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Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA)

Constructing Sea-Level Scenarios for Impact and Adaptation Assessment of Coastal Areas: A Guidance Document

TGICA Technical Guidelines
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Preface

This document is intended to provide guidance on the construction of sea-level scenarios to support impact, vulnerability and adaptation assessments. It summarises key material from previous IPCC Working Group (WG) I and WG II assessments on sea level change and places some relevant post-AR4 (IPCC Fourth Assessment Report) literature, published prior to 30 June 2010, in a context based on those assessments. Material included here from the post-AR4 literature has not been subject to the formal review and scrutiny of an IPCC assessment process. The TGICA does not have a mandate to provide a review or assessment of new literature, and this guidance note does not attempt to provide such an assessment. The quantified scenarios remain within the full range of uncertainties signalled in the AR4. There is no intent, expressed or implied, that this document be treated as a formal update to the AR4.

Some aspects of this document are exploratory, but are designed to assist those compiling impact assessments, where the range of assessed material is insufficient. They may also help authors of the Fifth Assessment Report to understand how different types of information can be brought together in developing coastal adaptation frameworks.

The views expressed in this document and any aspects of expert judgment that go beyond those documented in the Third and Fourth IPCC Assessment Reports are solely those of the authors.

The terminology for likelihood of occurrence/outcome, except where explicitly stated, follows that used in AR4. This approach is fully explained in the AR4 uncertainty guidance document available from https://www.ipcc-wg1.unibe.ch/publications/wg1-ar4/wg1-ar4.html and is summarised below:

Virtually certain	> 99% probability of occurrence
Very likely	> 90% probability
Likely	> 66% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Exceptionally unlikely	< 1% probability

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R.J. Nicholls[1], S.E. Hanson[1], J.A. Lowe[2], R.A. Warrick[3], X. Lu[4], A.J. Long[5] and T.R. Carter[6],

Executive Summary

Global-mean sea-level rise is one of the more certain impacts of human-induced global warming and it will drive local impacts and adaptation needs around the world's coasts. A key element in assessing these issues is the development of sea-level rise scenarios (or plausible futures). This guidance document summarises key relevant material concerning sea-level rise scenario development for the 21st Century from previous Working Group I and Working Group II assessments of the IPCC.

The document describes the mechanisms which contribute to sea-level change and a methodology for combining available data on these mechanisms to create suitable sea-level rise scenarios for impact and adaptation assessments. Each component of the sea-level rise scenario, including the global volume of the ocean, regional effects due to differential thermal expansion of the ocean and dynamic effects and vertical land movements due to various natural and anthropogenic causes, are reviewed and methods to estimate these changes are considered that are consistent with the IPCC SRES emission scenarios. Procedures for developing relevant scenarios are illustrated, including the minimum requirements, and example sea-level scenarios are also included

In the period between publication of the fourth IPCC assessment (AR4) and before the publication of the fifth assessment (AR5) in 2013-2014, this Guidance Document considers the different needs of impact assessment, adaptation planning and long-term decision-making. This includes consideration of sea-level rise during the 21st Century, which may be of high consequence, though of low or unquantifiable probability, that exceeds the projections of the quantifiable portions of sea-level budget reported in the AR4. In the absence of assessed results for such changes, this is not quantified here, but merely discussed in the context of its possible application in sensitivity studies and long-term vulnerability assessments. The quantified scenarios that are presented remain consistent with the full range of uncertainties signalled in the AR4.

It is planned for an update of this sea-level scenario guidance to be prepared following the release of the AR5.

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Constructing sea-level scenarios for impact and adaptation assessment of coastal areas: a guidance document

1 Introduction

Global-mean sea-level change is one of the more certain impacts of human-induced global warming and one which is expected to continue for centuries due to the time scales associated with climate processes and feedbacks even if greenhouse gas (GHG) emissions concentrations were to be stabilised (Meehl *et al.*, 2007). Given the large and growing concentration of population and economic activity in the coastal zone, as well as the importance of coastal ecosystems, the potential impacts of sea-level change have evoked widespread concern for more than two decades (Barth and Titus, 1984; Milliman *et al.*, 1989; Warrick *et al.*, 1993).

Some potential impacts of a change in sea level have already been assessed locally, nationally, regionally and globally (e.g. Bijlsma *et al.*, 1996; McLean *et al.*, 2001). However, the scope of assessment and the methodologies employed have varied significantly (e.g. de la Vega-Leinert and Nicholls, 2001; Nicholls and Mimura, 1998). Most of these studies have been based on scenarios: alternative images of the future, which help in the assessment of future developments in complex systems that are either inherently unpredictable, or have high scientific uncertainties. The reliability of scenarios, and difficulties associated with their development and use, have emerged as major problems and constraints for impact and adaptation studies.

To assist scientists, engineers and policy analysts who are assessing impacts of and potential responses to sea-level change, this guidance document aims to explain why and how sea-level scenarios are developed. It also provides guidance on the use of observational and scenario sea-level data within such studies, as well as associated caveats. Scenarios are mainly developed for periods between 30 and 100 years into the future, as this corresponds to the decade to century scale of most impact studies, but brief consideration is also given to post-2100 scenarios. This guidance considers the full range of situations from cases of little data and few or no previous studies to those where significant data and experience of earlier studies are available.

The need for sea-level change scenarios as part of impact and adaptation assessments is considered, followed by discussion of the strengths and limitations of sea-level observational analysis and scenario development. Most information is drawn from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and the discussion on sea-level change which it has stimulated, with some reference back to earlier reports such as the Third Assessment Report (TAR), as appropriate. For example, in the AR4, the quantified range of projected global mean sea-level rise is between 18 and 59 cm by the 2090s, representing the model-based range of sea-level change due to thermal expansion, melting of small glaciers or surface melting of the main ice sheets (see Table SPM3 in IPCC (2007c)); in the TAR, global-mean sea levels were estimated to rise between 9 and 88 cm from 1990 to 2100 (Church *et al.*, 2001). This change in range is due to a combination of newer modelling techniques, better understanding of processes and better use of observational constraints, but it excludes the larger potential contribution of sea-level rise from dynamic ice discharge or collapse of the Greenland and Antarctic ice sheets (Meehl *et al.*, 2007). The AR4 highlighted the potential for sea level rise to exceed current model-based projections, but did not quantify the potential additional contributions as a sufficient basis in the literature was lacking (IPCC, 2007a;c). However, the AR4 provided an illustrative estimate of the additional sea-level change if observed dynamic discharge processes were to increase linearly with temperature. In that case, global average sea levels would exceed model-based projections by an additional 0.1 to 0.2m by the 2090s, but even higher contributions from this source could not be excluded (IPCC, 2007a p.45; 2007c p.14). While large sea-level rise scenarios ($\geq$ 1m rise) resulting from dynamic ice loss of the polar ice sheets are generally considered as having lower probability during the 21st century, they cannot be ruled out based on our current understanding. It is important to remember that the magnitudes of the potential impacts associated with high sea-level rise scenarios are of sufficient concern to merit consideration in impact, vulnerability and adaptation studies (Nicholls and Cazenave, 2010).

In addition, other relevant climate change parameters and non-climate scenarios for coastal areas considered relevant in the AR4 assessment are briefly introduced (Nicholls *et al.*, 2008a; Nicholls *et al.*, 2007). Such scenarios might be important in more detailed coastal impact and adaptation assessments.

2 Potential impacts of a change in relative sea level

The main physical impacts associated with changes in sea level are summarised in **Table 1**.

Table 1: The main physical impacts of relative sea-level rise, which require sea-level scenarios for their analysis[1].

Physical Impacts	
1. Inundation, flood and storm damage	a. Surge (sea)
	b. Backwater effect (river)
2. Long-term wetland loss (and change)	
3. Altered patterns of erosion and accretion (direct and indirect morphological change)	
4. Saltwater Intrusion	a. Surface Waters
	b. Ground-water
5. Rising water tables/ impeded drainage	

These impacts will vary spatially in line with variations in sea level, which can be significant (see **Figure 1**), reflecting the processes occurring at each location. For instance, Nezugaseki, Japan, exhibits a sudden abrupt sea-level change due to a natural phenomenon (an earthquake) which would cause significant and unavoidable changes; Bangkok, Thailand, shows acceleration in the rate of sea-level rise due to increasing human intervention (more rapid subsidence due to groundwater extraction)

[1] Other classifications of the physical impacts of relative sea-level rise are found in the literature, but they are all similar and can be mapped onto the scheme shown in Table 1.

which can be anticipated; sea level at Helsinki, Finland, appears to be falling due to postglacial isostatic uplift of the land surface which may offset the potential impacts of any rise in sea level. **Figure 1** also illustrates that substantial inter-annual and inter-decadal variability in sea level occurs. This means that for individual periods of a year to several decades, sea-level change can deviate from the long-term observed trend, even showing the opposite tendency, making it particularly important that the long-term underlying trend is identified in impact studies.

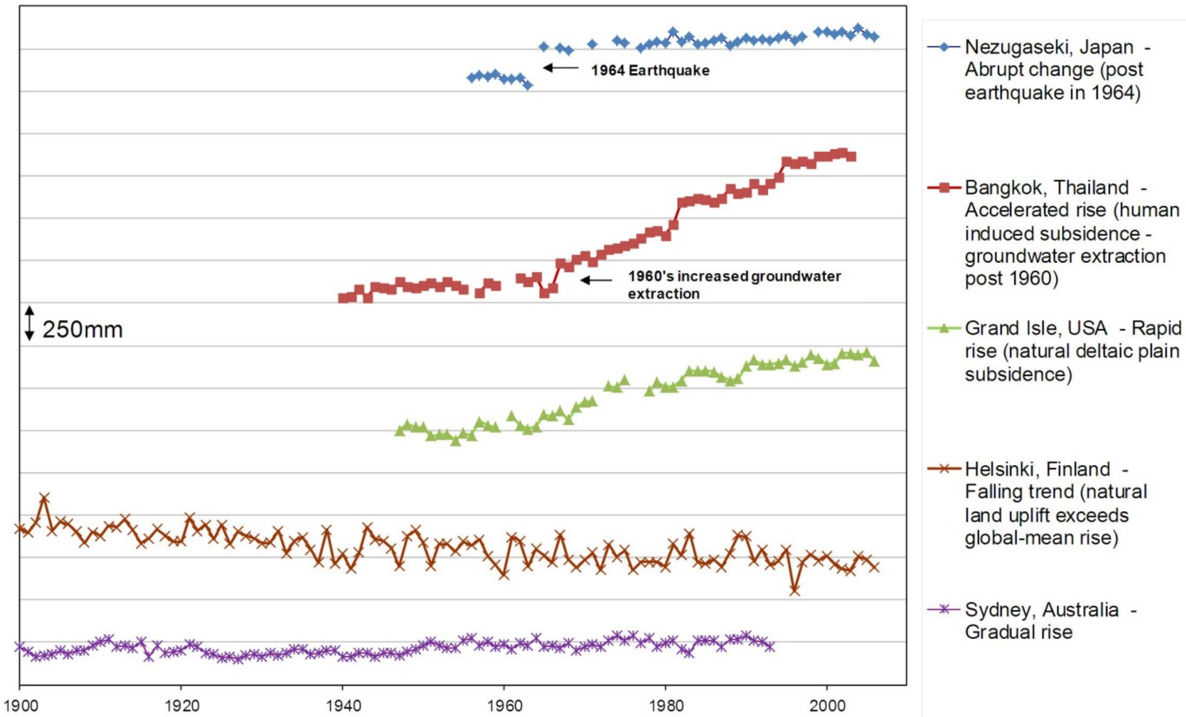

Figure 1: Selected observed sea-level records over the 20th/early 21st centuries, illustrating different types of relative sea-level change (vertical axis, increments of 250 mm). The offsets between records are for display purposes. Data from the Permanent Service for Mean Sea Level (http://www.pol.ac.uk/psmsl/).

The standard impact approach is often described as top-down because it combines scenarios downscaled from global climate models to the local scale with a sequence of analytical steps that begin with the climate system and move through biophysical impacts towards socio-economic assessment (Carter *et al.*, 1994). As part of this framework it is necessary to determine *relative* sea-level change which is composed of the sum of global, regional and local trends related to changing oceans and land levels (see Section 3.1). These components and their drivers are commonly linked within an impact assessment as illustrated in **Figure 2.**

It is important to remember that at all stages of a scenario-building process, a diverse range of uncertainties are encountered. A large uncertainty surrounds future GHG emissions and the possible evolution of their underlying drivers, as reflected in a wide range of future emissions pathways in the literature. This uncertainty is further compounded in going from pathways to greenhouse gas concentrations in the atmosphere; from concentrations to global and regional climate change; from climate change to potential and actual impacts; and finally from these to the formulation of adaptation and mitigation measures and policies. These uncertainties are discussed further in the following sections.

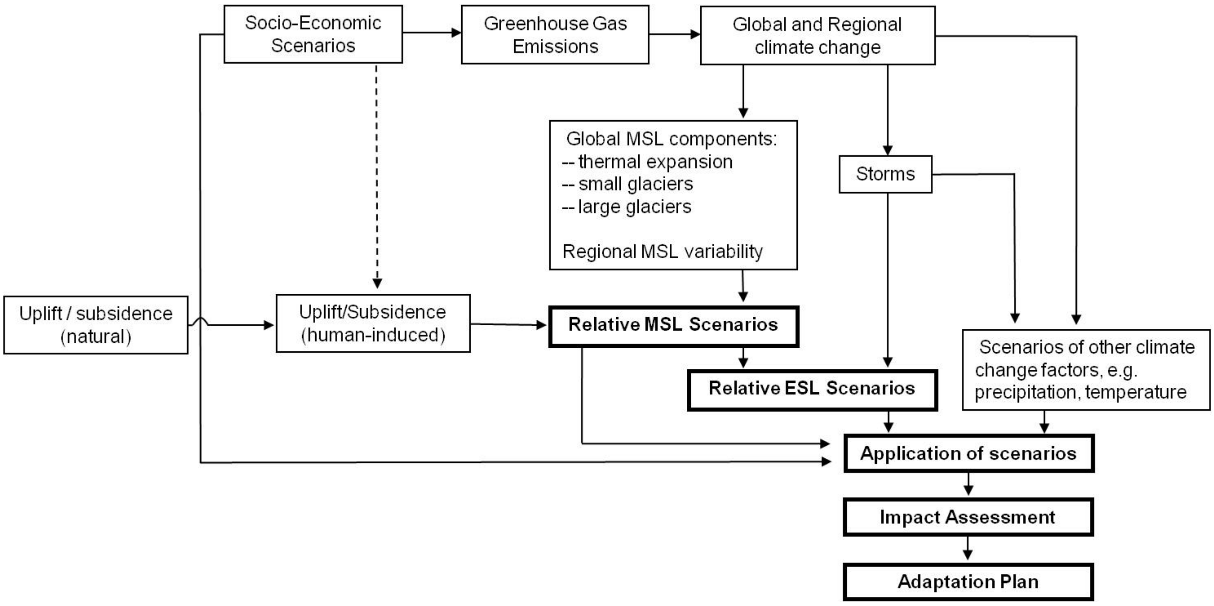

Figure 2: Summary of a methodology commonly applied for developing sea-level scenarios for impact assessment and adaptation planning. MSL – mean sea level; ESL – extreme sea level.

3 Understanding relative sea-level change

3.1 Components of relative sea-level change

Relative sea level can change over a wide range of timescales from seconds to centuries. For instance, significant sea-level variability can occur over years or even several decades due to a range of processes and large-scale atmospheric circulation changes such as the El Niño-Southern Oscillation (ENSO) phenomenon or the North Atlantic Oscillation (NAO), depending on the location (e.g. Basharin, 2004; Lombard *et al.*, 2005).

However, this guidance is concerned with changes in sea level over the next 30-year to 100-year period, where relative sea level is the sum of two major components:

1. *Global-mean sea-level change* (ΔSL_G), a result of the change in the global volume of the ocean. In the 20th/21st Century, this is expected to be primarily due to: (1) thermal expansion of the ocean as it warms, (2) the melting of small glaciers and ice caps due to human-induced global warming (Bindoff *et al.*, 2007; Meehl *et al.*, 2007), and (3) changes in the mass balance of the Greenland and Antarctic ice sheets, which is less certain (Shepherd and Wingham, 2007). Estimates of the recent rates of sea-level change associated with individual components and their sum reported in AR4 are illustrated in **Figure 3**.

   Modification to global sea level is also possible due to changes in the hydrological cycle, including global groundwater depletion, impoundment of water in reservoirs and land drainage (e.g. Chao *et al.*, 2008). However, Bindoff *et al* (2007 p.419) conclude that "the land contribution is either small (<0.5mm/yr) or is compensated by unaccounted or underestimated contributions" and it is not considered further in this guidance.

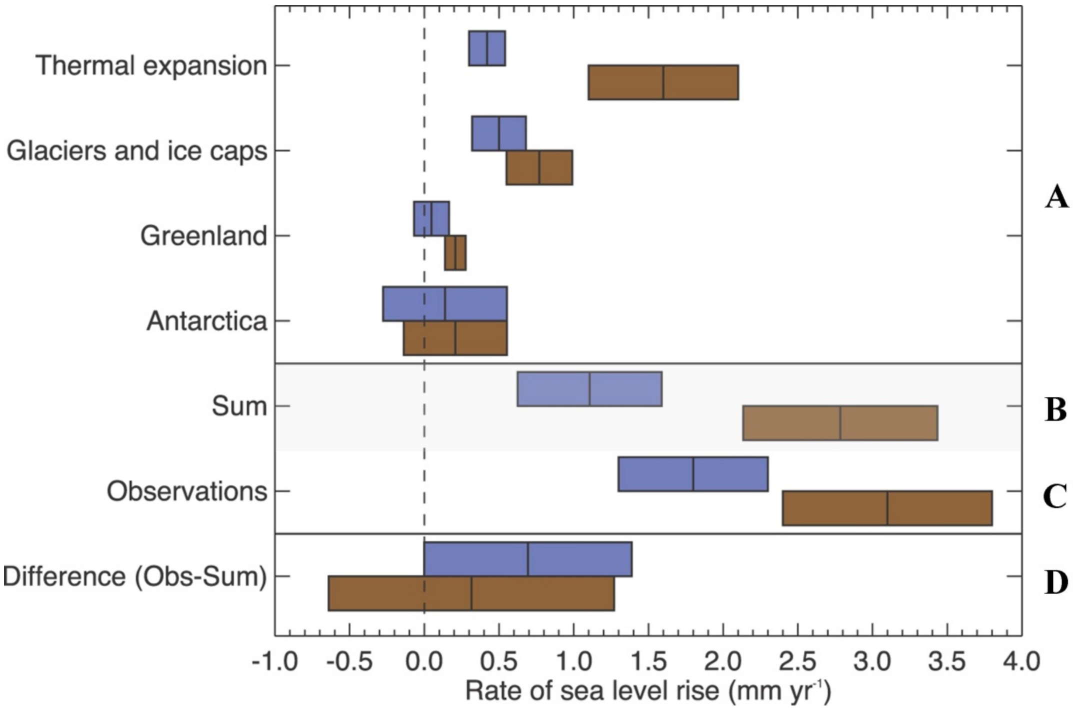

Figure 3: The estimated budget of the components of global mean sea level change (A), their sum (B) compared to the observed rate of rise (C). The blue (or upper) bar represents the 90% error range for 1961 to 2003 and the brown (or lower) bar, the 90% error range for 1993 to 2003. The difference between the estimated budget and observed rate of sea-level change (D), illustrates that, whilst agreement has improved in the more recent period, there is still a tendency to under predict observed sea-level rise. For the sum, the error has been calculated as the square root of the sum of squared errors of the contributions. Likewise the errors of the sum and the observed rate have been combined to obtain the error for the difference (adapted from Figure 5.21 in Bindoff *et al.*, 2007).

2. *Regional and/or local spatial variations* in sea-level change due to three causes:

   a. *Meteo-oceanographic factors* (ΔSL_{RM}), including differences in the rates of oceanic thermal expansion, changes in long-term wind and atmospheric pressure, and changes in ocean circulation (such as the Gulf Stream - e.g. Lowe and Gregory, 2006) and in the Indian Ocean - Han *et al.*, 2010). These factors could be significant, causing large regional departures of up to 50-100% from the global average value for the thermal expansion component of sea-level change. However, coupled atmosphere-ocean climate models of these effects under global warming do not agree where these larger-than-average changes will occur (Meehl *et al.*, 2007; Pardaens *et al.*, 2011). At a local scale too, shifts in wind (wave) climate can raise sea levels markedly in lagoonal systems (Malhadas *et al.*, 2009), which can have a dramatic effect on local coastal systems/resources. This regional component of sea-level change has tended not to be included in impact assessments to date, although the UKCIP02[2] scenarios did include guidance (Hulme *et al.*, 2002). Some procedures to include it in future assessments are included in this guidance.

   b. *Changes in the regional gravity field of the Earth* (ΔSL_{RG}) due to ice melting (caused by redistribution of mass away from Greenland, Antarctica as well as small glaciers). This means that global sea-level change caused by the melting of an ice sheet will not be evenly distributed as a single "global eustatic" or

[2] UK Climate Impacts Programme http://www.ukcip.org.uk/

global-mean value (see Section 5.5.4.4 in Bindoff *et al.*, 2007). If a polar ice sheet melts, then the volume of water in the oceans increases, but at the same time, the gravitational pull from the ice sheet on the oceans close to the ice sheet falls. The net effect of these processes is that sea-level rise occurs faster in areas further away from the source of the melting. For example, in the case of melting Greenland ice, there would be less sea-level rise than the global average in the North Atlantic, near to Greenland, progressing to an enhanced sea-level rise (compared to the global eustatic value) at low latitudes and in the southern oceans (Plag, 2006). Each potential mass source or sink (Greenland ice sheet, Antarctic ice sheet, small glaciers, water storage on land) will produce its own pattern or "fingerprint" of sea-level change measured at the coast (e.g. Mitrovica *et al.*, 2001).

c. *Vertical land movements (uplift and subsidence)* (ΔSL_{VLM}), due to various natural and human-induced geological processes (Christensen *et al.*, 2007, Box 11.5; Emery and Aubrey, 1991; Ericson *et al.*, 2006; Peltier, 2004; Syvitski, 2008). Vertical land movement occurs in most places. Natural causes include: (1) neotectonics, (2) glacio-isostatic adjustment (GIA), and (3) sediment compaction/consolidation. These changes can be regional, slow and steady, as in the case of GIA, but also localised, large and abrupt, for example as associated with earthquakes (e.g., Nezugaseki, **Figure 1**).

   In addition, human activity has often influenced rates of subsidence in susceptible coastal lowlands such as deltas by land reclamation and by lowering water tables through water extraction and improved drainage (Nicholls *et al.*, 2007). These human-enhanced processes are generally localised to Holocene-age deposits and can locally exceed the magnitude of changes expected due to climate change through the 21st Century (Bird, 1993; French, 1997; Long *et al.*, 2006; Nicholls, 1995) (e.g., Bangkok, **Figure 1**).

Other processes such as changes in discharge near the mouth of large rivers may also influence mean sea level, and this might also be investigated within an impact assessment, if relevant.

The inclusion of regional components of relative sea-level change is important when developing scenarios for impact and adaptation assessment, since they provide a link between (global) climate change and (regional to local) coastal management strategies (Christensen *et al.*, 2007; Nicholls *et al.*, 2007).

3.2 Combining the components of sea-level change

Relative sea-level change for a specific location needs to consider the contributions from the components at the global, regional and local scales already discussed. It is possible to integrate these for a given site using Equation 1 which also outlines the ideal way that each component could be considered:

$$\Delta RSL = \Delta SL_G + \Delta SL_{RM} + \Delta SL_{RG} + \Delta SL_{VLM} \qquad \text{Equation 1}$$

Where,

ΔRSL is the change in relative sea level

ΔSL_G is the change in global mean sea level

ΔSL_{RM} is the regional variation in sea level from the global mean due to meteo-oceanographic factors

ΔSL_{RG} is the regional variation in sea level due to changes in the earth's gravitational field

ΔSL_{VLM} is the change in sea level due to vertical land movement

Using Equation 1, relative sea-level scenarios can be developed according to the data available.

4 Sea-level scenario development

There are several different methods of determining appropriate sea-level scenarios according to the purpose of the assessment and available data. These include using observed data (Section 4.1), process-based or statistical models (Sections 0 and 4.3), sensitivity analysis (Section 4.4) or synthetic methods, including consideration of extreme sea-level rise (Section 4.5). In addition, common technical challenges confronting analysts include reconciling global scenarios with local needs (Section 4.6) and specifying scenarios over different time horizons (Section 4.7).

4.1 Extrapolated trends

Extrapolation of sea-level trends from observed data is useful as a direct method for creating relative sea-level scenarios for more localised impact assessments as historic records will include changes in water level due to both vertical land movements and changes in the level of the sea surface.

The main source of information for extrapolated trends is tide gauge records, and a major global data source is the Permanent Service for Mean Sea Level (PSMSL)[3]. Instrumental records of sea-level change measured with tide gauges are available both locally and globally and users should regularly consult the PSMSL and other data providers as, in addition to new measurements, important long-term historic measurements are sometimes added to the archive (Douglas, 1997; Haigh *et al.*, 2009; Woodworth *et al.*, 2009b). Other sources of sea-level data such as the World Ocean Circulation Experiment (WOCE)[4], the National Oceanographic Data Centre (NODC)[5] and National Tidal Centre of Australia[6] may also offer suitable data, while national and port and harbour authorities should be consulted for data as well[7]. However, high quality datasets most useful for this method are strongly biased towards the developed world, with very limited long-term data in some regions (e.g. small islands, Africa, much of the southern oceans). The longest record possible should be used as long-term (>50 year) measurements of mean sea level are required to determine the most robust trends (Douglas, 1992). While a trend can be extracted from any length of record, short-term records (particularly shorter than 36 years, or two lunar nodal cycles) should

[3] http://www.pol.ac.uk/psmsl/
[4] http://www.bodc.ac.uk/projects/international/woce/
[5] http://www.nodc.noaa.gov/General/sealevel.html
[6] http://www.bom.gov.au/oceanography/projects/ntc/ntc.shtml
[7] Data archaeology is important in sea-level studies (Woodworth, 2006). If you identify historic data that is not in one of these archives, this data should be reported to the PSMSL.

be used with caution and the length of sea-level record which has been analysed should be explicitly reported.

Based on the available sea-level records, a global average mean sea-level rise over the 20^{th} Century of 0.17 $\pm$ 0.05 m has been estimated by the IPCC (Bindoff *et al.*, 2007). From 1961 to 2003 the average rate was 1.8 $\pm$ 0.5 mm/yr, while the rate was even greater between 1993 and 2003 when satellite measurements show that it increased to 3.1 $\pm$ 0.7 mm/yr. It is unclear if this post-1993 trend reflects short-term variability in global-mean sea-level rise or indicates a systematic acceleration in the rate of global-mean sea-level rise: this is a question that further monitoring can help to resolve. Satellite observations of sea levels are now collected routinely (e.g. Leuliette *et al.*, 2004) and some recent work (Church and White, 2006; Holgate and Woodworth, 2004; Woodworth *et al.*, 2009a) has combined the altimeter record with tide gauges to produce gridded sea-level data sets. These can extend back to the 1950s or earlier but have not yet, to our knowledge, been used for sea-level scenario development.

In areas of rapid subsidence such as delta plains, or subsiding cities, analysis of shorter records can still provide a constraint on the rate of subsidence (e.g. Bangkok in **Figure 1**) or the Louisiana coastal plain (Penland and Ramsey, 1990). For example, groundwater and other sub-surface fluid withdrawals have produced significant subsidence in susceptible areas over the 20th Century, greatly exceeding the climate-induced trends. Such subsidence is most severe in cities built on deltas, many of which can be found in Asia as shown by the examples given in **Table 2**. Grossi and Muir-Wood (2006) and Syvitski (2008) both found recent subsidence to have been a contributory factor to the flooding of New Orleans by Hurricane Katrina in 2005(). In the agricultural area of the Fens, UK, oxidation and loss of peat has led to a decline in land levels of over 4 metres since 1851 (Waltham, 2000). Appropriate projections of the net human-induced subsidence through the 21^{st} Century need to be assessed as part of overall scenario development, including socio-economic factors (Nicholls *et al.*, 2007, see Table 6.1).

Table 2: Examples of maximum reported human-induced subsidence in coastal cities during the 20^{th} Century (adapted from Nicholls, 1995).

<table>
<tr><th>City</th><th>Maximum Subsidence (m)</th><th>Current Status</th></tr>
<tr><td>Tokyo</td><td>5</td><td rowspan="5">Slowed to near natural rates due to reduced groundwater extraction.
Note: in Bangkok more widespread and slower human-induced subsidence has spread to areas outside the central city (IGES, 2007; Phien-wej et al., 2006). Similar trends may apply elsewhere.</td></tr>
<tr><td>Osaka</td><td>3</td></tr>
<tr><td>Tianjin</td><td>2</td></tr>
<tr><td>Shanghai</td><td>3</td></tr>
<tr><td>Bangkok[8]</td><td>2</td></tr>
<tr><td>Jakarta</td><td>>1</td><td rowspan="2">Ongoing, little management response – sea flooding reported in Jakarta in December 2007, Metro Manila discussed by Rodolfo and Siringan (2006) and groundwater</td></tr>
<tr><td>Metro Manila</td><td>>0.5</td></tr>
</table>

[8] See Figure 1

		extraction(Delinom, 2008; Delinom *et al.*, 2009)
New Orleans	3	Ongoing, difficult to manage as primarily related to drainage, rather than groundwater extraction

It is also important to remember that impacts are often more related to temporal extremes of sea level (storm surges), rather than the annual average value. Records of observed water levels can provide evidence for these extreme levels with return periods at specific locations. Long-term studies of extreme sea levels through the 20th Century trend (Haigh *et al.*, 2010; WASA Group, 1998; Woodworth and Blackman, 2004; Zhang *et al.*, 2000) have concluded that there is little evidence of systematic departure from the global-mean trend, i.e. any change in extreme levels is the same as the mean sea-level change. However, for the future this situation may change, as projections for the 21st Century suggest that it is likely that intense tropical cyclone activity will increase (Knutson *et al.*, 2010; Solomon *et al.*, 2007). Looking to the 21st Century, the potential for more intense storms is a factor that must be considered in the development of sea-level scenarios (see **Table 3** and Section 5.2).

4.2 Model based global-mean sea-level change

Climate model simulations are commonly undertaken to estimate the magnitude and rate of sea-level change resulting from global warming related factors. To address the uncertainty associated with climate system dynamics and future GHG emissions, the IPCC developed a range of 'alternative' futures (scenarios) related to how varying socio economic and technological factors may influence future emissions and climate change (see Appendix 4). In addition, for each future scenario a range for potential sea levels was presented, rather than a single 'best estimate', based on an ensemble of climate model outputs. Continued development of emissions scenarios is to be expected, including scenarios where greenhouse gas emissions are stabilised or peak and then decline. Indeed, the current IPCC SRES scenarios are expected to be superseded in the IPCC Fifth Assessment (AR5) by a community-led Representative Concentration Pathway (RCP) approach (Moss *et al.*, 2010).

The AR4 provides projections for the quantifiable components of the sea-level budget **(Figure 3)** using a hierarchy of models. These range from coupled Atmosphere-Ocean General Circulation Models (AOGCMs) through Earth Systems Models of Intermediate Complexity (EMICs) to Simple Climate Models (SCMs) forced by a variety of emissions scenarios to model global sea-level change (a discussion of the different models can be found in Randall *et al.* (2007). For each SRES marker scenario, change is represented by 5 to 95% ranges based on the spread of AOGCM results, not including uncertainty in carbon cycle feedbacks (see **Figure 4**).

The ranges are narrower than in the TAR mainly because of improved information about some uncertainties in the projected contributions but the midpoint of the each range is within 10% of the TAR model average for the same period. However, due to limited understanding of some interactions, and because these models do not incorporate future changes in dynamic ice discharge from polar ice sheets, neither a best estimate nor likelihood value is assigned to the ranges (Meehl *et al.*, 2007).

Figure 4 shows that during the 21st Century, thermal expansion is the dominant contribution to modelled sea-level change, with glaciers, ice caps and the Greenland Ice Sheet also projected to contribute positively. The results also show that although the overall range of sea-level rise has been reduced due to improved information on uncertainties, under all the SRES scenarios the average rate of sea-level rise is still expected to exceed the 1.8mm/yr rate observed between 1961 and 2003. As impact assessments often need to estimate impacts of sea-level rise for intermediate periods, the values provided in Table 10.7 of the AR4 report (Meehl *et al.*, 2007) can be used to generate time series of the projected sea-level rise under various SRES scenarios (e.g. Hunter, 2010). Section 4.7 offers a method for constructing intermediate sea-level rise scenarios based on Table 10.7 from Meehl et al. (2007) the results of which are tabulated in Table 5 of this document.

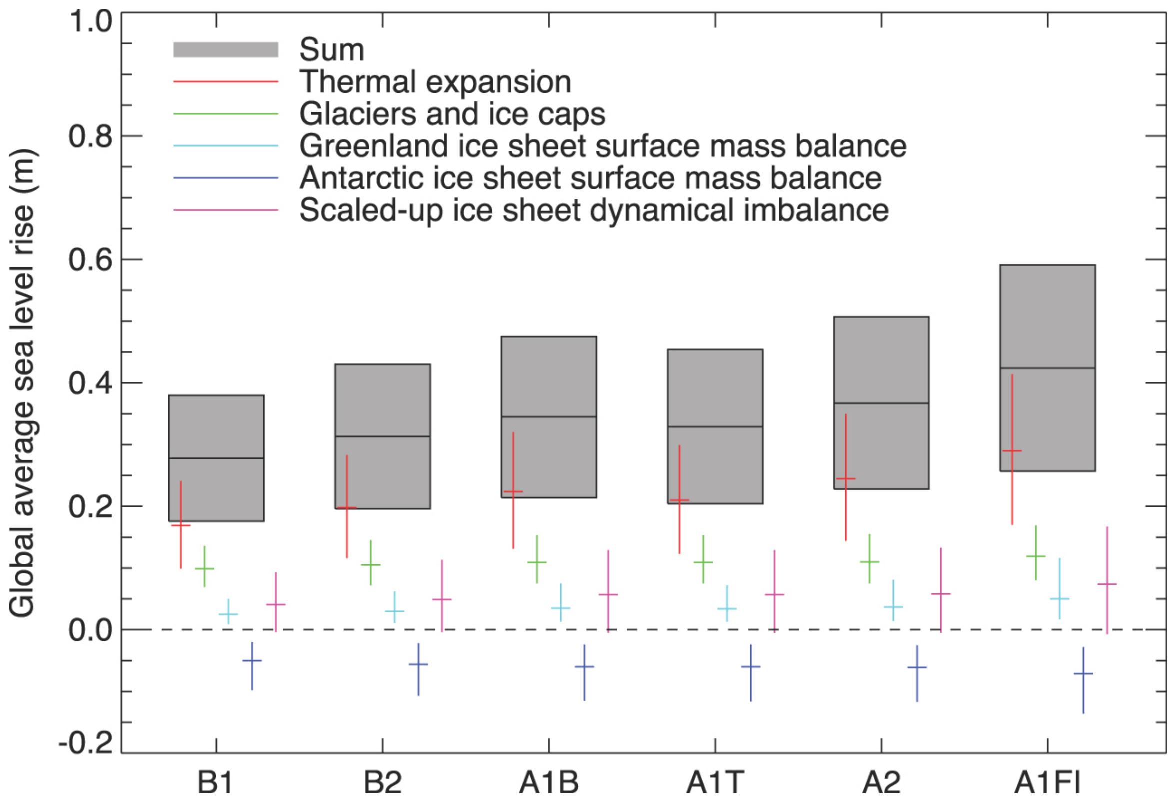

Figure 4: Global average sea-level rise projections and uncertainties (5 to 95% ranges) 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. Contributions from the individual components are also shown. Part of the present-day ice sheet mass imbalance due to recent ice flow acceleration is presumed to persist unchanged. (Source: Figure 10.33 Meehl *et al.*, 2007). The uncertainties from the individual sea-level change components and their combination are described in Appendix 1 in Meehl *et al.*,(2007).

4.3 Model-based regional sea-level change

To date, most coastal impact and adaptation assessments have ignored regional variations in sea-level scenarios, largely due to a lack of technical guidance and access to the necessary data in a usable form. Nevertheless, regional and local assessments would benefit from considering the components of sea-level change (Section 3) on a more individual basis, as the uncertainty for climate-induced sea-level change during the 21st century at any site is likely to be larger than the global-mean scenarios suggest.

4.3.1 *Meteo-oceanographic factors (SL_{RM})*

Regional variations in atmospheric circulation, ocean circulation and warming rates, spatial variations in mass redistribution and the interactions between them can lead to significant deviations of regional sea-level change from the globally-averaged trend. There are two main methods for estimating regional variations using modelled data.

4.3.1.1 General Circulation Models

a. *Single model outputs* - Complex climate models (AOGCMs) have been used to simulate the geographic distribution of sea-level change caused by ocean processes (Gregory *et al.*, 2001). Thermal expansion can be calculated from the change in three-dimensional ocean temperature structure in the ocean components of the models[9]. Model results for the thermal expansion component of sea level derived directly from the AOGCMs, reveal that some regions show a rise substantially more than the global average rise (up to twice the global average), and others show a sea-level fall for this component (Church *et al.*, 2001)[10]. Key features of such regional variations in sea-level rise and some possible underlying causes are analysed in Gregory *et al*. (2001). This lack of similarity in spatial patterns between the models means that confidence in regional sea-level projections is currently low.

b. *Ensemble model outputs* - AR4 has made more and newer results from models available (IPCC, 2007b), the combined (or ensemble) outputs of which are shown in **Figure 5**. As in the TAR results, this combined output shows a sea-level rise that is smaller than average in the Southern Ocean and larger than average in the Arctic. This variation has been attributed to enhanced freshwater input from precipitation and continental runoff, steric changes or wind stress change (Landerer *et al.*, 2007) or thermal expansion (Lowe and Gregory, 2006).

4.3.1.2 Pattern scaling

The regional pattern of thermal expansion under SRES forcing[11] can be approximated using a pattern-scaling method similar to that previously applied for other climate variables (e.g. Mitchell, 2003; Santer *et al.*, 1990). In applying the pattern-scaling method to sea level, "standardised" (or "normalised") patterns of regional thermal expansion change, as produced by coupled AOGCMs[12], are derived by dividing the average spatial pattern of change for a future period (e.g. 2071-2100) by the corresponding global-mean value of thermal expansion for the same period. The resulting standardised sea-level pattern is thereby expressed per unit of global-mean

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[9] The melting of mountain glaciers and small icecaps is usually calculated outside of the climate model using predictions of atmospheric surface temperature change and a model of glacier sensitivity to warming. The contributions of the large Greenland and Antarctic ice sheets are also often treated in a similar way, although increasingly (especially for Greenland), these are being represented by complex models that simulate thermodynamics and the ice dynamic response. Spatial patterns from coupled AOGCMs do not include vertical land movements, but these can be added locally for impact analysis.

[10] For small amounts of icemelt, their contribution to sea level can be considered globally uniform, as a first approximation. The spatial patterns will therefore remain dominated by the thermal expansion pattern and circulation changes.

[11] It is important to note, however, that pattern scaling has yet to be tested with emissions scenarios which consider peak and post-peak reductions in greenhouse gas emissions.

[12] Regional change indicated by AOGCMs also reflect changes in wind stress, ocean circulation and other factors, but are largely due to changes in thermal expansion. The patterns are therefore referred to as thermal expansion

thermal expansion. The pattern-scaling approach, has been formalised within an integrated assessment modelling system called SimCLIM (as described in Appendix 2) and used by Walsh *et al,* (1998), who produced scaled scenarios of regional sea-level rise for the Gold Coast of eastern Australia using the outputs from a suite of simulations with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) general circulation model.

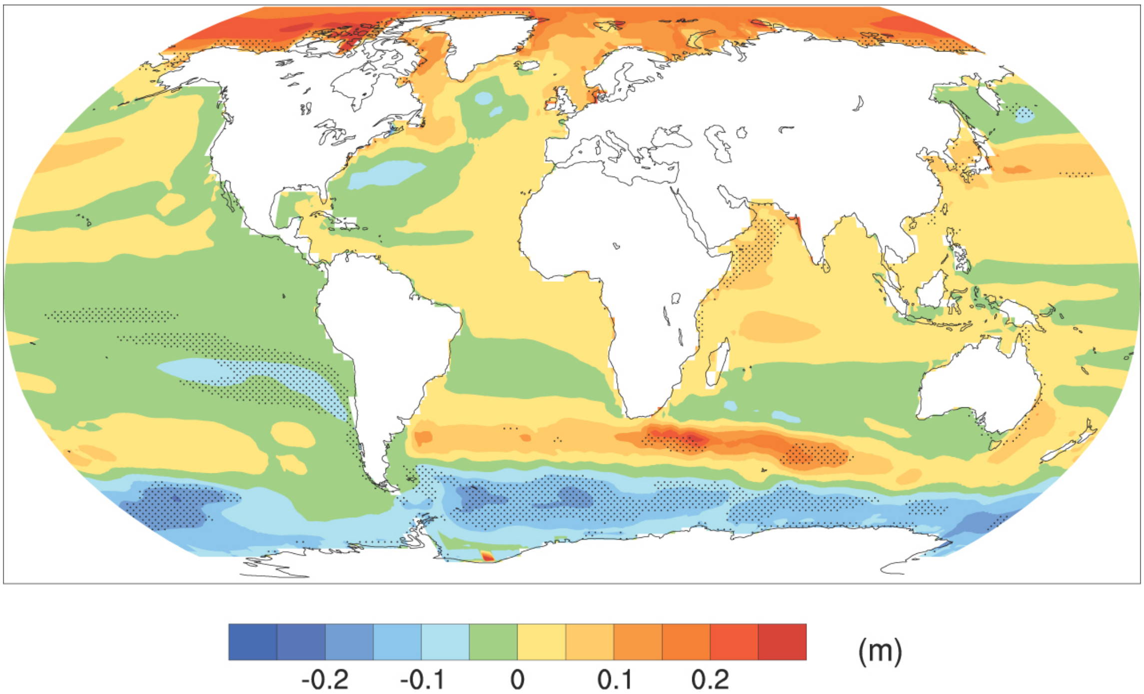

Figure 5: Variations in local sea-level change (m) from the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century with the SRES A1B scenario. Variation is due to ocean density and circulation. and is calculated as the difference between averages for 2080 to 2099 and 1980 to 1999 as an ensemble mean over 16 AOGCMs. Stippling indicates where the variation between the models is less than the ensemble mean. (Source: Figure 10.32 in Meehl *et al.*, 2007))

4.3.2 Changes in the regional gravity field of the Earth (ΔSL_{RG})

This factor has not been widely considered to date, but could be significant, especially under deglaciation of Greenland or Antarctica. A few studies are now starting to construct scenarios of future sea level that recognise that changes in the global and regional gravity field associated with mass exchange with the ocean will produce non-uniform patterns of rise that will deviate significantly from a single global value (Mitrovica *et al.*, 2001 - their Figure 1; Plag, 2006). This is particularly important for future scenarios with a large ice melt component, but less so for those dominated by thermal expansion. .

4.3.3 Vertical land movements (uplift and subsidence) (ΔSL_{VLM}),

Estimates of vertical land movement are essential to create relative sea-level rise scenarios for impact and adaptation assessment, especially in deltas and cities susceptible to subsidence (Christensen *et al.*, 2007; Nicholls *et al.*, 2007). Potential methods to develop these datasets are well discussed, compared and integrated in Bingley *et al*. (2007) but while newer technologies promise precise measurement in the medium- and long-term, assuming suitable observational networks are established, other methods are applied most readily at the present time.

Observed sea-level records have been used by simply extrapolating the observed relative sea-level change trend into the future. This is theoretically debatable as it fails to differentiate sea-level rise caused by historical climate change from changes attributable to local land movements. By superimposing the extrapolation of observed sea-level change trends onto the projections of global warming related sea-level rise (e.g. those from climate models), such a procedure would lead to the "double-counting" of any sea-level rise resulting from large-scale processes associated with global warming. Therefore, to estimate the contribution of local land movement to relative sea-level change in the future, the climate change related portion of sea-level rise needs to be subtracted from the observed local trend. Various methods have been advanced for adjusting this local trend (e.g. Titus and Narayanan, 1995), including the SimCLIM sea-level scenario generator (see Appendix 2) which uses pattern-scaling on 20th century changes to separate the two components (Warrick *et al.*, 2005). Historical experience is also unlikely to be a good guide to future changes in tectonically-active areas, as most vertical land changes may occur during infrequent earthquake events which are not predictable, and can even be in an opposite sense to trends occurring between earthquakes (Hamilton and Shennan, 2005; Long and Shennan, 1998; Zong *et al.*, 2003). Similarly, naturally subsiding areas, such as deltas, also need to be considered (cf. Vafeidis *et al.*, 2008) as subsidence can be significant, e.g. up to 8mm/yr within the Mississippi delta (Ericson *et al.*, 2006; Penland and Ramsey, 1990; Syvitski, 2008).

Where neither modelled nor observed sea-level records are available, a global dataset on the GIA vertical component based on the models of Peltier (2000; 2004) is available for download[13]. However, note that all the other natural and human-induced geological components of sea level are not included.

Human-induced subsidence

Human-induced subsidence can also be important and needs to be captured in sea-level impact studies (Nicholls and Cazenave, 2010), although as many of the cases in **Table 2** demonstrate, human-induced subsidence can be alleviated and avoided by careful planning of groundwater withdrawal (Nicholls, 1995). Where data on this aspect of vertical land movement is lacking, as a sensitivity analysis the interpretation of the environmental attitudes embedded in global scenarios might be used to derive assumptions about the relative magnitude of human-induced subsidence (e.g. using the SRES storylines). Following earlier work (Nicholls, 2004; Nicholls *et al.*, 2008b), the following associations might be made:

1. A1/A2 worlds – human-induced subsidence is more likely;
2. B1/B2 worlds – human-induced subsidence is less likely.

This qualitative information then needs to be translated into quantitative scenarios where historical experience and/or hydrogeological analysis is required to provide realistic limits to the selected scenarios. Based on **Table 2**, in appropriate locations quite large magnitudes of subsidence might be considered in the worst case. For

[13] Peltier GIA datasets ; http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/

example Wang *et al.* (1995) considered scenarios of up to 1 m human-induced subsidence in Shanghai from 1990 to 2100, while (Nicholls *et al.*, 2008a) considered a worst-case human-induced subsidence up to 0.5 m from 2005 to the 2070s in all large port cities built on deltas.

4.4 Sensitivity analysis

Other approaches for constructing local sea-level scenarios based on SRES-forcing make qualitative use of available information. For example, Nicholls *et al* (2007) noted that where the local deviations from the global mean from a set of climate models are not available, a $\pm$50% factor based on global-mean change can be applied (see also Hulme *et al.*, 2002).

It is possible to employ the maximum/minimum global-mean sea-level rise data set available at the IPCC Data Distribution Centre, which is based on the nine cases considered in Gregory *et al.* (2001), or preferably updates based on the IPCC AR4. This method gives a global set of scenarios combining global-mean and regional meteo-oceanographic effects that is globally applicable and this approach has been used in several UK coastal impact assessments. Arguably, this approach overstates the uncertainty in local sea-level change and pattern scaling may be a superior approach, especially as understanding of the patterns improves.

4.5 Synthetic methods, including consideration of extreme sea-level rise

Even where no data are available or the alternative ways of generating sea-level scenarios are not considered to be applicable, it is still possible to carry out an impact or sensitivity analysis to sea-level rise. This may be done by using a nominal value for the change in local sea level (e.g. 0.5m, 1m, 1.5m), where a specific time period may or may not be defined. The method has been successfully used in a number of studies from country to global scales (e.g. Nicholls *et al.*, 2008a; Snoussi *et al.*, 2008). A range of values can be used to develop an appreciation of the potential impacts or determine thresholds in the magnitude of impacts, vulnerabilities and adaptation options. A synthetic approach also provides an option for addressing the issue of extreme sea-level rise, which is now considered in more detail.

As our scientific understanding improves, a common objective is to narrow the uncertainty range of expected sea-level rise based on model studies. However, because understanding of some important effects driving sea level rise is too limited, the AR4 did not provide a best estimate or an upper bound for sea-level rise, or assess its likelihood (IPCC, 2007a p 45; Solomon *et al.*, 2007). For example, the sea level projections do not include uncertainties in climate-carbon cycle feedbacks nor do they include the full effects of changes in ice sheet flow. Dynamic processes related to ice flow could increase the vulnerability of ice sheets to warming and increase sea-level rise, and these dynamic processes were not included in the models used to provide quantitative projections (IPCC, 2007c). The AR4 emphasised that additional contributions to sea-level rise from polar ice sheets on century time scales could lead to larger increases than the numerical sea-level rise estimates presented in their Table 10.7 (Meehl *et al.*, 2007).

However, the potential for rises in sea level in excess of 1 m is of particular relevance to impact, vulnerability and adaptation assessments as it allows analysts to consider risk in the context of the lifetime and nature of assets that would be affected by such large sea-level rise scenarios (see e,g, Tol *et al.*, 2006) [14]. This guidance document does not attempt to quantify this extreme range, and for its application analysts are encouraged to seek advice from global sea-level and ice sheet experts, complemented with new information being assessed by the IPCC, as it appears, including the IPCC AR5 (due to be approved in 2013/2014). A published example of an extreme scenario (called the H++ scenario) for the UK coast is provided by Lowe *et al.* (2009) and is described in Appendix A3.6. A similar synthetic case is also included in the scenarios offered as examples in **Table 5** below.

4.6 Global to local scenario integration

Computer models have been developed to facilitate the development of relative sea-level change scenarios integrating global, regional and local contributions to sea-level change. SimCLIM (Warrick, 2009) is such an example and a full description of how it facilitates site-specific sea-level change scenarios can be found in Appendix 2.

Figure 6 shows multiple outputs of SimCLIM for two grid box locations representing zones of present-day relative sea-level rise (Buenos Aires) and sea-level fall (Stockholm). Note the spread in projections based on a range of assumptions concerning global sea-level response to climate and different SRES emissions scenarios. With the projected increase in the eustatic rate of sea-level rise during the 21st century, by 2100 many regions currently experiencing relative sea-level fall owing to GIA could instead have a rising relative sea level (for example, Stockholm as shown in the right-hand panel in **Figure 6** and as discussed by Johansson *et al.*, 2004).

Ideally, given the large uncertainty about the future global-mean and other components of sea-level rise, adaptation and planning assessments need to assess a range of scenarios to define the relevant response surface for sea-level rise (and other change scenarios, as appropriate), and test the robustness of different adaptation measures. However, it is impractical to consider the full range, and a sub-set reflecting the range, as in **Figure 6**, is should be selected. There are two approaches to such an analysis:

1. Drive the analysis with individual downscaled global-mean scenarios (taking account of global, regional and local changes), so that results for the selected scenario will have immediate meaning;
2. Drive the analysis with a suite of scenarios that <u>*encompasses*</u> the range of the downscaled global-mean scenarios. This is a guided sensitivity analysis that will provide a response surface, which can then be used for interpolation of any intermediate scenario.

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[14] Remember that here the main focus is on changes in the 21st Century– up to a 100 year timescale

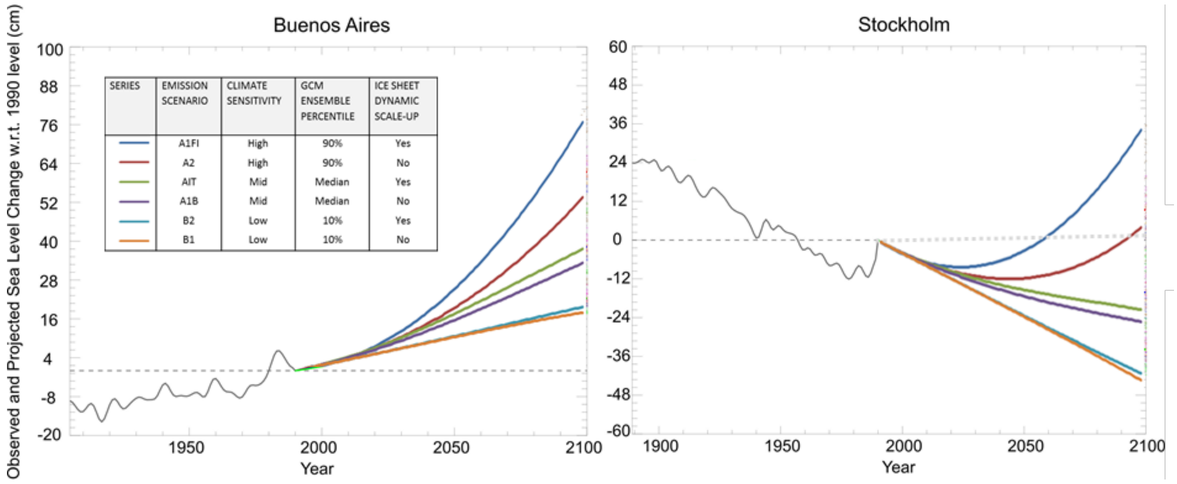

Figure 6: Six projections of sea-level change for Buenos Aires (left) and Stockholm (right) for the period 1990-2100 generated using the SimCLIM system (see Appendix 2 for details). Also plotted are the observed changes in sea-level as derived from the respective local tide gauge records, referenced to 1990 with a 10-year filter applied (grey lines in the figure). The observed local trends in relative sea-level change are +1.57 mm/yr and -3.94 mm/yr for Buenos Aires and Stockholm, respectively, and are included in the future projections. The six projections are selected to span a range of uncertainty in future GHG emissions, the climate sensitivity, spatial differences in rates of change (primarily from oceanic thermal expansion, as projected by AOGCMs) and ice sheet dynamics, as consistent with IPCC AR4.

Superficially these approaches are very similar, but the second approach places less emphasis on scenario downscaling as the first analytical step, and leaves some of the detailed scenario questions for later in the analysis. This can be helpful as the scenario development and interpretation is more integrated into the overall analysis rather than being "front-ended" as in the former case. This is particularly suitable if only sea-level rise is being considered. However, as the number of scenario types being considered increases, so the combination of scenarios increases and linking the downscaled scenarios in a more 'traditional' impact assessment may become more appropriate.

4.7 Intermediate time periods

In order to decide when and where to respond to the implications of sea-level change, it is useful for impact and adaptation assessments to consider intermediate time periods (see example Appendix A3.6). This information is not available directly from AR4 but it is possible, using a variety of methods, to create interpolated sea level curves. It must be remembered however that the values created are generally based on a statistical, rather than physics, approach and can therefore only be used for guidance.

One simple interpretation for global-mean sea level can be achieved using Equation 2, below; assuming sea-level rise in 1990 is zero. This form of curve was chosen because it has the same number of tuneable parameters as the constraints to which the curve can be fitted; namely the estimated rate and amount of sea-level rise at the end of the 21st Century and, for the limited number of cases for which actual physical model-derived time series were available, a quadratic was found to give a good fit.

$$\Delta SL_G = a_1 t + a_2 t^2 \qquad \text{Equation 2}$$

Where,

ΔSL_G = change in global sea level (since 1990)

t = number of years since 1990

a_1 = trend in sea level change

a_2 = change in the rate of the sea-level trend

Figure 7 shows the sea-level curves created by Equation 2 for the range of scenarios reported in AR4 (estimated upper and lower limits are based on the 5[th] and 95[th] percentile reported).

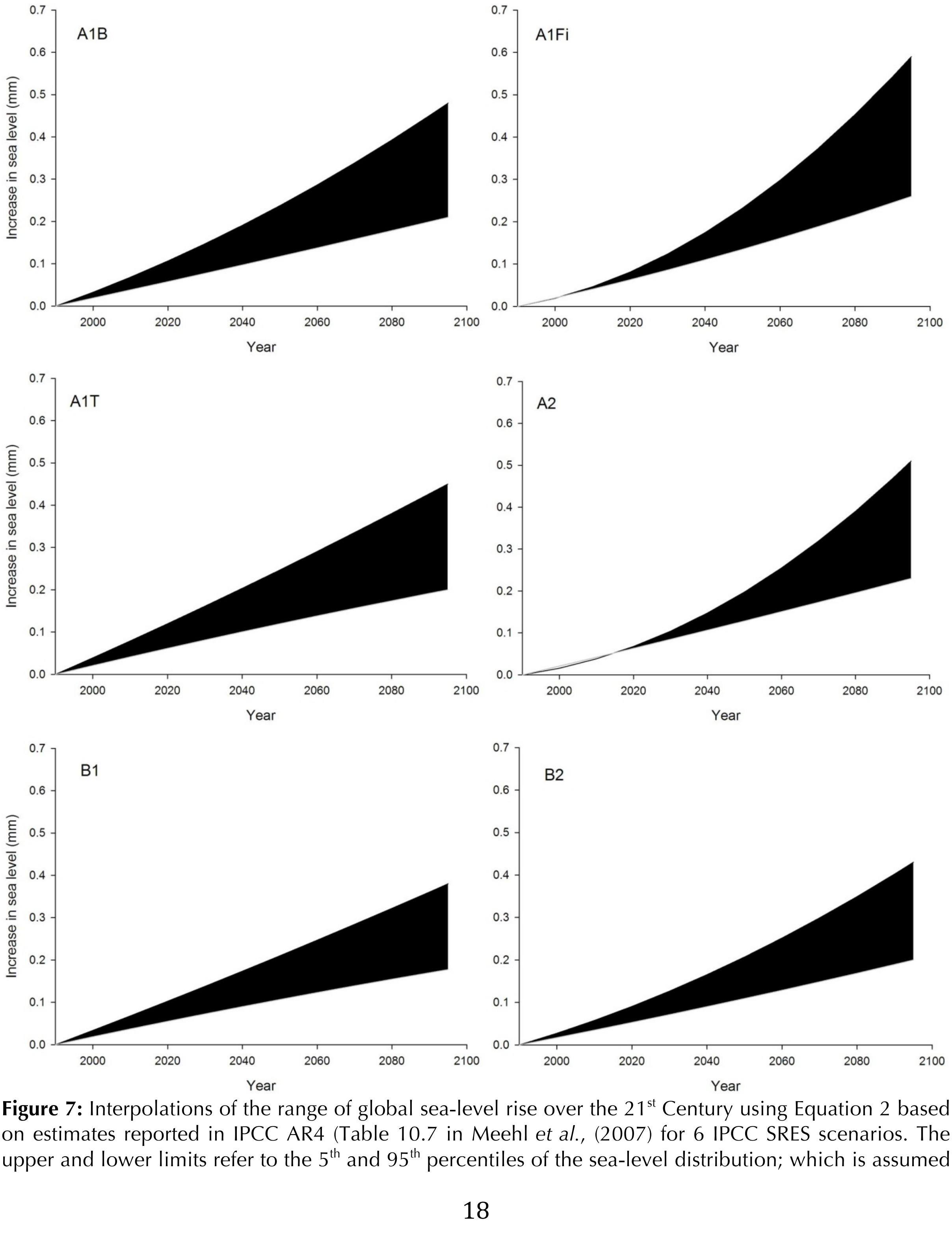

Figure 7: Interpolations of the range of global sea-level rise over the 21[st] Century using Equation 2 based on estimates reported in IPCC AR4 (Table 10.7 in Meehl *et al.*, (2007) for 6 IPCC SRES scenarios. The upper and lower limits refer to the 5[th] and 95[th] percentiles of the sea-level distribution; which is assumed

to be Gaussian. Note: other influences on relative sea levels (e.g. subsidence) need to be added to these interpolations for regional or local assessments.

5 Scenario choice and availability for impact and adaptation assessment

The scenario development discussed in Section 4 is largely quantitative, but in many cases a high precision may neither be required nor appropriate given the large range of potential sea-level rise under alternative future scenarios. As an example, when looking at flood risk management, extreme water levels are typically required to 10 cm accuracy (Araujo and Pugh, 2008). For a local study, if resources are available, the impact assessment could consist of local socio-economic scenarios and downscaled/processed sea-level data combined with a surge model and vertical land movement observations. However, it is also important to remember that as impact assessments are commonly based on elevation data, there is no requirement for a sea-level scenario with 10 cm accuracy when the topographical data set generally has a vertical precision of 30 cm at the very best[15].

Table 3: Summary table of sea-level components showing how they can be combined for impact and adaptation assessment. Requirements for different levels of assessment are indicated.

Sea-level component		Level of assessment		
		Detailed	Intermediate	Minimum
Socio-economic scenario		Downscaled SRES scenario[16] or other relevant local scenario	Global SRES (or baseline[17])	
Global sea-level change (including ice melt)	SL_G		IPCC AR4 (and extreme scenario if applicable for impact studies)	
Regional sea-level change	SL_{RM}	Meteo-oceanographic driven deviations from individual models in AR4 for appropriate scenario	Scaled up local deviations from A1B diagram in AR4 (Figure 10.32); use pattern scaling equation or software e.g. SimCLIM	Use ± 50% (based on Hulme *et al* 2002)
	SL_{RG}	Correction for gravity effects	Scale predictions according to Mitrovica *et al*. (2001, Figure 1)	Assume globally uniform eustatic sea-level rise
Natural vertical land movement	LM_N	Detailed local observations e.g. GPS, long time series local tide gauge or relevant geological data[18]	Regional patterns of land motions inferred from geological data / GIA model estimates	Assume no change

[15] 30 cm accuracy can be accomplished using LIDAR (Light Detection And Ranging) for detailed case studies, but for national and larger-scale studies the accuracy will be lower.
[16] Downscaled population and GDP data available with guidance from: http://ciesin.columbia.edu/datasets/downscaled/
[17] If baseline (present-day) conditions are used, this needs to be made explicit
[18] Consider a range of values if methods do not agree (see Section 4.3.3)

Human induced vertical land movement	LM_H	Analysis of subsidence potential and relevant human actions[19]	Assume arbitrary changes based on geological setting	Assume no change
Changes in storm surge		Detailed local modelling using regional models or statistical downscaling driven by climate models	Run sensitivity study with no change in storminess component, then range of increase over 50/100 year period[20]	Assume no change

Table 3 summarises how sea-level scenarios might be developed with different levels of data availability including the minimum requirements for an impact assessment. Using as little information as: (i) a hard copy of IPCC reports for global socio-economic scenarios, (ii) global sea-level rise projections ±50% to account for regional variations, (iii) an assumption of no change in vertical land movement, and (iv) integrating these via Equation 2, the resulting sea-level change scenarios will still produce impact assessments which can inform adaptation requirements. As more research on sea level is conducted, so future scenarios can be improved, for example adding factors such as uplift/subsidence and/or improved meteo-oceanographic drivers.

However, impact assessment need not be delayed until such information is available. Rather, sea-level rise scenarios can evolve with the impact and adaptation assessments from a first scoping of the problem and its issues towards a more detailed understanding of impacts and ultimately to adaptation measures. This stresses that adaptation assessment for sea-level change can be considered a process rather than expecting a single assessment to address all issues to conclusion. Some examples of sea-level rise scenario development under different levels of data availability are illustrated in Table 4 and explained further in Appendix 3. Users of this guidance need to make judgements on the appropriate level of precision that they require.

Table 4: Examples of sea-level scenarios used for impact analysis (see Appendix 3 for details).

Reference	**Level of assessment**	**Area of interest**
(Katsman *et al.*, 2008)	Detailed	Northeast Atlantic Ocean
(Snoussi *et al.*, 2008)	Minimum - synthetic	Country level (Morocco)
(Dennis *et al.*, 1995)	Minimum	Country level (Senegal)
(Nicholls *et al.*, 2008a)	Intermediate	Global
(DEFRA, 2006)	Intermediate	Local-regional (England/Wales)
(Lowe *et al.*, 2009)	Detailed	Country level (UK)

The choice of sea-level scenarios will also vary with the focus and objectives of the assessment being carried out (see **Figure 8**). Impact assessments should aim to identify the magnitude of any thresholds for impacts and adaptation options across the full range of projected sea levels (e.g. from the AR4) as well as through sensitivity studies

[19] For example, ground water extraction. Note that human-induced subsidence can increase or decrease according to the management option selected

[20] Based on the estimates of Lowe and Gregory (2005) for the UK in the future and additional knowledge of previous surge events: suggested range ± 33%.

using extreme scenarios, where applicable; the extreme ranges being based on available knowledge (global and local) with clear reasoning provided.

For adaptation assessments the selection of sea-level scenarios should be informed by the lifetime and nature of assets at risk, planning horizons, risk aversion of affected communities and decision-makers, and the ability to up-scale or change adaptation responses over time. In practice, many adaptation assessments or strategies with limited time horizons or limited lifetimes of assets at risk may tend to focus on the range reported in the AR4. However, there may be interest in the potential adaptation options under an extreme range, and their consistency to the adaptation options identified for the AR4 range. For instance, if the preferred or feasible adaptation option changed from protect to retreat if the rise in sea level increased above the model-based AR4 range, this would raise difficult questions concerning the preferred near-term adaptation choices given the risk of locking-in large-scale infrastructure such as human settlements in the coastal zone.

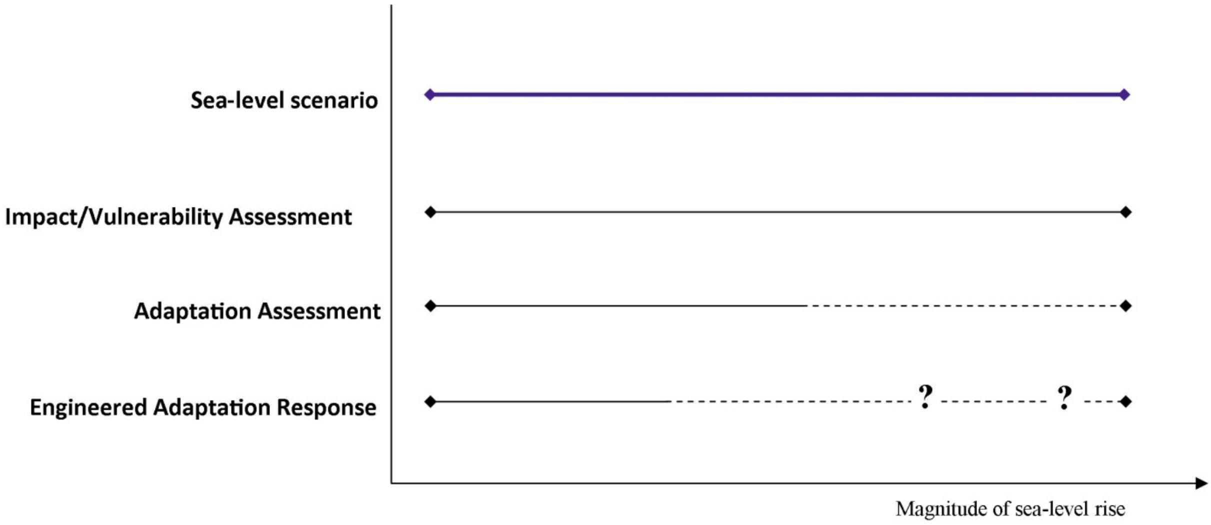

Figure 8: Possible relationship between sea-level scenarios, impact and adaptation.

Engineered adaptation responses, if selected within the adaptation assessment, will often be limited by technological or budgetary constraints to an ultimate single "design" scenario. As such engineered adaptation can be a costly exercise, it is assumed that the design scenario will be carefully evaluated and the uncertainty across the full range of scenarios, along with the potential consequences and remedial adaptation options if sea level were to exceed the chosen design scenario, will again be a key consideration. This may lead to a planned sequence of adaptation measures such as those being developed in the Thames Estuary 2100 Project for London (see Chapter 7 in Lowe *et al.*, 2009).

5.1 Range of Scenarios

While uncertainties remain large, it is prudent to consider a wide range of scenarios so that the full range of uncertainties and risks can be explored, and to avoid estimates of sea-level change impacts being rendered invalid every time new sea-level projections become available. It is also advisable to use the most detailed data available and appropriate for the scale of the impact analysis. As a basis for adaptation planning, the minimum requirement is to use the full range reported in the AR4 which represents the best available projections for the currently quantifiable parts of the sea-level budget for the 21st century. The consideration of a range of scenarios, including an extreme scenario, allows uncertainty, sensitivity, risks and long term adaptation planning to be included in the analysis, particularly where assets of high economic, social or environmental value and long lifetimes are concerned, and where near-term adaptation choice could constrain the ability to up-scale adaptation responses at a later stage. However, it is important to note that the literature underpinning any values can be expected to alter as scientific understanding develops. Constraining future sea-level change projections has been identified as a major scientific priority in a recent IPCC Workshop[21], for the Sea-Level Change chapter of the approved outline of the IPCC Working Group I AR5, and by Alley *et al.* (2008).

Based on this, **Table 5** provides the range of global-mean sea-level scenarios calculated from the interpolation described in Section 4.7 and other information discussed in this guidance.

5.2 Short term variations, including extreme events

Short term variations (<30 years) are not considered in depth in this guidance, although it must be recognised that many impacts on the coast and inshore marine environments will result from extreme events affecting sea level such as storm surge. The magnitude of extreme events at any particular time or place is influenced by tidal conditions, storm severity, decadal-scale variability and regional mean sea level. While these phenomena are not formally additive, for a first approximation they can be summed as demonstrated by Lowe *et al.* (2001) for the North Sea. Analysis of the high quality Newlyn tide gauge record suggests this was a reasonable assumption for the 20th Century (Araujo and Pugh, 2008; Haigh *et al.*, 2010).

To date future changes in storm surges due to meteorological change have only been simulated at a small number of locations, with significant differences in the response depending on the region. While it is desirable to include changes in extreme water levels that result from changes in atmospheric storminess, the method of so doing will depend on the scope of the individual impact study. Where time permits, employing both dynamic simulation of storm surges and statistical down-scaling approaches is the most comprehensive approach (e.g. Hunter, 2010).

However, it is important to note that flood levels will increase and become more frequent as sea level rises even if storm intensity and behaviour remains unchanged (see Figure 9). The addition of current surge, tide (and wave) levels to projected changes in sea level can provide a first approximation for impact and adaptation assessments. In addition, for assessments in regions affected by storm surges it is advisable to at least consider the impacts of increases of 10-20% across the range of return periods as a sensitivity analysis (cf. DEFRA, 2006). A new assessment of coastal impacts from extreme sea levels will be available in November 2011 as part of the IPCC SREX[22].

[21] http://www.ipcc.ch/pdf/supporting-material/SLW_WorkshopReport_kuala_lumpur.pdf

[22] IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX).

Table 5. Estimates of global-mean sea-level rise for the last decade of the 21st century (relative to 1980 to 1999) based on the interpolation calculations shown in Section 4.7 and **Figure 7**, and combining sea level rise with scaled up ice discharge[23] to create a low estimate for an extreme (*H++)* range for each SRES scenario. The upper estimate for the *H++* range comes from assuming 2m at 2100. Note that these estimates are one interpretation of AR4 WG 1 and are not meant to be regarded as an update to the values reported there.

			Illustrative estimates	SRES marker scenario					
				B1	B2	A1B	A1T	A2	A1FI
2025	*AR4 interpolated*	Range (m)	upper	0.12	0.11	0.13	0.14	0.09	0.10
			lower	0.06	0.06	0.07	0.08	0.07	0.07
	H++	Range (m)	upper	0.25	0.25	0.25	0.25	0.25	0.25
			lower	0.09	0.10	0.11	0.11	0.11	0.13
2055	*AR4 interpolated*	Range (m)	upper	0.23	0.23	0.26	0.27	0.23	0.26
			lower	0.12	0.10	0.12	0.15	0.13	0.15
	H++	Range (m)	upper	0.75	0.75	0.75	0.75	0.75	0.75
			lower	0.22	0.25	0.27	0.26	0.29	0.33
2085	*AR4 interpolated*	Range (m)	upper	0.34	0.38	0.42	0.40	0.43	0.50
			lower	0.16	0.15	0.17	0.22	0.19	0.23
	H++	Range (m)	upper	1.52	1.52	1.52	1.52	1.52	1.52
			lower	0.39	0.45	0.51	0.48	0.53	0.63
2095	*AR4 interpolated*	Range (m)	upper	0.38	0.43	0.48	0.45	0.51	0.59
			lower	0.18	0.16	0.19	0.24	0.21	0.26
	H++	Range (m)	upper	1.83	1.83	1.83	1.83	1.83	1.83
			lower	0.46	0.53	0.60	0.57	0.63	0.75

[23] Land ice sum comprises G&IC and ice sheets, including dynamics, but excludes the scaled-up ice sheet discharge

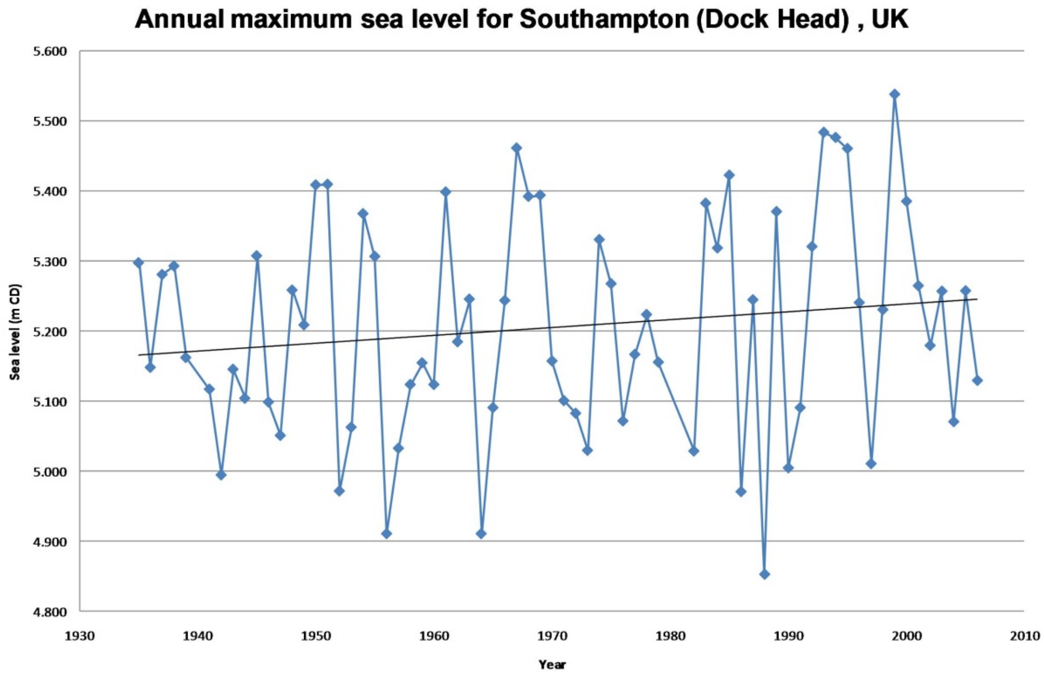

Figure 9: Time series of annual extreme sea levels at Southampton, UK - a rising trend is apparent and this is statistically similar to the rise in mean sea level (Haigh *et al.*, 2010).

6 Other climate change factors

As already noted, sea-level rise is only one aspect of possible changes to coastal climate given global warming. Other aspects of coastal climate can also be expected to change with many adverse and some beneficial effects that will often interact with sea-level rise (Nicholls *et al.*, 2008a; 2008b – see **Figure 2** and **Table 6**).

To date, most impact assessments of coastal areas have simply considered sea-level rise only and assumed all other climate factors are constant. However, other, relevant, climate scenarios should be considered where appropriate. The goal of this section is to draw attention to some of the factors that might be considered, although quantitative scenarios are beyond the scope of this guidance.

As indicated in Section 5.2, long-term variability in track location, intensity and frequency of coastal storms is of most concern, as this will change the occurrence of storm damage, including flooding and wave attack and has a high impact potential (e.g. Beersma *et al.*, 2000; Church *et al.*, 2001; von Storch and Woth, 2008).

The possibility of more intense tropical cyclones is a particular concern: it has been argued that increases in tropical cyclone intensity over the past three decades are consistent with the observed changes in sea surface temperature (Emanuel, 1987; Webster *et al.*, 2005), although this is controversial and being widely debated (Knutson *et al.*, 2010). Changes in other storm characteristics are less certain and the number of tropical and extra-tropical storms might even reduce (Meehl *et al.*, 2007). A new assessment of tropical and extra-tropical cyclones is also included in the forthcoming IPCC SREX[23].

Table 6: Main climate drivers for coastal systems, their trends due to climate change, their main physical and ecosystem effects, and the source of scenarios. Symbols for trends: □ increase; ? uncertain;

R regionally variable. Acronyms: GCM – General Circulation Models; RCM – Regional Climate Models. Adapted from Table 6.2 in Nicholls *et al.* (2007).

Climate Driver (trend)	Main physical and ecosystem effects on coastal systems	Possible source of scenarios
CO_2 concentration (□)	Increased CO2 fertilisation; decreased seawater pH (or 'ocean acidification') negatively impacting coral reef and other pH sensitive organisms.	Explicit scenario input to GCM simulations
Sea surface temperature (SST) (□, R)	Increased stratification/changed circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality; poleward species migration; increased algal blooms	GCM, RCM
Wave climate (?, R)	Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach planform.	GCM, RCM and ocean models
Run-off (R)	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply.	GCM, RCM and catchment models

Given the combination of high concern and scientific uncertainty, this factor may be best considered by sensitivity analysis – or a "what if?" analysis of an adverse increase in storminess in addition to sea-level rise. However, it is also important to note that there is a high interannual and interdecadal variability of storm occurrence (e.g. WASA Group, 1998; Zhang *et al.*, 2000), and it is difficult to discern long-term changes from natural variability in observations unless long time series (>50-60 years) are available.

7 Concluding remarks

Sea-level change is one of the observed consequences of global warming, and future sea-level rise is inevitable in a warming world, but the rates and geographical patterns of this rise remain uncertain (IPCC, 2007b). However, it is possible to develop useful scenarios of sea-level rise at any location, conduct an impact/vulnerability assessment and start to consider suitable adaptation policies/planning. The choice of specific scenarios and robustness of these results will vary according to the data available and/or the assumptions made for each sea-level change component, as well as the nature and lifetime of the potential assets at risk, so these should therefore always be made clear within the assessment report.

Importantly, scenario development is only one step in a process, and the effort made towards scenario development should be proportional to the resources of the overall study and the question being posed. As noted in the text, scenarios are expected to develop and improve as part of the on-going adaptation assessment process; this guidance is expected to continue to evolve with our improving scientific understanding. Similarly, the understanding of sea level rise will improve, and the demand for scenarios of sea-level rise is one factor that will facilitate this improvement.

Lastly, given the large uncertainties in future conditions, there is some risk that sea-level rise assumed for a selected adaptation measures may be exceeded. Hence, in addition to scenario development, ongoing monitoring of actual sea-level rise as well as an appreciation of developments in understanding of future sea-level rise in the scientific literature are essential so that additional measures can be implemented in a timely manner, if required.

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Appendices

Appendix 1. AR4 Source data

Table A 1: The IPCC projected global-average sea-level rise and its components under the six SRES marker scenarios during the 21st century. For each component, the upper row shows the 5 to 95% range (m) of the rise in sea level between 1980 to 1999 and 2090 to 2099; the lower row shows the range of the rate of sea-level rise (mm/yr) during 2090 to 2099. (Source: Table 10.7 in Meehl *et al.*, 2007).

Sea-level component		SRES marker scenarios											
		B1		B2		A1B		A1T		A2		A1FI	
Thermal expansion	m	0.10	0.24	0.12	0.28	0.13	0.32	0.12	0.30	0.14	0.35	0.17	0.41
	mm yr^{-1}	1.1	2.6	1.6	4.0	1.7	4.2	1.3	3.2	2.6	6.3	2.8	6.8
Glaciers and ice caps	m	0.07	0.14	0.07	0.15	0.08	0.15	0.08	0.15	0.08	0.16	0.08	0.17
	mm yr^{-1}	0.5	1.3	0.5	1.5	0.6	1.6	0.5	1.4	0.6	1.9	0.7	2.0
Greenland Ice Sheet SMB[30]	m	0.01	0.05	0.01	0.06	0.01	0.08	0.01	0.07	0.01	0.08	0.02	0.12
	mm yr^{-1}	0.2	1.0	0.2	1.5	0.3	1.9	0.2	1.5	0.3	2.8	0.4	3.9
Antarctic Ice Sheet SMB	m	-0.10	-0.02	-0.11	-0.02	-0.12	-0.02	-0.12	-0.02	-0.12	-0.03	-0.14	-0.03
	mm yr^{-1}	-1.4	-0.3	-1.7	-0.3	-1.9	-0.4	-1.7	-0.3	-2.3	-0.4	-2.7	-0.5
Land ice sum[31]	m	0.04	0.18	0.04	0.19	0.04	0.20	0.04	0.20	0.04	0.20	0.04	0.23
	mm yr^{-1}	0.0	1.8	-0.1	2.2	-0.2	2.5	-0.1	2.1	-0.4	3.2	-0.8	4.0
Sea-level rise[32]	m	0.18	0.38	0.20	0.43	0.21	0.48	0.20	0.45	0.23	0.51	0.26	0.59
	mm yr^{-1}	1.5	3.9	2.1	5.6	2.1	6.0	1.7	4.7	3.0	8.5	3.0	9.7
Scaled-up ice sheet discharge	m	0.00	0.09	0.00	0.11	-0.01	0.13	-0.01	0.13	-0.01	0.13	-0.01	0.17
	mm yr^{-1}	0.0	1.7	0.0	2.3	0.0	2.6	0.0	2.3	-0.1	3.2	-0.1	3.9

[30] Surface Mass Balance

[31] Land ice sum comprises glaciers and ice caps and ice sheets, including dynamics, but excludes the scaled-up ice sheet discharge.

[32] Sea-level rise comprises thermal expansion and the land ice sum. Note that the lower/upper bound for sea-level rise is larger/smaller than the total of the lower/upper bounds of the contributions, since the uncertainties of the contributions are largely independent

Appendix 2. The SimCLIM sea-level scenario generator

The relative change in sea level at specific locations is attributable to factors at global, regional and local levels (Section 3). To enable robust coastal vulnerability and adaptation assessment, sea-level change scenarios should integrate these factors in an internally consistent fashion. One software tool that accomplishes this task is the sea-level scenario generator contained within SimCLIM, an integrated modelling system for assessing impacts and adaptation resulting from climate variability and change (Warrick, 2009; Warrick *et al.*, 2005). The data and methods used by the sea-level scenario generator have been updated to be consistent with the AR4 Assessment, as described below.

The user interface of the SimCLIM sea-level scenario generator is shown in Figure A 1. The overall method features a separate consideration of three components: (1) global-mean sea-level projections; (2) regional departures from the global-mean value due largely to thermal expansion effects; and (3) local non-climate-change trends in relative sea level due largely to local land movements (e.g. Section 3.2). The system is designed to allow the user to obtain high, mid and low projections for sites by selecting amongst a range of uncertainty for each.

For ***global-mean projections***, the system contains high, mid and low projections for the six SRES marker scenarios (AIB, A1FI, A1T, A2, B1, B2) which consistent with the values given in IPCC AR4. SimCLIM also has an option for scaling up the projections to take account of uncertainties in ice melt contributions due to ice sheet dynamics (in accordance with Meehl *et al.*, 2007, Table 10.7; see Appendix 1).

For any user-selected location, the global-mean projections are adjusted by the ***regional variations*** in sea-level change, which are due largely to differences in thermal expansion as produced by AOGCMs. SimCLIM uses pattern-scaling techniques (see Section 4.3.1.2) in which the spatial patterns of thermal expansion from an AOGCM for a future time period are "normalised" by dividing by the global-mean thermal expansion for the same period. For any given location, therefore, there is a ratio indicating whether the local thermal expansion will be greater than, equal to, or less than the global-mean value and by how much (a sample of normalised patterns of these ratios is shown in **Figure A 2**). SimCLIM contains thirteen normalised patterns from AOGCM runs carried out for AR4. These AOGCM patterns can be used individually, or in combination as a multi-model ensemble with a median value and user-defined percentile ranges. In order to obtain the regionally-adjusted projection for a selected location and future date (between 1990 and 2100), the thermal expansion component of the user-selected global-mean sea-level change projection is scaled by the selected AOGCM normalised pattern. This component is then re-combined with the ice-melt portion of the projection.

For the ***local land movement*** component, the user can input a value for the local sea-level trend. If the trend in relative sea-level change from vertical land movement is known, the user can simply enter the value (in mm/yr) and this is added to the future projection. Often, however, only the total undifferentiated trend is known (as estimated, for example, from tide-gauge data). As discussed in Section 4.3.3, this total trend cannot simply be added onto the future projection because it would run the risk of "double-counting" the effect that global warming has already had on observed sea-level rise and would therefore inflate the future projected rise.

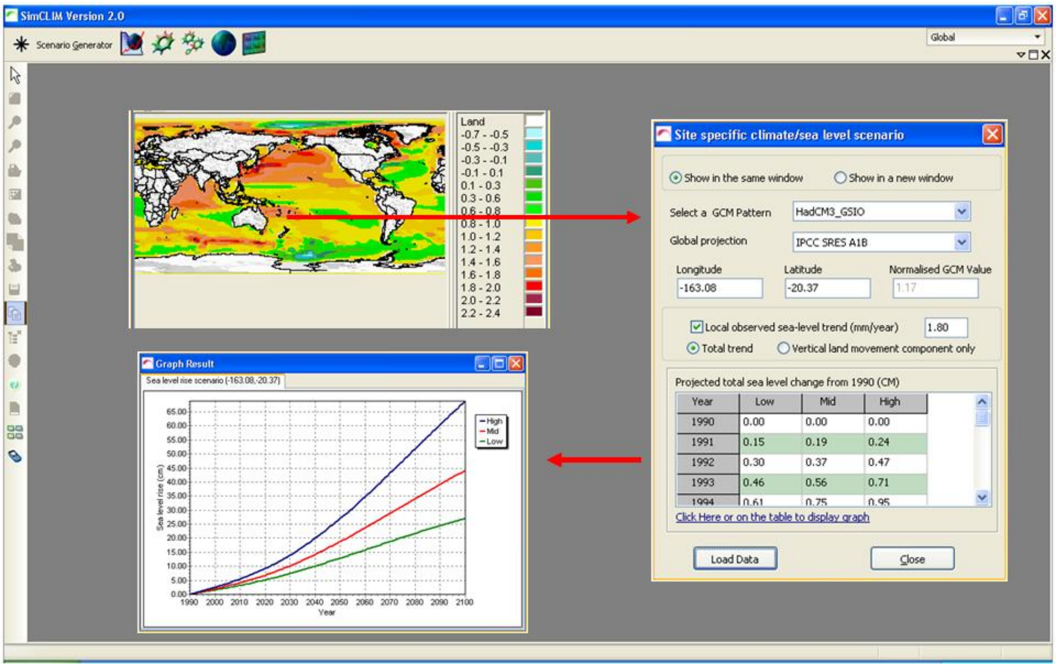

Figure A 1: The SimCLIM sea-level generator. In SimCLIM, global-mean, regional and local components are combined to produce location-specific projections of future change. The panel above shows the user interface, a selected AOGCM normalised pattern, and sample output of high, mid and low projections of sea-level rise.

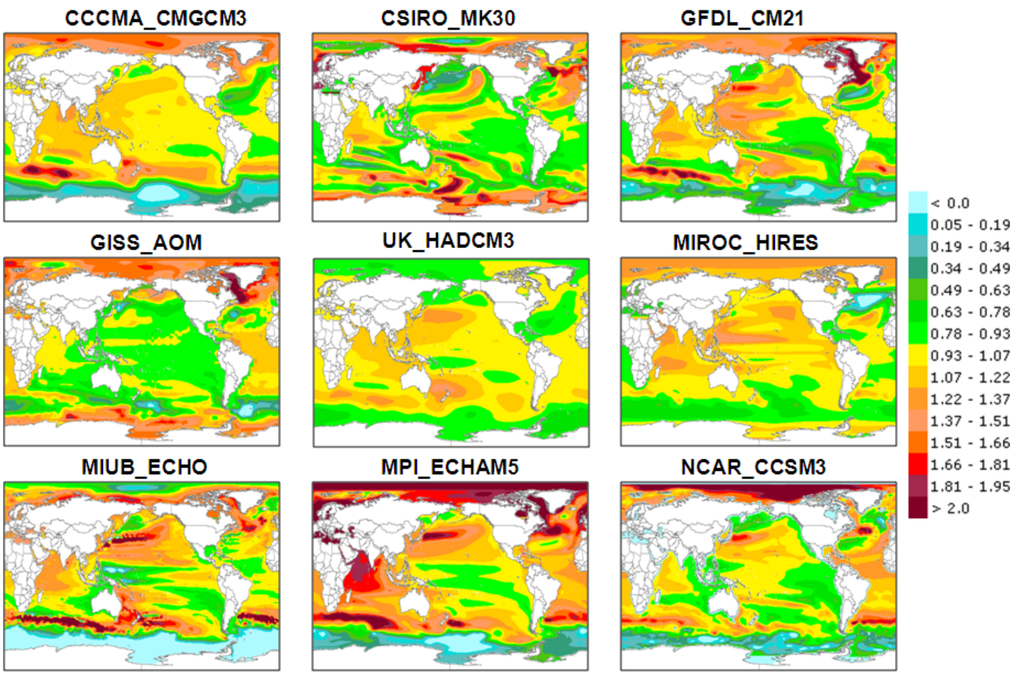

Figure A 2: Normalised sea-level changes (ratio of local sea-level change to the global average value; cm/cm) for thermal expansion as simulated by nine different AOGCMs, as developed for, and incorporated into, SimCLIM (AOGCM data provided by the Program for Climate Model Diagnosis and Intercomparison – PCMDI).

To avoid such double-counting, SimCLIM can estimate the non-climate-change-related component of the trend (OBS_{ncc}). This component is estimated by adjusting the observed global-mean trend (1.8 mm/yr) by the location-specific thermal expansion effect, based on the specific AOGCM selected by the user for future projections (in order to maintain consistency between observed trend and the future projection), as follows:

$$OBS_{ncc} = OBS_l - [GCM \times TE \times OBS_g + (1.0 - TE) \times OBS_g] \quad \text{Equation 3}$$

Where:

OBS_{ncc} is the non-climate-change local trend in sea-level (mm/yr);

OBS_l is the local observed trend, as typically derived from tide gauge data (mm/yr);

OBS_g is the estimated observed global-mean sea-level trend (1.8mm/yr);

GCM is the value of the GCM-specific normalised value of sea-level change, relating to thermal expansion only;

TE is the estimated proportion of observed global-mean sea-level rise due to thermal expansion.

$OBS_{ncc,}$ is often the result of vertical land movement, and is added to the regional pattern-scaled projection of sea-level change.

One of the distinct advantages of using automated methods such as the SimCLIM generator is that it allows rapid generation of place-based sea level scenarios which account for uncertainties within the bounds of reasonable combinations with emission scenarios and model parameters. For example, **Figure 6** in the text of this Guidance Document shows sea-level change projections for Buenos Aires and Stockholm for a multi-model ensemble of AOGCMS, model parameters and emission scenarios.

Appendix 3. Examples of sea-level scenarios used in impact assessments

This Appendix details a number of case studies of sea-level rise scenario development for impact assessments. A range of methods are presented to illustrate the range of methods described in **Table 4** from the simplest to the most comprehensive.

A3.1. Northeast Atlantic Ocean (Katsman et al., 2008)

This study used the most up-to-date data and climate models to determine sea-level rise in the northeast Atlantic Ocean for 2050 and 2100. The scenarios include changes in ocean density (global thermal expansion and local steric changes related to changing ocean dynamics) and changes in ocean mass (melting of mountain glaciers and ice caps, changes in the Greenland and Antarctic ice sheets, and (minor) terrestrial water-storage contributions). Given the current understanding of the various contributions and the uncertainty in emissions, best estimates of twenty-first century sea level rise in the northeast Atlantic Ocean have been produced,. For 2100, a local rise of 30 to 55 cm and 40 to 80 cm are estimated for moderate (2ºC) and large (4ºC) rises in global mean atmospheric temperature, respectively. Note that uplift/subsidence is not considered.

A3.2. Morocco (Snoussi et al., 2008)

The eastern part of the Mediterranean coast of Morocco is physically and socio-economically vulnerable to accelerated sea-level rise, due to its low topography and its high ecological and touristic value. As there are no long term measurements available, this study assessed potential land loss by inundation based on empirical approaches using a minimum inundation level of 2 m and a maximum inundation level of 7 m; where IPCC scenarios for future global sea-level rise range from 200 to 860 mm, with a 'best estimate' of 490 mm (IS92a emissions scenario - Warrick *et al.*, 1996). The results indicate that 24% and 59% of the area will be lost by flooding at minimum and maximum inundation levels, respectively, of which residential and recreational areas, agricultural land, and the natural ecosystem are the most exposed. The conclusion of this study's results draws attention to the importance of increasing awareness of decision-makers and planners to the potential future impacts of sea-level rise in an area where no sea-level data for the development of specific scenarios exists. The estimates for future sea-level rise were derived to represent 'worst case' and 'sustainable' scenarios.

A3.3. Senegal (Dennis et al., 1995)

This case illustrates an assessment where little hard data exists on sea level but the results can still provide valuable information.

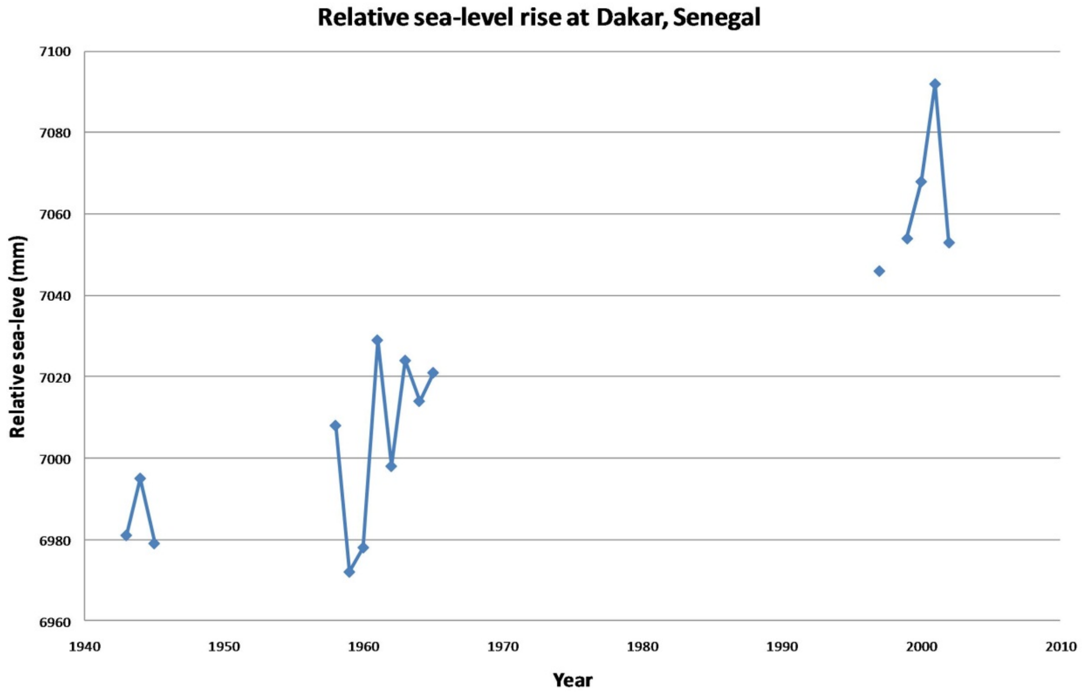

Figure A 3: Historical sea level record at Dakar, Senegal (data source PSMSL)

Senegal has a high proportion of its population and economic activity located in the coastal zone and is therefore considered vulnerable to sea-level rise; but there is lack of data (Dennis *et al.*, 1995) and the methods used illustrate the minimum requirements in **Table 3.**

The historical record of observed sea level at Dakar is shown in **Figure A 3**. The long-term linear trend found by Dennis *et al.* (1995) using the data between 1943-1965 was 1.4mm/yr, and the addition of data from 1997-2002 gives a mean rise of 1.5mm/yr, confirming the earlier trend was reasonable. Hence, any uplift or subsidence can therefore be assumed to be minimal and there does not appear to be any potential for human-induced subsidence, except possibly in the Senegal River delta. Therefore, it can be assumed that these conclusions are valid across the whole country and climate-induced sea-level rise scenarios can be directly applied to Senegal. Dennis *et al.* (1995) applied scenarios of 0.2 m, 0.5 m, 1.0 m and 2.0 m.

A3.4. Global ports (Nicholls et al., 2008a)

This global screening study made a first estimate of the exposure of the world's large port cities[33] to coastal flooding due to storm surge (and damage due to high winds). This assessment also investigated how climate change is likely to change each port city's exposure to coastal flooding by the 2070s, alongside subsidence and population growth and urbanisation. The work explicitly considered the potential for large changes as a bounding case and noted some of the large projected rises published since the AR4. Hence, the analysis was more focused on the extreme range than the AR4 range. Future sea-level scenarios were developed by combining data from DIVA (vertical land movement), with a global sea-level scenario of 0.5 m by the 2070s and a human-induced subsidence scenario for appropriate port cities – essentially those wholly or partly in major deltas. An increase in

[33] Those with more than one million people in 2005 – there were 136 such cities.

storm surge height was also included where considered possible by Meehl *et al.* (2007) (see Table A 2.

Table A 2: Data used for the global assessment of exposure to climate change for port cities in the 2070s.

		Sea-level change	
Relative sea-level component	ΔSL_G	Uniform global rate (0.5 m) assumed	
	ΔSL_{RM}	N/A	
	ΔSL_{VLM}	VLM_N	Variable based on Peltier (2000)
		VLM_H	Uniform amount (0.5 m) applied to port cities in deltaic settings
Storm surge		Increased by 10% in appropriate locations	

A3.5. Guidance for adaptation to coastal flooding due to sea-level rise (DCLG, 2006; DEFRA, 2006)

New coastal defences in England and Wales must consider the implications of accelerated sea-level rise and include this in engineering design, if appropriate. This is an extension of existing UK practice which was to include observed relative sea-level rise trends as measured with long-term tide gauges or other observational methods in engineering design.[34] The initial guidance was based on a 50 year time span and regional constant relative sea-level rise scenarios from 4 to 6 mm/yr, depending on the vertical land movements (DEFRA, 2000). The scientific basis was derived from the median scenario in the IPCC First Assessment report (Warrick and Orlemanns, 1990). This has been updated to a 100 year time horizon and is also being considered in coastal planning. The scenario is derived from the upper curve of the IPCC Third Assessment Report (Church *et al.*, 2001), and as such is taking a more precautionary view than the earlier guidance. The IPCC scenario ended in 2100, while scenarios are required for the early 22nd Century to address the 100 year timescale. Hence the IPCC curve was extrapolated from 2100 to 2115 and the allowance is time dependent rising to 13-15 mm/yr from 2085 to 2115. (Note that this Guidance is under review and revised guidance is expected to be released in 2011).

A3.6. TE2100, London, UK – the H++ scenario (Lowe et al., 2009)

London and the Thames Estuary have always been subject to flood risk and, due to the high value of property, London currently enjoys a high standard of protection (generally the 1000 year return level estimated for the year 2030). The Thames Estuary 2100 project (TE2100[35]) was established in 2002 with the aim of developing a long-term tidal flood risk management plan. Recognising that the estuary would continue to change, this plan would need to be adaptable and take into account factors such as changing sea levels and extreme water heights. The TE2100 project developed time series of quantitative sea-level and surge scenarios for this century in association with UK Climate Projections (UKCP)[36] using the projected uncertainty range of global sea level from the IPCC AR4 of the IPCC downscaled

[34] For instance, the Thames Barrier allowed 50 cm additional freeboard for rising extreme water levels based on trends in historic measurements at London Bridge (Gilbert and Horner, 1984), long before there were any concerns about human-induced global warming.

[35] http://www.environment-agency.gov.uk/homeandleisure/floods/104695.aspx

[36] http://ukclimateprojections.defra.gov.uk/

for the UK. These showed that sea-level rise in the Thames over the next century due to thermal expansion of the oceans, melting glaciers and polar ice is likely to be between 20cm and 90cm by 2100. The time series allowed the detection of thresholds of change which would require a response option to be implemented. In this way the timing and design of future flood defences, resilience of new and existing development against future water levels and the effectiveness of flood warning systems and emergency responses could all be determined.

During the project it was also recognised that current models does not include all of the processes that govern future sea-level rise (see IPCC, 2007b) with many uncertainties remaining over the contribution of polar ice melt to sea levels. Consequently an extreme, if highly unlikely during the 21st century, sea-level scenario was also included. This H++ scenario range provided an extreme but physically plausible range of change by 2100 (i.e. no time series was specified) which allowed investigation of contingency planning and the limits of adaptation. The H++ scenario is based on faster rates of melt for ice sheets which, while not currently predictable, can be estimated based on observations of the past and current understanding of ice sheet dynamics. The lower value for the H++ range was based on estimates reported in AR4 which recognised that accelerated ice flow with global mean surface temperature could produce up to an additional 17 cm of sea-level rise (for the High emissions scenario). This was added to the maximum sea-level rise previously calculated for London giving a lower estimate for the H++ range of 0.93 m. The upper estimate for the range was based on post AR4 publications which provided alternative, increased, estimates of ice melt (e.g. Pfeffer *et al.*, 2008). Combined with rates of thermal expansion and vertical land movement, this estimate of ice melt produced a worst case estimate at approximately 1.9 m. The H++ range was therefore between 0.93 and 1.9 m for London.

Appendix 4. Evolution of the IPCC socio-economic and emissions scenarios

Early IPCC assessment reports and some climate modelling use the IS92a global emissions scenario of the Intergovernmental Panel on Climate Change (Alcamo *et al.*, 1995; Leggett *et al.*, 1992). This scenario is often referred to as a "business-as-usual" scenario representing a plausible course for global emissions under a public policy that gives no consideration to climate change concerns. This scenario is not now widely used having been superseded by the IPCC SRES[37] based on a series of global socio-economic scenarios (Naki□enovi□ *et al.*, 2000).

Each of the SRES scenarios represents a specific quantitative interpretation of one of four storylines. Each storyline represents different demographic, social, economic, technological, and environmental developments, which attempted to encompass the current range of uncertainties of future GHG emissions. A total of six scenario groups cover wide and overlapping emission ranges (Naki□enovi□ *et al.*, 2000). Ideally, all scenarios should be included in any impact assessment. However, it is important to note that, as evident in both the TAR (Church *et al.*, 2001) and AR4 (IPCC, 2007a), and for sea-level rise from 1990 to 2100, the uncertainty in model (climate and ice melt model) tends to make a greater contribution to the variation in sea level than the uncertainty from the choice of emissions scenario.

In addition to driving emission scenarios, socio-economic scenarios can have other roles within impact and adaptation assessment (see **Figure 2** and Carter *et al.*, 2007). The socio-economic assumptions used within such assessments ideally should be consistent with those used to drive the emissions underlying the climate change scenarios being employed (Arnell *et al.*, 2004; Nicholls *et al.*, 2008b), although the definition of consistency depends on the geographic scale and scope of the study. This consistency allows exploration of the relative effects of climate versus socio-economic changes on impacts and responses to them, as illustrated for a detailed assessment of North-East Norfolk, UK by Dawson *et al.* (2007) and an analysis of global port cities by Nicholls *et al.* (2008a). Methods to describe the level of development and adaptive capacity in coastal areas, are outlined by Nicholls *et al.* (Nicholls *et al.*, 2008a; 2008b), and discussed in the context of human-induced subsidence in Section 4.3.3.

To make these scenarios more applicable at regional and local scales, it is possible to downscale the global IPCC SRES scenarios as illustrated in Gaffin *et al.* (2004), Solecki and Oliveri (2004), Grübler *et al.* (2007), Stendel *et al.* (2007), and van Vuuren *et al.* (2007; 2010). Continued development of emissions scenarios is occurring, including the development of sea-level scenarios where greenhouse gas emissions are stabilised (Moss *et al.*, 2010). The current scenarios will therefore almost certainly be superseded by the time of the next (5th) IPCC assessment. However, the issues presented in this guidance document will remain, and the approaches presented here are generic and will remain useful.

[37] Special Report on Emissions Scenarios

Appendix 5. Glossary

altimetry	Radar technique that measures global elevation of sea, land or ice surfaces compared to the centre of the earth
AG	Absolute Gravimetry
AOGCM(s)	Atmosphere-Ocean-Coupled General Circulation Model(s)
AR4	IPCC Fourth Assessment Report (2007)
downscaling	Any process by which large scale data are made applicable for use at smaller, more detailed scales
EMICs	Earth System Models of Intermediate Complexity
ENSO	El Niño-Southern Oscillation (commonly referred to as El Niño) is a large scale ocean-atmosphere oscillation (often with a 5 year timescale) associated with strong fluctuations in ocean currents and surface temperatures, primarily in equatorial regions within the Pacific Basin.
eustatic	Related to changes in the amount of water in the oceans
GCM	General Circulation Model
GIA	Glacial-Isostatic Adjustment (this has also been termed post-glacial rebound). The ongoing adjustment of land levels to the removal of the large ice sheets at the end of the last Ice Age. Beneath the sites of former ice sheets this is a vertical rebound (or sea-level fall), but both subsidence and slower uplift occur in the far field.
GPS	Global Positioning System.
Greenhouse gases	Trace gases such as carbon dioxide that absorb heat that is radiated from the surface of the earth and the atmosphere
HadCM3	Climate model developed by the Met Office Hadley Centre for Climate Prediction and Research
Hydrological Cycle	The continual flow of water between land, sea, and atmosphere, through evaporation, condensation, and precipitation.
Ice cap	A dome-shaped cover of perennial ice and snow, covering the summit area of a mountain mass so that no peaks emerge through it, or covering a flat landmass such as an arctic island; spreading outwards in all directions due to its own weight; and having an area of less than 50,000 square kilometres (Glacial geology glossary[a]).
Ice sheet	A glacier of considerable thickness and more than 50,000 square kilometres in area, forming a continuous cover of snow and ice over a land surface, spreading outward in all directions and not confined by the underlying topography. Ice sheets are now confined to polar regions (in Greenland and Antarctica), but during the Pleistocene Epoch they covered large parts of North America and northern Europe (Glacial geology glossary)
LIDAR	(Light Detection And Ranging) an optical remote sensing technology used to measure topography.
meteo-oceanographic	Interaction between meteorological and oceanographic processes
NAO	North Atlantic Oscillation is a climatic phenomenon in the North Atlantic Ocean due to fluctuations in the atmospheric pressure difference between the Icelandic

[a] http://www.homepage.montana.edu/~geol445/hyperglac/glossary.htm

	low and the Azores high. It is correlated with the strength and direction of westerly winds and storm tracks across the North Atlantic.
Neo-tectonics	The study of the motions and deformations of the Earth's crust (geological and geomorphological processes) which are current or recent in geologic time
OECD	Organisation for Economic Co-operation and Development: www.oecd.org
PSI	Persistent Scatterer Interferometry
RCM	Regional Climate Model
rheology	The study of the deformation and flow of matter under the influence of an applied stress
SCM	Simple Climate Model
SD	Statistical Downscaling:
SRES	IPCC Special Report on Emissions Scenarios:
TAR	IPCC Third Assessment Report (2001)
Thermal expansion	Expanson of the water volume of the oceans due to an increase in temperature
UD/EB model	Upwelling-Diffusion Energy-Balance model
WAIS	West Antarctic Ice Sheet: is the portion of the continental ice sheet that covers West (or Lesser) Antarctica.

Appendix 6. Useful Web Pages

A6.1. Data sources

DIVA model website: http://www.diva-model.net

Met Office Hadley Centre: http://www.metoffice.gov.uk/research/hadleycentre/

IPCC Data Distribution Centre: http://www.ipcc-data.org/

National Climatic Data Centre: http://www.ncdc.noaa.gov/oa/climate/globalextremes.html

National Environmental Satellite, Data and Information Service: http://www.nesdis.noaa.gov/

National Tidal Centre: http://www.bom.gov.au/oceanography/projects/ntc/ntc.shtml

NOAA Topex/Poseidon analyses: http://ibis.grdl.noaa.gov/SAT/hist/index.html

Program for Climate Model Diagnosis and Intercomparison: http://www-pcmdi.llnl.gov/

Permanent Service for Sea Level: http://www.pol.ac.uk/psmsl/

UK Climate Impacts Programme: http://www.ukcip.org.uk/

UK Climate Projections: http://ukclimateprojections.defra.gov.uk/

Peltier GIA datasets: http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/

A6.2. General information

Commonwealth Scientific and Industrial Research Organisation (CSIRO): http://www.cmar.csiro.au/

SURVAS: http://www.survas.mdx.ac.uk/

Tyndall Centre for Climate Change Research: http://www.tyndall.ac.uk/

United Nations Framework Convention on Climate Change: http://unfccc.int/adaptation/nairobi_workprogramme/compendium_on_methods_tools/items/2674.php

US Department of Transport: Centre for Climate Change and Environmental Forecasting: http://climate.dot.gov/about.html

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