METRICS FOR ASSESSING THE ECONOMIC BENEFITS OF CLIMATE CHANGE POLICIES: SEA LEVEL RISE
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1. Introduction

The purpose of this report is to explore issues and develop methods for estimates of the long-term (>100 years) damages of sea-level rise and of the benefits of actions to mitigate these risks for coastal areas. It has been known for at least 15 years that sea-level rise is relatively unresponsive to the mitigation of climate change when compared to other climate factors (WARRICK and OERLEMANS, 1990; WIGLEY and RAPER, 1993). This is due to the slow thermal response of the oceans which warm slowly producing a continuing thermal expansion. This has been termed the “commitment to sea-level rise” and, even if climate is stabilised, sea-level rise will continue for centuries or longer due to the historic greenhouse gas emissions (e.g. MEEHL et al., 2005; e.g. WIGLEY, 2005). Additional long-term rises in sea level may occur due to the irreversible deglaciation of the large Greenland and West Antarctic ice sheets, although this depends on future greenhouse emissions (GREGORY et al., 2004; RIDLEY et al., 2005; LOWE et al., 2006) and, especially in the case of the West Antarctic, the science remains poorly understood (VAUGHAN and SPOUGE, 2002; RAPLEY, 2006). A total global rise in sea level of up to 15 m is possible from these combined sources over a timescale of more than a millennium.

Mitigation of climate change has a potential role in controlling the ultimate commitment to sea-level rise, but even if climate change was stabilised immediately and all major ice sheet deglaciation avoided, a 1-m commitment of sea-level rise is still observed in the Hadley model (NICHOLLS and LOWE, 2004). The important policy implication of this commitment to sea-level rise is that while climate mitigation can stabilise global temperatures at timescales of the order of a century, it will only slow rather than stop sea-level rise, and many impacts are delayed rather than avoided (NICHOLLS and LOWE, 2004; LENTON et al., 2006; NICHOLLS and LOWE, 2006). Thus, independent of climate policy on greenhouse emissions, there is an ongoing “commitment to adaptation” for coastal areas due to the commitment of sea-level rise. The overall goal of climate policy assessment for coastal areas must therefore be the combined evaluation of mitigation (to slow the rise and minimise the final commitment) and adaptation (for the committed sea-level rise).

Given the large potential sea-level rise commitment held in the Greenland and West Antarctic ice sheets, ways to avoid deglaciation in both these systems would seem an important issue to explore. However, this may already be quite difficult to achieve as discussed for Greenland by GREGORY et al (2004) and LOWE et al (2006), while for Antarctica the knowledge base is much lower (VAUGHAN and SPOUGE, 2002; VAUGHAN, in press-a; in press-b).

This report contributes to the development of methods for assessing the defined problem, and develops an approach to estimate consistent and comparable estimates of the impacts of sea-level rise in both monetary and non-monetary terms for timescales of up to 500 years. This is much longer than most existing assessments, which with few exceptions only consider the 21st Century. As shown later in this report, an assessment of global-mean sea-level rise from 2000 to 2500 needs to consider global-mean rise scenarios in a range of 0.35 metre to about 9 metres. At the local scale, larger changes are possible in subsiding areas – such subsidence is difficult to predict, but in coastal areas such as deltas which are sensitive to groundwater withdrawal, the potential subsidence would be many metres over these long timescales (e.g. NICHOLLS, 1995a). The developed methods are designed to be useful to the climate policy process.

The study considered possible changes of sea-level rise over the next 500 years and methods to consider the resulting impacts in four main stages as outlined below:
1. Sea-level rise and related scenarios to 2500. The magnitude of sea-level rise for a range of unmitigated and stabilisation scenarios has been reviewed and synthesised based on existing runs from three models. These take account of contributions from thermal expansion, and changes to the Greenland ice sheet. One of these models considers the additional contribution from Antarctica and small glaciers. The IPCC TAR suggests that small glaciers could contribute 50 cm in total, while Antarctica’s contribution is considered by expert judgement. This analysis includes consideration of the relationship between global temperature rise and sea-level rise over a 500-year time scale. The issues around downscaling these global scenarios to local scenarios are also considered. Finally, other (mainly socio-economic) changes relevant to analysing impacts beyond the 21st Century are also considered, and the difficulties and assumptions necessary for impact analysis are highlighted.

2. Policy-relevant metrics for sea-level rise and its impacts. A range of metrics have been explored that associate the magnitude and timing of sea-level rise with the associated physical, biological and socio-economic impacts. This includes consideration of long-term change and large rises in sea level. The metrics have been selected based on their relevance to decision makers at different levels of government, and their utility for widespread communication. This aspect included a workshop of relevant coastal practitioners to review the utility of the selected metrics, and a wider exploration of attitudes to long-term sea-level rise and the most appropriate metrics using an exploratory questionnaire survey distributed via email.

3. Impact and economic valuation models for local to global surveys. The generic problems of climate impact analyses are considered and evaluated against a range of candidate methods and models, including important related issues such as discounting and intergenerational equity. Methods for exposure and impact assessments (the latter assessment including adaptation) are presented across a range of scales, but with an emphasis on broad-scale models which are relevant to climate policy, together with relevant information on datasets and selected integrated assessment models of coastal areas.

4. Application of some of the selected metrics for long-term analysis. Some of the metrics are illustrated in the context of the models and methods identified in the previous section, with an emphasis on sensitivity analysis via definition of areas of risk which was the preferred metric in the questionnaire. This section shows both the strengths and limitations of such analyses, and especially emphasises the difficulties of impact assessments with the existing modelling tools.

Each of these four stages of the analysis is now considered in turn, while Appendices summarise the detail of some of the background material, such as the sea-level rise scenarios, the metric questionnaire survey and the expert workshop.

2. Future scenarios from 2000 to 2500

The focus of this study is the impact of sea-level rise over the next 500 years. Section 2.1 considers potential global-mean sea-level rise over this timescale based on an analysis of three models with a range of scenarios, a literature review for Antarctica, and a synthesis of all these results. Other climate change factors are not considered in this report, following the terms of reference. Section 2.2 then considers issues concerning downscaling these results to relative sea-level rise, including more local changes such as uplift and subsidence. As impact and vulnerability analysis also requires scenarios of socio-economic factors such as population and GDP, Section 2.3 then briefly considers the difficulties in developing such scenarios compared to modelling scenarios of sea-level rise.
2.1  Sea-level rise scenarios for the next 500 years

2.1.1  Introduction

In this section the potential for sea-level increases beyond the 21st century is discussed. In addition to a brief review of the results in the Third Assessment report (Church et al., 2001) some new estimates of longer term sea-level rise estimates are provided from three models: (1) HadCM3 (plus the Greenland ice sheet component), (2) CLIMBER-2 and (3) GENIE-1. The first model is a complex coupled atmosphere-ocean general circulation model GCM. The latter two models are both coupled atmosphere-ocean models of intermediate complexity. Contributions from small glaciers and Antarctica are treated by expert judgement as they are not handled in detail in any of the three models. Finally, there is a synthesis across the available models to define the range of change due to contributions from thermal expansion and Greenland. This includes upper bounds on the total potential rise to 2500 using expert judgement regarding Antarctica and small glaciers.

2.1.2  Results from the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR)

In the IPCC TAR, Church et al (2001) provided a broad review of past climate change and future change up to 2100. It also provided some information on changes further into the future (section 11.5.4 of Church et al., 2001). The thermal expansion results are taken from nine climate model variants, mostly using models of intermediate complexity, and follow two idealised emissions scenarios.

In the first scenario the atmospheric carbon dioxide (CO$_2$) was increased at 1% per annum compounded until CO$_2$ concentration was doubled and then stabilised, corresponding to a radiative forcing of approximately 3.5 Wm$^{-2}$. This change is greater than the 21st century total global average radiative forcing for the SRES$^1$ B1 scenario, but less than that for the SRES B2 scenario. Estimates of thermal expansion after 500 years are in the range of approximately 40cm to 110cm (Figure 1). In the second idealised scenario, the 1% per annum compound increases were continued until CO$_2$ concentration was quadrupled, and then stabilised. This higher forcing is greater than the 21st century total global average radiative forcing for the SRES A2 scenario, but less than that for the SRES A1FI scenario. Estimates of thermal expansion after 500 years range from approximate 80cm to 220cm for this scenario.

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Figure 1. Global average sea-level rise from thermal expansion in model experiments with CO2 increasing at 1%/yr for 70 years and then held constant at 2x its initial (pre-industrial) concentration. Reproduced from TAR
Figure 2. Response of the Greenland Ice Sheet to three climatic warming scenarios during the third millennium expressed in equivalent changes of global sea level. The curve labels refer to the mean annual temperature rise over Greenland by 3000 AD as predicted by a two-dimensional climate and ocean model forced by greenhouse gas concentration rises until 2130 AD and kept constant after that. (From HUYBRECHTS and DE WOLDE, 1999.) Reproduced from TAR.

The long-term contribution of the Greenland ice sheet to sea level was assessed by CHURCH et al (2001) using a small number of studies that used dynamic models of the ice sheet. The report concludes that the resulting evolution of the ice sheet is a strong function of stabilisation temperature (Figure 2), with surface ice melting (ablation) changing much more than ice accumulation for large forcings. Discussion of the contribution to long-term future sea-level rise of the Antarctic ice sheet acknowledged that the current models (in 2001) did not include some of the key processes, such as an adequate representation of rapid ice streams, or the role of floating ice shelves in restraining (and stabilizing) the grounded ice sheet. The assessment of the contribution of the Antarctic ice sheet to sea-level rise is also complicated by the many factors (both climatic and non-climatic) that drive changes in the ice sheet.

These factors include:

- Increased snow accumulation (due to anthropogenic climate change) may already be thickening some portions of East Antarctica, and to a small degree, reducing the overall rate of sea-level rise (DAVIS et al., 2005).
A long-term readjustment to the (natural) climate change that occurred more than 10,000 years ago is extremely difficult to assess, but could be giving a continued (small) contribution to sea-level rise (STONE et al., 2003).

The recent (probably anthropogenic) climate change seen on the Antarctic Peninsula has caused the ice sheet in this area to begin ablating (i.e. melting), in a similar way to Greenland (VAUGHAN, in press-a), and has also led to the loss of ice shelves that have allowed more rapid discharge from some glaciers (SCAMBOS et al., 2004; RIGNOT et al., 2005). Together these effects are making a small contribution to sea-level rise.

Finally, there is a portion on West Antarctica, known as the Amundsen Sea embayment, where the ice sheet appears to be thinning at a substantial and concerning rate. This thinning appears to be caused by a warming or a circulation change in the ocean water coming into contact with the ice sheet, and so could plausibly have been caused by recent (anthropogenic) climate change. However, it is also possible that the change could have been caused by a longer-term (natural) change in the ocean or ice sheet. The significance of these observations is that this part of the ice sheet is suspected by some to be unstable, in that it rests on rock that is below sea level, and the ice sheet could retreat very rapidly adding substantially to sea-level rise.

While each of the processes described above is significant and must be evaluated and considered before defensible predictions of the total contribution of Antarctic to sea level can be made, it is the last of these factors that has the potential to cause the most rapid sea-level rise and so is considered to be the most important and of greatest policy concern.

2.1.3 Global temperature and sea-level rise scenarios (The time constant issue)

The relationship between temperature change and sea-level rise is of interest, as it is common practice to plot climate change impacts as a function of global temperature rise (e.g., ‘Millions at Risk’ (PARRY et al., 2001), or the ‘Burning Embers’ diagram (MCCARTHY et al., 2001), and it is also useful to understand the commitment to sea-level rise, stabilisation of atmospheric greenhouse gases and aerosols at various levels during the 21st century.

LOWE et al (2006) have followed a number of previous authors in highlighting that the time required to stabilise global-mean sea level following a stabilisation of atmospheric greenhouse gas concentrations may range from several centuries to more than one millennium. Both the ice sheet response and thermal expansion components of sea-level rise have long (but different) time constants. For example, although smaller glaciers and ice sheets can respond rapidly, the West Antarctic ice sheet may still be responding to changes that occurred thousands of years ago (Section 2.1.2). By contrast the rate of temperature change may be significantly reduced much more quickly after stabilisation of atmospheric greenhouse gas concentration.

This has some major implications for climate policy as already mentioned in Section 1. First, except during a period of rapidly increasing greenhouse gas concentration, air temperature and sea-level rise increase at different rates, as shown for both the thermal expansion and Greenland components in Figure 3. The dynamics of the West Antarctic ice sheet are less understood, but similar long timescales are expected after deglaciation begins. Therefore, it is only meaningful to include sea-level impacts in a table of impacts for a given temperature rise during periods of rapidly increasing greenhouse gas concentrations, as after the point of stabilisation of greenhouse gas forcing any direct relationship ceases to be meaningful. The plots of sea-level rise impacts versus temperature provided by PARRY et al (2001) and NICHOLLS and LOWE (2006) for the 21st Century are meaningful, but for
longer term impacts (after 2100) as considered in this report, such a representation would have little value and may be misleading.

Figure 3. **The thermal expansion and Greenland sea-level rise components plotted against global mean temperature rise for the 4xCO$_2$ experiment with HadCM3 coupled to the GISM ice sheet model (as discussed in Section 2.4.1).**

Second, if a stabilisation target is designed to avoid dangerous climate change then long after greenhouse gas concentrations have been stabilised, and rates of temperature increase greatly reduced, there will still be significant increases in sea level. Thus, a realistic stabilisation target is a long-term rate of sea-level rise, and under stabilisation some ongoing degree of adaptation will also be needed (NICHOLLS and LOWE, 2006). It is also important to note that there is a component of sea-level rise to which we are already committed from historical increases in climate forcing, and until we stabilise climate, so that commitment continues to grow (e.g. MEEHL et al., 2005; WIGLEY, 2005).

In conclusion, a more useful way of linking temperature rise and sea-level rise for policy purposes may be the relationship between temperature rise during the 21st Century, and the resulting committed rate of sea-level rise. This would remind policymakers that decisions about greenhouse gas
emissions during the 21st Century will continue to have significant effects on sea level during the following centuries. This is an important subject for further research.

2.2 *Total global-mean sea-level rise to 2500*

Since the TAR, there have been a limited number of model runs over 500 year timescales concerning the Greenland ice sheet and the thermal expansion component. Appendix A1 considers simulations using three different climate models: HadCM3; CLIMBER-2 and GENIE-1. Inter-comparison of the runs is not straightforward since the emissions scenarios are not the same and the simulations are not run to equilibrium. Thus each model with results is described individually. There are no long-term models for small glaciers and the Antarctic ice sheet, especially the West Antarctic ice sheet, so these sea-level rise components are treated by expert judgement in Appendix A1.

The total global-mean rise in sea level is the sum of the modelled thermal expansion and Greenland components already considered, plus the small glaciers and Antarctica contributions. For the small glacier term, there is no modelled data, and on a 500-year timescale, the contribution is likely to be much smaller than thermal expansion or the combined effects of the major ice sheets. While important over a 100-year timescale, it is not considered here except as an upper bound to the potential total rise. The uncertainty in the Antarctic contribution is dominated by uncertainty over collapse of the West Antarctic Ice Sheet (Appendix A1).

Figures 4 to 6 show the total rise for the thermal expansion and Greenland contributions from the three models, respectively, while Figures 7 and 8 combine the total rise for all three models on the same axes. The spread of results when all the scenarios presented earlier are included is a global-mean sea-level rise of 0.35m to 4.5m by 2500. However, three of these scenarios assume emissions exceeding all the conventional fossil fuel reserves: A1FI continuation scenario (for CLIMBER-2) and Scenarios E and F (for GENIE-1) (see Appendix A1). While these scenarios provide upper bounds to future greenhouse forcings and the climate and sea-level response, these are extreme forcings. If they are excluded and only the forcing scenarios that consider burning of conventional fossil fuel reserves are considered, the range of total sea-level rise between 2000 and 2500 is reduced to 0.35m to 3.3m. This includes both scenario and some model uncertainty, but we do not claim to have robustly sampled the full range of model uncertainty.

Adding the potential near-total melting of small glaciers and the near-total collapse of the West Antarctic ice sheet to the results in Figure 8 could increase the rise to about 9 m by 2500, although the Antarctic contribution is likely to be significantly lower. Taking the rise associated with 66% confidence levels reported by VAUGHAN and SPOUGE (2002): 0.2 m/century, translates into a 1-m rise by 2500, resulting in a maximum rise of about 4-m to 5-m by 2500 (when also considering the contribution from small glaciers). In the following discussion, a range of sea-level rise scenarios up to 2500 will be considered, with a focus on the 5-m rise scenarios and in some cases up to 10-m rise scenarios.

Given the above uncertainties, and the limited model runs that are available for other factors, long-term sea-level rise requires further research. In scientific terms, the most important gap is our understanding of Antarctica, and the West Antarctic ice sheet in particular. Further research is needed to

- explore the uncertainty space in much more detail than had been possible here with perturbed parameter ensembles;
- perform more simulations with the more complex version of the ice sheet model;
• investigate the reversibility of ice sheet changes;
• develop improved models of the Antarctic ice sheets, especially West Antarctica.

Monitoring of the mass balances of large ice sheets should be continued and extended to both help model development and provide an early warning of any rapid changes. In policy terms, linking different emission pathways through the 21st Century to their ultimate total rise in global-mean sea level, and the associated maximum rate of rise would be particularly useful. Implicit in this goal is the development of long-term stabilisation scenarios for sea-level rise which could be useful for a range of policy analyses.
Figure 4  Total sea-level rise for the CLIMBER-2 model, excluding the small glacier and Antarctica components

Figure 5  Total sea-level rise from the Hadley Centre simple models for a range of stabilisation
scenarios, excluding small glacier and Antarctica components (see Appendix A1).

Figure 5  Total sea-level rise from the Hadley Centre simple models for a range of stabilisation scenarios, excluding small glacier and Antarctica components (see Appendix A1).
Figure 6. Total sea-level rise for the GENIE-1 model for six emission scenarios, excluding small glacier and Antarctica components. (The scenarios are defined in Appendix A1).

Figure 7. Total sea-level rise for the combined Greenland and thermal expansion components – for all three models and all emission scenarios (see Appendix A1).
2.3 Relative sea-level rise scenarios for the next 500 years

Section 2.1 showed how global-mean sea-level rise scenarios have been developed. However, due to differences in oceanographic processes such as thermal expansion or changes in oceanic circulation, as well as geological processes, such as uplift and subsidence due to a range of causes relative (or local) sea-level change varies in space (Church **et al.**, 2001). Oceanographic processes could be important during the 21st Century (Gregory **et al.**, 2001), but the differences in response between ocean basins are unlikely to continue to grow beyond this timescale, and it has not been investigated at 500 year timescales. Further, it is not considered further here. In contrast, geological processes are incremental and could be significant over a 500 year timescale.

There are a range of geological processes that could be important, including subsidence in deltas, and glacial-isostatic adjustment (GIA) which are predictable to some degree. Deltas naturally subside and fluid (water, oil) withdrawal often exacerbates this subsidence (Emery and Aubrey, 1991), most extremely in urban areas where land has sunk up to 5 m (in Tokyo) in the vertical during the 20th Century (Nicholls, 1995a). Natural subsidence rates in deltas range up to 10 mm/yr (e.g. Penland and Ramsey, 1990; Ericson, 2005–2006)—translating into 0.5 to 5.0 m subsidence over 500 years. When considering human-induced subsidence, this could be much greater. This stresses that deltaic systems are highly vulnerable in the future to relative sea-level rise particularly in highly managed settings where sediment supply to offset subsidence is interrupted (Woodroffe **et al.**, 2005; Ericson, 2006). Global changes will exacerbate an already vulnerable situation.

GIA is still occurring due to changes in loading on the mantle from deglaciation at the end of the last ice age (from 18,000 to 6,000 years ago). Both subsidence and uplift are occurring and
Importantly, this process is amenable to quantitative global analysis and prediction (e.g. Tushingham and Peltier, 1991; Peltier, 2001). Hence, scenarios can be developed, including allowing for the deglaciation of the Greenland and West Antarctic ice sheets, which will modify the global GIA pattern that currently exists (Mitrovica et al., 2001).

As a consequence of these considerations, future sea levels are more complex than presented in Section 2.1. However, developing these more intricate scenarios is far from trivial and applying the global-mean scenarios directly can be permissible for exploratory analysis, as long as these assumptions are explicitly acknowledged. In what follows, this simplified view is adopted, but it is recognised that downscaled scenarios must be better developed if the implications of sea-level rise to 2500 is to be properly assessed.

2.4 Socio-economic scenarios for the next 500 years

While socio-economic scenarios have been developed and applied in climate impact assessment (e.g. Arnell et al., 2004) and other long-term assessments (Evans et al., 2004a), the uncertainties in such scenarios grow very rapidly from the present. Such scenarios are not normally developed beyond 2100 as they are not considered meaningful due to uncertainties about future conditions (Carter et al., 2001), and some analyses choose to stop earlier than this (e.g., 2050). At first sight, this makes detailed impact analysis using the long-term sea-level rise scenarios considered in Section 2.1 a difficult task, apart from assessment of simple metrics. An example of a simple metric might be land area that is threatened (but with no analysis of adaptation), or the 21st Century population that might be threatened by sea-level rise in subsequent centuries (e.g. Lowe et al., 2006). In the latter case there is an issue of timing and the population estimates are an indicator of impacts rather than a direct measure as they are in studies focussed on the 21st Century such as MIMURA (2000) and Nicholls and Tol (accepted).

Some analyses of the socio-economic impacts of sea-level rise have proceeded beyond the 2080s, as it was recognised that important insights might result due to the long timescale of sea-level rise (Section 2.1). Nicholls and Lowe (2004) examined the possible impacts of increased flooding and wetland change due to sea-level rise to the 2140s. This analysis considered impacts under unmitigated and stabilisation sea-level rise scenarios across a range of climate sensitivity under one business-as-usual socio-economic scenario. The socio-economic scenarios were derived from existing “business as usual” projections that extended into the 22nd Century. For population, World Bank scenarios were used (Bos et al., 1994), while for GDP, the Energy Modeling Forum (1995) Scenario 14 was used. These scenarios were consistent with the climate scenario, which was also business-as-usual (the IS92a scenario; Leggett et al., 1992). It is important to note that the authors saw these experiments as a “what-if analysis”, which provides broad insights into the sensitivities of the coastal system under a scenario of sea-level rise over 150 years. Several important insights emerged including:

- Losses of coastal wetlands are reduced much more by stabilisation than impacts of coastal flooding, as these impacts are related to the rate of rise and the absolute rise, respectively.

- More importantly, while coastal flooding is reduced under stabilisation scenarios, flood impacts still increase with time due to the sea-level commitment. Hence, for flooding in addition to climate stabilisation, adaptation will also be required over the long-term.

Another example of post-2100 scenarios are the FUND scenarios, which are also similar to the IS92a scenario (Link and Tol, 2004). The projections are for 16 world regions, and the population
change and per capita growth were assumed to be uniform for all countries within a region. After 2100, population is frozen, but per capita income continues to grow. There are also fundamental assumptions about adaptation technology: that it is mature, and options available today and the options available to future generations are broadly similar. For existing coastal protection technologies such as dikes and beach nourishment, this seems a reasonable assumption.

Following the approach of the FUND scenario, similar post-2100 scenarios could be developed for any pre-2100 scenarios, such as the SRES scenarios. But following the available post-2100 analysis, the results are better seen as ‘what if’ analyses rather than conventional scenario analyses which are grounded in plausibility. In what follows, the socio-economic scenarios are defined where used and are often the present day situation (an exposure analysis).


The sea-level rise scenarios of up to 9-m global-mean rise by 2500 (Section 2.1.4) threaten large areas around the world’s coasts with profound changes that may well exceed our ability to adapt to them. As shown in Figures 9 and 10, the areas that are threatened include the extensive coastal lowlands on the East and Gulf Coasts of the USA and Mexico, including most of southern Florida, the coastal lowlands around the southern North Sea, and many deltas such as the Rhone (France), the Ebro (Spain), the Po and adjoining North Italian Coastal Plain, the Mississippi (USA) and the Sacramento-San Joaquin Delta (USA). All coastal cities such as London, New York, Tokyo, St Petersburg and Istanbul are also threatened together with important cultural icons such as Venice and environmental treasures such as the Everglades and Louisiana coastal wetlands. Of course, new wetland areas have the potential to be created. Outside Figure 9 and 10, the densely populated delta plains of south, south-east and east Asia are also threatened as are many populated small islands.

To describe these threats appropriate metrics are required as a means of both analysing and communicating these problems. The metrics must have certain characteristics including being applicable to both large changes in sea level (ranging up to a 9-m rise) and long time scales (up to 500 years), as well as associating the magnitude and timing of sea-level rise with related physical, biological and socio-economic impacts. Metrics also need to be relevant to decision makers across a range of scales from global to sub-national.

In this section, first the potential impacts and adaptation responses given sea-level rise are considered, including the nature of impacts and adaptation under large sea-level rise scenarios (> 1-m rise). There is considerable experience of defining metrics for existing sea-level rise impact studies going back to the IPCC Common Methodology (IPCC CZMS, 1992). This experience is reviewed and then translated into potential metrics that are appropriate over long timescales and for large rises. An especially valuable element of this research was an Expert Workshop on Metrics (Appendix A2) and a Questionnaire on Metrics (Appendix A3). At the Expert Workshop, a group of coastal practitioners discussed the issues and challenges raised by long-term sea-level rise, and they were also able to comment on a range of draft metrics. The Questionnaire was linked to the Expert Workshop and explored the views of wider group of coastal practitioners from ten distinct professional perspectives and ten different coastal countries. The resulting insights are reviewed at the end of this Section.
Figure 9. Areas of North America below 10 m elevation above mean sea level (shown in red). These are the areas potentially threatened by a 9-m rise in sea level
Figure 10. Areas of Europe below 10 m elevation above mean sea level (shown in red). These are the areas potentially threatened by a 9-m rise in sea level.
3.1 Impacts and adaptation to sea-level rise

3.1.1 Impacts of sea-level rise

Sea-level rise has a wide range of effects on coastal processes (Nicholls, 2002). In addition to raising mean sea level, rising seas also influence all the coastal processes that operate around sea level. Therefore, the immediate effect of a rise in sea level is submergence and increased flooding of coastal land as well as saltwater intrusion of surface waters. Longer-term effects also occur as the coast adjusts to the new environmental conditions, including morphological change and saltwater intrusion into groundwater. These morphological changes interact with the more immediate effects of sea-level rise and will often exacerbate them, although the uncertainties should be stressed – geomorphological systems will be better able to respond given space for migration, a sediment supply and healthy ecosystems.

Table 1. The five major natural system effects of relative sea-level rise, including examples of possible adaptation responses (Nicholls, 2002; Nicholls and Tol, accepted). The possible adaptation responses are defined as [P] – Protection; [A] – Accommodation; and [R] – Retreat (see Table 3).

<table>
<thead>
<tr>
<th>NATURAL SYSTEM EFFECT</th>
<th>POSSIBLE ADAPTATION RESPONSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inundation, flood and storm damage</td>
<td></td>
</tr>
<tr>
<td>a. Surge(sea)</td>
<td>Dikes/surge barriers [P], Building codes/floodwise buildings [A],</td>
</tr>
<tr>
<td>b. Backwater effect (river)</td>
<td>Land use planning/hazard delineation [A/R].</td>
</tr>
<tr>
<td>Wetland loss (and change)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land use planning [A/R], Managed realignment/forbid hard defences [A/R], Nourishment/sediment management [P].</td>
</tr>
<tr>
<td>Erosion (direct and indirect morphological change)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coast defences [P], Nourishment [P], Building setbacks [R].</td>
</tr>
<tr>
<td>Saltwater Intrusion</td>
<td></td>
</tr>
<tr>
<td>a. Surface Waters</td>
<td>Saltwater intrusion barriers [P], Change water abstraction [A/R].</td>
</tr>
<tr>
<td>b. Ground-water</td>
<td>Freshwater injection [P], Change water abstraction [A/R].</td>
</tr>
<tr>
<td>Rising water tables/impeded drainage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upgrade drainage systems [P], Polders [P], Change land use [A], Land use planning/hazard delineation [A/R].</td>
</tr>
</tbody>
</table>

The most serious physical effects of sea-level rise, together with a range of possible adaptation responses are presented in Table 1. Self-evidently, the actual impacts will depend on the human response to sea-level rise, and not always in direct ways. For instance, increased flooding and inundation of coastal lowlands will promote wetland creation, while protection of coastal lowlands will exacerbate wetland losses, as no replacement of losses will occur.

The range of natural-system effects of sea-level rise in Table 1 have a wide range of potential socio-economic impacts (Klein and Nicholls, 1999), reflecting the diverse uses of the coastal zone. The IPCC Common Methodology defined three types of impacts (IPCC CZMS, 1992; Hoozemans et al., 1993):
VALUES AT RISK DUE TO INSTANTANEOUS CHANGES SUCH AS INCREASED FLOOD FREQUENCY AND DEPTH, AND STORM DAMAGE FOR PEOPLE, LAND AND INFRASTRUCTURE;

VALUES AT LOSS DUE TO LONGER-TERM EFFECTS SUCH AS LAND LOSS AND ABANDONMENT IN RESPONSE TO EROSION AND INUNDATION, AND ECOSYSTEM LOSS. THIS COULD INCLUDE DIRECT LOSS OF ECONOMIC, ECOLOGICAL, CULTURAL AND SUBSISTENCE VALUES THROUGH LOSS OF LAND, INFRASTRUCTURE, WATER RESOURCES AND COASTAL HABITATS;

VALUES AT CHANGE WHERE THE CONSEQUENCES OF SEA-LEVEL RISE ARE UNCERTAIN DUE TO INCOMPLETE KNOWLEDGE AND/OR THERE MAY BE BOTH POSITIVE AND NEGATIVE EFFECTS, SUCH AS FOR SOME HYDROLOGICAL CHANGES. FURTHER ANALYSIS WILL LEAD TO VALUES AT CHANGE BEING RECLASSIFIED TO THE OTHER TWO CATEGORIES, OR NO IMPACTS.

Table 2. Qualitative analysis indicating the more significant direct socio-economic impacts of sea-level rise on different sectors in coastal zones, including coastal biodiversity (adapted from Nicholls, 2002). (‘*’ direct impact; ‘?’ possible direct impact; ‘-’ no direct impact).

<table>
<thead>
<tr>
<th>SECTOR</th>
<th>NATURAL SYSTEM EFFECT (from Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inundation, flood and storm damage</td>
</tr>
<tr>
<td></td>
<td>Wetland loss</td>
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<tr>
<td></td>
<td>Erosion</td>
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<tr>
<td></td>
<td>Saltwater Intrusion</td>
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<tr>
<td></td>
<td>Rising water tables</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
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<tr>
<td></td>
<td>Ground</td>
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<tr>
<td>Water Resources</td>
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<td>Agriculture</td>
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<td>Human Health</td>
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<td>Fisheries</td>
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<td>Tourism</td>
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<td>Human Settlements</td>
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<tr>
<td>Coastal Biodiversity</td>
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</tbody>
</table>

Table 2 lists the most important socio-economic sectors in coastal zones, and indicates which natural system effects are expected to cause direct socio-economic impacts, including the cases where it is uncertain. Indirect impacts of sea-level rise are not shown as they are more difficult to analyse, but they have the potential to be important in many sectors, such as human health (McMichael et al., 2001). Examples of possible triggers of indirect health impacts include the nutritional impacts of loss of agricultural production in coastal areas (cf. Hoozemans et al., 1993), the release of toxic materials from land fills as they are reworked in extreme storms, or under general coastal retreat (Flynn et al., 1984; Neumann et al., 2001), and possible effects due to waterlogging and rising water tables. Thus, sea-level rise can produce a cascade of impacts through the socio-economic system.

3.1.2 Adaptation (and other responses) to sea-level rise

Given the high impact potential already discussed and the commitment to sea-level rise independent of emission scenarios, a rational response to sea-level rise and climate change in coastal areas would be to identify appropriate mixtures of mitigation and adaptation where a combination of policies will be most effective (Nicholls and Lowe, 2004; 2006). Adaptation acts to reduce the impacts of sea-level rise and climate change, as well as other changes (as well as exploiting benefits), and addresses the commitment to sea-level rise, while mitigation will reduce the future rate of sea-level rise and the ultimate total commitment. These decisions need to be made in the face of the large uncertainty about future climate (and many other factors) (Section 2), so there is a need to think in a...
risk- and uncertainty-based manner rather than looking for deterministic solutions. In the following
discussion, focus is on the adaptation response.

Considering the large and growing concentration of people and associated activity in the
coastal zone (e.g. Aagaard et al., in press), autonomous (or spontaneous) adaptation processes are
unlikely to be sufficient to respond to sea-level rise (Klein and Nicholls, 1998). Further, adaptation
in the coastal context is widely seen as a public responsibility (Klein et al., 2000). Therefore, all
levels of government have a key role in developing and facilitating appropriate adaptation measures,
comprising both specific adaptation measures and broader integrated coastal management policies that
promote adaptation planning across the coastal zone (e.g. Cicin-Sain et al., 1997). Planned adaptation
options to sea-level rise are usually presented as one of three generic approaches (Table 3), although
there are other classifications (Nicholls and Klein, 2005).

Table 3. Adaptation approaches to sea-level rise (from IPCC CZMS, 1990; Klein et al., 2001)

<table>
<thead>
<tr>
<th>Adaptation Approach</th>
<th>Definition</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retreat</td>
<td>Natural system effects are allowed to occur and human impacts are minimised by pulling back from the coast</td>
<td>Land use planning, Managed retreat/realignment, Unplanned retreat after disasters</td>
</tr>
<tr>
<td>Accommodation</td>
<td>Natural system effects are allowed to occur and human impacts are minimised by adjusting human use of the coastal zone</td>
<td>Land use planning, Building codes</td>
</tr>
<tr>
<td>Protection</td>
<td>Natural system effects are controlled by engineering, reducing human impacts in the zone that would be impacted without protection.</td>
<td>Coastal defence/hard engineering, Soft engineering/nourishment</td>
</tr>
</tbody>
</table>

Through human history, improving technology has increased the range of adaptation options
in the face of coastal hazards, and there has been a move from retreat and accommodation to hard
protection and active seaward advance via land claim (in extensive coastal lowlands and areas of high
sediment supply). Rising sea level is one factor calling universal reliance on hard protection into
question, and the appropriate mixture of protection, accommodation and retreat are now being more
seriously evaluated (Nicholls and Klein, 2005; Rupp-Armstrong and Nicholls, accepted). Klein et al. (2001) has given examples of appropriate technologies for each of these measures. In
cpractice, many responses may be hybrid and combine elements of more than one approach: for
example, combining coastal defences with flood warnings to manage residual risk when the defences
are overtopped or breached. Also, adaptation for one sector may exacerbate other impacts such as
costal squeeze of coastal ecosystems due to hard defences. In general, there is a need to consider the
balance between protecting socio-economic activity and the ecological functioning of the coastal zone
under rising sea levels (Nicholls and Klein, 2005).

The most appropriate timing for a response needs to be considered in terms of anticipatory
versus reactive planned adaptation (or in practical terms, what should be done today, versus wait and
see until tomorrow?) (Nicholls, 2002). Anticipatory decisions are made with more uncertainty than
reactive decisions, which will have the benefit of future knowledge, and wait and see is likely to
increase the potential for losses and coastal disasters. Anticipatory adaptation therefore needs to be
carefully considered as the implications of many decisions may leave future generations with more
limited choices. Examples of anticipatory adaptation in coastal zones include high design standards
(increased freeboard) for new coastal infrastructure (e.g., flood defences, waste water discharges, land
claim and transport infrastructure), land and building regulations that promote more appropriate land
use and robust buildings, and building setbacks to prevent development in vulnerable areas where protection is inappropriate.

While there is limited experience of anticipatory adaptation for climate change and sea-level rise, there is considerable experience of adapting to climate and sea-level variability, and we can draw on this experience to inform decision making under a changing climate (KLEIN et al., 1999). An analysis of the evolution of coastal zone management in the Netherlands, UK and Japan shows that adaptation to coastal problems is a process, rather than just the implementation of technical options. Four stages in the adaptation process related to (1) information and awareness building, (2) planning and design, (3) evaluation, and (4) monitoring and evaluation were evident within multiple policy cycles, as well as various constraints on approaches to adaptation due to broader policy and development goals. An explicit “learning by doing” approach accepts uncertainty and sees any intervention in the environment as an educated experiment and an opportunity to learn via monitoring and evaluation (e.g. NATIONAL RESEARCH COUNCIL, 1995). It also recognises that the criteria for assessing adaptation are likely to evolve due to improving scientific and technical knowledge and/or changing societal values.

With a few exceptions, climate change will largely exacerbate existing pressures and problems, so there are important synergies in considering adaptation to climate change in the context of existing coastal problems and wider coastal management (NICHELLS and KLEIN, 2005). This may include broader measures to enhance adaptive capacity. In many countries there is limited capacity to address today’s coastal problems, let alone consider tomorrow’s problems, including sea-level rise. Therefore, such capacity building should include developing coastal management, as already widely recommended (AGARDY et al., in press; KAY and ADLER, 2005).

3.1.3 Impacts and adaptation to sea-level rise (beyond the 21st Century)

The preceding discussion in Sections 3.1.1 and 3.1.2 are most relevant to impacts and adaptation for sea-level rise during the 21st Century, with scenarios of <1 m. As one considers larger sea-level rise scenarios the impacts in Table 1 will still occur and increase in magnitude, but the focus increasingly moves towards land loss due to inundation (i.e. permanent submergence), as this is the easiest impact to analyse, it threatens large areas, and much greater uncertainties exist for the other impacts. This equates to large potential shifts in shoreline position and the popular perception of sea-level rise where well-known landmarks in coastal cities such as London or New York City are depicted as partly submerged. The loss of whole island nations is quite feasible with a rise of the order of 1-m (e.g. NURSE et al., 2001): a magnitude of rise which Section 2.1 suggests is highly likely in the 500 year timescale of this study. While the potential for adaptation to sea-level rise in small islands is poorly understood, as the magnitude of rise increases, so it would appear to make many islands unviable regardless of external help. While adaptation guidance for small islands is being developed (TOMPKINS et al., 2005), a loss of faith in the future could trigger island collapse well before they become physically uninhabitable (BARNETT and ADGER, 2003; GIBBONS and NICHELLS, in press). This raises the wider concern that the commitment to sea-level rise could trigger wider loss of confidence in other vulnerable coastal areas, such as deltas. This is an important issue, but it remains poorly understood and difficult to capture in a metric.

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2 As an example, recent research by WALKDEN and DICKSON (2006) suggests that an increase of sea-level rise from 0.2 to 1.0 to 2.0 m/century (consistent with Section 2.1) would lead to a two to three fold increase in cliff recession rates on soft cliffs with limited beach development. This is significant but not unmanageable compared to some other changes in this paper.
Even in continental settings, land loss impacts are more than just the loss of the land and its uses, but must consider the widespread disruption of all the systems with which they are associated. This may include marine and land transportation and the loss of major cultural and historical assets. What would US residents feel about the loss of the Plymouth Rock, Massachusetts, or the Jamestown settlement in Virginia which are economically of no consequence, but culturally are fundamental to the nation?

The view that retreat is inevitable in the face of long-term sea-level rise is widely apparent, including within the Questionnaire results where ‘hold the line’ policies were not seen as viable in the long term, assuming sea-level rise (Appendix A3). This view can be debated, and there is plenty of empirical evidence that inundation is not inevitable given sea-level rise, as coastal societies can protect threatened areas. Several coastal Asian cities subsided several metres (equating to a large relative sea-level rise) during the 20th Century due to artificial groundwater withdrawals and these subsided areas were protected rather than abandoned, including in Tokyo where the subsidence was up to 5-m, taking large areas below mean sea level (Nicholls, 1995a). In the Netherlands, roughly 10 million people live below high tide levels thanks to defence and water management technology. In Japan, about 2 million people are similarly living below normal tides. But as shown by the 31 January/1 February 1953 storm surge in the North Sea (McRobie et al., 2005), as well as the landfall of Hurricane Katrina near New Orleans (29 August 2005), areas below sea level are very vulnerable when defences fail, and there is significant potential for loss of life, in addition to catastrophic flood damages in urban areas. Thus, while life below high tide is technically and economically possible, it is associated with noteworthy and growing risks.

This suggests a simple metric for sea-level rise which has already been discussed in Section 2.3: land area at risk (independent of defences). This might distinguish those areas that are at risk of temporary flooding (i.e. areas above normal high tide), and those areas that would be permanently submerged if defences were removed (i.e. those areas below normal high water). Significant areas around the world’s coast are already below mean sea level, including areas in Venezuela, USA, UK, Netherlands, Germany, Denmark, Poland, Italy, China and Japan. These areas have often been created by land claim and subsidence, but sea-level rise will increase the risks to these areas, and increase their size in the future, especially the higher scenarios in Section 2.1.

### 3.2 Conventional impact and vulnerability metrics

Extracting consistent impact and vulnerability metrics from the existing studies on sea-level rise was an important component of the SURVAS Project (De la Vega-Leinert and Nicholls, 2001. www.survas/mdx.ac.uk). These studies mainly consider the impacts of a 1-m rise in sea level over the 21st Century. They generally followed the definitions developed by the IPCC Common Methodology (IPCC CZMS, 1992), or could be interpreted in the terms of this methodology. The Common Methodology has been applied in national studies (e.g. Vietnam Toms et al., 1996) regional to global syntheses (IPCC CZMS, 1992; Nicholls, 1995b; Nicholls and Mimura, 1998), and global assessments (Hoozemans et al., 1993; Nicholls et al., 1999). Based on this extensive experience, the following vulnerability indicators were considered as defined in Table 4.

These metrics cover the first three impacts shown in Table 1, and the protection costs in terms of dikes and beach nourishment. Hence, it is important to recognise that Table 4 is not comprehensive and other metrics could be proposed to consider these three impacts in more detail (e.g., cultural sites at risk), or other impacts of sea-level rise (e.g., damage to agriculture due to salinisation and waterlogging).
Coastal Vulnerability Indices (CVI) are another approach to characterise the relative vulnerability of the coast to sea-level rise (Gornitz et al., 1994; Thielert and Hammar-Klose, 2000; Thielert, 2000). These produce a numeric CVI based on the sum of a range of natural factors such as tidal range and coastal geomorphology. As it is a relative index, it is useful to rank different areas, but it provides little additional information if the sea-level rise is large or small – hence, this type of index is not considered further here.

As considered at the Metrics Workshop (Appendix A2), an alternative approach to develop metrics is provided by the recent United Kingdom, Foresight assessment of Flood and Coastal Defence (Evans et al., 2004a; 2004b). This is based on a conceptual model of Sources, Pathways and Receptors as shown in Table 5. Interestingly, for the receptors (i.e. impacts), broadly similar metrics to those given in Table 44 are the result and they appear meaningful across all the scales that are considered. This shows the robustness of these metrics.
Table 4. The impact metrics for sea-level rise used in the SURVAS Project (De la Vega-Leinert and Nicholls, 2001), and how they relate to the impacts in Table 1

<table>
<thead>
<tr>
<th>Impact metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>People in the hazard zone (PHZ)</td>
<td>Number of people living in the area that, in the absence of any existing sea defence, will be subject to inundation or flooding at least once per 100 years, i.e. the population that is potentially exposed to flooding. (Impact 1)</td>
</tr>
<tr>
<td>People at risk (PaR)</td>
<td>Number of people living in the hazard zone, multiplied by the probability of flooding (this has also been termed ‘average annual people flooded’). This gives an estimate of the number of people who might actually be affected by flooding in an average year under the scenarios considered. Note PaR &lt; PHZ. (Impact 1)</td>
</tr>
<tr>
<td>People to respond to flooding (PtRF)</td>
<td>Number of people living in the hazard zone where the probability of annual flooding is 100% (this has also been termed ‘people to be moved’). This gives an estimate of the number of people who might be affected by flooding so often under the scenarios considered that some response (retreat, accommodate or protect) is necessary. Note PtRF &lt; PaR. (Impact 1)</td>
</tr>
<tr>
<td>People to respond to erosion (PtRE)</td>
<td>Number of people displaced by erosion due to sea-level rise. (Impact 1 and 3)</td>
</tr>
<tr>
<td>Land at risk (LaR)</td>
<td>Area of land at risk of flooding, calculated as the probability of annual flooding times the land area. (relates to PaR above) (Impact 1)</td>
</tr>
<tr>
<td>Land at loss (LaL)</td>
<td>Area of land where the probability of annual flooding is 100% (relates to PtR above), and also the land lost due to erosion. (These land loss parameters due to inundation and erosion might be separated). (Impact 1 and 3)</td>
</tr>
<tr>
<td>Wetlands at loss (WaL)</td>
<td>Coastal wetlands that will be lost due to the sea-level rise scenario. (Note: most assessments ignore wetland response to sea-level rise overestimating actual losses (Nicholls, 1995b; Nicholls et al., 1999) (Impact 2)</td>
</tr>
<tr>
<td>Capital at risk (CaR)</td>
<td>Capital value of the dry land and infrastructure at risk of flooding, multiplied by the probability of flooding, as described in LaR. (Impact 1)</td>
</tr>
<tr>
<td>Capital at loss (CaL)</td>
<td>Capital value of the dry land and infrastructure where the probability of annual flooding is 100%, and the land lost due to erosion. (Impact 1 and 3)</td>
</tr>
<tr>
<td>Adaptation cost</td>
<td>Capital and maintenance cost of adaptation</td>
</tr>
</tbody>
</table>

Table 5. Metrics for the decision making process developed loosely on the Foresight approach of Evans et al (2004a; 2004b) developed at the Expert Workshop on Metrics – from Appendix A2.

<table>
<thead>
<tr>
<th>MANAGEMENT LEVEL</th>
<th>Trans-national</th>
<th>National</th>
<th>Regional (Sub-national)</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivers</td>
<td>Greenhouse gas emissions</td>
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</tr>
<tr>
<td>Sources</td>
<td>Global mean sea-level rise</td>
<td>Sea level patterns</td>
<td>Geological processes</td>
<td></td>
</tr>
<tr>
<td>Pathways</td>
<td>Extremes</td>
<td>Defence standards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receptors</td>
<td>Areas at risk</td>
<td>Assets at risk</td>
<td>People at risk</td>
<td></td>
</tr>
<tr>
<td>Evaluation</td>
<td>Evaluation of significance (risk assessment)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Responses</td>
<td>Evaluation of coping capacity</td>
<td>Identification of and preparation for tipping points (time independent)</td>
<td>Mitigation (buys time and in the long-term (100+ years) may avoid impacts</td>
<td></td>
</tr>
</tbody>
</table>
3.3 **Potential metrics for assessing the long-term (> 100 years) impact of sea-level rise**

Given that we are considering changes up to 500 years into the future, metrics need to be fairly simple, easily evaluated and of interest and use to a range of relevant policymakers. Across the scales of interest, there is the potential for a diversity of metrics, and what is meaningful at the global scale may not be meaningful at the local (sub-national) scale and vice versa.

Based on the existing impact and vulnerability assessments discussed in Section 3.2, there are two distinct approaches to develop relevant metrics:

- **Exposure metrics** which can be estimated using a GIS approach (and can consider exposure to sea-level rise under the present socio-economic situation, or exposure under future socio-economic scenarios). This develops an inventory of assets and resources that are threatened assuming no adaptation and can be considered as potential or ‘worst-case’ impacts.

- **Impact metrics** that are consistent with integrated assessment models such as FUND or DIVA (see Section 4). Starting with estimates of exposure, estimates of residual impacts after adaptation are made under dynamic climate and socio-economic scenarios and appropriate decision-making approaches. Hence these are resources and objects that are assumed lost after adaptation has occurred and are the actual impacts given that adaptation strategy. Additionally the costs of the adaptation also need to be considered.

As an extreme, one could consider a Total Protection response for the entire coastal area under study, as followed in many early coastal impact analyses (Nicholls, 1995b; Nicholls and Mimura, 1998). However, this is not meaningful in policy terms as there are large areas that it makes little sense to protect even against the smallest changes in sea level (or other drivers of land loss) (e.g. the Arctic North of Russia, Canada and the USA). Therefore, it makes more sense to explore an optimum response in terms of a policy decision-making process: benefit-cost analysis has been widely applied in integrated assessments.

Following this philosophy, Tables 6 and 7 summarise the results of the exposure and impact metrics that can be used for long-term sea-level rise for exposure and impact analysis, respectively. Comparing Tables 6 and 7 shows that the metrics are very similar: the largest difference is that in Table 7 the actual damages will be smaller than the potential damages in Table 6, but these results in additional adaptation costs. (Under benefit-cost decision analysis, the total costs with adaptation should always be lower than without adaptation). The methods for evaluating these metrics are considered in Section 4.

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3 So current socio-economic conditions are not appropriate for an impact analysis, except as part of a sensitivity analysis.
Table 6. **Recommended exposure metrics for the impacts of long-term sea-level rise.** Note that this list is not comprehensive and other exposure metrics might be defined based on individual needs. Methods to estimate these metrics in conjunction with geographic information system techniques are elaborated in Section 4

<table>
<thead>
<tr>
<th>Metric</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land area at risk</td>
<td>Threatened area (absolute: km², or relative impact: % available area)</td>
<td>The preferred metric in the Questionnaire (Appendix A3) – can distinguish land above and below high water.</td>
</tr>
<tr>
<td>People at risk</td>
<td>Number of people (absolute or relative impact: % population)</td>
<td>Scenario dependent</td>
</tr>
<tr>
<td>Ecosystems at risk</td>
<td>Threatened area of ecosystems (km²)</td>
<td>Scenario dependent</td>
</tr>
<tr>
<td>Economic value at risk</td>
<td>Monetary value (absolute: monetary value or relative impact: % GDP)</td>
<td>Scenario dependent</td>
</tr>
<tr>
<td>Important human infrastructure at risk</td>
<td>Inventory approach (e.g., threatened transport corridors)</td>
<td>Based on existing distribution</td>
</tr>
<tr>
<td>Cultural/heritage at risk</td>
<td>Inventory approach (e.g., threatened UNESCO World Heritage sites)</td>
<td>Based on existing distribution</td>
</tr>
<tr>
<td>Possible changes in event frequency</td>
<td>Reduction in return period without adaptation (e.g., present 100 year event would have a return period of x years)</td>
<td>Relevance diminishes with increasing magnitude of sea-level rise (submergence increasingly dominates)</td>
</tr>
<tr>
<td>Potential rates of change (e.g. erosion)</td>
<td>Total shoreline retreat without adaptation (m or km, as appropriate), or rate of retreat (m/yr)</td>
<td></td>
</tr>
</tbody>
</table>

It is worth noting that TITUSTITUS (2004) has strongly argued for a map-based approach showing land areas at risk to support local planning decisions under sea-level rise in the USA. This links low-lying areas, existing coastal ecosystems and the likelihood of protection. While it focuses on the 21st Century, rises of up to 5-m in sea level are considered.
Table 7. Recommended impact metrics for the impacts of long-term sea-level rise. Note that this list is not comprehensive and other impact metrics might be defined based on individual needs. Methods to estimate these metrics in conjunction with integrated assessment models are elaborated in Section 4.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land area loss</td>
<td>Lost area (absolute: km2, or relative impact: % available area)</td>
<td>The preferred metric in the Questionnaire (Appendix A3)</td>
</tr>
<tr>
<td>People displacement</td>
<td>Number of people (absolute or relative impact: % population). Cost of displacement (absolute: monetary value or relative impacts: % GDP)</td>
<td>Scenario dependent</td>
</tr>
<tr>
<td>Ecosystems loss/change</td>
<td>Threatened area of ecosystems (km2). Cost of losses/changes (absolute: monetary value or relative impacts: % GDP)</td>
<td>Scenario dependent</td>
</tr>
<tr>
<td>Economic value loss</td>
<td>Monetary loss (absolute costs in monetary terms or relative costs: % GDP)</td>
<td>Scenario dependent</td>
</tr>
<tr>
<td>Human infrastructure loss</td>
<td>Inventory of losses (e.g., list of disrupted transport corridors)</td>
<td>Based on existing distribution</td>
</tr>
<tr>
<td>Cultural/heritage loss</td>
<td>Inventory of losses (e.g., list of lost UNESCO World Heritage sites)</td>
<td>Based on existing distribution</td>
</tr>
<tr>
<td>Adaptation costs</td>
<td>Monetary cost absolute costs in monetary terms or relative costs: % GDP</td>
<td>Usually comprise protection – capital and running costs can be distinguished. For protection, related output metrics might include defended length and defence height.</td>
</tr>
<tr>
<td>Changes in event frequency</td>
<td>Reduction in return period with adaptation (e.g., present 100 year event would have a return period of x years)</td>
<td>Relevance diminishes with increasing magnitude of sea-level rise (as submergence increasingly dominates), but there may be exceptions.</td>
</tr>
<tr>
<td>Rates of change (e.g. erosion)</td>
<td>Total shoreline retreat with adaptation (m or km, as appropriate), or rate of retreat (m/yr)</td>
<td></td>
</tr>
</tbody>
</table>

Several questions are raised by these recommended metrics, including:

1. How do we capture residual risk under protection scenarios in a meaningful manner? As Hurricane Katrina shows, those risks can be much higher than realised if the quality of the flood defences is ignored. Even with good defences there will be the occasional but inevitable (in a statistical sense) catastrophic failures when extreme events exceed the design level. This effect will be exacerbated as coastal flood events will have increasingly severe consequences for those affected as sea levels continue to rise relative to the land. It suggests that estimates of people affected and damage costs during infrequent floods might usefully be included with the impact metrics, which to a first order will be captured by the exposure metrics – many coastal cities would be so identified as exposed irrespective of their existing defences and economic wealth.

2. How is it best to capture impacts that are little studied, especially salinisation and water supply issues, which are important in many densely populated coastal settings, and arguably could be triggers for coastal abandonment and retreat, in addition to the flood and inundation risk that is more normally considered? This requires further work, but is an important issue in some low-lying coastal settings such as islands and deltas.
3. How sensitive are impact metrics to different policy response to sea-level rise (e.g., protect versus retreat)? – ideally metrics should be relevant to all policy decisions. Our first analyses suggest that the metrics are still meaningful.

These questions require further exploration and possible modification to the metrics as our knowledge base in this area grows.

3.4 Insights from the workshop and questionnaires

The Expert Workshop and Questionnaire results (Appendices 2 and 3) provided some important inputs into the selection of metrics. First, it identified that while timescales of more than 100 years are nearly always discounted in the policy process, in this case there is concern about the issue of long-term sea-level rise. While respondents were not panicked by these long-term changes, there was a desire for more information so that strategic decisions could ‘steer’ in sensible directions that will minimise future problems. While we cannot claim that the survey was representative, there was a strong feeling that retreat is inevitable in the face of several metres of sea-level rise. However, respondents were unclear when society would ‘bite the bullet’ and move from a ‘hold the line’ approach to a ‘retreat’ approach. This suggests that the metrics need to be applicable to retreat adaptation responses, as well as protection which is the dominant adaptation option within integrated assessment models.

The questionnaire identified that the preferred metric was overwhelmingly land area at risk shown on a map, as it is the basis for further analysis and an effective means to communicate the risks of long-term sea-level rise to others. It is worth noting that when it comes to communicating long-term sea-level rise, the media shares this view as the lead author is surprisingly frequently contacted with requests for maps showing those areas that might be lost with a 5-m rise in sea level (due to major ice sheet loss).

The Workshop and Questionnaire combined with the authors own experience also show that there are different constituencies of interest concerning long-term sea-level rise. These comprise climate policy experts, who are used to thinking at broad scales up to the globe about issues concerned with mitigation and increasingly adaptation policy, and coastal management experts who are thinking at national and usually smaller scales and are thinking about coastal management policy down to operational levels. The metrics presented in Tables 6 and 7 address the needs of climate policy experts, but they may not address the needs of coastal managers.

At the Expert Workshop on Metrics (Appendix A2), it became apparent that while the exposure and impact metrics are quite familiar to those working in climate impact assessment, at national and smaller scales, these metrics do not necessarily relate well to coastal management and planning. An alternative approach to focussing on impacts is to focus on the sensitivities in the system response to sea-level rise and higher extreme water levels, rather than focussing on specific scenarios and their impacts (Figure 11).
Figure 11. The threshold or “tipping point” methodology, as applied to considering the impacts of sea-level rise (adapted from Appendix A2). This is a continuous process of assessment and monitoring.

1. Maintenance/learning/knowledge (“Triggers of concern”)
2. Identify/analyse key tipping points
3. Identify/analyse possible response actions (consider feasibility, sustainability)
4. Identify/analyse timing of tipping points (including benefits of mitigation) (NEED SEA-LEVEL RISE SCENARIOS)
5. Implement long-term (slower) response options, and ‘wait and see’ for immediate (faster) response options
6. Continue monitoring/prediction of change (sea level, high water levels etc.)

This is based on the identification of key ‘tipping points’ – either the point at which existing or future management approaches are no longer viable, or the limit to which adaptation is possible. These thresholds can be identified independent of timescale, so this step of the analysis is independent of sea-level rise scenarios. The approach works well engineered systems such as major flood defence infrastructure where the failure criteria are fairly easily defined. Several tipping points can be identified for flood defence infrastructure such as:

- when will rising extreme water levels require upgraded defences?
- when will storm surge barriers require upgrade/replacement?
- when will gravity drainage cease to be effective, and pumped drainage will be required?

Having identified these tipping points, the next question is when these tipping points might be reached, which is a matter of linking the tipping points to the timing of climate change and sea-level rise scenarios. The timescale will be uncertain, but the range of timings will give a sense of how much time might be available for response, and what strategic decisions might increase long-term flexibility, and help with managing the tipping point. Such an analysis should consider the possibility of new technologies, changes in socio-economic values, and the role of flexible adaptation. There is likely to be a link with climate mitigation policy, as this will certainly buy time before the tipping point is reached as shown in Section 2, and specifically for the Thames Barrier by Hall et al (2005), and might even avoid the threshold altogether. Monitoring is also a fundamental part of this methodology as having identified the tipping point; progress towards the potential breakdown is required to plan appropriate and timely responses.

(Note that the notion of tipping points may also find application with geomorphological and ecological systems where we know that thresholds and non-linear behaviour are important.)

A word of caution raised in the Questionnaire (Appendix A3) is that this method is appropriate when applied to well understood systems (e.g., engineered flood defences under sea-level rise), but cannot be applied more widely (e.g. an entire country under sea-level rise), as the system is
too complex to understand in these simple terms of a threshold. For these cases, a series of metrics as
developed earlier are required.

4. Impact and economic valuation models from local to global scales

Superficially there are a wide range of models available that are suitable to calculate some or
all of the metrics outlined in Tables 6 and 7 in Section 3. However, when the available models are
considered in more detail, only a limited number of methods are suitable for long-term (100+ years)
analysis and can be characterised as:

- Exposure assessments based on GIS methods which integrate elevation, sea-level rise
  scenarios and other data to estimate parameters associated with exposure.

- Impact and economic assessments which consider exposure together with algorithms that
  consider actual impacts for given adaptation scenarios.

These two approaches can be applied across all the relevant scales, and are now considered
in more detail. The issues of discounting and intergenerational equity, as well as valuation methods of
coastal areas, are also considered.

4.1 Exposure assessments

Exposure analysis is based on combining a series of datasets at the relevant scale of analysis
within a GIS environment. The basic assumption is that all areas below regular tidal elevations are
threatened with total abandonment, while the associated flood plain above this elevation is threatened
with regular flooding. As already noted, exposure does not translate into impacts as shown by the
many coastal locations that are presently below mean high water and even mean sea level, but are
habitable due to coastal defences and water management.

While there are still many issues with the quality of datasets, especially at regional to global
scales, this type of analysis is applicable at any scale. A summary of how to calculate exposure metrics
at regional to global scales is provided in Table 8, with more information on some of the regional to
global datasets in Appendix A6. The results of the metrics questionnaire strongly favoured this kind of
analysis across all the scales of interest, with the most favoured metric being land area at risk
(Appendix A3). Many respondents felt that seeing the areas that are threatened was a powerful
approach of analysis for both themselves and to communicate the consequences of these changes to
others. Further, once the threatened land area is defined, then subsequent analysis with other layers of
geographic information can allow a range of other metrics to be developed, as shown for more generic
metrics in Table 8, or more specialist metrics as desired. As already noted, many of the metrics in
Table 8 (following page) can be further divided into those associated with land areas between extreme
tidal levels (e.g., the 100-year extreme water level) and normal tides, and those below normal tides.
All the metrics can also be calculated at more detailed scales than considered in Table 8, and for some
metrics (e.g., important human infrastructure at risk), this may be more appropriate.

It is also worth noting that even if the areas defined are protected, as with all defences there
is always a residual risk. Therefore, the exposure results in Table 8 are relevant even if areas are
protected. For instance, it would have highlighted the potential vulnerabilities for New Orleans that
Hurricane Katrina made plain to see.
Table 8. Date requirements and possible sources (regional to global scale) to estimate the exposure metrics in Table 6. All metrics require global sea-level rise scenarios (and better ‘local’ sea-level rise scenarios) and most require elevation data

<table>
<thead>
<tr>
<th>Metric</th>
<th>Data requirements</th>
<th>Possible sources at the regional to global scale (see Appendix A5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Local’ sea-level rise scenario</td>
<td>Global sea-level rise scenario, uplift/subsidence data</td>
<td>Results from Section 2.1, and uplift/subsidence datasets like the DIVA database (Vafeidis et al., 2004; in review); GIA models such as Peltier (2000); Euroson database (for EU15 only) (see comments in Section 2.2).</td>
</tr>
<tr>
<td>Land area at risk</td>
<td>Elevation, tidal range, extreme water levels</td>
<td>SRTM Enhanced Global Map developed by ISciences (2003); USGS SRTM elevation data; USGS GTOPO30 elevation data; SPOTIMAGE (high resolution) elevation data; LOICZ typology; DIVA database (Vafeidis et al., 2004; in review)</td>
</tr>
<tr>
<td>Land use at risk</td>
<td>Land Use, Elevation</td>
<td>IMAGE Team (2002); CORINE Land Use data; USGS EROS Data Center Global Land Cover Characterisation; IFPRI FAO Land use-land cover map; NASA DMSP land-use land-cover change data; Euroson database (EU15 only)</td>
</tr>
<tr>
<td>People at risk</td>
<td>Population, Elevation</td>
<td>GPW3 (CIESIN and CIAT, 2004); LANDSCAN (2003)</td>
</tr>
<tr>
<td>Ecosystems at risk</td>
<td>Ecosystem Distribution4</td>
<td>UNEP-WCMC Atlases (e.g., mangroves, coral reefs, seagrasses); DIVA database (Vafeidis et al., 2004; in review); Euroson (EU15 only)</td>
</tr>
<tr>
<td>Economic value at risk</td>
<td>Land Use, Economic Assets, Elevation</td>
<td>IMAGE Team (2002); Economic datasets derived from national statistics; Gridded economic output database (Nordhaus, 2006)</td>
</tr>
<tr>
<td>Human infrastructure at risk</td>
<td>Transport networks, harbours, airports, power stations (esp. nuclear), land fills</td>
<td>Numerous geographic datasets, including land use above and other more specialist datasets; Euroson database (EU15 only) May be more appropriate at more detailed scales</td>
</tr>
<tr>
<td>Cultural/heritage at risk</td>
<td>Cultural and heritage sites, elevation</td>
<td>UNESCO World Heritage Sites; DIVA database (Vafeidis et al., 2004; in review)</td>
</tr>
<tr>
<td>Changes in event frequency</td>
<td>Present return periods of events</td>
<td>DIVA database (Vafeidis et al., 2004; in review)</td>
</tr>
<tr>
<td>Rates of change (e.g., erosion)</td>
<td>Observed/modelled erosion rates</td>
<td>DIVA database (Vafeidis et al. 2004; in review); Euroson database (EU15 only)</td>
</tr>
</tbody>
</table>

4 Elevation is implied for coastal ecosystems at risk, as by definition, these systems are at or very near present sea level.

4.2 Impact and economic assessments

Impact and economic assessments are more sophisticated than simple exposure estimates, as while they may estimate metrics that are related to exposure, they are normally focused on considering aspects of society’s response to damage (in this case to sea-level rise), and hence adaptation and decision models are included (Nicholls et al., accepted-a). There is a significant diversity in the available models, as some focus on impacts such as people affected, or people at risk, while others are strongly economic in their focus (Nicholls and Tol, accepted). The new DIVA model combines these approaches into a common model with a high degree of spatial precision compared to earlier global models (DINAS-COAST CONSORTIUM, 2004). The DIVA model is still being tested and experience developed, but this is likely to be a particularly useful framework for such analyses.

Table 9 summarise a range of existing impacts and/or economic models that deal at least partly with coasts across the range of relevant scales, and hence support a wide range of policy tasks.
across climate and coastal management policy. In principle, all these approaches can be made suitable for long-term analysis.

Any long-term (100+ years) analysis of impacts and economic consequences is an ambitious goal, especially at regional to global scales, because the conventional methods of climate change impact analysis breakdown under large changes of sea-level rise. For changes up to a 1-m rise in sea level, which is the maximum scenario considered in the vast majority of studies, the changes can be considered as a marginal change, not in the sense of not being important, but in the formal, mathematical sense of the word. That is, a rise of up to 1-m in sea level would perturb the current situation, and the size of the perturbation can be studied with an essentially linear model, which characterises most of the models in Table 9. On the other hand, larger rises in sea level would have impacts that extend beyond the coastal zone, and alter the coastal zone in a dramatic manner as already discussed in Section 3.1.3. For instance, the analysis of Olsthoorn et al (2005) suggests that the harbour of Rotterdam (and by implication other harbours on the North Sea such as Antwerp, Bremen and Hamburg) may be abandoned under a 5-m sea-level rise, which would radically change transport patterns across the whole of Western Europe. In contrast, a 1-m sea-level rise would increase costs for Rotterdam Harbour, but would not fundamentally affect its operations, and its competitors are similarly affected.
Table 9. Examples of impact and economic evaluation models for sea-level rise studies that are potential suitable for long-term (100+ year) assessments, and their relationship to climate and coastal management policy across scale\(^5\). The FUND and DIVA models are described in Appendix A7.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Impact/ Economic Models</th>
<th>Sample Sources</th>
<th>Policy Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Climate</td>
</tr>
<tr>
<td></td>
<td>FUND(^6)</td>
<td>TOL (2004); NICHOLLS \textit{et al.} (2005)</td>
<td>International Cooperation</td>
</tr>
<tr>
<td></td>
<td>DIVA(^7)</td>
<td>DINAS Consortium (2004); HINKEL and KLEIN (accepted in press); NICHOLLS \textit{et al.} (accepted-bin press) <a href="http://www.dinas-coast.net/">http://www.dinas-coast.net/</a></td>
<td>Mitigation Support, Adaptation Support, Strategic Guidance</td>
</tr>
<tr>
<td>Sub-National/ Local</td>
<td>Tyndall Coastal Simulator (UK)</td>
<td>HALL \textit{et al.} (2005b); NICHOLLS \textit{et al.} (2005) <a href="http://www.tyndall.ac.uk/">http://www.tyndall.ac.uk/</a></td>
<td>Adaptation Implementation</td>
</tr>
</tbody>
</table>

Given that existing models are designed for a maximum of 1-m rise over 100 years this is a difficult problem. NICHOLLS \textit{et al.} (2005) conducted a global analysis using FUND of extreme sea-level rise driven by the collapse of the West Antarctic ice sheet over 300 years. They adapted FUND in two distinct ways. Firstly, they examined the basic data on exposure to sea-level rise. Whereas a 1-m sea-level rise has about twice the impact potential as a 0.5-m sea-level rise, a 5-m sea-level rise does not have 10 times the impact potential and the underlying data was tuned to actual distributions as a function of elevation based on the best available datasets. Secondly, they adapted the existing linear model of the costs of coastal protection and examined the effects of non-linear defence costs, which is much more realistic. This immediately affects the associated model of the level of coastal protection.

\(^5\) Note that scale can be ambiguous – many US, Canadian and Australian states are larger than many European nations, and the USA, Canada and Australia are similar in size to the whole of Europe.

\(^6\) \textit{Climate Framework for Uncertainty, Negotiation and Distribution (FUND)}

\(^7\) \textit{Dynamic Interactive Vulnerability Assessment (DIVA)}
which is now also non-linear. While these two adjustments do not solve all the problems of a linear model, they make the results much more realistic. But they do draw attention to the areas where caution is required in using these models in terms of absolute change in sea level (or possibly rate of sea-level rise) and issues concerned with timescale (summarised in Figure 12).

Figure 12. Sea-level rise and timescale constraints for linear modelling. For large rises in sea level (> 1 m), non-linear impact analysis is required, while for long timescales (> 100 years), socio-economic scenarios are problematic

As an alternative approach to apply full non-linear approaches, the national adaptation analysis of the USA by Yohe et al (1995; 1996) is also based on cost-benefit analysis, but it is based on a representative sample of individual sub-national coastal segments, rather than a full national coverage. Dynamic programming (with a numerical solution) is used to determine whether to protect or not for each coastal segment. As numerical optimisation is computationally expensive, Yohe et al (1996) used a sample of coastal segments to upscale their results to the entire US coast. While these numerical techniques allow for non-linear relationships and more realistic behaviour to be analysed, they can only be applied at a fine resolution and are presently too computationally expensive to apply at a global scale. A combination of representative detailed case studies and upscaling is more feasible for a global analysis, but has yet to be done. In the long run, such non-linear methods provide a good approach to analyse the impacts of long-term sea-level rise. Table 10 summarises how the Impact and Economic Models in Table 9 may provide the metrics defined in Table 7.
Table 10. Impacts and Economic Models that will potentially provide the metrics outlined in Table 7 by scale. ‘?’ indicate may not be available.

<table>
<thead>
<tr>
<th>METRIC</th>
<th>IMPACT AND ECONOMIC MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global/ Regional (National)</td>
</tr>
<tr>
<td></td>
<td>Land area loss</td>
</tr>
<tr>
<td></td>
<td>People displacement</td>
</tr>
<tr>
<td></td>
<td>Ecosystems loss/change</td>
</tr>
<tr>
<td></td>
<td>Economic value loss</td>
</tr>
<tr>
<td></td>
<td>Important human infrastructure loss</td>
</tr>
<tr>
<td></td>
<td>Cultural/heritage loss</td>
</tr>
<tr>
<td></td>
<td>Adaptation costs</td>
</tr>
<tr>
<td></td>
<td>Changes in event frequency</td>
</tr>
<tr>
<td></td>
<td>Rates of change (e.g., erosion)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3 Discounting and intergenerational equity

Another fundamental constraint for impact and economic assessments are our attitudes about the future. Sea-level rise is a slow process. The sea will continue to rise for centuries after the atmospheric concentration of greenhouse gases have stabilised. In the medium to long term, the benefits of emission reduction are mainly from postponing the impact of sea level, although more time to adapt can of itself be a useful benefit of emission reduction. In the short-term, impacts are only avoided if they are dependent on the rate of sea-level rise which emissions reduction will lower (e.g., loss of coastal wetlands), and in the longer term if they are dependent on the absolute magnitude of sea-level rise (e.g., flood risk) (ARNELL et al., 2002; NICHOLLS and LOWE, 2004; TOL, 2004).

Because of this, the issues of discounting and intergenerational equity are important considerations when considering policy responses to these issues. Time discounting arises from the opportunity cost of capital. If money is put in the bank, it earns interest. Therefore, future money does not have the same value as present money. At a 5% interest rate, $100 today is equivalent to $105 in a year. Or, $100 in a year is equivalent to about $95 today. Because of discounting, the present value of benefits in the far future is vanishingly small. $100 in 100 years is worth 8 cents today at a 5% interest rate.

Discounting can also be explained by economic growth and impatience. If future people are wealthier than today, we would need to worry less about putting the same absolute monetary burden on them. But people also discount the future because they are impatient (i.e., they care less about the future simply because it is not today). Although many philosophers and economists have argued that discounting for impatience is impermissible, the fact of the matter is that people do this. Also governments, who are supposed to take the long term view and to be the guardian of future
generations, apply discounting. See Arrow et al (1996) for an overview of discounting applied to climate change.

One approach may be to discard discounting for measuring the impacts of sea-level rise. However, consistency demands that one would then discard discounting for all other matters too, which would revolutionise all spending. A less radical and more elegant solution would be to argue that discounting does not hold between generations, or perhaps only within bounds. For instance, one may argue that it is our duty to hand a “functional planet” to our children. Continued, rapid sea-level rise sits awkwardly with that goal. Note, however, that this merely replaces one difficult question (whether and how much to discount the future) with another one (what sort of world do we want to pass to the next generation). See Portney and Weyant (1999) for an overview of the range of opinions on discounting for climate change.

Another potential solution lies in declining discount rates. In conventional discounting, the relative distance between year 10 and year 11 equals the relative distance between year 100 and year 101. One may argue that the distance between year 10 and year 11 should equal the distance between year 100 and year 110. Indeed, people seem to behave this way (Henderson and Bateman, 1995). This implies that the discount rate should fall as the time horizon of the problem expands. Arguments of uncertainty (Weitzman, 2001) and heterogeneity (Gollier and Zeckhauser, 2005) point in the same direction. A long term problem such as sea-level rise would have a lower discount rate than a medium term problem such as education. The long term impacts of sea-level rise would still be discounted compared to today, but much less than with classical methods.

These concepts have been applied to the impacts of climate change in general, but not yet specifically to the impacts of sea-level rise, identifying an important research gap. These issues need to be addressed as part of the policy assessment and response to long-term sea-level rise. As a minimum, any assessment and the resulting metrics need to be explicit about the assumptions that are made in terms of discounting, and any related assumptions.

### 4.4 Valuation methods

Impacts of sea-level rise are often expressed in money as this allows for a comparison with other impacts of climate change, and a comparison with the costs of emission reduction. A monetised impact estimate also gives an idea of the relative seriousness of the problem. Finally, monetised impacts inform the trade-off between the costs of coastal protection and its benefits in terms of avoided impacts.

Some impacts are readily expressed in money. The loss of farmland can be approximated by the price of land times its quantity. If the amount of farmland lost is small, this is a good approximation of the welfare loss. If more land were lost, one would need to worry about the effect on land prices, agricultural production, and the rest of the economy. There are standard methods for this, which have been applied to sea-level rise (Darwin and Tol, 2001; Bosello et al., 2004). They suggest that countries with large land areas tend to benefit via competitive advantage.

Other impacts are not traded on markets, so one would need to resort to other methods to estimate a price. Some methods are based on revealed preference methods, which look at the actual behaviour of people to see how they respond to differences in the environment. For instance, although natural beauty is not bought and sold, it does affect house prices. Other methods use stated preferences, that is, people are interviewed about what they would be willing to spend under certain specific circumstances. Stated preference methods are less reliable than revealed preference methods. Fortunately, most coastal resources can and have been valued with revealed preference methods. See
CHAMP et al (2003) for a general overview, and TURNER et al (2001) for details on coastal wetlands (See also COSTANZA et al. (, 1997))

The impact of sea-level rise on coastal wetlands may be substantial (HOOZEMANS et al., 1993; NICHOLLS and LOWE, 2004). Coastal wetlands provide a range of services to humans, including buffering against storms and surges, filtering water, providing hatcheries for fish, providing areas for recreation, and providing food resources. The value of most of these services can be estimate by their replacement value. If a wetland stops providing food, people would need to buy food and produce it elsewhere, presumably at a higher cost. If mangroves no longer protect the coast against storms, artificial replacement forms of coastal defence are needed with a cost. While superficially simple, the appropriate level of substitution is difficult to determine and so the protection value of the mangroves if often quite uncertain. For recreation, the travel cost method is more appropriate. This method uses the time and money people spend to derive their demand curve (and hence the value) for recreational facilities, in this case, wetlands. BROUWER et al (1999) review the literature.

The travel cost method can also be used to estimate the value of coral reefs. However, in this case, there is another valuation problem. Whereas wetlands would change and probably shrink because of sea-level rise, coral reefs may be hit much harder as they are also sensitive to temperature rise (e.g. DONNER et al., 2005) this implies one should also consider the intrinsic value of coral, and the effects on biodiversity in addition to travel costs. However, these values are notoriously hard to estimate, because one has to rely on stated preference methods. See, for instance, (CESAR et al., 1997). As most sea-level rise impact studies to date have omitted impacts on coral reefs, these valuation problems do not affect published estimates in the literature.

As impact studies become more comprehensive, so this type of issue will need to be addressed.

Therefore, while we can value many of the impacts of sea-level rise, there are still important issues to address, most especially in comprehensive assessments of the impacts of sea-level rise.

5. Application of some selected metrics for long-term analysis.

In section 5, some of the metrics proposed in Tables 6 and 7 are developed with the methods outlined in Section 4. There is a strong emphasis on the exposure metrics developed with GIS analysis, with this technique being applied and illustrated across a range of scales, from global to national. One example of impact metrics developed with the FUND model is provided to illustrate both the potential and current limitations of the methods. Lastly, some national to sub-national assessments based on examples raised at the Expert Workshop are presented, including illustrating the threshold-based analyses

Global Exposure Analysis Using GIS
At the global scale, there is interest in the total area of land, the number of people and the economic activity that might be exposed to extreme sea-level rise. Figure 13 shows global functions of this exposure to sea-level rise (based on present socio-economic conditions) as a simple function of elevation above mean sea level (so tides are not considered). This includes the land area based on the SRTM data (excluding Antarctica), the population based on GPW3 and Landscan, and estimates of their total income (measured at market exchange rates (MER) as well as at purchasing power parity (PPP) (Nicholls et al., 2005). Given the uncertainties in these global datasets, it is important not to over-interpret the results, and they should only be considered indicative (Small and Nicholls, 2003).

The distributions are broadly linear up to a 10-m rise, with the exception of land area which increases more rapidly from 0-m to 1-m elevation. This almost certainly reflects the large areas of coastal wetlands and associated land claim in densely populated coastal areas, which both tend to be concentrated near mean sea level. Land occupying 3.5 million km² is located within 5-m of mean sea level, with 5.4 million km² within 10-m elevation of mean sea level. This translates into 2.6% and 4% of the total land area (excluding Antarctica). The GPW3 and Landscan data are remarkably similar – Landscan estimates a larger population below 10-m elevation. Total population below 5-m elevation is 280 to 300 million people, with 540 to 620 million people below 10-m elevation. This translates into 4.6 to 5.0%, and 8.9 to 10.3% of the world’s population in the year 2000, respectively. Hence, it indicates the significant exposure of people to the impacts of sea-level rise both during the coming century, and given the long-term sea-level rise scenarios considered in Section 2.1.4. Economic exposure is less when measured in MER than in PPP, indicating that a substantial part of the exposure is in developing countries.

The analysis can be repeated relative to estimates of mean high water, as opposed to mean sea level. The results for a 1-m and 5-m rise in sea level are shown in Table 11. For a 5-m rise in sea level relative to mean high water, the land area exposure is 15% larger, while the population exposure is 44% larger. Hence, as we use a more realistic reference frame, so the potential impacts increase...
significantly. The national numbers that underpin Table 11 were used to tune the global analysis using FUND described in Section 5.5.

Table 11. The global exposure of population, land area and total income as a function of sea-level rise, calculated relative to high water (rather than mean sea level). Based on 2000 data (adapted from Nicholls et al., 2005).

<table>
<thead>
<tr>
<th></th>
<th>1-m rise</th>
<th>5-m rise</th>
<th>% Increase compared to mean sea level reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (millions)</td>
<td>131</td>
<td>410</td>
<td>44</td>
</tr>
<tr>
<td>Land area (thousand Km2)</td>
<td>2,463</td>
<td>4,107</td>
<td>15</td>
</tr>
<tr>
<td>GDP, N, MER (billions US $)</td>
<td>1,015</td>
<td>2,425</td>
<td></td>
</tr>
<tr>
<td>GDP, R, MER (billions US $)</td>
<td>1,009</td>
<td>2,482</td>
<td></td>
</tr>
<tr>
<td>GDP, N, PPP (billions US $)</td>
<td>1,132</td>
<td>2,959</td>
<td></td>
</tr>
<tr>
<td>GDP, N, PPP (billions US $)</td>
<td>1,239</td>
<td>3,342</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Global analysis of national land area at risk as a function of sea-level rise. The number of countries with >10%, >25%, >50% and up to 100% of their land area below mean sea level is shown as a function of elevation (or a globally uniform rise in sea level). Data is taken from PLACE (CIESIN, 2002).

5.2 Global Analysis Using the PLACE Database

The globally-aggregated results that are presented in Section 5.1 show that exposure to long-term sea-level rise is significant and worthy of further consideration. It also raises the question of where is this exposed land and people. The ‘Population, Landscape, and Climate Estimates’ (PLACE) database developed by CIESIN (2002) allows a national scale investigation of land area and population versus elevation above mean sea level, and for illustrative purposes, such an analysis is presented here. In the future, a similar analysis could be conducted relative to mean high water following Section 5.1. Again, the socio-economic inputs are the present situation as this is an exposure analysis.
Figure 14 suggests that 58 countries (out of 179 coastal countries) have more than 10% of their national land area within 5-m of mean sea level. It further suggests that 11 countries have all their national area below 5-m, and hence their very survival as nations is threatened by the changes considered here. All these countries are small islands which have long been recognised as being highly threatened, with the existence of five nations being threatened by a 1-m rise in sea level (Bulsma et al., 1996; Nurse et al., 2001). It also shows the limitations of such analysis, as these 11 countries identified using the PLACE database include five Caribbean islands that as far as the author is aware have substantial land areas above 5-m elevation – hence the result is partly a function of the digital elevation model that has been used. If larger rises in sea level are considered, so the number of countries with significant areas beneath mean sea level would increase, but not dramatically over the range considered here (up to 15-m elevation). This reflects that there are a large number of small countries in terms of area, with large proportions of those areas close to present sea levels as shown in Figure 15.
5.3 Regional Exposure – the North Sea and environs

Moving downscale from a global analysis, one can also consider present exposure at the regional scale with GIS techniques.

Northern Europe has extensive areas that are already at risk from coastal flooding (e.g., as demonstrated in the 1953 and 1962 North Sea storm surges), and due to the low elevations in the coastal zone, these areas will expand significantly with sea-level rise. Figure 17 illustrates this regional exposure by showing the areas below 1-m, 5-m and 10-m elevation, while Table 12 quantifies the land areas by nation. The 1-m elevation is taken to very roughly indicate those areas below normal tidal levels today and the 5-m and 10-m contours translate roughly into 3 to 4-m and 8 to 9-m rises in sea level (so scenarios that can be related to Section 2.1.4). The areas that are already below normal tidal levels are extensive, especially around the southern North Sea, and most particularly in the Netherlands and to a lesser extent in Germany. These areas contain large populations (Table 13), who already depend on flood defences and water management to be able to live in these areas.

Figure 16. Global analysis of the national population at risk as a function of sea-level rise. The number of countries with >10%, >25%, >50% and up to 100% of their population (as in the year 2000) below mean sea level is shown as a function of elevation (or a globally uniform rise in sea level). Data is taken from PLACE (CIESIN, 2000)
### Table 12. Exposed land area by national as shown in Figure 17.

<table>
<thead>
<tr>
<th>Country</th>
<th>National land area below (km²)</th>
<th>Total National Area (km²)</th>
<th>Area below 10 m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-m</td>
<td>5-m</td>
<td>10-m</td>
</tr>
<tr>
<td>Denmark</td>
<td>3177</td>
<td>8437</td>
<td>14707</td>
</tr>
<tr>
<td>Germany</td>
<td>13910</td>
<td>22211</td>
<td>31873</td>
</tr>
<tr>
<td>Netherlands</td>
<td>20277</td>
<td>26611</td>
<td>32889</td>
</tr>
<tr>
<td>Poland</td>
<td>3781</td>
<td>5410</td>
<td>7360</td>
</tr>
<tr>
<td>Belgium</td>
<td>1148</td>
<td>3209</td>
<td>5680</td>
</tr>
<tr>
<td>France</td>
<td>513</td>
<td>1091</td>
<td>1436</td>
</tr>
<tr>
<td>Russia</td>
<td>2016</td>
<td>3188</td>
<td>4501</td>
</tr>
<tr>
<td>Norway</td>
<td>67</td>
<td>249</td>
<td>439</td>
</tr>
<tr>
<td>Sweden</td>
<td>510</td>
<td>2399</td>
<td>5539</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>2540</td>
<td>8230</td>
<td>10795</td>
</tr>
</tbody>
</table>

Incomplete national coverage

### Table 13. Exposed present population by nation as shown in Figure 17.

<table>
<thead>
<tr>
<th>Country</th>
<th>Population below contour (thousands)</th>
<th>National Population (thousands)</th>
<th>Population below 10 m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-m</td>
<td>5-m</td>
<td>10-m</td>
</tr>
<tr>
<td>Denmark</td>
<td>155</td>
<td>501</td>
<td>998</td>
</tr>
<tr>
<td>Germany</td>
<td>1565</td>
<td>2866</td>
<td>4018</td>
</tr>
<tr>
<td>Netherlands</td>
<td>5139</td>
<td>7717</td>
<td>9627</td>
</tr>
<tr>
<td>Poland</td>
<td>345</td>
<td>556</td>
<td>714</td>
</tr>
<tr>
<td>Belgium</td>
<td>262</td>
<td>1071</td>
<td>2007</td>
</tr>
<tr>
<td>France</td>
<td>80</td>
<td>276</td>
<td>375</td>
</tr>
<tr>
<td>Russia</td>
<td>91</td>
<td>156</td>
<td>229</td>
</tr>
<tr>
<td>Norway</td>
<td>1</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Sweden</td>
<td>33</td>
<td>177</td>
<td>387</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>372</td>
<td>1562</td>
<td>2689</td>
</tr>
</tbody>
</table>

Incomplete national coverage

TOTAL 8043 14890 21059
Figure 17. Land areas below (a) 1 m, (b) 5 m and (c) 10 m elevation above present sea level in Northern Europe
Considering the higher contours, the exposed land area and population increases significantly in all cases, and the southern North Sea in particular is an area that is highly exposed to large rises in sea level: both increasing the risks within the existing flood plain, and expanding the area of those flood plains landward. Lastly, as a caveat, it is worth noting that these numbers do not always agree with national-scale vulnerability assessments (www.survas.mdx.ac.uk), and the estimated exposed population for the Netherlands appears too low. This probably reflects problems with the global datasets that were used for the analysis and again stresses that they only provide indicative estimates. As a general principle, as the scale of analysis is reduced, so it is better to move to more specific datasets, if they are available.

5.4 National exposure analysis

A national exposure analysis of Great Britain based on the 5-m contour is shown in Figures 18 and 19 (following page). The analysis evaluates those areas that will be below mean sea level after a uniform 5-m rise in sea level, and much of the areas shown are already below normal high waters. Taking into account a typical high tide elevation of about 2-m above mean sea level (with substantial variation), this translates into a 3-m rise on the high water mark. Extensive areas are threatened around the entire coast, but particularly on the east coast, where a large proportion of the nation’s best agricultural land would be threatened (although it is important to note that much of these areas are already threatened with flooding today). The total land area that is threatened is 16,309 km² (about 6.6% of land area), and the current population of these areas is about 3 million people (about 5% of national population).

Figure 18. Land areas below 5-m elevation showing extensive potential land loss in eastern England, although the biggest potential impacts are along the Thames estuary (in London)
Figure 19. **areas below 5-m elevation and the present main transport network. While there is potential disruption to the transport network around the entire coast, the circled areas show those areas where it could be most serious.**

Figure 19 shows the threatened areas in relation to the present national transport network, as an additional indicator of exposure. While there would be potential disruption around the entire coast (which would be better analysed at a more local scale), even at this national scale major areas of potential disruption are apparent.

### 5.5 Sub-national analyses

At sub-national scales, one can repeat the exposure methods explored above with more sophisticated datasets and understanding of the areas that are being investigated. Rather than explore this application in the theoretical domain, two case studies based on real planning for long-term sea-level rise in the United Kingdom are presented. Here the example of the Thames Barrier is considered to illustrate the threshold approach to analysing the flood management system for London, while recent changes in coastal planning policies of the National Trust represent a fundamental shift in philosophy in coastal management due to an expectation of ongoing widespread coastal erosion and the need to create space for that erosion to occur.

Relating these case studies to other national settings, London’s flood defences are managed by the Environment Agency, which is a government agency that covers England and Wales and has parallels with the US Army Corps of Engineers, or the Rijkswaterstaat in the Netherlands. The National Trust (www.nationaltrust.org.uk) is a significant coastal landowner in the UK with 1,130km of the British coastline within its care. The National Trust (NT) was founded in 1895 as an independent charity to hold and manage in perpetuity (i.e. forever), for the benefit of the nation,

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countryside and historic buildings in England, Wales and Northern Ireland. While it is an independent charity, the principles that it is applying could apply to any major coastal land owner who is managing the natural environment and coastal heritage for the long-term such as the US National Park Service, the Parks Canada Agency, the Australian Department of the Environment and Heritage, and the Dutch, Danish and German authorities around the Wadden Sea, or other non-governmental organisations such as the New Zealand National Parks and Conservation Foundation which is promoting conservation.

5.5.1 Assessment of the Thames Barrier and associated flood defences

When analysing the effects of sea-level rise on specific systems, different types of metrics might be useful based on the sea-level rise associated with key thresholds, or tipping points, or even qualitative trends such as a tendency for the coast to retreat. These will often occur when a key decision is required (often the choice between abandonment or major investment in upgrade). Details will vary between the systems and detailed cases being considered.

The Thames Barrier and associated defences protect London from flooding due to storm surges from the North Sea. Designed after the disastrous 1953 storm surge, the existing barrier includes freeboard for rising sea levels (based on historic observations rather than global warming as the barrier’s completion predates these concerns) (see Gilbert and Horner, 1984). The design standard is against a 1 in 1000 year event and given rising sea levels and possibly more intense surges and greater flood river flows in the Thames, the barrier and associated defences will probably need to be upgraded in the next few decades. Due to the commitment to sea-level rise discussed in this paper, this upgrade is the first of a cycle of upgrade that may well be required. The Environment Agency is responsible for the Thames Barrier and they are leading the Thames Estuary 2100 project which is assessing the needs for upgrade (Lavery and Donovan, 2005). As well as sea-level rise, an eastern expansion on London (the Thames Gateway urban regeneration) will also increase the exposed assets and population.

When thinking about these changing risks, especially the more extreme possibilities, Environment Agency staff have found it useful to think about the problem in terms of rises in extreme water level that would cross key thresholds, or tipping points where a major decision will be required in terms of system upgrade, or system abandonment (equating in this case to abandoning large parts of London). The tipping points are physically-based thresholds such as the amount of sea-level rise which will necessitate:

- Upgrade of the Thames estuary defences – downstream of the Barrier;
- Upgrade of the Thames river defences – upstream of the Barrier;
- Construction of a new barrier (possibly in a downstream position);
- A move to pumping of the Thames flow to the sea, rather than depend on gravity (which could be a limit to sustainable adaptation for this system).

In the case of the Thames Barrier, each of these tipping points is described by a rise in relative extreme water levels, so various combinations of subsidence, ocean rise and changes in storms and river flows could lead to the tipping point. Having recognised these issues, the Environment Agency is now exploring the science to understand when these tipping points might be reached. It is also possible to evaluate the benefits of mitigation in terms of delaying sea-level rise and hence the need to invest in upgraded defences (Hall et al., 2005).
5.5.2 The National Trust

The National Trust (NT) cares for 1,130km of coastline within the UK. It was founded in 1895 as an independent charity to hold and manage in perpetuity (i.e. forever), for the benefit of the nation, countryside and historic buildings in England, Wales and Northern Ireland\(^9\). Consequently, it has a commitment to take a comprehensive, long-term and strategic approach to the coastal zone (coastal land, shallow seas and estuaries) and has recently undertaken a large-scale study to identify the risks for its coastal holdings due to sea-level rise and other climate change (HALCROW, 2005). This recognised that much of their coastal holdings are likely to experience erosion through the 21st Century, while many other coastal areas are at a growing risk of flooding.

The new management policy adopted by the National Trust favours working with the dynamic nature of the coastal system; conserving and enhancing assets as far as practicable, but not necessarily preserving them indefinitely. A number of clear management principles provide a framework for local decision making, with the aim of allowing time and space to adapt decisions as coastal conditions alter and help raise public awareness and understanding. They commit the Trust to work with the natural processes of coastal erosion and accretion and wherever possible removing coastal management interventions which fix the coast. Interference with natural coastal processes is only supported where there is an overriding benefit to society in social, economic or environmental terms. Decisions must take a long-term view in the context of predicted sea-level rise; support flexible management solutions which can enable, or adapt to, the processes of coastal change and favour coastal realignment wherever this can reasonably be accommodated. Coastal protection is only seen as a measure to buy time, to allow for adaptation and relocation of people and infrastructure away from the coastal risk zone. Communication is also fundamental to win support for this quite radical shift in thinking – both with other managers, organisations and communities for management purposes and with the wider public to promote enjoyment and understanding of the coast.

These principles have already been successfully applied on several of the Trust’s properties to identify management options and, with consideration of local conditions and opinion, allow a suitable decision to be taken. This has included the landward location of car parks and footpaths, detailed recording of archaeological sites prior to loss and relocation of residents and demolition of buildings at risk rather than attempting to protect them. Also, more strategically, the NT is expanding their coastal land holdings to create space for a landward retreat of the shoreline over the coming centuries, and advocating better information on future coastal change, such as the definition of erosion hazard zones in the UK, complimenting existing flood hazard zones. It will be interesting to monitor this initiative over the coming decades, especially when it confronts ‘difficult’ decisions.

These approaches could be applied elsewhere (e.g., all coastal national parks might aim to acquire the hinterland across which the shoreline will retreat as sea levels rise, if possible). Further details of the National Trust’s Coastal Policies can be found on their website and the ‘Shifting shores’ pamphlet on http://www.nationaltrust.org.uk/main/w-shifting_shores.pdf.

5.6 Global Integrated Assessment using the FUND model

In climate impact and economic analysis integrated assessment models such as FUND are often utilised to explore actual impacts and associated protection costs. The coastal module of FUND examines the potential implications of sea-level rise in terms of dryland and wetland losses, and then applies an economically optimum assessment of the benefits of defence. Hence a range of outputs are computed includes damages and defence costs, as illustrated in Appendix A7. An important

\(^9\) Scotland has the independent National Trust for Scotland.
implication of the results of this type of assessment is that costs of defences are much smaller than the costs of abandonment, and defence is likely to be a widespread response to sea-level rise (Nicholls and Tol, accepted). Here we consider an application of FUND to an extreme sea-level rise scenario as discussed by Nicholls et al (2005). The FUND coastal module is explained in some detail in Appendix A7, including how it was adapted for application beyond 2100. The results are preliminary and exploratory and illustrate what an integrated assessment approach might achieve. But as is discussed here, the results need to be interpreted with caution, and at the present time, these types of analyses might be best seen as scientific experiments rather than policy advice.

The FUND analysis considered here explored a range of arbitrary sea-level rise scenarios that are linked to assumptions about the rapid collapse of the West Antarctic Ice Sheet (WAIS) as illustrated in Figure 20. Only scenarios that are consistent with those presented in Section 2.2 are considered. This analysis illustrates the issues of economic assessment of sea-level rise beyond 2100 to large changes in sea level. To be consistent with an impact analysis, the socio-economic scenarios are also dynamic and use the FUND scenarios: population grows to 2100 and is then constant, but GDP continues to grow. Also note that discounting at 1% above the growth rate of the economy is included in the analysis. Wetland losses are included in the evaluation, but have limited effect on the results. To take account of the real distribution of people and assets, FUND was tuned to the distributions presented in Section 2.1. To take account of the non-linear rise in defence costs with sea-level rise, bilinear costs were considered, up to a 100 times increase in unit defence costs. This allows investigation of how sensitive defence decisions are towards these rising costs.

An important message of the analysis is that even under the extreme scenarios considered here; a benefit-cost evaluation suggests that while certain areas will be abandoned, widespread protection of developed coasts remains economically optimum (Figure 21). While this is sensitive to assumptions about the increase in costs, even if they are assumed to rise 100 times, about one third of the world’s developed coast would still be rationally protected, according to the FUND analysis (Figure 21). However, this protection is not free, and substantial investment will need to be diverted from other needs to coast defences to accomplish this goal. Further undefended areas will be abandoned and their resident populations will need to be relocated as illustrated in Figure 22.

Figure 20. Sea-level rise scenarios as used by Nicholls et al (2005) which are consistent with Section 2.1.4. WAIS collapse is assumed to start in 2030. The notation indicates the year when
WAIS collapse is complete and has contributed 5 metres to global sea levels, and hence global sea-level rise slows significantly. ‘never’ refers to a case of no WAIS collapse.

Figure 21. Fraction of developed coast protected under different cost factors, assuming a 5-m to 6-m rise in sea level over 500 years. Even if unit defence costs are assumed to be 100 times those of today, about one third of the world’s developed coast (or about 250,000 km) would be protected following the FUND benefit-cost analysis.

Discussing these results, the amount of protection suggested by the FUND model is surprising, as there is a subsiding coastal city such as Tokyo which subsided up to 5-m due to groundwater withdrawal (Nicholls, 1995a). Nonetheless, the response to such large relative sea-level rise was always to protect, and coastal cities such as Tianjin, Shanghai, Tokyo, Osaka and Bangkok presently have large areas below normal tides which are dependent on flood defences and pumped drainage to avoid flooding.

In contrast, the global model appears to conflict with the three detailed case studies conducted within the same Atlantis project (Nicholls et al., 2005). The case studies all suggest a greater tendency towards coastal abandonment and retreat than the global model even in major urban areas such as London and the Netherlands (see Table 14). This difference partly reflects factors that are not considered in the FUND, such as an overall loss of confidence due to the rapid sea-level rise, which in turn, may trigger a cycle of decline. In the Netherlands, response costs where estimated at 3% to 4% of GDP, which was considered prohibitive in terms of other demands on the national economy. It was also observed in the Thames Estuary case study that paralysis which might well delay an adaptation response too long for it to be effective, leaving retreat as the only viable option. Again this process is not included in the global model which assumes perfect adaptation if it has an appropriate cost-benefit ratio. Events like Hurricane Katrina in New Orleans demonstrate the great vulnerability of coastal areas when defences are not planned and constructed to appropriate levels of safety, or growing risks are ignored.
Table 14. Summary of the response of three detailed case studies to the Atlantis sea-level rise scenario (5-m rise from 2030 to 2130). (taken from Nicholls et al., 2005)

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Impacts</th>
<th>Response</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands</td>
<td>&gt; 10 million people threatened together with one of the world’s largest economies</td>
<td>Abandon the northwest and southwest of the Netherlands, but possibly protect the Ranstad (Amsterdam to Rotterdam area). Likelihood of intense political conflict and very large response costs in proportion to GDP</td>
<td>Olsthoorn et al. (2005)</td>
</tr>
<tr>
<td>Thames estuary</td>
<td>2 million people threatened with a rapidly increasing flood risk without a response, even allowing for expected upgrades. Also much of London’s financial sector including Canary Wharf.</td>
<td>Indecision may lead to forced abandonment, but there are adaptation options – especially a new downstream barrier</td>
<td>Lonsdale et al. (2005)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dawson et al. (2005)</td>
</tr>
<tr>
<td>Rhone delta</td>
<td>Compared to the other case study sites, human impacts are minimal, but significant natural values are threatened.</td>
<td>After an initial ‘wait and see’, abandon the delta.</td>
<td>Poumadere et al., (2005)</td>
</tr>
</tbody>
</table>

lanned and constructed to appropriate levels of safety, or growing risks are ignored. Hence, while integrated assessment models such as FUND are powerful tools for thinking about the future, the resulting metrics need to be interpreted with great caution, and further work is required to develop these methods for the analysis of long-term sea-level rise.

6. Discussion/Conclusions

This report has explored simple methods for assessing sea-level rise and its impacts over long timescales of up to 500 years. The relevance to climate policy is due to the long timescale of sea-level rise which means that decisions made in the 21st Century will have a major influence on sea levels over the next 500 years and even longer. The magnitude of that rise will depend on historic and future emissions of greenhouse gases: earlier climate stabilisation could reduce the future commitment to sea-level rise substantially, especially when considering the 500 year perspective. This report aims to identify methods and reliable metrics which can be used to assess the benefits of stabilization policies by applying several methods to estimate market and non-market effects.

This analysis shows that projections of future sea levels and other changes (e.g., socio-economic scenarios) over 100+ year timescales are very difficult. The three sea level models of Greenland and thermal expansion considered here, combined with expert judgement for small glaciers and Antarctica, suggest that global-mean sea levels over the next 500 years could range between a 0.35-m and about 9-m rise. While probabilities cannot be assigned, an upper bound of < 5-m global-mean rise is much more likely. The magnitude of sea-level rise remains uncertain largely because the long-term changes in Greenland and Antarctica are difficult to predict. Relative (or local) sea-level rise will depart from this global-mean rise due to a variety of causes, especially uplift/subsidence. For these reasons, many subsiding coastal areas (e.g. populated deltas in Asia) will experience a larger rise in sea level than the global-mean rise and this adds further to the uncertainty. To simplify these issues, this report has made the assumption that these processes can be ignored. Future work could explore local/regional aspects in greater detail.

It is also difficult to develop socio-economic scenarios beyond the 21st Century. This paper has suggested the simple assumptions of either taking the present distribution, or assuming that populations stabilize during this century and that modest economic growth continues over the
forthcoming centuries. Recognizing these limitations, it is possible to consider two distinct classes of metrics to assess the impacts of sea-level rise:

1. exposure metrics which define areas and associated populations and resources that may be potentially threatened (usually based on present socio-economic characteristics); and

2. impact metrics which aim to estimate actual impacts under different dynamic sea-level and socio-economic scenarios using integrated assessment of both exposure and adaptation decisions based on criteria such as benefit-cost analysis.

In both cases, about eight more detailed metrics related to land area, population, ecosystems, etc. can be defined. The two classes of metrics are superficially similar, but as the impact metrics take into consideration the potential for adaptation, the estimates of “actual impacts” can be much smaller than the estimates of “potential impacts”. This raises the important, but difficult question about how effective adaptation and especially protection might be, and the strategic choices coastal societies face between a ‘hold the line’ or a ‘retreat’ policy in the face of sea-level rise.

Based on a survey undertaken as part of this paper, there was a strong preference for “land area at risk” depicted on a map as a significant, yet simple exposure metric that is economically relevant easy to communicate to decision makers and stakeholders. “Land area at risk” is independent of the scenario problems raised above, and it was seen to contain the base information needed for a wide range of more individual specific analysis. In addition to highlighting threatened population and economically-important centres and transport corridors, “land area at risk” also indicates the numerous cultural and historic assets that are threatened such as Jamestown, VA, Plymouth Rock, MA, and Venice, Italy.

Exposure and impact metrics are quite consistent with existing broad-scale assessment methods, including global-scale assessments for climate policy analysis. An additional assessment method, appropriate at more local scales in the context of coastal management, is threshold or tipping point analyses. These are used to examine when rising sea level (or extreme water levels) would compromise specific ecological systems or infrastructure, such as flood defences, water supply systems, or transport corridors. Having defined these thresholds, the possible timing of a system being compromised can be explored using sea-level rise and other scenarios, together with adaptation and mitigation options to extend the life of the system. Threshold analysis is especially appropriate for well understood and defined infrastructure systems, such as the Thames Barrier and associated flood defences and is also appropriate for ecological and geomorphological systems which are known to show non-linear threshold responses.

A number of methods/tools can make use of metrics to explore different questions and issues. Exposure analysis using a geographical information system, can generate information that can be translated into distributions of land, people or assets as a function of sea-level rise and facilitate subsequent analysis of what might be threatened. A number of different global to national exposure analysis tools have been used in this paper to illustrate what can be achieved. Exposure metrics are also applicable at sub-national scales, although in these cases it is important to use the best-available datasets to maximise the credibility of the resulting metrics.

The impact metrics are more difficult to apply than the exposure metrics for a number of fundamental reasons:

- existing integrated assessment models of coastal impacts are based on linear assumptions that breakdown as we consider rises in sea level exceeding 1 metre;
• socio-economic scenarios are essential to any analysis, but become problematic beyond 2100;

• assumptions concerning discount rate (in essence how we value the future) will have a profound effect on the final results over the long timescales considered in this paper.

One example of a global analysis for large sea-level rise beyond 2100 has been provided to illustrate these problems, including tuning the exposure to observed rather than linear distributions, and considering the quadratic (or greater) rise in unit defence costs as sea level rises. This shows that long-term impact analyses are technically feasible and could support climate policy, but require more research before they can be widely applied.

There is a range of further work that this analysis suggests would be beneficial for better analysis of long-term sea-level rise, including metric development:

• Explore the relationship between temperature rise during the 21st Century, and the resulting committed rate of sea-level rise, to enable better communication that decisions about greenhouse gas emissions during the 21st Century will continue to have significant effects on sea levels for centuries.

• Improve long-term sea-level rise scenarios that could be analysed with the metrics presented here and raised within long-term policy processes, such as coastal planning.

• Explore the application of emerging socio-economic data sets, such as economic output data on a regular grid (NORDHAUS, 2006), in conjunction with the metrics identified in this report and projections assessments of “land area at risk” to estimate the global economic benefits of different climate change policies.

• Conduct one or more regional/local case studies, including relative sea-level rise scenarios, to identify metrics at the micro scale as they relate to important cultural, ecological, and economic systems. This should include exploration of the application of metrics under different response options from protection to retreat, and the relevance of the threshold approaches presented here.

• More exploration of the impact metrics and integrated assessment beyond the 21st Century, which raises the fundamental questions of how best to handle non-linear analysis, socio-economic scenarios and discounting.

• More consideration of the issue of appropriate methods for discounting in long-term coastal analyses, which value the future appropriately, as well as exploration of appropriate valuation methods in the face of dramatic change, and lastly, the analysis of indirect economic effects of major coastal impacts and/or demands for resources for coastal protection.

Lastly, it is important to remember that sea-level rise is not the only driver of coastal change, and ultimately a more holistic understanding of the coastal system under sea-level rise and climate change is required.
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APPENDIX A1

COMPONENTS OF LONG-TERM SEA LEVEL RISE (TO 2500)
Appendix A1 considers the four major components of global-mean sea-level rise up to 2500. Results on the Greenland ice sheet and thermal expansion are available from three models, but inter-comparison is not straightforward since the emissions scenarios are not the same and the simulations are not run to equilibrium. Thus each model with results is described individually. Small glaciers and the Antarctic ice sheet, especially the West Antarctic ice sheet are treated by expert judgement. All this information is combined in Section 2.1.5 in the main report to develop global-mean sea-level rise scenarios to 2500.

**HadCM3**

HadCM3 is a non flux-adjusted coupled model with an atmospheric resolution of 2.5°x 3.75° and 19 levels in the atmosphere. The ocean is a 20 level rigid-lid model with a horizontal resolution of 1.25°x1.25° and 20 levels. More details of the model and its parameterisations are given by Pope et al. (2000) and Gordon et al. (2000).

Figure A1-1. *Time series for the thermal expansion and Greenland components for 4xCO₂ experiments.*

Recently, this model was used to simulate around 1000 years for an experiment in which atmospheric carbon dioxide concentration was increased from a pre-industrial level of approximately 285ppm at 2% compound per annum, then stabilised after 70 years at four times the pre-industrial value for the remainder of the simulation. An increase in atmospheric carbon dioxide to four times pre-industrial atmospheric carbon dioxide corresponds to a radiative forcing of around 7.5 Wm⁻², which is comparable to the 6.7 Wm⁻² increase in forcing between years 2000 and 2100 for the SRES A2 scenario and 7.8 Wm⁻² for SRES A1FI (McCARTHY et al., 2001 Appendix A2). In a second simulation, HadCM3 was coupled to a 20km resolution dynamic ice sheet model (HUYBRECHTS et al., 1991; RIDLEY et al., 2005) and used to simulate more than 3000 years of ice sheet evolution. Importantly, the coupling method allowed changes in climate to influence the evolution of the ice sheet and changes in the ice sheet to feedback on the climate, affecting its subsequent evolution (Figure A1-1).
In addition to the 4xCO\textsubscript{2} simulations, efforts at the Hadley Centre has also focussed on tuning simple models to those of the complex HadCM3. In these simple models both temperature change and the thermal expansion component of sea-level rise are represented using Green’s functions. The Green’s functions are taken as the sum of two exponential modes derived from the 1000 year HadCM3 stabilisation experiment without an ice sheet. Predictions were made with the simple model by convolving either the temperature Green’s function, or sea-level rise Green’s function, with an estimate of the radiative forcing. These simple models have only been used here to extend more complex Hadley Centre model results further into the future, or to scale to alternative emissions scenarios (Figures A1-2 and A1-3).
CLIMBER-2 (CLIMate-BiosphERE model) is a low-resolution climate system model designed for simulation of large-scale processes on time scales from seasonal to millennia and longer (PETOUKHOV et al., 2000; GANOPOLSKI et al., 2001). CLIMBER-2 could be classified as a model of intermediate complexity, placed between simple models, usually 1- or 2-D, on the one hand, and 3-D climate GCMs on the other. It presently consists of the following modules: atmosphere, ocean, sea ice and terrestrial vegetation. The atmosphere module of CLIMBER-2 is a 2.5- dimensional statistical-dynamical model which has many features in common with more sophisticated models (GCMs). The CLIMBER-2 model has a low spatial resolution which only resolves individual continents (subcontinents) and ocean basins. Latitudinal resolutions is the same for all modules (10°). In the longitudinal direction the Earth is represented by seven equal sectors (roughly 51° longitude) in the atmosphere and land modules. The ocean model is a zonally averaged multi-basin model, which in longitudinal direction resolves only three ocean basins (Atlantic, Indian, Pacific). Each ocean grid cell communicates with either one, two or three atmosphere grid cells, depending on the width of the ocean basin. Very schematic orography and bathymetry are prescribed in the model, to represent the Tibetan plateau, the high Antarctic elevation and the presence of the Greenland-Scotland sill in the Atlantic ocean. A model of the Greenland ice sheet is incorporated.

Three climate change experiments were run with CLIMBER-2. These corresponded to SRES A1T, A1B and A1FI. The thermal expansion and Greenland ice melt contributions to these scenarios are shown in Figure A1-4 and A1-5 respectively. In addition to these terms, the sea level component from smaller ice caps and glaciers, and from the Antarctic ice sheet were also determined (but ignoring any possible contribution from the West Antarctic ice sheet) (Figure A1-6).
Figure A1-4. The thermal expansion component from CLIMBER-2 experiments.

Figure A1-5. The Greenland component from CLIMBER-2 experiments.
Figure A1-6. The glacier and Antarctic terms in the CLIMBER-2 experiments, marked GL and AN respectively. The axis ranges have been chosen to be +/- the range of Figures 12 to 15, which show the model totals, excluding the small glaciers and Antarctic contributions.

GENIE 1

GENIE-1 is a new Earth system model of intermediate complexity (EMIC), developed in the UK in collaboration between the Natural Environment Research Council (NERC) funded GENIE project (www.genie.ac.uk) and the Tyndall Centre for Climate Change Research (EDWARDS and MARSH, 2005). GENIE-1 has a fully 3-dimensional ocean with a 2-dimensional (latitude-longitude) single layer atmosphere. GENIE-1 has a simple parameterization of Greenland ice sheet melt. It has a fully interactive carbon cycle, so can be forced with CO₂ emissions scenarios and predicts atmospheric CO₂ concentrations. The “traceable” version of the model was used here.

Six different climate change experiments were run with GENIE-1 (Table A1-1) to explore the effects of emitting different amounts of fossil fuel carbon and of emitting the same amount at different rates. The scenarios span a range of plausible total fossil fuel emissions, and have been used in previous work, thus aiding inter-comparison. ‘A’ is a minimum emissions scenario. ‘B’ is the baseline scenario. ‘C’ and ‘D’ explore the effects of emitting all conventional fossil fuel resources rapidly (C) or slowly (D). ‘F’ takes an upper limit of 15,000 GtC fossil fuel resources, including both exotic plus conventional sources. ‘E’ is simply intended to fill the large gap in total emissions between scenarios C/D and F, and it amounts to emitting 9000 GtC after 1990. Figures A1-7 and A1-8 show the thermal expansion of Greenland components, respectively.
Figure A1- 7. The thermal expansion component from the GENIE-1 experiments.

Figure A1- 8. The Greenland component from the GENIE-1 experiments.

Note that these 1,000 year simulations were conducted for the Environment Agency (of England and Wales) who required climate scenarios beyond 2100 for long-term planning processes (LENTON et al., 2006).
Table A1-1. Long-term fossil fuel CO\textsubscript{2} emissions scenarios used in the long-term GENIE-1 experiments over 1,000 years (2000 to 3000) (LENTON et al., 2006); In this paper, only the sea-level results to 2500 are considered.

<table>
<thead>
<tr>
<th>Label</th>
<th>Total emission to year 3000 (GtC)</th>
<th>1990-2010</th>
<th>Beyond 2100</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1130 IS92c</td>
<td></td>
<td>Linear decline to zero in 2200</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2660 IS92a</td>
<td></td>
<td>Linear decline to zero in 2200</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>4000 IS92a</td>
<td></td>
<td>Linear decline to zero in 2332</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4000 1990 level</td>
<td></td>
<td>Linear decline to zero in 2926</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>9210 IS92a</td>
<td>+0.16 GtC/yr/yr to 2150 then linear decline to zero in 2599</td>
<td>Emissions exceed conventional fuel reserves\textsuperscript{10}</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>15000 IS92a</td>
<td>+0.16 GtC/yr/yr to 2250 then linear decline to zero in 2634</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maximum small glacier contribution (2000 to 2500)

Church et al (2001) concluded that the maximum contribution to sea-level rise was 0.5 ± 0.1 m, after which all small glaciers will have disappeared. A significant proportion of this ice could melt during the 21\textsuperscript{st} Century, and by 2500 it is possible that nearly all of the small glaciers will have melted, leading to a worse-case contribution of 0.5 m.

Antarctica expert interpretation (2000 to 2500)

Computer models of Antarctica are not yet able to credibly simulate many of the important dynamic features of the ice sheet, such as rapidly moving ice streams. Therefore, in this report, an expert analysis based on observation is presented.

In 2001, a risk estimation exercise was conducted to determine the level of scientific agreement concerning the potential of the West Antarctic Ice Sheet (WAIS) to make a substantial contribution to sea level rise in the next 200 years (VAUGHAN and SPOUGE, 2002). The conclusion to this study stated “that a significant sea level rise in the next 200 years is unlikely, but that this assessment retains considerable uncertainty – a 5% probability of collapse (causing sea level rise at least 1 m/century) and a 30% probability of significant sea level rise (over 0.2 m/century) due to WAIS in the next 200 years.” Since that report was completed, improved understanding gained from satellite observation studies suggests that no dramatic changes are presently occurring over much of WAIS. Hence, the likelihood of complete collapse in a few hundred years is now reduced. However, the fact that the Amundsen Sea embayment is now known to be changing at a significant rate, raises the likelihood of partial retreat, with the implication that contributions in the lower range discussed by Vaughan and Spouge are higher than suggested at that time (evidence reviewed by RAPLEY, 2006; VAUGHAN, in press) Looking further than 200 years, our uncertainty concerning the WAIS response grows substantially, and there are many who still argue that collapse of the entire ice sheet is possible within 500 years (leading to a net 5-m rise in sea level). Others suggest that this is not possible, but few disagree, that a contribution of several metres is possible on this timescale. Thus, this remains a controversial subject and a 5-m rise over 500 years remains a plausible, albeit unlikely occurrence.

\textsuperscript{10} ‘Conventional’ resources (including coal, oil and gas) are estimated at 4000-5000 GtC, but there are ‘exotic’ resources (including methane hydrates) which if exploited with new technology, could total a further 10,000-20,000 GtC, giving a global total of 15,000-25,000 GtC as an upper bound on potential sources of emissions (HASSELMANN et al., 1997)
REFERENCES


APPENDIX A2

METRICS WORKSHOP REPORT
Workshop on Metrics held at
School of Civil Engineering and the Environment
Southampton University
10th and 11th November 2005

Attendees

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robert Nicholls</td>
<td>Southampton University</td>
</tr>
<tr>
<td>Susan Hanson</td>
<td>Southampton University</td>
</tr>
<tr>
<td>Jason Lowe</td>
<td>Meteorological Office (Hadley Centre)</td>
</tr>
<tr>
<td>David Vaughan</td>
<td>British Antarctic Survey</td>
</tr>
<tr>
<td>Tim Reeder</td>
<td>Environment Agency</td>
</tr>
<tr>
<td>Helen Dalton</td>
<td>Environment Agency</td>
</tr>
<tr>
<td>Jan Vermaat</td>
<td>Vrije Universiteit, Amsterdam</td>
</tr>
<tr>
<td>Rob Jarman</td>
<td>National Trust (for England, Wales and Northern Ireland)</td>
</tr>
</tbody>
</table>

The structure of the workshop was for a series of presentations followed by group discussion of points raised. Main outcomes from these discussions are highlighted in italic type.

Day One (Thursday 10th November)

Robert Nicholls introduced the overall aims of the project and the purpose of the workshop. Jason Lowe then presented a review of the main predictive models illustrating the issues of uncertainty within different methodologies which lead to a substantial range in predicted sea-level rise over the next 500+ years. It was also shown that a continuing rise in sea level would be expected even if greenhouse gas and aerosol concentrations were stabilised, with a stable sea level not occurring until thousands of years into the future.

*During the following discussion, it was suggested that, given the large uncertainties of quantification, for management purposes it might be more advisable to use the inevitability of a rise to focus the attention of the wider community on adaptive measures other than ‘hold the line’. This would involve dissemination of information regarding the processes and consequences of sea-level rise. An example where this was successfully applied was quoted by Rob Jarman: following initial opposition, a local community accepted the loss of a harbour at an unspecified future date despite its economic importance after explanation of the inevitable long-term consequences of sea-level rise.*

Robert Nicholls presented various methodologies of determining the impacts of sea-level rise and raised questions regarding the need to consider changes over a 500 year time span.

*Scale issues were apparent. Workshop participants found the regional to global scale analyses typical in climate policy analysis did not relate well to their concerns, and different audiences require different types of information. It was also apparent that it need not be more detailed: knowing the long-term trend is shoreline retreat, combined with shoreline monitoring can be sufficient to manage many situations.*
The main reasons for predicting sea-level rise beyond the <100 year planning horizon used by the majority of policy makers were identified as:

1. It promotes strategic thinking within the policy making area and steerage towards more desired futures. One is flood management – e.g., there are many coastal locations where we can protect for the coming 50 years, but we might want to abandon over longer timescales (The question was raised “When do we begin this retreat?”). Another example is the National Trust (who are mandated to manage assets forever) who are buying land to create a buffer at the coast and give space for landward coastal migration;

2. It ensures any policy decisions are flexible enough to be adaptable to future conditions; i.e. today’s choices should not restrict future decision making;

3. It focuses attention on risk management aspects of long-term change within the coastal and marine environments including consequences in areas not so readily (or easily) considered (e.g. energy industry (especially nuclear power stations), waste management (especially implications for land fill sites), water resources, insurance, implications of long-term changes for ecological systems, transport pathways).

4. The importance of high water levels and extremes, and their trends (as opposed to mean conditions and their changes) when making policy decisions

5. The long-term role of climate mitigation (reducing greenhouse gas emissions). While the benefits of this policy are slow to be realised in terms of reducing sea-level rise (as there is a commitment to sea-level rise due to thermal expansion and possibly irreversible breakdown of the Greenland and West Antarctic Ice Sheets), the benefits of mitigation increase substantially if you consider hundreds of years into the future and have some capacity to “choose” future rates of sea level if we act soon.

6. Raising public awareness of sea-level rise and the prudence of mitigation and adaptation options. Engagement can occur at many scales from individual communities to countries and inter-governmental processes.

Day Two (Friday 11th November)

Robert Nicholls presented existing methods of identifying and calculating vulnerability – GIS based and using integrated assessment models – and illustrated potential metrics which could be used to communicate this. Susan Hanson gave an overview of responses from completed questionnaires and issues that had been highlighted.

Suggestions were made for revising the questionnaire to make it easier to understand and complete. These included defining the term ‘metric’ (which is not used widely and hence not instantly understood); the possibility of giving more examples without ‘leading’ the respondent; and establishing the relative importance of individual metrics. (However, when examining the questionnaire with one of the delegates, detailed changes appeared more minor, and it was agreed that while the questionnaire could be improved, this is probably marginal).

Suggested example metrics which are common across policy making levels although differing in detail according to purpose.

- Areas at risk;
• Magnitude
• Location
• Scale
• Value of assets in area at risk;
• Socio-economic
• Natural
• Cultural
• Extreme events;
• Frequency
• Magnitude
• Individual (sea level) and combined (sea level plus other extremes)
• Other;
• User defined

Area at risk is probably the most useful metric as it is the basis of many other metrics such as people or assets at risk. Under ‘Other’, the mapping of relevant coastal types for integrated coastal management was thought to be relevant, such as identifying resilient and unresilient coasts, both with and without defences. It was also recognised that policy is often set at high levels (e.g. national) and set the agenda for more local scales.

Other important discussion outcomes were, 

Although the questionnaire focussed on impact metrics, other metrics are useful for policy as illustrated in the recent UK Office of Science and Technology, Foresight Flood and Coastal Defence Study (EVANS et al., 2004a; , 2004b). This study used several conceptual models of erosion and flooding, including the Driver-Source-Pathway-Receptor. TableA2. 1 summarises the discussion of this framework at the workshop, including examining issues of evaluation of the issues raised and response measures. Figure A2.1 was developed after the Workshop and considers how these metrics can be linked to modelling approaches. While the fundamental driver and source that we are considering are trans-national, the effects of pathways occur at national scales, or smaller. For receptors, as long as we identify common metrics, we can aggregate from small scales to larger scales and ultimately the globe.

An alternative approach to focussing on impacts is to focus on the sensitivities in the system response, rather than possible impacts (Figure A2.1). It is based on determination of ‘tipping points’ – either the point at which any adopted policy is no longer viable or the limit to which adaptation is possible – and can be identified independent of timescale, and if the tipping point is <2 m can probably be considered inevitable although the timing is uncertain. The approach works well for major flood defence infrastructure such as the Thames Barrier, and a tipping point is a water level when a new barrier would be required. Have identified these tipping points, another question is when these tipping points might be reached, which is a matter of linking changes in water levels with climate scenarios. The timescale will be uncertain, but the range of timings will give a sense of how much time might be available for response, and what strategic decisions might increase flexibility, and help with
managing the tipping point. The analysis should consider the possibility of new technologies, changes in socio-economic values, and the role of flexible adaptation. Mitigation will buy time.

A concern about scale – much human infrastructure is concentrated near sea level on steep coasts (e.g., south-west England) but it is not resolved by broad-scale assessments (this is a generic and valid criticism of most regional to global-scale models).

Main outcomes

- The metrics developed before the Workshop are relevant to regional to global analysis, but as the scale of interest becomes smaller, and the threatened systems become more specific, so these metrics may become less useful to the relevant practitioners (essentially coastal managers). In these cases the threshold (or tipping point) approach and managing the qualitative trend may become more useful depending upon the problem being addressed.

- There is a need to explore the tipping point approach to see how generally it might be applicable (as elaborated in Table A2.2).
REFERENCES


Table A2-1. **Metrics for the decision making process (based on the Foresight approach)**

<table>
<thead>
<tr>
<th>Management level</th>
<th>Trans-national</th>
<th>National</th>
<th>Regional (Sub-national)</th>
<th>Local</th>
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<td><strong>Drivers</strong></td>
<td>Greenhouse gas emissions</td>
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</tr>
<tr>
<td><strong>Sources</strong></td>
<td>Global mean sea level rise</td>
<td>Sea level patterns</td>
<td>Geological processes</td>
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</tr>
<tr>
<td></td>
<td>Sea level patterns</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Extremes</td>
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<td></td>
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<tr>
<td><strong>Pathways</strong></td>
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<td></td>
<td>Human behaviour</td>
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<td></td>
<td>New pathways</td>
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<tr>
<td></td>
<td>Morphology</td>
<td></td>
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<tr>
<td><strong>Receptors</strong></td>
<td>Coastal processes</td>
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<tr>
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<td>Areas at risk</td>
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<td>Assets at risk</td>
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<tr>
<td><strong>Evaluation</strong></td>
<td>People at risk</td>
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<tr>
<td></td>
<td>Evaluation of coping capacity</td>
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<tr>
<td></td>
<td>Identification of and preparation for tipping points (time independent)</td>
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<tr>
<td></td>
<td>Mitigation (buys time and in the long-term (100+ years) may avoid impacts</td>
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Table A2- 2. **Draft tipping points**

<table>
<thead>
<tr>
<th>SECTOR</th>
<th>THRESHOLD</th>
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<th>POTENTIAL ADAPTATION</th>
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<td>Significant habitat loss</td>
<td>Habitat area</td>
<td>Replacement areas</td>
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<td></td>
<td>Habitat/Bird directive requirements</td>
<td>Species number/distribution</td>
<td>Artificial restoration/nourishment</td>
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<td></td>
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<td>Available areas</td>
<td>Zoos (i.e. ‘artificial’ conservation)</td>
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<tr>
<td>Flood defence</td>
<td>Defence standard</td>
<td>Water level</td>
<td>Defence height</td>
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<td>Overtopping frequency</td>
<td>Temporary water storage</td>
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<td>Realignment</td>
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<td>Global/regional sea change (currents/inundation)</td>
<td>Alteration of shipping routes</td>
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<td>Re-siting of infrastructure</td>
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<td></td>
<td></td>
<td>Extreme water level/frequency</td>
<td>Adaptation of infrastructure</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Productivity</td>
<td>Area (by agricultural type)</td>
<td>Regime change (arable/animal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Salinity levels</td>
<td>Crop change</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>New areas</td>
</tr>
<tr>
<td>Insurance</td>
<td>Government policy (e.g. standard and location</td>
<td>Flooding frequency</td>
<td>Premium levels</td>
</tr>
<tr>
<td></td>
<td>of defences)</td>
<td>Flooding extent</td>
<td>Variation in insurance cover</td>
</tr>
<tr>
<td>Landfill management</td>
<td>Defence standard (?)</td>
<td>Erosion rate</td>
<td>Increase protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Relocate hazardous materials</td>
</tr>
<tr>
<td>Water management</td>
<td>Drought threshold</td>
<td>Storage capacity (natural and artificial)</td>
<td>Desalination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Restructure water system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Importation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Storage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Restrict supply (metering)</td>
</tr>
<tr>
<td>Energy industry</td>
<td>Cost/Benefit balance</td>
<td>Vulnerability of infrastructure</td>
<td>Alternative energy sources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emissions/Pollution</td>
<td>Movement of plant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Selling price</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reserve levels</td>
<td></td>
</tr>
</tbody>
</table>
Figure A2-1. **Suggested methodology for decision making using tipping points**

1. Maintenance/learning/knowledge
2. Identify/analyse tipping points
3. Identify/analyse possible actions (consider feasibility/sustainability)
4. Identify/analyse timing of tipping points (including mitigation)
   Need to refer to sea-level rise scenarios (Section 2)
5. Implement long-term (slow) options, and 'wait and see' for immediate (fast) options
6. Continue monitoring/prediction of change (sea level, high water levels, etc.)
APPENDIX A3

METRICS QUESTIONNAIRE ANALYSIS
Background

Stage 1 of the "Improving Methodologies to Assess the Benefits of Policies to Address Sea-Level Rise" project reviewed sea-level rise predictions from a variety of models and produced an interim range of potential sea-level rise scenarios in the range 0.3 to about 9.4 m over the next 500 years covering the range of uncertainty, including emissions11.

Given the high potential impact of these scenarios, consideration by all management sectors within the coastal zone (e.g. commercial, industrial, energy, agriculture, town planning) would appear to be beneficial. However the extent to which such long-term scenarios would be considered or incorporated within future strategic planning decisions by such disciplines is relatively unknown beyond the coastal management community. A short questionnaire was therefore designed as a scoping study to elicit responses to an illustrated range of sea level scenarios and opinions on the usefulness of such predictions from a range of coastal experts and coastal practitioners whose work might consider sea-level rise within strategic planning.

By extending the distribution of the questionnaire beyond those directly concerned with sea-level rise, it was also hoped implications or concerns not immediately considered by the coastal community might be highlighted. Questions therefore aimed to identify issues associated with long timescales and metrics (indicators) relevant for strategic decision makers across a range of disciplines and different (spatial) levels. It was also designed to be answered within a short period of time to encourage responses.

From the outset, locating individuals who were interested and would be willing to participate in the project, particularly within the private sector, was a difficulty. Consequently, it was decided to circulate the questionnaire as widely as possible even if a low response rate was achieved. Initially, the questionnaire (Appendix A4) was distributed by direct emailing focusing on sectors/individuals directly concerned with issues regarding sea-level rise. The preliminary results from the 23 responses were discussed during a workshop held on 10th-11th November 2005 at Southampton University to review metrics (see Appendix A2). Following these discussions, the questionnaire was slightly amended and an additional question (Q6) was included to elicit responses to an alternative sensitivity-based methodology for using the sea level predictions (Appendix A5). This revised questionnaire was then distributed using the Coastal Mailing Service (CMS) hosted by Dr Bob Earll (http://www.coastms.co.uk) which covers expertise in a wide range of coastal and water-based disciplines. 42 additional responses were received via this route within the two week time limit, which provided valuable additional input for the project. Responses were analysed using Qualitative Research Software QSR N6.

The total number of responses is quite small and the representativeness and significance of this sample and their responses are open to question. This limitation is recognised, but in the absence of other information on people’s views and attitudes on long-term sea-level rise this remains a valuable source of information to this assessment. Investigation of people’s attitudes to long-term sea-level rise appears ripe for further more detailed research.

In the following analysis of the questionnaires, references in brackets indicate Respondent ID (alphabetical IDs denote respondents to the first questionnaire circulated, numerical references to the second) and sections in italics are direct quotes.

11 Note that the final more detailed assessment suggests a smaller range (see Main Report Section 2).
Respondents

Section 1 of the questionnaire provided base information regarding the occupation and expertise of respondents for comparative purposes.

The majority of the 65 questionnaires returned were UK based (42) but responses were also received from Ireland (2), Morocco (1), Australia (2), Spain (2), Germany (4), France (1), Italy (1), the Netherlands (2), the USA (1) with the remaining 7 undeclared. Representation was found across the predefined levels and organisation types (see Figures A3.1 and A3.2 on following page) and included individuals from Local, Regional and National government, Universities, Waste, Energy, Shipping, Conservation organisations, Finance and Management consultancies.

Information provided regarding profession/ work description was used to indicate the range of disciplines covered by respondents – this entailed the combination of individual job descriptions into broad categories for example - biodiversity covered all those indicating a main responsibility/interest in conservation, biology or ecology. ‘Non specific’ was indicated where a generic term such as environmentalist or scientist was used. Table A3.1 indicates the resulting distribution.

Table A3-1. Sectoral distribution of questionnaire respondents

<table>
<thead>
<tr>
<th>SECTOR</th>
<th>NUMBER OF RESPONDENTS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>25.0%</td>
</tr>
<tr>
<td>Offshore</td>
<td>11.0%</td>
</tr>
<tr>
<td>Culture or heritage</td>
<td>4.8%</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>14.0%</td>
</tr>
<tr>
<td>Policy and Planning</td>
<td>17.3%</td>
</tr>
<tr>
<td>Academic</td>
<td>16.0%</td>
</tr>
<tr>
<td>Potable water management</td>
<td>3.2%</td>
</tr>
<tr>
<td>Climate change</td>
<td>6.3%</td>
</tr>
<tr>
<td>Financial</td>
<td>3.2%</td>
</tr>
<tr>
<td>Non specific</td>
<td>17.0%</td>
</tr>
</tbody>
</table>
Figure A3-1.

Decision-making levels covered by questionnaire respondents (%)

Figure A3-2.

Percentage distribution of respondents by organisation type
Long-term sea-level rise

The second part of the questionnaire aimed to identify the following:

- use of long-term sea-level rise predictions for current strategic decision-making,
- metrics for assessing and communicating the impacts of sea-level rise,
- issues and challenges raised by long-term (500 year) sea-level rise projections.

Four plausible projected levels of sea-level rise for the next 500 years from a range of predictive models were presented, illustrating the large range of uncertainties in future emissions of greenhouse gasses and sea level response to the resulting global warming. These included the collapse of the Western Antarctic Ice Sheet over a 400-year timescale in the high-end scenario.

Current strategic planning

Perceived restrictions to the use of long-term sea-level rise projections within current strategic planning were clearly demonstrated in answers to Questions 2 and 3. It was clear that current planning horizons rarely extend past 100 years, except within research based organisations which concentrate on national or international levels.

Figure A3-3. Time spans for strategic decision-making. UK and non-UK respondents are distinguished for comparative purpose.

83% of respondents indicated strategic decisions would be made over time periods ≤ 100 years. As shown in Figure A3.3, the relative pattern in time span selection for both UK and non-UK respondents is similar with 75-100 years being most frequent. Many of the 47% of UK respondents who selected 75-100 years, specifically indicated 100 years; this was often associated with the
influence of Shoreline Management Plans (SMPs: DEFRA, 2001) and other DEFRA grant aided coastal protection works (D). SMPs, although non-statutory, are a requirement within the England and Wales coastal planning framework and this high percentage reflects the number of respondents working in Government management and policy organisations (e.g. 24, 36, 40).

Other strategic planning frameworks, both in the UK and elsewhere, rarely seem to extend beyond 50 years with the shortest time spans (5 – 10 years) associated with particularly restrictive political, commercial or financial pressures (see Box A3-1).

It was recognised by a number of respondents that in reality a variety of timescales needed to be integrated within any planning framework; for example, a short-term rolling timescale for revisable decisions such as provision of defences and a longer time span (approx.100 year) for major infrastructure (transport, sewage, storm water drainage) decisions both within a longer view of other issues such as the future location of a city, energy provision or the consequences of major global changes such as the opening of the Northwest passage as a major trade route (1, 16, 19, I).

The fact that most respondents are focussing on ≤100 years as a planning horizon also appeared to influence the answers to Question 2 in which respondents indicated which of the projected sea-level rise curves would be used when making decisions (see Box A3-2). Limiting their choice to this timeframe, when outputs from the different climate models show least variation in future sea-level rise, and Curve B corresponds with sea-level rise figures in IPCC and UKCIP publications (Church et al., 2001; Hulme et al., 2002), the distribution shown in Figure A3.4 may not be surprising. Answers may have differed if the range in sea-level rise during the 21st century was larger (i.e. collapse of the Western Antarctic Ice Sheet began prior to 2100 (12)) or planning decisions were made

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Box A3-1. **Examples of current planning horizons**

"Asking people to look at over a 100 years doesn’t elicit interest and is beyond any current requirement for financial planning" (4)

"...can only focus on the next five years - the art to consultancy is being able to (link) oneself into emerging markets quickly" (28)

"Unfortunately, even under the new spatial planning system, strategic plans do not look further than 20 years ahead" (A)

"by and large strategic planning within industry is usually over a fairly short term eg 20 - 50 years max"(I)

*They are not really useful within the time scales of current planning regimes, ie up to 30 years max, and more typically 10 years(6)*

"My organisation is politically driven and consequently does not tend to consider the long-term situation" (24)

"Politically driven decision-making is inherently short-term, looking at time scales exceeding 100 years may overstress both the capability and the willingness of administrations and politicians to deal with SLR and related problems; the basis for decisions at the national / regional level of decision-making often changes after 4-6 years"
over a longer time span (33). However, as such dramatic sea-level rise is considered unlikely within this time frame (VAUGHAN and SPOUGE, 2002) this was not illustrated.

Nevertheless, Figure A3.4 indicates a recognition that “All curves need to be considered, including a “worst” case scenario” (20) and “b, c and d would cause the most problems and as such would require strategic planning” (30). In addition, a significant number of individuals (23%) remained uncommitted regarding the sea level curves due either to concerns regarding the basis for the models (see Section 3.3.1) or that the curves would not be used within their particular occupation (M, 14, 26).

### Box A3-2. Restrictions to selection of sea-level projection

“Present Government guidance for our area requires us to use 6mm per year. The nearest Curve is Curve B” (G)

“curve C or B for the first 100 years” (32)

“Probably B but until 2100 all but A are very similar” (28)

“Curve D as a worst case scenario but very little difference between BCD till 2100” (23)

“Anyone, because only middle term (less than a century) are realistic for any strategic planning decision” (C)

![Figure A3-4. Percentage occurrence for each sea level curve which would be considered within strategic planning](image-url)

92
Impact metrics for sea-level rise

Question 4 (i and ii) of the survey aimed to identify the means by which the impacts of sea-level rise are assessed and whether there are any differences between those used internally and to communicate these impacts to the wider community.

To assess the impact of sea-level rise the majority of respondents utilised the examples given in the questionnaire although some were more specific (e.g. harbours and marinas affected, loss of territories - small island states, particular company infrastructure). The choice of metric showed a consistency across disciplines and decision-making levels and recognised area at risk as the primary indicator (Figure A3.5). This is mainly due to its use as the basis for calculating most of the other metrics identified (6, 13, 24), spatial distribution and associated land-use being considered particularly important additional aspects. Economic impact was also found across decision-making levels but was composed of different elements. At the local scale it was usually associated with the costs of adaptation (e.g. defence building), whereas at the national and international levels additional concern was shown for both direct and indirect impacts on the economy (e.g. loss of resources).

Whilst recognising that the choice of metric for communicating the impact of sea-level rise will vary according to the audience (9, 26), the same range of metrics was selected for communicating the impacts of sea-level rise to the wider community. Area at risk remains the most important with the visualisation and ‘personalisation’ of this being of prime importance. Fourteen respondents particularly mention the use of GIS software, three-dimensional representation and digital terrain models, and model simulations to convey this information to the wider community.

Box A3.3. Spatial distribution of areas at risk is the most important metric

“If people can see mapped areas at risk I feel that they can readily estimate the effects on community (numbers of people affected, disruption etc)” (20)

“Identifying places where people live and work and which they presently take for granted as they are not perceived to be at risk of SLR” (H)

“Implications for personal leisure eg beach loss, link golf courses destroyed (useful for businessmen!” (F)

“More precise topographic maps and digital elevation models”(12)

“Area the others can be determined from this” (24)

“For us, a line or area shown on a map would be most useful as we are aware of our assets within that area” (42)

“Different sea level and flood prone area change maps with thematic background information (e.g. landuse, etc)”(B)
Figure A3- 5. **Comparison of metrics used for assessing and communicating the impact of sea-level rise**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Assessment metric</th>
<th>Communication metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area at risk</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Infrastructure at risk</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>People at risk</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Biodiversity changes</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Property at risk</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Heritage/Culture at risk</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Economic impact</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Associated events</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Rate of change</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Associated risk level</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Number of occurrences
Issues and challenges

The majority (60%) of respondents, who expressed an opinion (Question 5), felt that long-term sea-level rise predictions are useful when making strategic planning decisions, but raise many issues including those illustrated in Box A3-4. Again, there were no strong correlations between opinions expressed and particular types or level of organisation (although examples given were specific to different professions). Practical issues raised included extent and rates of coastal flooding and erosion; increased fluvial flooding in coastal areas; changes in land use; transport planning; economic degeneration; social impacts, decommissioning timescales, sustainability of long term waste storage options, opportunities for and threats to biodiversity on land, freshwater and at sea which result in increased pressures on organisations which manage the coast and adjoining sea.

Despite the range of practical concerns, there was a consensus that the main benefit of long-term sea level projections is its use as a prompt to start thinking and serious debate about truly long term implications of climate change and raising issues regarding the current decision-making process (A). Within this debate, respondents were clearly divided in outlook; those who regarded the sea level projections as an opportunity/basis to communicate and/or alter the limitations of current policy and planning frameworks in the face of an inevitable rise in sea level and those concerned that the uncertainties associated with such projections undermine their acceptance as a basis for decision-making (8).

Uncertainty

Uncertainty was an important issue for many respondents. The limits of use and the uncertainties needed to be well explained and discussed in detail as the level of uncertainty within the illustrated predictions was considered substantial and confidence levels are an important factor (see Box A3-5).
Some respondents felt it would have been useful to have been given more details on the underlying models or alternatively, an indication of probability and/or error estimates associated with each curve along with “VERY careful explanation” (20) of how these were determined.

The global nature of the projections also caused some concern and “downscaling to the regional context” (9) would be required in order to be really useful for planning purposes. In addition to a more localised focus, some respondents also felt it would be “...preferable to have more than just SLR as a variable to react to” (7). Inclusion of “What changes wave climate and storm surge risk will follow from these scenarios” (O) and “...indication of the increase in cliff recession that may ensue” (19) would be the ideal situation.

Given these concerns, two respondents felt very strongly that it was inadvisable to use such projections (see Box A3-6) and some concerns over possible misuse to raise public anxiety were raised particularly regarding the insurance industry.

However; despite concerns regarding the sea level curves many respondents agreed that “if more confidence in these projections can be reached then on some commission we should start to look to longer time horizons” (8) and “Acknowledging concerns with the magnitude of the lines presented

Box A3-5. **Need additional information regarding the models**

“I would like to call into question the validity of these predictions as there is no error figure estimated. Predictions in 1988 have been shown to be incorrect by up to 300%” (17)

“Without seeing the references and supporting data, I am unable to chose any one line before another” (35)

“I have little confidence that the rate of warming will be slowed significantly, and discussions suggest that not all known feedbacks have been accommodated in models” (7)

“.But for us to use them we would need to understand the process and scientific credibility of each outcome” (O)

Box A3-6. **Doubts regarding the use of uncertain scenarios**

“My audiences are mainly senior businessmen, major insurance companies, and civil servants around the world. The challenge for me is persuading them to believe there is any problem at all. Most are not interested in the long-term” (12).

“I cannot inform my (political) superiors that in about 100 to 200 years we MIGHT have to abandon 25% of our State. I would be ignored and definitely not be taken seriously” (N)
above, these scenarios are of use and the increasingly energised coastal system in the coming century
(and beyond) will present society with a range of management problems” (35).

Communication of issues

The sea-level scenarios were considered useful as they are set over an unusually long timescale
so that they focus the mind on the implications for future generations (20) and the need to consider
many generations ahead despite the lack of experience in planning over these timescales particularly
within commercial and political circles (F, 12, 26).

The communication of these issues outside of the scientific community was one of the main
concerns raised in answer to Question 1. However this was seen as a major difficulty, particularly for

<table>
<thead>
<tr>
<th>Box A3-7. Difficulties with communicating issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>“I am not sure whether it is good or sound to publish these kind of long-term scenarios (being so premature and uncertain), as they might even further disrupt the populations trust in the future. One century ago, nobody would believe what is possible nowadays (for example 800 persons flying in one aeroplane, computers, colour television, etc. So, how will the world really look like in 100 years? Definitely NOT as we think/predict it today! So, at least we should wait until we can prove that scenarios B through D will become reality” (N)</td>
</tr>
<tr>
<td>“Given this large range, in my opinion it is useless to show the trends for 400 years. Decision making and makers, 50 years from now will be completely different in mentality and in assigning weights to the indicators. It would be much more useful to concentrate the efforts and zoom on the first 100 years and put more effort on predicting for specific areas if this is possible” (32)</td>
</tr>
<tr>
<td>“However the same information could be used by some such as the insurance industry to create great hardship unnecessarily due to a premature reaction to anticipated loss of defences or protection.</td>
</tr>
</tbody>
</table>

those working within political and financial arenas (Box A3-7) where forward planning is rarely
beyond 10-20 years and sometimes as short as 4 years (K).
As a starting point for discussion (26), the illustrated sea level curves can increase awareness in those who may not consider sea-level rise to be an issue that concerns them or one that can be left for later generations to deal with. However managing the coastal zone (including potential disruption/historic loss/provision of services and leisure activities) has wider implications that to those immediately affected, e.g. food supplies, energy provision (39, 28)

Some concern was raised that the general approach to considering the future effects of sea-level rise is negative and a more balanced view of looking for positives and negatives should be pursued (see Box A3-8). Most commonly found when biodiversity change is of major importance (loss of one habitat/species results in an opportunity for another or where erosion is required to maintain habitats (C, 1, 21), this view was also taken by those who felt that acceptance of ‘retreat’ in the face of inevitable sea level rise and how to cope with this needed to become the prevailing approach.

**Box A3-8. Need to change negative connotations of sea-level rise**

“Current indicators appear biased towards negative issues of 'change', whereby change is 'bad'. Change is of course continuous, and the debate is currently, disingenuously, equating change with negative consequences. So, indicators are required which give a

**Future planning**

Most respondents were of the opinion that adaptation and mitigation were the future policies of choice. ‘Hold the line’ policies in the face of inevitable sea-level rise were not seen as viable options in the long-term. Use of long-term (500 year) sea-level rise predictions offer the opportunity of developing a new philosophy (Ł, 27, 9), the main difficulty being the need to embrace uncertainty as part of the planning process, “The real challenge would be to transport the (very uncertain) scenarios B to D into policy and strategic planning” (N), and the communication of this both the public and relevant policy makers. As this is usually based on affordability and acceptability (public perceptions) it may be regarded “as more of a social engineering nature than a technical problem” (36) but any information that is easily assimilated by the general public would help in the management of expectations and preparation of long term plans by local government and investors.
For those in engineering disciplines this included communicating that “...there are two types of flood defences, those that have failed and those that have yet to.....” (35) and defences should be viewed as “flexible structures” that guarantee full defence for the selected reasonable level and partial defence for higher levels for at least 30 to 50 years in order to give sufficient time for monitoring the sea level rise trend and plan and execute supplementary interventions and/or measures” (32). However the question of the timing of changes in sea level and hence the speed of adaptation is a key issue (36).

In effect, many respondents thought that current policies should be seen as a ‘holding’ plan while the more difficult decisions are taken. Some respondents noted that each generation faces relatively small changes, but across generations the changes could be much larger (27) so there is the danger that this approach “always makes it easier to put off hard choices” (H), and the fact “that events rather than careful planning ahead that will (at least initially) tend to dictate those (long-term) types of decisions e.g. New Orleans” (20).

An alternative approach?

Following discussions during a workshop held at Southampton University, Question 6 was added to the questionnaire. This proposed a methodology based on sensitivity analysis (or ‘tipping points’) in which a threshold is established and the sea level projections can be used to determine when this threshold might be reached. In this way, an estimate of ‘available’ time in which an alternative management strategy would be developed could be calculated. This was a difficult idea to convey within a short questionnaire, but of the 35 responses to Question 6, the suggested sensitivity approach included in the second of the two questionnaires, a generally positive response was received (Box A3-9)

The methodology was seen as a way of providing tangible representations of possible futures, focussing attention for researchers, stake holders and the public on the seriousness of sea level and climate change risks. Establishment of thresholds would be particularly useful if there was integration with other processes, regardless of the assumptions the information is based upon (16, 30), since simplistic figures of sea level rise could be dismissed as insignificant (13) or not close enough to perceived reality to be taken seriously in a commercial environment (33).
A similar risk-based approach based on varying acceptable return periods for flooding for different types of properties, for example 1,000 years for hospitals, 200 years for housing etc. has been used within the insurance industry and a similar approach has been adopted by the Scottish Executive and most Scottish planning authorities (12).

By defining limits, discussion of issues such as when people/commerce/industry may need to move, may need to find alternative food sources, or compliance with legally binding instruments such as the EU Habitats Directive become jeopardised (39) will have to be undertaken with the knowledge of the risks that the limit will be reached. In this way, it would also highlight the benefits of a more integrated means of planning so that ‘joined-up thinking’ between different disciplines takes place with the potential for resolving conflicts of interest before they occur.

However a cautionary comment was raised regarding this approach (see Box A3-10).

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**Box A3-9 Example responses to the proposed sensitivity methodology**

“(System sensitivity) …would be crucial in analysing the true risk and level of risk to the area under consideration. The quantification of that risk would allow strategic decision making on required actions to be balanced and pro-active” (38)

“Could be more useful. …preservation of infrastructure to maintain the business is fundamental. A scenario which effectively removes the entire estate is not close enough to perceived reality to be taken seriously in a commercial environment today” (33)

“This would probably be more understandable than the current methodology which use standard of protection – a measure that appears abstract and defuses the threat” (4)

“These sort of scenarios would allow us to plan improvements to schemes rather than simply reacting when they fail. This is something that we are trying to do at present in terms of whole life costings and incorporating flexibility for future proofing works. (42)
A major aspect of achieving useful outcomes lies in the defining of ‘the selected reasonable level’ mentioned in the above quote. Although physical limits can be relatively easily set (see Appendix A2, Table A2-2), this would largely be based on perception i.e. what would be perceived in the public eye as an acceptable cost/change or expendable (2). “Valuing nature and people’s lifestyles/stress would be hard” (39) as this will vary over time and space and thresholds may need to be locally or regionally specific and linked directly to the companies, industry, employment, health and safety issues for a specific location. Integration of thresholds across natural and anthropogenic system is therefore essential when attempting to achieve the maximum gain for the natural system whilst avoiding significant negative social and economic impacts (21). This may well contribute to the proliferation of outcomes and attendant difficulties referred to in Box A3-10

Conclusions

As an initial investigation into attitudes about long-term (100+ year) sea-level rise and its impacts, this short survey has provided some useful insights. Firstly, it indicates that many people do consider long-term sea-level rise as an important issue, which is worthy of consideration within strategic planning. This concern seemed to be shared across nations and across decision-making scales. However, current planning frameworks and perceptions of the issue severely limit such planning at present. The ability to alter these timeframes for management is felt to be limited because of the perception that others, especially those higher in authority where the changes most need to occur, do not share their concerns. It is noteworthy that in the UK, government initiatives in shoreline management do seem to have engendered a longer-term (100 year) perspective in coastal management as evidenced in many responses in the UK.

Many respondents felt that in the face of the long-term sea-level rise scenarios presented in the questionnaire that a retreat from the present shoreline was the inevitable, ultimate response. However, they were unclear when ‘society’ would grasp this point, and reconsider the viability of the ‘hold the line’ policy which is implicit in most coastal countries at the moment. Currently, such evaluation typically only occurs as a result of individual extreme events or disasters (e.g. the current debate about the future of New Orleans after Hurricane Katrina), and it was felt that proactive adaptation approaches currently only had limited applicability to coastal planning, most particularly to managing natural systems, rather than social/economic issues. This is a wider challenge for coastal management than the long-term sea-level rise issue being addressed here.

The most favoured metric for both assessing and communicating the impacts of sea-level rise was the definition of areas at risk, shown on a map. This allows individuals to readily understand and
communicate what areas might be lost/require protection and facilitates further analysis to suit individual requirements. The idea of system analysis and tipping points also attracted favourable comments, as it related directly to decision makers concerned with managing these systems, and their understanding of the system vulnerabilities. Most respondents felt that this approach is probably most applicable when dealing with well-defined systems at relatively small scales (e.g. the Thames Barrier and its upgrade (see Appendix A2). However, application at broader scales could become complicated or abstract due to both the difficulties in understanding the coastal system at these scales, and spatial variations in acceptable thresholds and tipping points.

This survey also highlighted important areas of research for the future, including:

- more robust and credible long-term sea-level rise scenarios that could be raised within long-term planning processes (24)
- the development of better methods of balancing long-term environmental and human requirements (21).
- the more detailed examination of the social science perspective of these issues, including decision, behaviours, preparedness (J)

Lastly, while these issues have been raised by a climate policy issue; impacts of sea-level rise over 100+ year timescales; many of these issues also have wider relevance to coastal management. Following other studies, the results shown here can be taken to indicate that coastal management needs to take a longer-term more strategic perspective. Mainstreaming response to long-term sea-level rise as one issue within coastal management may be mutually beneficial to climate and coastal policy.
REFERENCES


APPENDIX A4

METRICS QUESTIONNAIRE (VERSION 1)
Metrics Questionnaire (Version 1)

“Improving Methodologies to Assess the Benefits of Policies to Address Sea Level Rise”

METRICS QUESTIONNAIRE

I would like to invite you to participate in a short survey for the above OECD funded project which is considering potential sea-level rise over the next 500 years and how this challenge might be best addressed by the policy process.

In Stage 1 of the project a review of sea-level rise predictions from a variety of models has been conducted. This has produced a range of potential sea-level rise scenarios of up to nearly 10 metres over the next 500 years. In response to these scenarios, Stage 2 involves the development of policy relevant metrics for strategic decision makers across a range of disciplines and at different levels while remaining understandable by the wider community. The purpose of this survey is to explore attitudes to long-term sea-level rise amongst a range of experts and practitioners with a long-term perspective and to develop metrics/measures which would be useful within and across different disciplines. Responses will contribute to a list of practical metrics linking sea-level rise with associated impacts and risks over long timescales (≤ 500 years) being developed within the project.

I would be extremely grateful if you could support this research by completing the attached questionnaire. This should take less than 10 minutes of your time (depending on your answers) and may I assure you that all answers will be treated in accordance with the University’s code of ethical research, which guarantees the confidentiality, anonymity and protection of all research participants.

I look forward to receiving your completed questionnaire in the near future.

Thank you in advance,

Dr. Robert J. Nicholls
Professor of Coastal Engineering
School of Civil Engineering and the Environment
University of Southampton
Southampton SO17 1BJ
r.j.nicholls@soton.ac.uk
“Improving Methodologies to Assess the Benefits of Policies to
Address Sea Level Rise”

METRICS QUESTIONNAIRE

SECTION 1 – Professional details.

(Please note: use the tab key to navigate the questionnaire; boxes will expand as information is added)

1. Please give your profession and nationality

2. Into which categories does your organisation belong?

<table>
<thead>
<tr>
<th>Type</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governmental - management</td>
<td>Local</td>
</tr>
<tr>
<td>Governmental - policy</td>
<td>Regional</td>
</tr>
<tr>
<td>Charitable organisation</td>
<td>National</td>
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<tr>
<td>Research – other</td>
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<tr>
<td>Private company</td>
<td></td>
</tr>
<tr>
<td>Other: (Please define)</td>
<td></td>
</tr>
</tbody>
</table>
SECTION 2 – Sea-level rise.

The above figure illustrates plausible projected levels of sea-level rise for the next 500 years from a range of predictive models. The large range reflects uncertainties in future emissions of greenhouse gasses and sea level response to the resulting global warming.

1. Taking a professional perspective, what issues and challenges might these possible changes raise for your organisation?

2. Which of the four curves (if any) would form the basis for any strategic planning decisions?

3. How far into the future would these scenario(s) be considered as part of any planning decision?

4. Which indicator(s) would be most beneficial
(i) to gauge the implications of sea-level rise for your organisation e.g. area at risk

(ii) for communication of these implications to colleagues and the wider public e.g., number of hectares of wetlands lost

5. Do you find these scenarios useful for your organisation?

6. Any other comments?

Thank you for participating in this research. If you require further information or have any questions regarding this research, please do not hesitate to contact me on r.j.nicholls@soton.ac.uk.

Please note: all of your answers will be treated in accordance with the University’s code of ethical research, which guarantees the confidentiality, anonymity and protection of all research participants.

Thank you.
APPENDIX A5

METRIC QUESTIONNAIRE (VERSION 2)
Questionnaire (Version 2)

OECD project:

“Improving Methodologies to Assess the Benefits of Policies to Address Sea Level Rise”

QUESTIONNAIRE

SECTION 1 – Professional details

(Please note: use the tab key to navigate the questionnaire; boxes will expand as information is added)

Please give your profession and nationality

Into which categories does your organisation belong?

<table>
<thead>
<tr>
<th>Type</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governmental - management</td>
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<td>Private company</td>
<td></td>
</tr>
<tr>
<td>Other: (Please define)</td>
<td></td>
</tr>
</tbody>
</table>
SECTION 2 – Sea-level rise

The above figure illustrates plausible projected levels of sea-level rise for the next 500 years from a range of predictive models. The large range reflects uncertainties in future emissions of greenhouse gasses and sea level response to the resulting global warming.

7. Taking a professional perspective, what issues and challenges might these possible changes raise for your organisation?

8. Which of the four curves (if any) would form the basis for any strategic planning decisions?

9. How far into the future would these scenario(s) be considered as part of any planning decision?
10. Which indicator(s) would be most beneficial
   (iii) to gauge the implications of sea-level rise for your organisation e.g. area at risk; people at risk; infrastructure at risk; heritage/culture at risk; property at risk etc

   (iv) for communication of these implications to colleagues and the wider public

11. Do you find these scenarios useful for your organisation?

12. Would an alternative approach based on system sensitivity be useful? You might define a value at which the system(s) you are managing would be significantly affected by the magnitude or rate of sea-level rise. Would establishing such threshold(s) and their timing using the figure be a useful alternative methodology? For example,
   (i) given a design specification of flood defences, identification of when the frequency of overtopping of flood defences would become unacceptable would indicate the time span over which alternative management regimes or investment programme would need to be prepared
   (ii) having decided the point at which a coastal ecosystem starts to significantly decline (e.g. area), when this point is likely to be reached.

If yes, please expand on the issues that are raised.

13. Any other comments?

Thank you for participating in this research. If you require further information or have any questions regarding this research, please do not hesitate to contact me on r.j.nicholls@soton.ac.uk.
Please note: all of your answers will be treated in accordance with Southampton University’s code of ethical research, which guarantees the confidentiality, anonymity and protection of all research participants.

Thank you.
APPENDIX A6

REGIONAL TO GLOBAL DATASETS
Elevation data

One of the best available global elevation datasets at the moment is the SRTM Enhanced Global Map developed by ISciences (2003). The dataset has a resolution of 30 arc seconds (around 1km at the equator) and is based on data acquired from the Shuttle Radar Topography Mission (SRTM), which cover 80% of the earth's land surface. The SRTM data were supplemented with GTOPO30 elevation data for land areas that are covered in the SRTM30 dataset and also with ocean bathymetry data from ETOPO2.

Another dataset covering the largest part of the globe at a much higher resolution is the elevation dataset that has been produced by the SRTM. This mission has produced digital topographic data for 80% of the Earth's land surface (all land areas between 60º north and 56º south latitude), at a 3 arc-second (around 90m) grid. The absolute vertical accuracy of the elevation data is 16 meters (at 90% confidence). This is the most accurate and complete topographic map of the Earth's surface that has ever been assembled.

Population data

There are two gridded population datasets available for global analysis:

- The Gridded Population of the World, version 3 (GPW3) (CEISIN and CAIT, 2004);
- Landscan (2003) (see also DOBSON et al., 2000) provide gridded population data for the globe.

The LandScan dataset is a worldwide population database compiled on a 30×30 arcseconds latitude/longitude grid (about 1 km at the equator). Census counts (at sub-national level) were apportioned to each grid cell based on likelihood coefficients derived from a series of variables such as proximity to roads, slope, land cover, night time lights, and other data. The resulting data is ambient population, which reflects an estimate of the actual population distribution, rather than the distribution accorded in a census, which is based on residence. Hence as an example, city centres with low resident populations, may show much higher ambient populations.

The GPW3 is the latest update of the GPW dataset: earlier versions have been extensively employed in a range of global population studies (COHEN et al., 1997; SMALL and NICHOLLS, 2003). GPW adopts a simple population distribution algorithm gridded at the same scale as Landscan, but putting more emphasis on the collection of the input data rather than modelling distributions (NELSON and BALK, 2003).

As with all global data, there are considerable uncertainties in these data sets (e.g. SMALL and NICHOLLS, 2003).

Tidal range data

The tidal range dataset is available at a 1-degree resolution global dataset compiled according to the small-scale map of Davies (1980) containing a global overview of tidal range classes. The data used is derived from the LOICZ typology dataset (MAXWELL and BUDDEMEIER, 2003). Tidal range is presented as five classes, which were interpreted as average tidal range values and hence high water (tidal range/2).
Land use data

Land use dataset that was developed by the IMAGE Team (2002). This dataset contains the global distribution of 19 principal land use types at $0.5^\circ \times 0.5^\circ$ resolution.

- Global Land Cover Characterization dataset available at the United States Geological Survey (USGS), Earth Resources Observation and Science (Eros) Data Center. The dataset was created with Advanced Very High Resolution Radiometer (AVHRR) data (1km resolution).

- Land use-land cover map of the world made by International Food Policy Research Institute IFPRI of the Food and Agricultural Organisation (FAO). The map takes in consideration occurrence of cropland, pasture, forest and others at a grid resolution of 30 arc seconds and is available at the FAO-UN geonetwork.

- NASA land-use land cover-change data developed by the Defence Meteorological Satellite Program (DMSP), available at the National Geophysical Data Center (NGDC) at a 1km grid.

- Corine Land Cover 2000 (CLC2000) is an update for the reference year 2000 of the first Corine Land Cover database which was finalised in the early 1990s as part of the European Commission programme to COoRdinate Information on the Environment (Corine). It provides consistent information on land cover and land cover changes during the past decade across Europe, at a resolution of 100m.

Administrative unit boundaries

A dataset of the 1095 first-level sub-national administrative boundaries is included in the Digital Chart of the World (DCW) (Deichmann et al., 2001; ESRI, 2002). The DCW has been partially employed for the generation of the GPW3.

Economic data

This is normally available at the scale of nations, or sometimes sub-national scales (e.g., DIVA Consortium, 2004). Hence the data does not integrate well with datasets which are presented on a grid basis, such as elevation or more recently population, or even night lights (related to urban extent) (see SMALL and NICHOLLS, 2003). A new dataset has just become available that has transformed economic data to a spatially-gridded format greatly facilitating analysis. This data set is called GECON 1.1, and it measures output with a resolution of $1^\circ$ latitude by $1^\circ$ longitude, covers 25,572 terrestrial grid cells (see NORDHAUS, in press). For further details see http://gecon.yale.edu/pnas.html.
REFERENCES


APPENDIX A7

SELECTED IMPACT AND ECONOMIC MODELS
The FUND model and its application to long-term and extreme sea-level rise impacts are briefly described. The DIVA model is also briefly outlined.

**FUND**

The *Climate Framework for Uncertainty, Negotiation and Distribution (FUND)* model is an integrated assessment model for climate change impacts and adaptation analyses with a number of linked modules. Here, only the coastal impact module is considered as described in Tol (2002a; 2002b). While it was designed to operate over the 21st Century under rises in sea level of ≥ 1 metre, it has also been adapted and applied to arbitrary extreme sea-level rise scenarios by Nicholls *et al* (2005)12. This impact analysis up to 2300 is considered in this paper. The essential features are outlined below. Version 2.8n which resolves 207 countries is used here.

Essentially, FUND2.8n consists of a set of exogenous scenarios on which impacts are calculated. The model runs from 1995 to 2100 (or longer) in time steps of five years. Any population and economic growth scenario can be analyzed, but most analyses follow the FUND scenario, which is close to the IS92a scenario (LEGGETT *et al*., 1992). Carbon dioxide concentrations, global mean temperature and sea-level rise are calculated with the FUND2.8 model (LINK and TOL, 2004).

FUND considers the following impacts of sea-level rise: (1) land loss, (2) wetland loss, (3) protection costs, and (4) forced migration, all assuming perfect adaptation based on cost-benefit analysis (Figure A7-1). These impacts interact with one another. For example, if land is fully protected, no land will be lost, but the associated costs of protection will be maximised, and any adjacent wetlands will experience maximum losses. The total impact of sea-level rise depends on the adaptive policy chosen, and hence so does the estimated damage. For instance, Hoozemans *et al* (1993) uses the ad hoc rule that all land with a population density above 10 people/km2 will be protected, while Fankhauser (1994; 1995) and Yohe *et al* (1995; 1996) employ models which choose the economically optimal level of protection. The resulting difference in estimated impacts can be substantial.

The coastal length of all countries in the world was taken from the Global Vulnerability Assessment (GVA) (Hoozemans *et al*., 1993). Other sources, such as the World Coast 1993 Conference (Bijlsma *et al*., 1994), Nicholls and Leatherman (1995a; 1995b) and Fankhauser (1995), use (occasionally widely) different estimates of the length of the coast of particular countries. However, the length of a coast depends on the measurement procedure. The GVA is based on an internally consistent, globally comprehensive data-set, and is used here.

Wetland losses for a 1-m sea-level rise were taken from the GVA and, where available, replaced with results from country studies as reported by Bijlsma *et al* (1996) plus Nicholls and Leatherman (1995a; 1995b). The GVA reports wetland losses both with and without coastal protection; the country-specific ratio between the two was used to derive wetland losses with protection according to Bijlsma *et al* (1996). Without coastal protection, following the GVA, wetland loss is assumed to be

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12 These were based on a scenario of WAIS collapse over 100 to 1000 years, resulting in a 5-m rise in global-mean sea level. It is important to note that the authors noted that the more extreme changes considered may be impossible, but by looking at an extreme change, important insights about the adaptation process are apparent – insights that are also applicable to smaller rises in sea level but more difficult to observe (Tol *et al*., 2006). Hence, this research is relevant to long-term sea-level rise as considered in this paper.
linear in sea-level rise. While the resulting wetland model is simple and based on incomplete data, it is well understood and hence used in this exploratory analysis.

Land losses are not reported in the GVA, but they are provided by Bijlsma et al (1996) for 18 countries. The GVA reports people-at-risk, which is the number of people living in the one-in-1000-year flood plain, weighted by the probability of flooding. Combining this parameter with the GVA's coastal population densities, allows area-at-risk to be estimated. The exponential of the geometric mean of the ratio between area-at-risk and land loss derived from the data in Bijlsma et al (1996) was used as a correction factor to derive land loss for all other countries. In the GVA, without protection, land loss is assumed to be linear in sea-level rise. Here, we use a power function, \( D = \alpha S^\beta \); \( \alpha \) is such that the impacts are as in the GVA for \( S=1 \); \( \beta \) is estimated, for each country individually, from the data presented in Section 3. On average, \( \beta = 0.39 \), but it ranges from \( \beta = 0.00 \) in Monaco and Nauru, where there is little land between 1 and 5 metres, to \( \beta = 1.72 \) in the Lebanon, where there is little land below 1 metre.

The monetary value of the loss of one square kilometre of land was on average $4 million in OECD countries in 1990 (cf. FANKHAUSER, 1994). Land value is assumed to be proportional to GDP per square kilometre. Wetland losses were valued at $2 million per square kilometre on average in the OECD in 1990 (cf. FANKHAUSER, 1994). The wetland value is assumed to have logistic relation to per capita income.

Land loss is assumed to lead to forced migration, which is a major concern under large rises in sea level, as considered in this paper. Following Tol (1995), forced migration equals area lost times population density.

Coastal protection against sea-level rise is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze. The level of protection is derived by Fankhauser (1994):

\[
L = \min \left\{ 0, 1 - \frac{1}{2} \left( \frac{PC + WL}{DL} \right) \right\}
\]

(1)

\( L \) is the fraction of the coastline to be protected. \( PC \) is the net present value of the protection if the whole coast is protected. The GVA reports average costs per year over the 21st century. \( PC \) is calculated assuming annual costs to be constant. This is based on the following three assumptions:

the coastal protection decision makers anticipate a linear sea-level rise and linear land loss, even though these are not linear in actuality; if the anticipation were based on a non-linear model, Equation (1) could not be written explicitly as a function, but would become the solution to a numerical optimisation problem.

coastal protection comprises large infrastructural works which have a life of decades.

considered costs are direct investments only, and the relevant technologies are mature.

Throughout the analysis, a pure rate of time preference, \( \rho \), of 1% per year is used. The actual discount rate lies thus 1% above the growth rate of the economy, \( g \). The net present costs of protection \( PC \) thus equal
where \( PC_a \) is the average annual costs of protection. The average annual costs of protection are taken from the GVA, and assume linearity. Because protection costs are at the heart of Equation (1), to deal with non-linear defence costs, for analysis of extreme sea-level rise, Equation 1 was replaced with a bilinear equation:

If sea-level rise is less than 1 cm per year, protection costs are as the GVA; if not, they are \( x \) times as high.

In the analysis reported in the paper, values of \( x \) from 1 to 100 are considered as part of a sensitivity analysis.

\[ WL = \sum_{t=0}^{\infty} \left( \frac{1}{1 + \rho + g} \right)^t WL_0 = \frac{1 + \rho + g}{(\rho + g)^2} WL_0 \]  

\[ DL = \sum_{t=0}^{\infty} \left( \frac{1}{1 + \rho + g} \right)^t DL_0 = \frac{(1 + g)(1 + \rho + g)}{\rho^2} DL_0 \]  

where \( WL_0 \) denotes the value of wetland loss in the first year.

\( DL_0 \) denotes the value of land loss in the first year.

Following Nicholls et al (2005), the population and per capita income scenarios used in this paper are the FUND scenarios (LINK and TOL, 2004). These projections are for 16 world regions. Population change and per capita growth were assumed to be uniform for all countries within a region.

Using the population and economic scenarios, as well as the corresponding scenarios on technological progress, the full FUND model, version 2.8,\(^{13}\) was used to generate scenarios of climate change and sea-level rise. CO2 concentrations rise to 870 ppm by 2100, the global mean temperature is 3.5ºC above pre-industrial levels, and the global-mean sea level rises by 66 cm above 1990 levels.

\(^{13}\) That is, the version with 16 regions rather than 207 countries.
For extreme sea-level rise (which in Nicholls et al. (2005) equates with a WAIS collapse mechanism), we assume a wide range of scenarios ranging upwards from an additional contribution of 0.5 m/century up to the most extreme scenario of an additional sea-level rise of 5 metres between 2030 and 2130. For the slower sea-level rise scenarios, we do not vary the start date for the WAIS collapse, but move the end date of the 5-m rise (or collapse) to 2230, 2230, 2330, 2430, 2530 and 3030, respectively. For comparative purposes, the IS92a scenario is also shown. Figure 2 shows the assumed scenarios of global-mean sea-level rise, allowing for both the WAIS and other sea-level contributions.

In all cases, calculations deliberately proceed beyond the arbitrary time limit of 2100 to the year 2300, so that we can see a more complete response, at least for some of the more extreme scenarios.

DIVA

While results are not considered in this paper, the Dynamic Interactive Vulnerability Assessment (DIVA) tool (DINAS-COAST CONSORTIUM, 2004) is relevant as it could be similarly adapted for analysis over 500 year timescales, following the discussion of FUND. DIVA considers most of the impacts of sea-level rise, together with three selected adaptation approaches where a generalised broad-scale approach is feasible (Figure A7-3; Table A7-1). It is the most comprehensive tool available for looking at sea-level rise impacts, and combines a new global database on coastal zones with a suite of algorithms authored by a group of people within the DINAS-COAST research consortium. Unlike earlier models which only resolved broad regions or at best individual countries as the base polygons of analysis (e.g. Hoozemans et al., 1993; Tol, 2004), DIVA has divided the world’s coast into 12,148 segments of variable length, and developed a database containing about 100 parameters based on this functional typology (Vafeidis et al., 2004a; Vafeidis et al., 2004b; McFadden et al., 2005 accepted). A major benefit of DIVA is that consistent perspectives can be developed across the range of sea-level rise impacts, including a range of adaptation responses, from no adaptation to total adaptation. An intermediate ‘optimal’ adaptation option from an economic benefit-cost perspective is included.
REFERENCES


Table A7-1. The four major physical impacts of sea-level rise, plus the adaptation approaches that are considered in the DIVA tool.

<table>
<thead>
<tr>
<th>PHYSICAL IMPACTS OF SEA-LEVEL RISE</th>
<th>ADAPTATION APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Inundation, flood and storm damage</td>
<td>a. Surge (sea)</td>
</tr>
<tr>
<td></td>
<td>b. Backwater effect (river)</td>
</tr>
<tr>
<td></td>
<td>Dikes</td>
</tr>
<tr>
<td>2. Wetland loss (and change)</td>
<td>Nourishment</td>
</tr>
<tr>
<td>3. Erosion (direct and indirect morphological change)</td>
<td>Nourishment,</td>
</tr>
<tr>
<td>4. Saltwater Intrusion</td>
<td>a. Surface Waters</td>
</tr>
<tr>
<td></td>
<td>b. Groundwater</td>
</tr>
<tr>
<td></td>
<td>Adaptation not considered'</td>
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</tbody>
</table>
Figure A7-1. Summary of the sea-level rise impact assessment methodology within the FUND model

- Socio-Economic Scenarios
  - Sea-Level Rise
  - Threatened Coastal Resources
    - Cost-Benefit Analysis
      - IMPACTS AND RESPONSES
        - 'Optimum Protection', Dike Height, Dike Length, Protection Costs
        - Dryland Loss, Population Displacement, (including Protection)
        - Wetland Loss (including Protection)
Figure A7-2. The global-mean sea-level rise scenarios used in the analysis, including the baseline IS92a scenario without any significant contribution from Antarctica (from Nicholls et al, 2005).
Figure A7-3. Schematic view of the operation of the DIVA tool.