaptation because this depends on the specific adaptation decision confronted with (Hinkel and Bisaro, 2014; PROVIA, 2013). For selecting an appropriate decision-making framework, the following two criteria need to be considered:

- **Risk preferences:** Those who decide and those affected by the decision may have different preferences towards climate risks and these need to be taken into account when selecting decision making frameworks and relevant climate and socio-economic scenarios. The more risk-averse people are the more extreme and unlikely scenarios need to be considered in adaptation decision making. This is generally the case if the value at risk is high. For example, people living in coastal areas with high densities of populations and assets are generally very risk averse and hence decision making must also consider high-end sea-level rise scenarios that are unlikely to occur (Hinkel et al., 2015; Lowe et al., 2009).
- **Decision horizon:** The choice of scenarios and decision-making frameworks also depends on the length of the decision horizon. Long-term decisions, which are decisions involving options with long lead and life times, require different approaches and scenarios than shorter-term decisions. For example shorter-term decisions may ignore emission scenario uncertainty but not necessarily socio-economic uncertainty, because the former only becomes relevant beyond 30 years into the future.

Figure 4-5: Different kind of coastal adaptation decisions in terms of risk aversion and decision horizon)

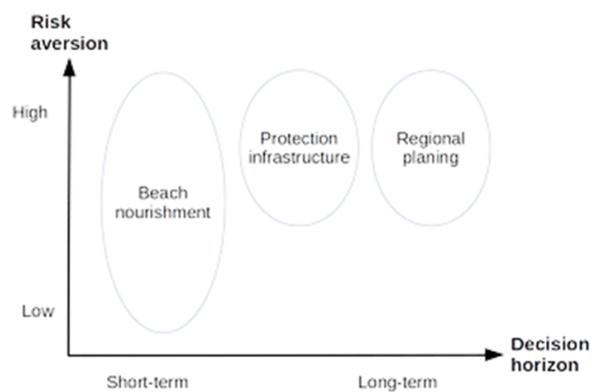


Figure 4-5 characterizes some coastal decisions according to those two criteria. Major coastal water works such as storm surge barriers, for example, may take a decade or two to plan and implement and coastal infrastructure and land-use planning decisions may have effects the last several decades or even over a century.

4.3.2. Decision making frameworks

Decision analysis is a wide field including a great variety of methods that may be applied for assessing adaptation options. Here, we limit ourselves to presenting four general criteria and associated frameworks that are relevant for appraising coastal adaptation options.

- **Maximization of expected utility:** Widespread approaches for decision-making under uncertainty are based on the maximization of expected utility of some sort. These include

cost-benefit analysis (CBA), cost-effectiveness analysis (CEA) and minimization of net present value etc. These approaches applied under uncertainty rely on the calculation of the mathematical expectation of the effects of the adaptation options in terms of reducing costs, impacts or losses. This requires the availability of a probability distribution over all possible outcomes of a chosen option, either monetary (for CBA) or otherwise (for CEA).

- **Minimization of losses or impacts under the worst-case scenario (Minimax):** An alternative approach is to minimize (or avoid all) losses or impacts under the worst case scenario that could possible happen. In this so- called Minimax approach, all adaptation options are assessed against the worst-case scenario, instead of against an average case attained by computing the expected utility as done in the former approach.
- **Robustness of options under all scenarios:** A further alternative framework for decision making under deep uncertainty (i.e. without probabilities), is robust decision making, which aims at finding adaptation options that are *robust* against all (or most) scenarios (Lempert and Schlesinger, 2001, 2000). In this case, each option is evaluated against each scenario. The evaluation may use a variety of criterion including cost-benefit ratio or cost-effectiveness ratio. Note that using the cost-benefit or cost-effectiveness ratio for evaluating an option *within* a single scenario is not identical to applying CBA or CEA as decision-analysis method for choosing between options as described above.
- **Flexibility of options under all scenarios:** A further decision-making criterion that becomes relevant for decision making under deep uncertainty is flexibility, which aims at keeping future options open by favoring flexible options over non-flexible ones (Hallegatte, 2009). An option is said to be *flexible* if it allows to switch, at low cost, to other options that might be preferable in the future once more information is available about the changing climate. For example, beach nourishment is a flexible option to reduce flood risk, because it can be abandoned, without much cost, at any point in the future. On the contrary, building dikes is less flexible because of large upfront investment costs. Flexible decision-making is applicable if a decision can be broken down into steps (that is not everything needs to be decided today) and additional information may become available in the future, which is the case for many long-term sea-level rise decisions. In fact, there is often no need to have the full information about 21st century SLR today (Hinkel et al., 2015). While building defenses and establishing other adaptation measures does take time, this can usually be done much faster than sea-levels rise. Thus, a sound strategy can be to (1) invest in measures that keep an area safe in the near term (say to 2030) and keep longer-term options open; (2) monitor sea level and the emergence of new SLR scientific over time, and based on this, (3) update the assessment and implementation of longer-term options, as appropriate.
- **Adaptation pathways:** The adaptation pathways approach, for example, combines both the criteria of robustness and flexibility. It does so by characterizing options in terms of two attributes: i) adaptation turning points (ATP), which are points beyond which options are no longer effective (Kwadijk et al., 2010), and ii) what alternative options are available once a turning point has been reached (Haasnoot et al., 2012). Importantly, the exact time

when an ATP is reached does not matter, it is rather the flexibility of having alternative options available. Prominent applications of this approach include the Thames Estuary 2100 Project (Environment Agency, 2012, Ranger et al., 2013) and the Dutch Delta Programme (Kabat et al., 2009, Stive et al., 2011). The Thames Estuary 2100 Project and the adaptation pathway approach applied are discussed in Box 1.

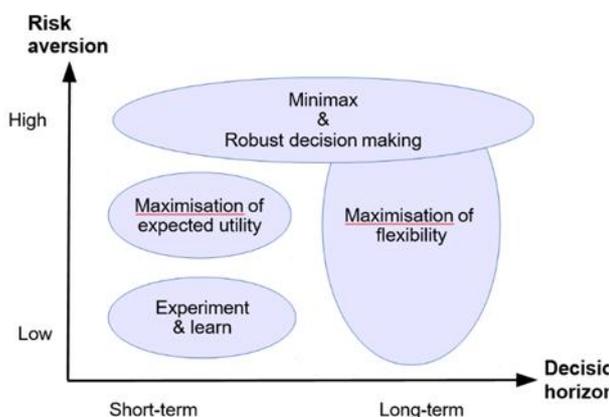
4.3.3. Choosing a suitable decision making framework

Figure 4-6 summarizes the applicability of the decision-analysis frameworks reviewed above based on the two characteristics of the adaptation situation introduced earlier in this section of the Primer. For low to medium risk and short-term decisions, the maximization of expected utility is a suitable decision making approach, if probabilistic forecasts of the climate hazard (here, sea-level rise) is at hand. In this case, expected losses, impacts or net present values could be computed and standard approaches for decision making under uncertainty such CBA or CEA could be applied. For example, consider a municipality deciding on beach nourishment to protect eroding beaches. This decision might be informed through probabilistic information on extreme-water levels. Based on this information, damages for different extremes may be simulated to calculate the yearly expected loss of sand and to derive an annual demand of sand to be applied in nourishment.

Alternatively, if the risks are very low and the decision horizon is very short, it would also be possible to experiment & learn without assessing adaptation options ex-ante. Experimentation means to take adaptation action, monitor the outcome and then adjust the option ex-post once impacts have begun to occur. Coming back to the above beach nourishment example, the municipality could also simply start by applying a given amount of sand in the first year and then update this amount in subsequent years, based on the observed effectiveness of nourishment in previous years. This kind of approach is in line with the adaptive management paradigm (Holling, 1978, Walters, 1986), and often applied in the managements of coastal ecosystems (e.g. Walters, 1997).

For long-term climate adaptation decisions, the maximization of expected utility is no longer possible, because probabilistic forecasts of the climate hazard (here, sea-level rise) are not available any more, which means that mathematical expectations cannot be computed. Long-term information on climate hazards can only be provided in the form of scenarios (without probabilities attached), because the magnitude of the climate hazard depends on a greenhouse gas (GHG) emission scenario assumed and for these it is difficult or, not desirable, to derive probabilities, both in theory as well as in practice (Lempert and

Figure 4-6: Applicability of decision-making framework in terms of two characteristics of the adaptation decisions



Schlesinger, 2001, Hallegatte, 2009). For short term decisions, this can be neglected, because GHG scenario uncertainty is small. For longer-term decisions, GHG scenarios uncertainty is significant and can not be ignored, which means that probabilistic forecasts can be attained and expected utility approaches cannot be applied. Instead, approach for deciding under deep uncertainty (without probabilities) such as *Minmax or robust decision making* or must be used. If the decision can be broken down into steps, a further important consideration for long-term decision making is the flexibility of the options applied. In this case, the *adaptation pathways* approach, which combines both the criterion of robustness and the criterion of flexibility, is a suitable approach.

Generally, when facing *high-risk decisions*, it is not advisable to apply an approach based on the maximization of expected utility. The goal of high-risk decision making is to avoid major damages under all circumstances. An adaptation strategy developed based on, e.g., minimizing mathematical expectation of damages may not full fill this goal. The specific focus of high-risk decision making must therefore lie on the tail-ends of what could possible happen under climate variability and change, in order to make sure that people are prepared in the worst case to come. *Robust decision making and Minimax* are suitable approaches.

4.3.4. Choosing suitable sea-level rise scenarios

Choosing an appropriate sea level rise scenario is central to coastal planning and decision making under climate change. For *low-risk* decision making, sea level rise scenarios that cover the middle range of sea-level rise uncertainty for each emission scenario, such as the IPCC scenarios, are applicable. For *high-risk, long-term* sea-level rise decision making, however, the single most important piece of information is the upper tail end of possible sea-level rise during the decision horizon.

Towards this end, the IPCC scenarios are not helpful, because they have not been designed for high-risk decisions (Hinkel et al., 2015). As noted earlier in this Primer, the likely range of the IPCC scenarios means that there is a 0-33% probability of global mean SLR lying outside of this range, which is not tolerable from a risk-averse perspective. Deriving high-end sea-level rise scenarios is not a straight forward exercise, because there is no generally accepted way of doing so. The AR5 authors have concluded that the current state-of-knowledge does not allow to come up with such a worst-case scenario (Church et al., 2013). High risk management thus needs to proceed by pragmatically approximating such as worst case. This can be done, for example, by combining the maximum values of all components of global and regional/local sea-level rise. The very risk averse decision maker could also add an additional safety margin on top of this. Generally, the more risk averse planners and decision makers are, the wider the range of sea level rise scenarios that should be considered.

For global mean SLR, this would mean to consider all plausible runs of process-based models and also the other approaches of semi-empirical models, physical constraints on ice-sheet dynamics and evidence from past climate. This approach has, for example, been taken by Nicholls et al (2014) to develop what is termed H++ scenario range, which includes a worst case 21st SLR of 2.4 meters. For a detailed description of a comprehensive approach to constructing a worst case scenario for London, including regional and local mean sea-level change components, as well as extreme sea-level, see the report on the Thames Estuary 21000 Project (Environment Agency, 2012), which is briefly described in Box 4-1.

5. Next steps

The preceding sections have provided an overview of the various elements related to climate change induced sea level rise that planners in the UAE and the surrounding region will likely confront in the years ahead. It is important to note

that the Sea Level Rise Primer is a redesign from the original intent of sub-project #8 of the LNRCCP which called for a regional study focusing on a quantitative assessment of the impact of sea level rise on the extent of land inundation. Ideally, the results of Sub-project #2 on regional ocean modeling of the Arabian Gulf under climate change would have served as direct inputs into the intended tool for the analysis. However, the regional ocean modeling study could directly estimate only the dynamic sea level rise component - the smallest of three contributors to sea level rise (see discussion in Section 2) - and found only up to 10 cm of dynamic sea level rise by the late 21st century. Hence, the original option of using these outputs to directly model sea

level rise impacts on Arabian Gulf countries would necessarily lead to negligible impacts from climate change, a misleading result at best. Hence, over the course of several internal meetings, it was decided to redesign the sub-project to focus on the development of a Sea

Box 4-1: Thames Estuary 2100 Project

The considerations of high-risk coastal decision making and planning are well illustrated in the Thames Estuary 2100. (TE2100) Project, which developed strategies for keeping London dry during the 21st century. One core motivation for the TE2100 Project was concern that accelerating sea-level rise would not allow sufficient time to upgrade or replace the Thames Estuary Barrier, because such large engineering tasks require 25–30 years for planning and implementation (Wong et al., 2014). The Thames Estuary Barrier was built after the severe North Sea flood of 1953 to prevent storm surges entering the Thames Estuary and flooding London. This project considered initially a local 21st century sea-level rise of about 4m as an upper bound for decision making attained through expert judgement based on linearly combining current high-end estimates of the components of 21st century sea level (Environment Agency, 2012, Ranger et al., 2013). Later, this upper bound was replaced with a high-end scenario of 2.7m (which also includes allowance for larger surges during extreme events), attained through a pragmatic combination of insights from observations of average rates of sea-level rise during the last interglacial period taken from (Rohling et al., 2008), physical arguments presented in (Pfeffer et al., 2008), as well as uncertainties in downscaling and regional and local factors. Through the application of the adaptation pathway approach, the project found that there is sufficient time to postpone the decision of upgrading the Thames Estuary Barrier, because there is an adaptation pathway (i.e. a sequence of measures) that can be realized even in the worst case of rapid sea-level rise. Furthermore, it was found that there are alternative adaptation pathways which are more attractive should sea-level rise be lower.

Level Rise Primer whose purpose would be to improve the awareness of policymakers and planners in the Arabian Gulf region generally, and the UAE specifically, on how to begin addressing the prospects of future sea level rise, given the current limitations in regional ocean modeling. As the preceding sections have shown, this represents a non-quantitative approach to the issue of sea level rise focusing on a qualitative discussion of the range of assessment and planning issues.

Nevertheless, the preceding sections are a first step in equipping regional planners for future sea level rise. As an interface between sea level rise - a topic that is highly technical and multi-faceted - and planners/decision-makers, the Primer should ideally be considered as a “working document”. That is, as knowledge evolves on modeling sea level rise and it becomes clearer what the magnitude of the risks to the UAE, the Primer could be updated to reflect this new information. Specifically, several questions/areas are worthy of attention in the months and years ahead, as briefly outlined below.

- Are there any relevant research gaps at the local / regional level? Is there a need develop a local / regional research agenda to support adaptation? What are some of the relevant models that could be applied?
- What is the current state of SLR monitoring locally / regional and of impacts? Is there a need to develop a local / regional monitoring program (perhaps more broadly that SLR)? What are some of the strategies being applied elsewhere?
- Based on other work (regional modeling or desal study), are there any relevant linkages to salinity or PH modeling or perhaps biodiversity loss that might be relevant for local / regional consideration? For example, is there a need to assess cumulative impacts (perhaps within the risk assessments)?
- What are some of the governance models being applied to coordinate SLR adaptation (e.g. ICZM programs, climate science boards)

6. List of References

- Alley, R. B., Berntsen, T., Bindoff, N. L., Chen, Z., Chidthaisong, A., Friedlingstein, P., Somerville, R. (2007). IPCC- AR4 - Summary for Policymakers. Assessment Report 4 - IPCC.
- Alothman, A. O., Ayhan, M. E., & Arabia, S. (n.d.). Detection of Sea Level Rise within the Arabian Gulf, using space based CNSS Measurements and insitu Tide Gauge data: preliminary results (pp. 1–12).
- Antarctic Climate & Ecosystems (ACE), 2009. "Position analysis: polar ice sheets and climate change: GLOBAL impacts," Cooperative research Centre.
- Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC), 2008, *Position Analysis: Climate change, sea-level rise and extreme events: impacts and adaptation issues*. PA01
- Antonov, J., Levitus, S., and Boyer, T., 2005. "Thermosteric sea level rise, 1955-2003", *GEOPHYSICAL RESEARCH LETTERS*, VOL. 32, L12602.
- Bamber, J.L., Layberry, R., and Gogenini, S., 2001. "A new ice thickness and bed data set for the Greenland Ice Sheet 1: Measurement, data reduction, and errors", *Journal of Geophysical Research*, **106**, 33,773-33,780.
- Barnes, D. and Kaiser, S., 2009. "FISHERIES AND AQUACULTURE – Melting of Polar Icecaps: Impact on Marine Biodiversity", British Antarctic Survey, N.E.R.C., High Cross, Madingley Road, Cambridge, UK
- Brown, S., Nicholls, R.J., Woodroffe, C.D., Hanson, S.E., Hinkel, J., Kebede, A.S., Neumann, B., Vafeidis, A.T., 2013. Sea-level rise impacts and responses: a global perspective., in: C.W. Finkl (Ed.): *Coastal Hazards*. Springer, Netherlands, pp. 117–149.
- Calov, R., Greve, R., Abe-Ouchi, A., Bueler, E., Huybrechts, P., Johnson, J., Pattyn, F., Pollard, D., Ritz, C., Saito, F., and Tarasov, L., 2010. "Results from the Ice-Sheet Model Intercomparison Project–Heinrich Event INtercOmparison (ISMIP HEINO)," *Journal of Glaciology*, Vol. 56, No. 197,
- Cambers, G., 1998. *Planning for Coastline Change: Coastal Development Setback Guidelines in Antigua and Barbuda*. UNESCO, Paris.
- Cazenave, A., Dieng, H., Meyssignac, B., von Schuckmann, K., Decharme, B., and Berthier, E., 2014. "The rate of sea-level rise", *Nature Climate Change*, 4, 358–361
- Charbit, S., Ritz, C., and Ramstein, G., 2002. "Simulations of Northern Hemisphere ice-sheet retreat:: sensitivity to physical mechanisms involved during the Last Deglaciation," *Quaternary Science Reviews Volume 21, Issues 1–3*, January, Pages 243–265
- Church, J. A., & Clark, P. U. (2013). *Sea Level Change - executive summary*. IPCC-AR5 - Executive Summary, Sea Level Change.

- Church, J. A., & Clark, P. U. (2013). Sea Level Change - Supplementary Material. IPCC - 13SM, 1–8. Retrieved from www.climatechange2013.org
- Church, J., Woodworth, P., Aarup, T., and Wilson, W., 2010. "Understanding Sea-level Rise and Variability," Wiley Press
- Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D. and Woodworth, P.L. (2001). Changes in Sea Level. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (eds. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell and C.I. Johnson). Intergovernmental Panel on Climate Change, Cambridge
- Church, J.A., P.U. Clark, and others, 2013. "Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.climatechange2013.org/images/report/WG1AR5_Chapter13_FINAL.pdf
- CLIMATIC CHANGE 45, 387–401. doi:10.1023/A:1005698407365
- Cornforda, S., Martinb, S., Gravesb, D., Rankenc, D., Le Brocqd, A., Gladstonea, r., Paynea, A., Ngb, E., and Lipscombc, W., 2012. "Adaptive mesh, finite volume modeling of marine ice sheets," *J. Comput.Phys.*, 232, 529
- Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D., and Yan, J., 2007. "The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis" World Bank Policy Research Working Paper 4136, February.
- de Vries, H., Katsman, C. and Drijfhout, S., 2014. "Constructing scenarios of regional sea level change using global temperature pathways", *Environ. Res. Lett.* 9
- Fencl, A., and Klein, R. (2008). CLIMATE CHANGE, Impacts, Vulnerability & Adaptation – Coastal Zone. Environment Agency - Abu Dhabi.
- Environment Agency, 2012. Managing flood risk through London and the Thames Estuary: TE2100 Plan. Environment Agency, London, UK.
- European Environment Agency, 2013. Climate-ADAPT: European Climate Adaptation Platform. : European Environment Agency. Copenhagen, Denmark.
- French, P.W., 2001. Coastal defences: Processes, Problems and Solutions. Routledge, London, U.K.
- Griffies, S. M., & Adcroft, A. J. (2008). Formulating the Equations of Ocean Models. Geophysical Monograph Series 177, 281–318.
- Griffies, S. M., & Greatbatch, R. J. (2012). Physical processes that impact the evolution of global mean sea level in ocean climate models. *Ocean Modelling*, 51, 37–72. doi:10.1016/j.ocemod.2012.04.003

- Griffies, S. M., Adcroft, A. J., V. B., Danabasoglu, G., Durack, P. J., Gleckler, P. J., ... Taylor, K. E. (2014). Sampling the Physical Ocean in CMIP6 Simulations CLIVAR Ocean Model Development Panel (OMDP) (Vol. 6).
- Griffies, S. M., Pacanowski, R. C., & Hallberg, R. W. (2000). Spurious Diapycnal Mixing Associated with Advection in a z -Coordinate Ocean Model. *Monthly Weather Rev*, (Levitus 1982), 538–564.
- Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E., van Deursen, W.A., 2012. Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change* 115, 795– 819. doi:doi:10.1007/s10584-012-0444-2
- Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change, Traditional Peoples and Climate Change* 19, 240–247. doi:10.1016/j.gloenvcha.2008.12.003
- Hanna, E., Navarro, F., Pattyn, F., Domingues, C., Fettweis, X., Ivins, E., Nicholls, R., Ritz, C., Smith, B., Tulaczyk, S., Whitehouse, P., and Zwally, H., 2013. “Ice-sheet mass balance and climate change,” *Nature*, 498, 51–59
- Hassanzadeh, S., Kiasatpour, A., Hosseinibalam, F., 2007. “Sea-level response to atmospheric forcing along the north coast of Persian Gulf”, *Meteorol. Atmos. Phys.* 95, 223–237
- Hellyer and Aspinall (Editors), 2005. “The Emirates: A Natural History”
- Hillen, M.M., Jonkman, S.N., Kanning, W., Kok, M., Geldenhuys, M., Vrijling, J.K., Stive, M.J.F., 2010. Coastal Defence Cost Estimates. Case Study of the Netherlands, New Orleans and Vietnam. TU Delft, Delft, The Netherlands.
- Hinkel, J., Bisaro, A., 2014. Methodological choices in problem-oriented adaptation research: a diagnostic framework. *Regional Environmental Change*. doi:10.1007/s10113-014-0682-0
- Hinkel, J., Jaeger, C.C., Nicholls, R.J., Lowe, J., Renn, O., Peijun, S., 2015. Sea-level rise scenarios and coastal risk management. *Nature Climate Change*.
- Holland, D., 2001. “An Impact of Subgrid-Scale Ice–Ocean Dynamics on Sea-Ice Cover,” *American Meteorological Society, Journal of Climate*, Volume 14.
- Holland, D., 2013. “Ocean Circulation and Climate: Chapter 16. The Marine Cryosphere” *International Geophysics Series*, Volume 103
- Holland, D., and D. Holland (2015), On the rocks: The challenges of predicting sea level rise, *Eos*, 96, doi:10.1029/2015EO036667. Published on 19 October 2015.
- Holling, C.S. (Ed.), 1978. Adaptive environmental assessment and management. Wiley, Chichester, New York.
- Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., X, D., ... Johnson, C. (2001). *CLIMATE CHANGE 2001 - The Scientific Basis. Third Assessment Report (TAR) - IPCC*.

http://www.lib.utexas.edu/maps/ united_arab_emirates.html, accessed Oct. 29, 2016

- Hussain, M. and Javad, A., 2016. "Assessing impacts of sea level rise on seawater intrusion in a coastal aquifer with sloped shoreline boundary," Journal of Hydro-environment Research, Volume 11, Pages 29–41
- Huybrechts, P & Oerlemans, J., 1988. "Evolution of the east antarctic ice sheet: a numerical study of thermo-mechanical response patterns with changing climate. Ann. Glaciol. 11, 52–59.
- Huybrechts, P., 1990. "A 3-d model for the antarctic ice sheet: a sensitivity study on the glacial-interglacial contrast. Clim. Dyn. 5, 79–82.
- IPCC, 2007. "*Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*", (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York
- IPCC, 2016, "PRESS RELEASE 14 April 2016 IPCC agrees special reports, AR6 workplan. Available at https://www.ipcc.ch/news_and_events/pdf/press/160414_pr_p43.pdf
- IRGC, 2005. Risk governance - towards an integrative approach. White Paper no 1. International Risk Governance Council.
- Jaeger, C.C., Renn, O., Rosa, E.A., Webler, T., 2001. Risk, Uncertainty, and Rational Action. Earthscan, London, UK.
- Jarosch, A., 2008. "Icetools: A full stokes finite element model for glaciers. Computers and Geosciences 34 (8), 1005–1014.
- Jones, R.N., Patwardhan, A., Cohen, S.J., Dessai, S., Lammel, A., Lempert, R.J., Mirza, M.M.Q., von Storch, H., 2014. Foundations for decision making, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Kabat, P., Fresco, L.O., Stive, M.J.F., Veerman, C.P., van Alphen, J.S.L.J., Parmet, B.W.A.H., Hazeleger, W., Katsman, C.A., 2009. Dutch coasts in transition. *Nature Geoscience* 2, 450–452.
- Kirshen, P., and Wake, C., 2014. "Sea-level Rise, Storm Surges, and Extreme Precipitation in Coastal New Hampshire: Analysis of Past and Projected Future Trends"
- Klein, R.J.T., Nicholls, R.J., Ragoonaden, S., Capobianco, M., Aston, J., Buckley, E.N., 2001. Technological Options for Adaptation to Climate Change in Coastal Zones. *Journal of Coastal Research* 17, 531– 543.
- Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H., and Tebaldi, C., 2014. "Probabilistic 21st and 22nd century sea level projections at a global network of tide-gauge sites," *Earth's Future*, 2, 383–406.

- Kuhn, M. Featherstone, W., Makarynskyy, O., and Keller, W. 2010. “Deglaciation-induced spatially variable sea level change: a simple-model case study for the Greenland and Antarctic ice sheets”, *International Journal of Ocean and Climate Systems*. 1 (2): pp. 67-83
- Kwadijk, J.C.J., Haasnoot, M., Mulder, J.P.M., Hoogvliet, M.M.C., Jeuken, A.B.M., van der Krogt, R.A.A., van Oostrom, N.G.C., Schelfhout, H.A., van Velzen, E.H., van Waveren, H., de Wit, M.J.M., 2010. Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews-Climate Change* 1, 729–740. doi:doi:10.1002/wcc.64
- Lempert, R., Schlesinger, M., 2000. Robust strategies for abating climate change - An editorial essay.
- Lempert, R., Schlesinger, M., 2001. Climate-change strategy needs to be robust. *NATURE* 412, 375. doi:10.1038/35086617
- Lindsey, R., 2002, “Collapse of the Larsen-B Ice Shelf”, Earth Observatory, National Aeronautics and Space Administration (NASA), <http://www.earthobservatory.nasa.gov/Features/WorldOfChange/larsenb.php>
- Linham, M.M., Green, C., Nicholls, R.J., 2010. AVOID Report on the Costs of adaptation to the effects of climate change in the world’s large port cities. (No. AV/WS2/D1/R14).
- Linham, M.M., Nicholls, R.J., 2010. Technologies for Climate Change Adaptation - Coastal Erosion and Flooding. UNEP Riso Centre on Energy and Climate and Sustainable Development, Roskilde, Denmark.
- Little, C., Horton, R., Kopp, R., Oppenheimer, M., and Yip, S., 2014. “Uncertainty in Twenty-First-Century CMIP5 Sea Level Projections”, *JOURNAL OF CLIMATE VOLUME 28*, pp838-852
- Lombard, A., Cazenave, A., DoMinh, K., Cabanes, C., and Nerem, R., 2005. “Thermosteric sea level rise for the past 50 years; comparison with tide gauges and inference on water mass contribution”, *Global and Planetary Change, Volume 48, Issue 4, October, Pages 303–312*
- Lønne, I. and Lyså, A., 2005. “Deglaciation dynamics following the Little Ice Age on Svalbard: Implications for shaping of landscapes at high latitudes”, *Geomorphology, Volume 72, Issues 1–4, December 2005, Pages 300–319*.
- Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S., 2009. Marine and coastal projections, in: *UK Climate Projections Science Report*. Met Office Hadley Centre and Exeter, UK.
- Milne, G. A., Gehrels, W. R., Hughes, C. W., and Tamisiea, M. E., 2009. “Identifying the causes of sea-level change, *Nature Geosci.*, 2, 471–478, 2009
- Morris, L., 2010, “Developers plan to keep the sea at bay” **The National published on January 18.**

- Murray, T., Nettles, M., Selmes, N., Cathles, L., Burton, J., James, T., Edwards, S., Martin, I., O'Farrell, T., Aspey, R., Rutt, I, and Baugé, T., 2015. "Reverse glacier motion during iceberg calving and the cause of glacial earthquakes", *Science*, 17 VOL 349 ISSUE 6245
- National Snow and Ice Data Center. (n.d.). Ice Shelves. State of the Cryosphere. Retrieved April 6, 2010.
- National Snow and Ice Data Center (NSIDC), (2014) <http://nsidc.org>
- Nicholls, R. and Cazenave, A., 2010. "Sea-Level Rise and Its Impact on Coastal Zones," *Science*, Vol. 328, Issue 5985, pp. 1517-1520.
- Nicholls, R.J., Hanson, S.E., Lowe, J.A., Warrick, R.A., Lu, X., Long, A.J., 2014. Sea-level scenarios for evaluating coastal impacts. *WIREs Climate Change* 5, 129–150. doi:doi:10.1002/wcc.253
- Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas, in: Parry, M.L., Canziani, O.F., Palutikof, J.P., Linden, P.J. van der, Hanson, C.E. (Eds.), *Climate Change 2007: Impacts and Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 315–356.
- Nicholls, R., Marinova, N., Lowe, J., Brown, S., Vellinga, P., de Gusmão, D., Hinkel, J., Tol, R., 2011. "Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century," *Phil. Trans. R. Soc. A* (2011) 369, 161–181
- NRC, 2012., "Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press. http://www.nap.edu/catalog.php?record_id=13389
- Pardaens, A. K., Gregory, J. M., and Lowe, J. A., 2011. "A model study of factors influencing projected changes in regional sea level over the twenty-first century", *Clim. Dynam.*, 36, 2015–2033
- Pattyn, F., Perichon, L., Aschwanden, A., Breuer, B., De Smedt, B., et al.. 2008. "Benchmark experiments for higher-order and full Stokes ice sheet models (ISMIP-HOM). The Cryosphere Discussions," *Copernicus*, 2008, 2 (1), pp.111-151.
- Payne, A., Huybrechts, P., Abe-Ouchi, A., CALOV, R., Fastook, F., Greve, R., Marshall, S., Marsiat, I., Ritz, C., Tarasov, L., and Thomassen, M., 2000. "Results from the EISMINT model intercomparison: the effects of thermomechanical coupling," *Journal of Glaciology*, Vol. 46, No. 153.
- Price, P., Payne, A., Howat, I., and Smith, B., 2011. "Committed sea-level rise for the next century from Greenland ice sheet dynamics during the past decade," *Proceedings of the national academy of sciences of the united states of America*
- Price, S. F, Conway, H, Waddington, E. D, & Bindschadler, R. A., 2008. "Model investigations of inland migration of fast-flowing outlet glaciers and ice streams," *J. Glaciol.* 54, 49–60.

- Price, S., Lipscomb, W., Hoffman, M., Hagdorn, M., Rutt, I., Payne, T., Hebel, F., and Kennedy, J., 2015. "CISM 2.0.5 Documentation"
- PROVIA (Ed.), 2013. PROVIA Guidance on assessing climate change vulnerability, impacts and adaptation.
- Pugh, D., 2004. "Changing sea levels. Effects of tides, weather and climate", Cambridge University Press, 280pp.
- Rahmstorf, S., 2012. "Modeling sea level rise", *Nature Education Knowledge* 3(10):4
- Ranger, N., Reeder, T., Lowe, J.A., 2013. Addressing "deep" uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes* 1, 233–262. doi:doi:10.1007/s40070-013-0014-5
- Renn, O., 2008. Risk governance: coping with uncertainty in a complex world. Earthscan.
- Richardson, K., Steffen, W., and Liverman, D., (eds) 2011. "Climate Change: Global Risks, Challenges and Decisions," Cambridge university press.
- Riebeek, H. (2009, April 8). Wilkins Ice Bridge Collapse. NASA's Earth Observatory. Retrieved April 7, 2010.
- Rignot, E., Bamber, J. L., van den Broeke, M. R., Davis, C., Li, Y., van de Berg, W. J., & van Meijgaard, E. (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geoscience*, 1(2), 106-110.
- Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B., 2014. "Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011," *Geophys. Res. Lett.*, 41, 3502–3509, doi:10.1002/2014GL060140.
- Rignot, W., 2008. "Changes in West Antarctic ice stream dynamics observed with ALOS PALSAR data", *Geophysical Research Letters* 35, L12505,
- Robel, A. and Tziperman, E., 2016. "The role of ice stream dynamics in deglaciation ", *Journal of Geophysical research* Volume 121, Issue 8, Pages 1540–1554
- Rochette, J., du Puy-Montbrun, G., Billé, R., 2010. Coastal setback zones in the Mediterranean: A study on Article 8-2 of the Mediterranean ICZM Protocol. IDDRI.
- Rohling, E.J., Grant, K., Helmleben, C., Siddall, M., Hoogakker, B. a. A., Bolshaw, M., Kucera, M., 2008. High rates of sea-level rise during the last interglacial period. *Nature Geosci* 1, 38–42. *Nature Geoscience* 1, 38–42. doi:doi:10.1038/ngeo.2007.28
- Rutt, I. C, Hagdorn, M, Hulton, N. R. J, & Payne, A. J., 2009. "The glimmer community ice sheet model," *J. Geophys. Res.* 114
- Scambos, T. A., Bohlander, J., Shuman, C., & Skvarca, P. (2004). Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophysical Research Letters*, 31(18).

- Scambos, T. A., Hulbe, C., Fahnestock, M., & Bohlander, J. (2000). The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of Glaciology*, 46(154), 516-530.
- Shows, E.W., 1978. "Florida's coastal setback line – an effort to regulate beachfront development", *Coastal Management* 4, 151–164.
- Slovic, P., 1987. Perception of risk. *Science* 236, 280.
- Stocker, T. F., Qin, D., Plattner, G., Tignor, M. M. B., Allen, S., Boschung, J., ... Midgley, P. M. (2013). IPCC, Intergovernmental Panel on Climate Change - The Physical Science Basis (p. 27). IPCC - AR4. Retrieved from http://www.climatechange2013.org/images/uploads/WGI_AR5_SPM_brochure.pdf
- Tri, N.H., Adger, W.N., Kelly, P.M., 1998. Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam. *Global Environmental Change* 8, 49–61.
- UKCIP, 2003. Climate adaptation: Risk, uncertainty and decision-making. UK Climate Impacts Programme. Walters, C., 1997. Challenges in adaptive management of riparian and coastal ecosystems.
- Vaughan, D., 2008. "West Antarctic Ice Sheet collapse the fall and rise of a paradigm", *Climatic Change* 91(1):65-79
- Vaughan, D.G., Comiso, J., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T., 2013. "Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Walters, C., 1986. *Adaptive Management of Renewable Resources*. MacMillan, New York.
- Willows, R. I. and Connell, R. K.. 2003. Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report
- Wong, P.P., Losada, I.J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y., Sallenger, A., 2014. Coastal systems and low-lying areas, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.361–409.
- Yin, J. (2012). Century to multi-century sea level rise projections from CMIP5 models. *Geophysical Research Letters*, 39(17), n/a–n/a. doi:10.1029/2012GL05294