Sustain Sci (2008) 3:89–102
DOI 10.1007/s11625-008-0050-4

SPECIAL FEATURE: ORIGINAL ARTICLE

Sea-level rise

# Climate change and coastal vulnerability assessment: scenarios for integrated assessment

**Robert J. Nicholls · Poh Poh Wong · Virginia Burkett · Colin D. Woodroffe · John Hay**

Received: 1 January 2008 / Accepted: 7 February 2008 / Published online: 1 April 2008


**Abstract** Coastal vulnerability assessments still focus mainly on sea-level rise, with less attention paid to other dimensions of climate change. The influence of non-climatic environmental change or socio-economic change is even less considered, and is often completely ignored. Given that the profound coastal changes of the twentieth century are likely to continue through the twenty-first century, this is a major omission, which may overstate the importance of climate change, and may also miss significant interactions of climate change with other non-climate drivers. To better support climate and coastal management policy development, more integrated assessments of climatic change in coastal areas are required, including the significant non-climatic changes. This paper explores the development of relevant climate and non-climate drivers, with an emphasis on the non-climate drivers. While these issues are applicable within any scenario framework, our ideas are illustrated using the widely used SRES scenarios, with both impacts and adaptation being considered. Importantly, scenario development is a process, and the assumptions that are made about future conditions concerning the coast need to be explicit, transparent and open to scientific debate concerning their realism and likelihood. These issues are generic across other sectors.

**Keywords** Coasts · Impacts · Adaptation · Scenario · Storyline

R. J. Nicholls (✉)
School of Civil Engineering and the Environment and Tyndall Centre for Climate Change Research,
University of Southampton, SO17 1BJ Southampton, UK
e-mail: r.j.nicholls@soton.ac.uk

P. P. Wong
Department of Geography, National University of Singapore, Singapore, Singapore

V. Burkett
United States Geological Survey, Many, LA, USA

C. D. Woodroffe
University of Wollongong, Wollongong, NSW, Australia

J. Hay
Institute for Global Change Adaptation Science (ICAS), Ibaraki University, Mito, Japan

## Introduction

As the certainty that human-induced climate change is a reality has increased (Solomon et al. 2007), so the assessment of potential impacts to identify key vulnerabilities and adaptation and mitigation needs becomes more pressing (Parry et al. 2007). Such assessment needs to take place in the context of sustainable development and must address both climate and non-climate drivers as appropriate. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) assessment of 'Coastal Systems and Low-Lying Areas' (Nicholls et al. 2007a) noted that coastal vulnerability assessments still focus mainly on sea-level rise, with less attention to other dimensions of climate change. The influence of non-climatic environmental change or socio-economic change is even less considered and is often completely ignored. This paper considers the range of scenarios that are needed to support more integrated assessment of coastal areas, with an emphasis on relevant non-climate scenarios.

Coastal areas are densely populated and highly productive regions (Small and Nicholls 2003; McGranahan et al. 2007). Hence, the threat posed by sea-level rise and climate change has rightly raised concerns about impact potential and appropriate management responses for more than 20 years (e.g. Barth and Titus 1984; Broadus et al. 1986; Warrick et al. 1993). However, coastal areas across the globe have changed profoundly through the twentieth century due to a range of human-induced drivers, linked to a growing global population and economy, and its direct and indirect expression in the coastal zone (Buddemeier et al. 2002; Valiela 2006). Hence, the impacts of climate change and sea-level rise through the twentieth century are difficult to isolate. The impacts of rising temperatures are most unambiguous, both on high latitude coasts subject to increased erosion as sea ice and permafrost melts, and on low latitude coral reef coasts subject to increased bleaching and mortality (Nicholls et al. 2007a). Elsewhere, non-climate drivers appear to make more important contributions to coastal change (Crossland et al. 2005; Agardy et al. 2005), and the issue of multiple, interacting stresses is relevant for all coastal areas (Bijlsma et al. 1996).

Without policy measures, most non-climate coastal drivers will almost inevitably grow in magnitude with rising population and wealth throughout the twenty-first century. Hence, any realistic analysis of the implications of climate change needs to be set in the context of these other changes, such that the relative importance of the different drivers of change and their interactions can be understood, and appropriate management strategies formulated: in short, coastal assessments require an integrated assessment approach where all the relevant change factors are considered, including their interactions. However, integrated assessments that consider all the relevant drivers of change are underdeveloped relative to climate-focussed analysis of coastal areas in general, and assessments of sea-level rise in particular. This omission is in spite of long-standing recommendations to consider a range of change factors from e.g. IPCC CZMS (1992), Klein and Nicholls (1998, 1999) (see Table 1) and Turner (2000).

The goal of this paper is to promote more integrated assessment of coastal areas, including explicit descriptions of the underlying assumptions concerning future environmental and socio-economic states other than those factors driven by climate change. The paper explores how climate, environmental and socio-economic scenarios can be elaborated and applied more widely in coastal impact analysis in general, although details of the application will vary with the scale and scope of analysis. These issues are illustrated using the well-known Special Report on Emissions Scenarios (SRES) (Nakićenović and Swart 2000), which has been widely used to model future climate and assess potential impacts, including in the IPCC AR4.

We will first consider the nature of scenarios and the SRES framework in particular, before going on to consider climate and non-climate drivers relevant to coastal zones and their scenarios, including adaptation issues. The issues raised are discussed and the conclusions drawn will be presented.

## Scenarios, coastal scenarios and SRES storylines

Scenarios provide a not implausible description of possible future conditions and are generally developed to inform decision-making in conditions of uncertainty. Scenarios can be used to help people explore a range of plausible future states and their challenges (Shell International 2003). Scenarios are distinct from assessments, models, and other decision-support activities, although they can provide important inputs to these activities. Scenarios can also be distinguished less sharply from other types of future statements used to inform decisions, such as projections, predictions, and forecasts. Compared to these, scenarios tend to presume lower predictive confidence, because they are based on processes in which causal relationships or longer time horizons increase uncertainty (Parson et al. 2007).

The development of appropriate and self-consistent environmental and socio-economic scenarios for climate change assessment requires a coherent view of the future, including its socio-economic and technological characteristics, and

**Table 1** A typology for the different types of scenarios that can be used in coastal vulnerability assessment [from the UNEP Handbook methodology for coastal areas (Klein and Nicholls 1998, 1999)]

| | Environmental changes | Socio-economic developments |
|---|---|---|
| Climate-induced | Accelerated sea-level rise | Autonomous adaptation |
| | Changes in rainfall patterns | Planned adaptation |
| | Changes in sea-surface temperature | |
| | Changes in wind, wave patterns | |
| | El-Niño-related changes | |
| | Sediment-budget changes | |
| Not climate-induced | Vertical land movement | Population changes |
| | Sediment-budget changes | Land-use changes |
| | | Changes in gross domestic product |

**Table 2** A summary of the most important characteristics of each Special Report on Emissions Scenarios (SRES) Storyline (Nakićenović and Swart, 2000). The SRES scenario names are a national interpretation by the United Kingdom Climate Impacts Programme (2001) among others

| "A1 World" (world markets) | "B1 World" (global sustainability) |
|---|---|
| Increasing globalisation/ convergence | Increasing global co-operation/ convergence |
| Rapid global economic growth | Environmental priority |
| Materialist/consumerist | Clean and efficient technologies |
| Rapid uniform technological innovation | |
| **"A2 World" (national enterprise)** | **"B2 World" (local stewardship)** |
| Heterogeneous world | Heterogeneous world/local emphasis |
| Rapid regional economic growth | Environmental priority |
| Materialist/consumerist | Clean and efficient technologies |
| Diverse technological innovation | |

hence the likely greenhouse emissions that can then be used to drive climate models. These in turn produce scenarios of climate change whose potential impacts and adaptation needs can be analysed using the "world" that produced these changes, assuring more self-consistency in the results.

The IPCC has produced three sets of scenarios of human development patterns throughout the twenty-first century, which have been used primarily as a basis for estimating human contributions to future greenhouse-gas concentrations (Parson et al. 2007). The most ambitious and comprehensive efforts in this regard were the SRES scenarios (Nakićenović and Swart 2000). The four SRES storylines or global "futures" (A1, A2, B1, and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns (Table 2).[1] They represent internally consistent characterisations of how the world might evolve during the twenty-first century. Each storyline (or "Future") comprises a short narrative, which explores what might happen if political, economic, technical, and social developments took specific alternative directions at the global level, including considering potential regional differences and interactions. Hence, they develop distinct future world states based on plausible storylines, including quantitative estimates of the socio-economic drivers of greenhouse and aerosol emissions, including factors such as population, GDP, and technology. This in turn provides quantitative emission scenarios, and provides a consistent input to climate change models and impact assessments. Although the SRES emission scenarios were intended to inform climate change mitigation and adaptation decisions, most uses to date have had relatively indirect connections to such decisions (Parson et al. 2007), and they have attracted controversy (e.g. Castles and Henderson 2003; Grübler et al. 2004).

In terms of climate change, the SRES scenarios translate into six main greenhouse emission "marker" scenarios: one each for the A2, B1, and B2 worlds, and three scenarios for the A1 world A1T[(assuming non-fossil (low-carbon) fuel sources], A1B (assuming balanced fuel sources) and A1FI (assuming fossil-intensive fuel sources) (Nakićenović and Swart 2000). Each marker was run with several models, yielding 40 emission scenarios in total. B1 produces the lowest emissions and A1FI produces the highest emissions.

In terms of socio-economic scenarios, a big challenge in using the SRES in impact analysis is the large spatial scale of the analysis, which considers just a few large world regions. Hence, some form of downscaling is generally essential for impact and adaptation analysis (Arnell et al. 2004; Carter et al. 2007). One problem is that some socio-economic activities already lie outside the range of the SRES scenarios, e.g. the GDP and the growth rate of GDP in China, which exceed the largest A1 scenario. This illustrates how scenario development needs to be a dynamic process; however, this does not undermine the qualitative interpretation issues discussed later.

While the SRES storylines shown in Table 2 do not specifically address coastal issues, the associated narratives provide a basis to interpret the possible future state of the coastal zone, including a range of societal attitudes. It is useful to consider the range of possible input scenarios, and to interpret the results from impact models. SRES scenarios have been applied to global analysis of coastal areas in a few cases (e.g. Nicholls 2004; Nicholls and Tol 2006). The results showed that estimates of impact and vulnerability are sensitive to the socio-economic scenario, as well as to the magnitude of climate change, and that climate change is not always the most important change driver. National socio-economic scenarios have also been developed for policy analysis, which are often broadly consistent with the SRES scenarios, and hence can be linked to appropriate climate change scenarios (e.g. UK Climate Impacts Programme 2001). Some national socio-economic scenarios have then been applied to coastal areas, including the UK Foresight Flood and Coastal Defence analysis (Evans et al. 2004a, b; Thorne et al. 2007), and the US National Assessment (NAST 2000). At the sub-national scale, few examples are apparent. Exceptions include Hoegh-Guldberg and Hoegh-Guldberg (2004) who examined the impacts of climate change on tourism and the potential loss of that market for the Great Barrier Reef; the RegIS project, which considered two UK regions (Holman et al.

[1] Similar frameworks have been developed in other global assessments such as the Global Environmental Outlook (UNEP, 2007) and the Millennium Ecosystem Assessment (Carpenter et al. 2005).

2005a, b); and the analysis of a coastal sub-cell in the United Kingdom by Dawson et al. (2007).

In this paper, these examples and the approaches they used are developed and elaborated to a wider range of factors of relevance to coastal zones. There is an emphasis on the non-climate environmental and socio-economic scenarios, including societal attitudes and issues concerning adaptation. While the climate scenarios are usually direct model outputs for a given forcing, the environmental and socio-economic scenarios are less amenable to such analysis and engender much more debate. Hence, it is important to distinguish and make explicit two stages in the interpretation of the storyline:

(a) the qualitative (or conceptual) interpretation; and
(b) the quantitative realisation of (a).

Disagreement about the qualitative interpretation is much more fundamental than the quantitative realisation, and it is important to make these differences transparent, if they arise, such that a debate about these fundamental issues can follow. Even if a model-based approach is used to quantify some of the factors of interest, the underlying qualitative framework remains fundamental, as this might indicate that some models or approaches are not appropriate. In what follows, the main focus is the qualitative interpretation of the SRES storylines, as an illustration of how a set of consistent scenarios for coastal areas might be developed. While the scenarios that are developed extend well beyond the direct SRES storylines, we use the associated narratives to develop useful and consistent guidance on a range of likely changes.

## Climate and sea-level scenarios

Table 3 summarises the range of potential drivers of climate change impacts in coastal areas, including the new IPCC AR4 results from Solomon et al. (2007). In nearly all cases there will be significant regional variations in the changes, and any impacts will be the result of the interaction between these climate drivers and other drivers of change, leading to diverse effects and vulnerabilities.

Projected global-mean changes for selected parameters relevant to coasts are summarised in Table 4. A significant

**Table 3** Main climate drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects. Adapted from Nicholls et al. (2007a)

| Climate driver (trend)[a] | Main physical and ecosystem effects on coastal systems |
|---|---|
| $CO_2$ concentration (↑) | Increased $CO_2$ fertilisation; decreased seawater pH (or "ocean acidification") negatively impacting coral reefs and other pH sensitive organisms |
| Sea surface temperature (SST) (↑, R) | Increased stratification/changed circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality; poleward species migration; increased algal blooms |
| Sea level (↑, R) | Inundation, flood and storm damage; erosion; saltwater intrusion; rising water tables/impeded drainage; Wetland loss (and change) |
| Storm | |
| Intensity (↑, R) | Increased extreme water levels and wave heights; increased episodic erosion, storm damage, risk of flooding and defence failure |
| Frequency (?, R) | Altered surges and storm waves and hence risk of storm damage and flooding |
| Track (?, R) | |
| Wave climate (?, R) | Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach platform |
| Run-off (R) | Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply |

[a] ↑ increase, *?* uncertain, *R* regional variability

**Table 4** Projected global-mean climate parameters relevant to coastal areas at the end of the twenty-first century for the six SRES marker scenarios (as reported by Meehl et al. 2007)

| Climate driver | | | B1 | B2 | A1B | A1T | A2 | A1FI |
|---|---|---|---|---|---|---|---|---|
| Surface ocean pH (pre-industrial reference: 8.2) (baseline today: 8.1) | | | 8.0 | 7.9 | 7.9 | 7.9 | 7.8 | 7.7 |
| Sea surface temperature (SST) rise (°C) (relative to 1980–1999) | | | 1.5 | – | 2.2 | – | 2.6 | – |
| Sea-level rise (relative to 1980–1999)[a] | Best estimate (m) | | 0.28 | 0.32 | 0.35 | 0.33 | 0.37 | 0.43 |
| | Range (m) | 5% | 0.18 | 0.20 | 0.21 | 0.20 | 0.23 | 0.26 |
| | | 95% | 0.38 | 0.43 | 0.48 | 0.45 | 0.51 | 0.59 |

[a] Note that sea-level rise may exceed the upper bound (see text)

increase in atmospheric $CO_2$ concentration appears virtually certain. As atmospheric $CO_2$ levels increase, more $CO_2$ is absorbed by surface waters, thus decreasing seawater pH and carbonate saturation (Andersson et al. 2003; Royal Society 2005; Turley et al. 2006). While impacts of ocean acidification have not been observed to date, this change is of fundamental concern for calcareous-based organisms such as corals. Sea surface temperatures (SST) are also virtually certain to rise significantly (Table 4), although by less than the global-mean temperature rise. SST rise will not be spatially uniform, with possible intensification of ENSO and time variability, which suggests greater change in extremes, which again has important implications for coral reefs (Nicholls et al. 2007a). Hence, ocean acidification and rising SST illustrate multiple climate stresses for corals, but in ways that are still not fully understood.

The global-mean sea-level rise scenarios shown in Table 4 are based on thermal expansion and ice melt: the best estimate shows an acceleration of up to 2.4 times compared to the twentieth century. Superficially, these projections are smaller than those of Church et al. (2001), but this largely reflects differences in methodology (Church et al. 2007), and the IPCC (2007) synthesis report emphasises that the upper 95% range in Table 4 does *not* represent the upper boundary of global-mean sea-level rise during the twenty-first century, with the contributions from the major ice sheets (Antarctica and Greenland) being a major uncertainty [Church et al. 2008 (this volume)]. Several recent papers support the view that a rise in sea level of 1+ metres over the next century cannot be entirely discounted at present (Rahmstorf 2007; Rahmstorf et al. 2007; Rohling et al. 2007).

Importantly, local (or relative) changes in sea level depart from the global-mean trend due to regional variations in oceanic level change and geological uplift/subsidence: it is relative sea-level change that drives impacts and is of concern to coastal managers (Bird 1993; Harvey 2006). Meehl et al. (2007) found that regional sea-level change will depart significantly from the global-mean trends listed in Table 4: for the A1B scenario the spatial standard deviation by the 2080s is 0.08 m, with a larger than average rise in the Arctic. Hulme et al. (2002) suggested that impact analysis explore additional sea-level rise scenarios of ±50% the amount of global-mean rise, plus uplift/subsidence, to assess the full range of possible change. Furthermore, coasts subsiding due to natural or human-induced causes will experience larger relative rises in sea level, which must also be considered [Bird 1993; Nicholls 1995; Syvitski2008 (this volume)], as discussed further below in the section on "Environment and socio-economic scenarios" and Table 5.

Increases of extreme sea levels due to rising sea levels and changes in storm characteristics are of significant concern [Zhang et al. 2000; Nicholls et al. 2007a; von Storch and Woth 2008 (this volume)]. Meehl et al. (2007) found that models suggest that both tropical and extra-tropical storm intensity will increase—this implies more coastal impacts than attributable to sea-level rise alone, especially for tropical and mid-latitude coastal systems. Increases in tropical cyclone intensity over the past three decades are consistent with the observed changes in SST (Emanuel 2005; Webster et al. 2005). Changes in other storm characteristics are less certain and the number of tropical and extra-tropical storms might even reduce (Meehl et al. 2007). Similarly, wave climate is uncertain, although extreme wave heights will likely increase with more intense storms (Meehl et al. 2007). Changes in run-off driven by changes to the hydrological cycle appear likely, but the uncertainties are large. Milly et al. (2005) showed increased discharges to coastal waters in the Arctic, in northern Argentina and southern Brazil, parts of the Indian sub-continent, China and Australia, while reduced discharges to coastal waters are suggested in southern Argentina and Chile, Western and Southern Africa, and in the Mediterranean Basin. The additional effects of catchment management and water use also need to be considered as this may be a larger effect than climate change (Table 5).

## Environment and socio-economic scenarios

Table 5 summarises some of the more important non-climate coastal trends observed during the twentieth century and their likely trend consistent with the SRES storylines through the twenty-first century. Of the two axes in the SRES storylines: (1) the global versus regional axis; and (2) the economic versus environmental axis (Table 2), the latter seems more important in driving the differences in the coastal scenarios that emerge in this analysis. Sometimes, as show in Table 5, it is difficult to distinguish the A1/A2 worlds and the B1/B2 worlds. Of course, there are exceptions such as coastward migration. These points are elaborated further below.

Global and coastal populations increased significantly during the twentieth century. In all the SRES worlds, global population increases to 2050, but in the A1/B1 worlds the population subsequently declines, while in A2/B2 worlds it continues to grow throughout the twenty-first century, with the strongest growth in the A2 world. However, coastal population[2] depends also on coastward

[2] Note that coastal population is often overstated compared to quantitative GIS-based analysis, which suggests that about 1.9 billion people (or 37% of the global population) lived within 100 km of a coastline in 1990 (see Cohen et al. 1997; Gommes et al. 1998; Small and Nicholls 2003).

**Table 5** Selected global non-climatic environmental and socio-economic trends relevant to coastal areas for the twentieth and twenty-first centuries

| Environmental and socio-economic factors | | Twentieth century trend[a] | Twenty-first century trends (by SRES Future) | | | | Relevant studies (not necessarily SRES-based) |
|---|---|---|---|---|---|---|---|
| | | | "A1 World"[e] | "A2 World" | "B1 World" | "B2 World" | |
| Global | Population in 2100 (billions) | ↑ | ~7[b] | ~15 | ~7[b] | ~10 | Nakićenović and Swart (2000) |
| | GDP in 2100 (trillions US 1990 dollars) | ↑ | 525–550 | 243 | 328 | 235 | |
| | Average GDP/capita in 2100 (thousands US 1990 dollars) | ↑ | 75–79 | 16 | 47 | 24 | |
| Coastal areas | Coastward population migration (See Table 6) | ↑ | Most likely | Less likely | More likely | Least likely | Nicholls (2004); Nicholls and Lowe (2004); UNEP (2005) |
| | Infrastructure | ↑ | Largest increase | Large increase | Smaller increase | Smallest increase | Fankhauser (1995); Tol (2007); Nicholls et al. (2007b)—implicit treatment |
| | Human-induced subsidence[c] | ↑ (L) | More likely | | Less likely | | Nicholls (2004); Nicholls et al. (2007b) |
| | Terrestrial freshwater/sediment supply[d] | ↓ | Greatest reduction | Large reduction | Smallest reduction | Smaller reduction | Ericson et al. (2006)—little future analysis |
| | Aquaculture | ↑ | Large increase | | Smaller increase | | Cork et al. (2005) |
| | Extractive industries | ↑ | Larger increase | | Smaller increase | | – |
| | Tourism | ↑ | Highest growth | High growth | High growth | Lowest growth | Hamilton et al. (2005); Bigano et al. (2005) |
| | Marine renewable energy[e] | | Variable growth | Lowest growth | Highest growth | High growth | – |
| | Habitat destruction (direct and indirect) | ↑ | Continued loss | | Reduced loss, stability or even recreation | | Kennish (2002)[f]; Nicholls (2004); Hoegh-Guldberg and Hoegh-Guldberg (2004); Cork et al. (2005) |

Substantial regional and local deviations are expected and climate change will be an additional driver of change (see Table 3) (developed from Nicholls et al. 2007a)

[a] ↑ increase, ↓ decrease, *L* locally important

[b] In 2050, global population peaks at 8.7 billion

[c] Subsidence due to sub-surface fluid withdrawal and drainage of organic soils in susceptible coastal lowlands

[d] Changes due to catchment management (as opposed to climate change per se)

[e] Depends on which A1 variant is considered—lowest under A1FI and highest under A1T

[f] The coastal population scenario is much higher than realistic (see Table 6)

migration, which has been an important global trend throughout the twentieth century (Dang 2003; Wong et al. 2006; McGranahan et al. 2007). While global population could fall after 2050 as envisaged in the A1 and B1 worlds, net coastward migration within and between countries might offset this effect for coastal areas. Hence, a net increase in the population exposed to sea-level rise and climate change is likely across all the SRES scenarios. An interpretation of global coastal population is given in Table 6, which suggests that the main "outlier" for coastal population is the A2 world.

Global GDP grows by 12 to 22 times above 1990 levels by 2100 under the SRES storylines. The difference in GDP between world regions also reduces in all cases (i.e. there is economic convergence), but again at differing rates. As population growth is smaller than GDP growth, these scenarios assume that GDP/capita also grows substantially in all nations: most in the A1 world and least in the A2 world. An alternative scenario for GDP/capita based on observed trends would differ from all the SRES scenarios and would give quite different impact estimates for climate change (Nicholls 2004).

The amount of coastal infrastructure increased dramatically during the twentieth century and settlements at all scales are concentrated along the shoreline (Small and Nicholls 2003). UNEP (2007) recognised the urbanising coastal fringe as a major environmental issue. Given rising population and GDP/capita, the amount of coastal infrastructure will also increase significantly under all the SRES futures, which, together with population growth, will greatly increase the asset exposure in coastal areas to sea-level rise and climate change and displace other land uses from coastal areas: the growth is likely to be largest in the A1 world and smallest in the B2 world. However, global datasets on coastal infrastructure remain undeveloped.

Human-induced subsidence has been a major issue during the twentieth century in many coastal cities, especially in deltaic areas [Bird 1993; Ericson et al. 2006; Syvitski 2008 (this volume)], including New Orleans, which was devastated by Hurricane Katrina in 2005 (Burkett et al. 2002; Dokka 2006; Dixon et al. 2006). Vertical subsidence of up to 9 m was observed in coastal areas during the twentieth century (Nicholls 1995). While subsidence is often quite localised, the magnitude is often most pronounced where the population density is highest, so the human consequences are significant, both at the city and wider scale (Nicholls et al. 2007b). Despite this experience, new problems of human-induced subsidence appear to be emerging in Asian cities built on susceptible locations, e.g. Jakarta, Manila, and Hanoi, and some authors have even commented on a tendency for denial of these problems as opposed to the smaller global sea-level rise (Rodolfo and Siringan 2006). The more environmental (B1/B2) worlds may manage these issues, while the more market-orientated (A1/A2) worlds are more likely to continue to experience significant subsidence problems. Similarly, there has been a major decline in freshwater and sediment inputs from rivers to the coast due to increased regulation of the catchments [Syvitski et al. 2005; Syvitski 2008 (this volume)], and some major rivers such as the Nile have effectively no flow to the coast today. Nonetheless, there is much potential for further decline due to both planned dams and potential dams at the regional and global scale. Given the growing water demand pressures implied in all the SRES worlds (e.g. Arnell 2004), some further decline is envisaged in all cases. Again, the more environmental (B1/B2) worlds might manage sediment and fresh water delivery to the coast to some degree, while the more market-orientated (A1/A2) worlds are likely to undergo greater reductions in natural river flows to the coast.

Aquaculture has grown dramatically over the last 30 years in a variety of contexts, from salmon farming in Scottish and Norwegian fjords to conversion of mangroves to shrimp ponds across tropical and sub-tropical areas (Agardy et al. 2005). Growing populations combined with limited, and often declining, wild fisheries suggests

**Table 6** Possible interpretations of the near-coastal population[a] by the 2080s under the SRES scenarios. Currently, the migration factor[b] is about 2, but the variable migration factor across SRES Futures is more consistent with the storylines

| SRES future | Uniform migration factor across SRES futures | | | | Variable migration factor across SRES futures | |
|---|---|---|---|---|---|---|
| | Migration factor | Population (billions) | Migration Factor | Population (billions) | Migration factor (see Table 5) | Population (billions) |
| A1 | 1 | 1.8 | 2 | 2.4 | 2 | 2.4 |
| A2 | 1 | 3.2 | 2 | 5.2 | 1.5 | 4.2 |
| B1 | 1 | 1.8 | 2 | 2.4 | 2 | 2.4 |
| B2 | 1 | 2.3 | 2 | 3.4 | 1 | 2.3 |

[a] Population living both <100 m elevation above sea level and <100 km distance of the coast—uncertainty depends on assumptions about coastward migration (Nicholls and Lowe 2004). In 1990, it was 1.2 billion people

[b] Migration factor is the growth in near-coastal population relative to global population growth

ongoing growth through the twenty-first century. One would expect the largest increase under the A1/A2 worlds and a smaller increase in the B1/B2 worlds due to greater environmental regulation. Extractive industries such as oil and gas, salt and aggregates have also grown throughout the twentieth century. While the mix is expected to change because some materials may decline (e.g. hydrocarbons), the trend of growing population and wealth suggests continued growth with more controls and hence a smaller increase in the B1/B2 worlds. In part, soft engineering responses to climate change (e.g. Hamm and Stive 2002; Hanson 2003) may drive these increases as there is likely to be a growing demand for sand to nourish and sustain beaches against sea-level rise, especially in tourist areas (see below). For example, the Dutch national policy is to maintain their 1990 shoreline with beach nourishment (Koster and Hillen 1995). A move towards cell-based management of coasts, and a regime that treats all coastal sediments as a valuable resource (Leafe et al. 1998; Neumann et al. 2001; Nicholls et al. 2007c), may reduce some of these pressures. Tourism is an industry that has also grown dramatically in the last 50 years, and it is an industry that has a dominant presence on the coast (Hamilton et al. 2005; Becken and Hay 2007): continued growth seems inevitable—it is only the scale of this growth that is uncertain. The A1 world would seem likely to experience the greatest growth in both national and, especially, international tourism. Hamilton et al. (2005) found that tourism demand is proportional to population, and grows by 1.8% for every 1% increase in per capita income, so tourism scenarios can be directly calculated.

Marine renewable energy is an embryonic sector that is likely to grow tremendously throughout the twenty-first century (e.g. CarbonTrust 2004), most especially in the B1 world, and possibly under the low carbon A1T world. As this growth will be in part due to a desire for non-carbon energy, it illustrates how climate mitigation may have indirect effects in other sectors. While it has not been systematically assessed, exploiting marine renewable energy may have important coastal implications, as illustrated by renewed interest in a barrage across the Severn estuary that could generate roughly 5% of current UK energy demand (Sustainable Development Commission 2007), but could have significant effects on the estuary environment.

Finally, Table 5 considers direct and indirect habitat destruction in coastal areas, which has been significant globally during the twentieth century, with some exceptions in the more wealthy countries during the later part of the twentieth century (Agardy et al. 2005). This can be linked to many drivers, including the various land use pressures already discussed, and other changes such as falling sediment supplies. The loss of an estimated 1% or more of intertidal wetlands per year in the late twentieth century (Hoozemans et al. 1993; Wilkie and Fortuna, 2003) is one indicator, while a widespread decline in coral reefs is another (Gardner et al. 2003; Wilkinson 2004) Climate change has been a minor factor, although in the case of coral reefs, rising SST has been a contributory factor to increase bleaching in the last two decades (Nicholls et al. 2007a). Wilkie and Fortuna (2003) note that while mangrove deforestation continues, it has slowed from 1.9% per annum in the 1980s to 1.1% per annum in the 1990s. This probably reflects the fact that most countries have now banned the conversion of mangroves for aquaculture purposes and require environmental impact assessments prior to large-scale conversion of mangroves for other uses and/or the loss of the more easily converted sites.

Looking to the twenty-first century, the growth in population and economic activity in the coastal zone under all the scenarios remains a powerful driver of further destruction and degradation. However, the environmental attitudes of the B1/B2 storylines may see a significant change in the attitudes to habitat conservation (see the following section on Adaptation issues) and continued decline in destruction rates, and even active recreation to replace historic losses (cf. Rupp-Armstrong and Nicholls 2007). In contrast, the A1/A2 worlds are business-as-usual, and late-twentieth-century attitudes and losses will continue. In a global analysis, Nicholls (2004) concluded that direct destruction could be much more significant than sea-level rise, and the prognosis for coastal wetlands (mangroves, saltmarshes, and tidal flats) was poor in the A1/A2 worlds. Hoegh-Guldberg and Hoegh-Guldberg (2004) came to a similar conclusion for the Great Barrier Reef in Australia, with the implication that it is a generic conclusion across most coastal habitat types.

## Adaptation issues

Impacts in coastal areas will depend on the amount and success of adaptation to climate and other changes. This is a complex issue that remains quite poorly understood compared to the potential for impacts assuming constant management (Nicholls et al. 2007a), and this is a key area that requires much more research if we are to truly understand coastal vulnerability. Nonetheless, societal attitudes to adaptation issues can also be interpreted from the narratives of the SRES storylines, as shown in Table 7. The early part of the twentieth century was characterised by a low priority for coastal and hazard management, and a reactive approach. Although these issues have grown in importance with time, a reactive approach is still the global norm. The narrative concerning the A1/A2 worlds and the B1/B2 worlds suggests an important difference in their

**Table 7** Interpretation of attitudes to coastal adaptation and coastal management under the SRES narrative storylines (adapted from Nicholls 2004)

| Adaptation factors | Twentieth century trends | Twenty-first century trends (by SRES future) | | | |
|---|---|---|---|---|---|
| | | "A1 World" | "A2 World" | "B1 World" | "B2 World" |
| Adaptation timing | Reactive | More reactive | | More proactive | |
| Hazard risk management | Growing priority | Lower priority | | Higher priority | |
| Coastal management | Growing priority | Lower priority | | Higher priority | |

attitudes to coastal management, hazard preparedness, and the extent to which they will proactively respond to the threat of sea-level rise and climate change.

Cost-benefit analyses of the impact of sea-level rise, including a protection versus retreat (i.e. abandon the land) response (e.g. Fankhauser 1995; Tol 2007), assume a proactive approach to protection combined with perfect knowledge (Nicholls and Tol 2006). However, cost-benefit analyses are limited in their scope and take no account of the impact of coastal management on wider costs and benefits. Clearly, uncertainty is pervasive in all the issues discussed in this paper, and a risk-based approach to the analysis should be favoured (Carter et al. 2007; Yohe et al. 2007). Based on Table 7, a proactive approach is more likely in the B1/B2 worlds than in the A1/A2 worlds. This is due to the interpretation of societal attitudes, although the A1 world may have the wealth to adapt more reactively. Hence, the SRES perspective certainly helps to provide a broad interpretation of the significance of certain types of impacts. It might even suggest that multiple models of adaptation should be used, selected depending on the SRES scenario: more reactive models under the A1/A2 worlds and more proactive models under the B1/B2 worlds.

Table 8 shows an interpretation of broad adaptation preferences for some key sectors that will be impacted in the coastal zone. Again, there is a strong distinction between the A1/A2 worlds and the B1/B2 worlds. However, in some cases while the means might differ, the end results may be less different. For instance, there may be deliberate planned retreat to create intertidal coastal habitats in the B1/B2 worlds, and inadvertent unplanned retreat which creates intertidal coastal habitats in the A1/A2 worlds (cf. Watkinson et al. 2007). The extent of unplanned retreat in the A1/A2 worlds will also depend on urbanisation trends, as this is another land use that may displace coastal agriculture and increase the pressure to protect.

Potential contradictions within the SRES worlds are also apparent in Table 8. The B2 world implies a strong focus on local sustainable agriculture, and coastal habitat recreation. At the local scale, these goals can often be in conflict, most particularly in extensive coastal lowlands where historically there has been extensive land claim, as found in much of Europe and East Asia.

## Discussion

This paper has explored scenario development for coastal areas in the context of climate change and integrated assessment. A "scenario" has been defined as "a description of potential future conditions, developed to inform decision-making under uncertainty" (Parson et al. 2007, p 7). There are numerous historical examples of scenarios helping decision-makers explore the range of potential futures, confront critical uncertainties, and understand how today's decisions affect future outcomes (Carpenter et al. 2006; Parson et al. 2007). The practical use of socio-economic scenarios relating to climate change, however, has generally been limited to assessing the potential impacts of future human development activities on greenhouse gas concentrations, and the influence of those changes on the physical climate system. The use of socio-economic scenarios should be extended to climate change impact and adaptation analysis in the coastal zone for the same reasons that scenarios, rather than a single prediction of the future, are used in assessing future emissions and their influence on the climate.

Scenarios can be constructed for several particularly important forms of impact in the coastal zone, such as those impacts associated with an increase in the rate of sea-level rise, altered terrestrial fluxes of freshwater and sediment to the coast, and an increase in the intensity of tropical storms. Rather than select a mid-range sea-level rise scenario from the most recent IPCC report, decision makers in the coastal zone should be provided with a range of plausible sea levels based upon the best available scientific information. These scenarios should reflect local conditions and processes, such as natural and human-induced subsidence. When coupled with socio-economic scenarios, impact scenarios could provide policy makers with a more complete description of the range of possible future coastal conditions. A combination of internally consistent, plausible socio-economic and climate change impact scenarios in coastal regions is needed to help coastal decision-makers understand the wide range of potential futures, confront critical uncertainties, and understand how today's decisions may play out in the future. Since the usefulness of such scenarios will depend

**Table 8** Interpretation of adaptation preferences by coastal sector under the SRES futures

| Coastal sectors | Twenty-first century trends (by SRES future) | | | |
|---|---|---|---|---|
| | "A1 World" | "A2 World" | "B1 World" | "B2 World" |
| Water supply | Emphasis on increased supply via water transfers and significant use of desalination (with little consideration of energy sources). Demand control were there is no alternative. Less desalination in the A2 World. | | Emphasis on demand control, but increased supply also required, including growth in desalination, exploiting non-carbon energy sources and reducing costs. Less desalination in the B2 World | |
| Agriculture | Strong focus on market-led agriculture, and coastal agricultural areas may be abandoned where uneconomic (unplanned retreat), or protected for production using polders (and widespread displacement by coastal urbanization—see below) | | Strong focus on sustainable agriculture | |
| | Technologies such as genetic modification for salt tolerance might also be explored. | Less unplanned retreat than an A1 World. New technologies and breeds less available. | Globalised perspective allows selective abandonment of coastal agriculture for habitat recreation and coastal buffering purposes combined with planned coastal urbanisation. Protection using hard engineering is minimised. | Strong focus on maintaining local agriculture, which conflicts with aspirations for coastal habitat recreation (see below). Protection accomplished via a mixture of hard and soft engineering |
| Settlements and Industry | Strong largely uncontrolled urbanising trend greatly increases exposure and necessitates an often reactive hard protection response (so there are also increasing numbers of coastal disasters). Soft engineering approaches used to sustain eroding tourist areas. | | Widespread use of land use planning to accomplish retreat and accommodation for new and where possible existing settlements. Emphasis on soft engineering and natural buffers. | |
| | Favours unplanned urbanisation at all scales, including a number of large global cities requiring protection. | Global cities less favoured (with population fall?), leading to many more regional urban centres and their protection needs. | Favours planned urbanisation at all scales, including a number of large global cities. Favours soft measures, but hard protection used where necessary. | The least urbanised scenario, with numerous smaller settlements, so large-scale protection is least favoured (although agricultural areas may require protection). |
| Ecosystems and habitat conservation | Lower priority than the B1/B2 Worlds, but there may be inadvertent benefits due to unplanned retreat of uneconomic agricultural land in coastal areas (see above) | | Higher priority, with no-net loss and some coastal habitat recreation. | |
| | Habitat conservation may be promoted for global iconic species with economic value | Habitat conservation may be promoted for iconic species with economic or national value (e.g., national symbols) | Largest habitat recreation | Lesser potential than the B1 World for proactive habitat recreation due to desire to preserve local biodiversity, and conflict with other coastal land uses (e.g., agriculture) |

on how well they meet users' information needs, it is important that users be involved early in their development. An integrated coastal assessment is a multidisciplinary problem crossing many areas of human knowledge, and future assessments need to integrate engineering, natural and social sciences. When we consider the goal of sustainable development and linking climate change to integrated coastal management, the approaches illustrated here are essential.

One major constraint is present knowledge for adaptation measures into the future (Nicholls et al. 2007a). Many diverse adaptation options are available, but it is unclear how they will be utilised and in what combination. Empirical approaches that collect more data on how and why people adapt would be useful, and could support the approach advocated by Yohe and Tol (2002). Strategic approaches that assess the benefits of different portfolios of adaptation options would appear to offer much promise (Evans et al. 2004b). Certain environments, such as deltas, would appear to present particular adaptation challenges (e.g. Reker et al. 2006; Woodroffe et al. 2006), and the non-climate scenarios will again be important constraints on adaptation. Disasters may also produce step changes in how adaptation proceeds, as appears to be happening in New Orleans and the Mississippi delta post-Katrina (Constanza et al. 2006; EFGC 2006; National Research Council 2006).

These scenario approaches require data, which is often a major constraint on their application. A recent new coastal database was developed as part of the DINAS-COAST project, which represented the world's coast as approximately 12,000 variable-length linear sections associated with approximately 100 natural, ecological, and social parameters, including population and GDP scenarios based on simple scaling (Vafeidis et al. 2004, 2008; DINAS-COAST Consortium 2006). These efforts could be developed further drawing on the ideas presented in this paper.

The issues that are raised here are generic, and hopefully will inform new frameworks as they emerge, including ongoing post-IPCC AR4 discussions on new scenarios that will improve on SRES. There seems to be a move towards running fewer emission scenarios in the GCMs, which would raise the question of how to link them to socio-economic scenarios. Whatever path is taken, all existing frameworks are sparse in their description of the key issues that are most pertinent to the impacts and the adaptation in the coastal zone. Hence, there is a need for analysis to elaborate the storylines and to make explicit the assumptions made about the future. As the impacts are highly dependent on socio-economic scenarios and the treatment of adaptation, these critical issues must be made transparent so that the results of different studies can be debated and compared openly.

## Conclusions

This paper outlines the importance of placing climate change and sea-level rise in a broader context of coastal change and all its drivers in order to improve analysis of impacts, key vulnerabilities and adaptation needs. While sea-level rise is a profound change, it is important to set the resulting changes into the context of other climate change, as well as non-climate drivers. A wider range of relevant climate scenarios is emerging as shown in the IPCC AR4 (Solomon et al. 2007), but useful scenarios of non-climate environmental and socio-economic changes relevant to coastal areas are much less developed. This paper shows how they might be developed using one conceptual framework (the SRES storylines) for a range of applications for global- to local-scale analysis. The approach is illustrative and could be applied to other existing scenario frameworks, or integrated with new scenario frameworks as they emerge. Importantly, this approach encourages making the assumptions about the future more explicit, which will raise further debate on the realism of any assessment and its policy value. The development of scenarios is a process that needs to engage widely with relevant stakeholders so that the scenarios are both credible and cover the range of uncertainty. More systematic efforts towards coastal scenario development would be useful, and these issues and approaches may inform assessments in other sectors.

**Acknowledgments** This work was stimulated by the authors' involvement in the IPCC Fourth Assessment Working Group II Report: chapter on 'Coastal Systems and Low-Lying Areas'.

## References

Agardy T, Alder J, Dayton P, Curran S, Kitchingman A, Wilson M, Catenazzi A, Restrepo J, Birkeland C, Blaber S, Saifullah S, Branch G, Boersma D, Nixon S, Dugan P, Davidson N, Vörösmarty C (2005) Coastal systems. Millenium ecosystem assessment: ecosystems human well-being, vol 1; current state and trends. Island Press, Washington, pp 513–549

Andersson AJ, Mackenzie FT, Ver LM (2003) Solution of shallow-water carbonates: an insignificant buffer against rising atmospheric $CO_2$. Geology 31:513–516

Arnell NW (2004) Climate change and global water resources: SRES scenarios and socio-economic scenarios. Glob Environ Change 14:31–52

Arnell NW, Livermore MJL, Kovats S, Levy PE, Nicholls R, Parry ML, Gaffin SR (2004) Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. Glob Environ Change 14:3–20

Barth MC, Titus JG (eds) (1984) Greenhouse effect and sea level rise: a challenge for this generation. Van Nostrand Reinhold

Becken S, Hay JE (2007) Tourism and climate change: risks and opportunities. Channel View Publications, UK

Bigano A, Hamilton JM, Tol RSJ (2005) The impact of climate change on domestic and international tourism: a simulation study. Working paper FNU-58

Bijlsma L, Ehler CN, Klein RJT, Kulshrestha SM, McLean RF, Mimura N, Nicholls RJ, Nurse LA, Perez Nieto H, Turner RK, Warrick RA (1996) Coastal zones and small islands. In: Watson RT, Zinyowera MC, Moss RH, (eds) Impacts, adaptations and mitigation of climate change: scientific-technical analysis. (The Second Assessment Report of the Intergovernmental Panel on Climate Change, Working Group II), Cambridge University Press, pp 289–324

Bird ECF (1993) Submerging coasts. Wiley, Chichester

Broadus JM, Milliman JD, Edwards SF, Aubrey DC, Gable F (1986) Rising sea level and damming of rivers: possible effects in Egypt and Bangladesh. In: Titus JG (ed) Effects of changes in stratospheric ozone and global change, vol 4, US Environmental Protection Agency, Washington, pp 165–189

Buddemeier RW, Smith SV, Swaaney DP, Crossland CJ (2002) The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles. LOICZ reports and studies series No. 24

Burkett VB, Zilkowski DB, Hart DA (2002) Sea level rise and subsidence: implications for flooding in New Orleans, Louisiana. In: Prince KR, Galloway DL (eds) Subsidence interest group conference, proceedings of the technical meeting, Galveston, 27–29 November 2001. USGS water resources division open-file report series 03-308, US Geological Survey, Austin

Carbon trust (2004) UK, Europe and global tidal stream energy resource assessment. The Carbon Trust, London, p 47

Carpenter SR, Pingali PL, Bennett EM, and Zurek MB (eds.) (2005) Ecosystems and human well-being: scenarios, Findings of the scenarios working group of the millennium ecosystem assessment, vol 2. Island Press, Washington

Carpenter SR, Bennett EM, Peterson GD (2006) Scenarios for ecosystem services: an overview. Ecol Society 11(1):29. http://www.ecologyandsociety.org/vol11/iss1/art29/

Carter TR, Jones RN, Lu X, Bhadwal S, Conde C, Mearns LO, O'Neill BC, Rounsevell MDA Zurek MB (2007) New assessment methods and the characterisation of future conditions. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp 133–171

Castles I, Henderson D (2003) Economics, emissions scenarios and the work of the IPCC. Energy Environ 14:415–435

Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D, Woodworth PL (2001) Changes in sea level. In: Houghton JT, Ding Y, Griggs D J, Noguer M, van der Linden PJ, Xiaosu D (eds) Climate change 2001. The scientific basis. Cambridge University Press, pp 639–693

Church JA, Nicholls RJ, Hay JE, Gornitz V (2007) Section 6C. Ice and sea-level change. In global outlook for ice and snow, UNEP, Nairobi, pp 153–180

Church JA, White NJ, Aarup T, Wilson WS, Woodworth PL, Domingues CM, Hunter JR, Lambeck K (2008) Understanding global sea levels: past, present and future. Sustain Sci 3:9–22

Cohen JE, Small C, Mellinger A, Gallup J, Sachs J (1997) Estimates of coastal populations. Science 278:1211–1212

Constanza R, Mitsch WJ, Day JW Jr (2006) A new vision for New Orleans and the Mississippi delta: applying economics and ecological engineering. Front Ecol Environ 4:465–472

Cork S, Peterson G, Petschel-Held G, Alcamo J, Alder J, Bennett E, Carr ER, Deane D, Nelson GC, Ribeiro T (2005) Four scenarios. In: Carpenter SR, Pingali PL, Bennett EM, Zurek MB (eds) Ecosystems and human well-being: scenarios. Findings of the scenarios working group of the millennium ecosystem assessment, vol 2. Island Press, Washington, pp 223–294

Crossland CJ, Kremer HH, Lindeboom HJ, Marshall Crossland JI, Le Tissier MDA (2005) Coastal fluxes in the anthropocene. The land–ocean interactions in the coastal zone project of the international geosphere–biosphere programme series: global change—The IGBP series, p 232

Dang NA (2003) Internal migration policies in the ESCAP region. Asia-Pac Popul J 18:27–40

Dawson R., Dickson M, Nicholls R., Hall J.W., Walkden M, Stansby P, Mokrech M, Richards J, Zhou J., Milligan J, Jordan A, Pearson S, Rees J, Bates P, Koukoulas S Watkinson A (2007) Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change: Tyndall centre working paper 110, Tyndall Centre for Climate Change Research. http://www.tyndall.ac.uk/publications/working_papers/twp110.pdf

DINAS-COAST Consortium (2006) DIVA 1.0. Potsdam Institute for Climate Impact Research, Potsdam, CD-ROM

Dixon TH, Amelung F, Ferretti A, Novali F, Rocca F, Dokka R, Sella G, Kim S-W, Wdowinski S, Whitman D (2006) Subsidence and flooding in New Orleans. Nature 441:587–588

Dokka RK (2006) Modern-day tectonic subsidence in coastal Louisiana. Geology 34:281–284

EFGC (2006) Envisioning the future of the gulf coast. Final report and findings. In: Reed D (ed) America's wetland, campaign to save Coastal Louisiana, p 11

Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436:686–688

Ericson JP, Vorosmarty CJ, Dingman SL, Ward LG, Meybeck M (2006) Effective sea-level rise and deltas: causes of change and human dimension implications. Glob Planet Change 50:63–82

Evans EP, Ashley RM, Hall J, Penning-Rowsell E, Saul A, Sayers P, Thorne C, Watkinson A (2004a) Foresight: future flooding. Scientific summary: future risks and their drivers. vol I. Office of Science and Technology

Evans EP, Ashley RM, Hall J, Penning-Rowsell E, Sayers P, Thorne C, Watkinson W (2004b) Foresight: future flooding. Scientific summary: managing future risks. vol II. Office of Science and Technology

Fankhauser S (1995) Protection versus retreat: estimating the costs of sea-level rise. Environ Planning A 27:299–319

Gardner TA, Côté IM, Gill JA, Grant A, Watkinson AR (2003) Long-term region-wide declines in Caribbean corals. Science 301:958–960

Gommes R, du Guerny J, Nachtergaele F, Brinkman R (1998) Potential impacts of sea-level rise on populations and agriculture. SD-dimensions special, FAO, Rome. http://www.fao.org/sd/eidirect/EIre0045.htm

Grübler A, Nakicenovic N, Alcamo J, Davis G, Fenhann J, Hare B, Mori S, Pepper B, Pitcher H, Riahi K, Rogner H-H, La Rovere EL, Sankovski A, Schlesinger M, Shukla RP, Swart R, Victor N, Jung TY (2004) Emissions scenarios: a final response. Energy Environ 15:11–24

Hamilton JM, Maddison DJ, Tol RSJ (2005) The effects of climate change on international tourism. Clim Res 29:255–268

Hamm L, Stive MJF (eds) (2002) Shore nourishment in Europe. Coastal Eng 47:79–263

Hanson H (2003) Overview of beach nourishment projects in the European union-projects, practices and objectives. Shore and Beach 71(2):9–19

Harvey N (2006) Rates and impacts of global sea-level change. In: Glazer MP (ed) New frontiers in environmental research. Nova Science Publishers, Hauppauge, NY

Hoegh-Guldberg O, Hoegh-Guldberg H (2004) The implications of climate change for Australia's Great Barrier Reef. People and industries at risk. World Wildlife Fund and Queensland Tourism Industry Council, Brisbane

Holman IP, Rounsevell MDA, Shackley S, Harrison PA, Nicholls RJ, Berry PM, Audsley E (2005) A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: I methodology. Clim Change 71(1–2):9–41

Holman IP, Nicholls RJ, Berry PM, Harrison PA, Audsley E, Shackley S, Rounsevell MDA (2005) A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: II results. Clim Change 71(1–2):43–73

Hoozemans FMJ, Marchand M, Pennekamp HA (1993) A globalvulnerability analysis: vulnerability assessment for population, coastalwetlands and rice production on a global scale, 2nd edn. Delft Hydraulics,Delft, The Netherlands

Hulme, M., Jenkins GJ, Lu X, Turnpenny JR, Mitchell TD, Jones RG, Lowe J, Murphy JM, Hassell D, Boorman P, McDonald R, Hill S (2002) Climate Change scenarios for the United Kingdom. The UKCIP02 scientific report. Tyndall Centre for Climate Change Research, University of East Anglia, p 120

IPCC (2007) Climate Change 2007: Synthesis report, Intergovernmental Panel on Climate Change Fourth Assessment Report (Downloaded from http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_introduction.pdf on 3 January 2008)

IPCC CZMS (1992) A common methodology for assessing vulnerability to sea-level rise—second revision. Global climate change and the rising challenge of the sea. Report of the coastal zone management subgroup, response strategies working group of the Intergovernmental Panel on Climate Change, Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands, Appendix C, p 27

Kennish M (2002) Environmental threats and environmental future of estuaries. Environ Conserv 29(1):78–107

Klein RJT, Nicholls RJ (1998) Coastal zones. In: Feenstra JF, Burton I, Smith JB, Tol RSJ (eds) Handbook on climate change impact assessment and adaptation strategies, version 2.0, United Nations Environment Programme and Institute for Environmental

Studies, Vrije Universiteit, Nairobi, Kenya, and Amsterdam, The Netherlands, pp 7.1–7.35
Klein RJT, Nicholls RJ (1999) Assessment of coastal vulnerability to climate change. Ambio 28(2):182–187
Koster MJ, Hillen R (1995) Combat erosion by law: coastal defence policy for The Netherlands. J Coast Res 11(4):1221–1228
Leafe R, Pethick J, Townend I (1998) Realizing the benefits of shoreline management. Geogr J 164(3):282–290
McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban 19(1):17–37
Meehl GA, Stocker TF, Collins W, Friedlingstein P, Gaye A, Gregory J, Kitoh A, Knutti R, Murphy J, Noda A, Raper S, Watterson I, Weaver A, Zhao Z-C (2007) Global climate projections climate change 2007. In: Solomon S, Qin D, Manning M (eds) The physical science basis. Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press (in press)
Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438:347–350
Nakićenović N, Swart R (eds) (2000) Emissions scenarios. Special report of the Intergovernmental Panel on Climate Change. Cambridge University Press, p 599
NAST (2000) Climate change impacts in the United States, Overview. Report for the US global change research program. National Assessment Synthesis Team (NAST) members, p 154
National Research Council (2006) Drawing Louisiana's new map, addressing land loss in coastal Louisiana. National Research Council, National Academy Press
Neumann JE, Yohe G, Nicholls RJ, Manion M (2001) Sea level rise and its effects on global resources. In: Claussen E (ed) Climate change: science, strategies and solutions. Brill, Boston, pp 43–62
Nicholls RJ (1995) Coastal megacities and climate change. Geojournal 37(3):369–379
Nicholls RJ (2004) Coastal flooding and wetland loss in the twenty-first century: changes under the SRES climate and socio-economic scenarios. Glob Environ Change 14(1):69–86
Nicholls RJ, Lowe JA (2004) Benefits of mitigation of climate change for coastal areas. Glob Environ Change 14(3):229–244
Nicholls RJ, Tol RSJ (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Philos Trans R Soc Lond A 364:1073–1095
Nicholls RJ, Wong PP, Burkett, V, Codignotto J, Hay J, McLean R, Ragoonaden S, Woodroffe CD (2007a) Coastal systems and low-lying areas. In: Parry ML, Canziani OF, Palutikof JP, van der Linden P, Hanson CE (eds) Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovermental Panel on Climate Change. Cambridge, Cambridge University Press, pp 315–357
Nicholls RJ, Hanson S, Herweijer C, Patmore N, Hallegatte S, Corfee-Morlot J, Chateau J, Muir-Wood R (2007b) Ranking port cities with high exposure and vulnerability to climate extremes exposure estimates. Environment working Papers No. 1, Organization for Economic Co-Operation and Development, Paris. Downloadable at http://www.oecd.org/document/56/0,3343,en_2649_34361_39718712_1_1_1_1,00.html
Nicholls RJ, Cooper NJ, Townend IT (2007c) Coastal management and engineering. In: Thorne C, Evans E, Penning-Rowsell E (eds) Future flood and coastal erosion risks in the UK. Thomas Telford, London
Parry ML, Canziani OF, Palutikof JP,van der Linden P, Hanson CE (eds) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovermental Panel on Climate Change. Cambridge University Press, Cambridge
Parson E, Burkett V, Fisher-Vanden K, Keith D, Mearns L, Pitcher H, Rosenzweig C, Webster M (2007) Global change scenarios: their development and use. A report by the U.S. climate change science program and the subcommittee on global change science research. Department of energy, Office of Biological Environmental Research, p 102
Rahmstorf S (2007) A semi-empirical approach to projecting future sea-level rise Science 315:368–370
Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, Somerville RCJ (2007) Recent climate observations compared to projections. Science 316:709. doi:10.1126/science.1136843
Reker J, Vermaat J, van Winden A, Eleveld M, Janssen R, Braakhekke W, de Reus N, Omzigt N (2006) Deltas on the move: making deltas cope with the effects of climate change. Report Nr. 001/2006, National Research Programme Climate Change Spatial Planning, Amsterdam, p 97
Rodolfo KS, Siringan FP (2006) Global sea-level rise is recognised, but flooding from anthropogenic land subsidence is ignored around northern Manila Bay, Philippines. Disaster Management 30:118–139
Rohling EJ, Grant K, Hemleben CH, Siddall M, Hoogakker BAA, Bolshaw M, Kucera M (2007) High rates of sea-level rise during the last interglacial period. Nature Geosci Adv. Online publication http://www.nature.com/naturegeoscience
Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society, p 60, Ref. 12/05
Rupp-Armstrong S, Nicholls RJ (2007) Coastal and estuarine retreat: a comparison of the application of managed realignment in England and Germany. J Coast Res 23(6):1418–1430
Shell International (2003) Scenarios: an explorer's guide. Global business environment. at: http://www-static.shell.com/static/royal-en/downloads/scenarios_explorersguide.pdf
Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. J Coast Res 19:584–599
Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) (2007) Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Sustainable Development Commission (2007) Turning the tide: Tidal power in the UK. Sustainable Development Commission, London, p 148. downloadable at: http://www.sd-commission.org.uk/publications/downloads/Tidal_Power_in_the_UK_Oct07.pdf
Syvitski JPM, Vörösmarty CJ, Kettner AJ, Green P (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308:376–380
Syvitski JPM (2008) Deltas at risk. Sustain Sci 3:23–32
Thorne C, Evans E, Penning-Rowsell E (eds) (2007) Future flooding and coastal erosion risks. Thomas Telford, 350 pp
Tol RSJ (2007) The double trade-off between adaptation and mitigation for sea level rise: an application of FUND. Mitigation Adapt Strat Glob Change 12(5):741–753
Turley C, Blackford JC, Widdicombe S, Lowe D, Nightingale PD, Rees AP (2006) Reviewing the impact of increased atmospheric CO2 on oceanic pH and the marine ecosystem. In: Schellnhuber HJ, Cramer W, Nakicenovic N, Wigley TML, Yohe G (eds) Avoiding dangerous climate change. Cambridge University Press, pp 65–70
Turner RK (2000) Integrating natural and socio-economic science in coastal management. J Mar Sys 25:447–460
UK Climate Impacts Programme (2001) Socio-economic scenarios for climate change impact assessment: a guide to their use in the

UK climate impacts programme. UKCIP, Oxford. (downloaded at http://www.ukcip.org.uk/resources/publications/documents/34.pdf)

UNEP (2005) Assessing coastal vulnerability: developing a global index for measuring risk. United Nations Environment Programme (UNEP), Nairobi, 54pp

UNEP (2007) Global environmental outlook geo4. United Nations Environment Programme (UNEP), Nairobi, p 540

Vafeidis AT, Nicholls RJ, Mc Fadden L, Hinkel J, Grashoff PS (2004) Developing a global database for coastal vulnerability analysis: design issues and challenges. In: Altan MO (ed) The international archives of photogrammetry, remote sensing and spatial information sciences, International Society for Photograppmetry and Remote Sensing, vol. 35 (B). Istanbul, pp 801–805

Vafeidis AT, Nicholls RJ, Boot G, Cox J, Grashoff PS, Hinkel J, Maatens R, McFadden L, Spencer T, Tol RSJ (2008) A new global coastal database for impact and vulnerability analysis to sea-level rise. J Coastal Res (in press)

Valiela I (2006) Global coastal change. Blackwell, London

von Storch H, Woth K (2008) Storm surges: perspectives and options. Sustain Sci 3:33–44

Warrick RA, Barrow EM, Wigley TML (eds) (1993) Climate and sea level change: observations, projections, implications. Cambridge University Press, Cambridge

Watkinson A, Nicholls RJ, Sear D, Ledoux L (2007) Environmental context In: Thorne C, Evans E, Penning-Rowsell E (eds) Future flood and coastal erosion risks in the UK. Thomas Telford, London

Webster PJ, Holland GJ, Curry JA, Chang H-R (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309:1844–1846

Wilkie ML, Fortuna S (2003) Status and trends in Mangrove area extent worldwide—forest resources assessment working paper—63, FAO Rome. Downloadable at http://www.fao.org/docrep/007/j1533e/j1533e00.htm

Wilkinson C (ed) (2004) Status of coral reefs of the world. Australian Institute of Marine Science, Townsville

Wong PP, Lee BT, Leung MWH (2006) Hot spots of population growth and urbanization in the Asia-Pacific coastal zone. In: Harvey N (ed) Global change and integrated coastal management. Springer, Dordrecht, pp 161–193

Woodroffe CD, Nicholls RJ, Saito Y, Chen Z, Goodbred SL (2006) Landscape variability and the response of Asian megadeltas to environmental change. In: Harvey N (ed) Global change implications for coasts in the Asia-Pacific region. Springer, Berlin (in press)

Zhang KQ, Douglas BC, Leatherman SP (2000) Twentieth-century storm activity along the US east coast. J Clim 13:1748–1761

Yohe GW, Tol RSJ (2002) Indicators for social and economic coping capacity—moving towards a working definition of adaptive capacity. Glob Environ Change 12:25–40

Yohe GW, Lasco RD, Ahmad QK, Arnell NW, Cohen SJ, Hope C, Janetos AC, Perez RT (2007) Perspectives on climate change and sustainability.In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate Change 2007: impacts, adaptation and vulnerability. Contribution of working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 811–841