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Improving Information for Policy Makers

Case study on sea-level rise impacts

by

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FOREWORD

This paper was prepared for an OECD Workshop on the *Benefits of Climate Policy: Improving Information for Policy Makers*, held 12-13 December 2002. The aim of the Workshop and the underlying Project is to outline a conceptual framework to estimate the benefits of climate change policies, and to help organise information on this topic for policy makers. The Workshop covered both adaptation and mitigation policies, and related to different spatial and temporal scales for decision-making. However, particular emphasis was placed on understanding global benefits at different levels of mitigation -- in other words, on the incremental benefit of going from one level of climate change to another. Participants were also asked to identify gaps in existing information and to recommend areas for improvement, including topics requiring further policy-related research and testing. The Workshop brought representatives from governments together with researchers from a range of disciplines to address these issues. Further background on the workshop, its agenda and participants, can be found on the internet at: www.oecd.org/env/cc

The overall Project is overseen by the OECD Working Party on Global and Structural Policy (Environment Policy Committee). The Secretariat would like to thank the governments of Canada, Germany and the United States for providing extra-budgetary financial support for the work.

This paper is issued as an authored "working paper" -- one of a series emerging from the Project. The ideas expressed in the paper are those of the author alone and do not necessarily represent the views of the OECD or its Member Countries.

As a working paper, this document has received only limited peer review. Some authors will be further refining their papers, either to eventually appear in the peer-reviewed academic literature, or to become part of a forthcoming OECD publication on this Project. The objective of placing these papers on the internet at this stage is to widely disseminate the ideas contained in them, with a view toward facilitating the review process.

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EXECUTIVE SUMMARY

Global-mean sea-level rise occurred through the 20th Century, and continued rise is one of the more certain impacts of global warming. This is resulting in a range of impacts including increased flood risk and submergence, salinisation of surface and ground waters, and morphological change, such as erosion and wetland loss. The potential human and ecosystem impacts in the 21st Century are significant but uncertain. Actual impacts will depend on a range of change factors in addition to the amount of sea-level rise and climate change, including a number of factors which are human-controlled such as coastal land use and management approaches.

Importantly, there is a strong *'commitment to sea-level rise'* due to the long thermal lags of the ocean system and hence the response of sea-level rise to mitigation is slower than for other climate factors. Therefore, the main benefits of mitigation of climate change in terms of sea-level rise occur beyond the 21st Century. This means that the best response to sea-level rise and climate change in the coastal zone is an appropriate mixture of mitigation and adaptation. Hence, joint evaluation of mitigation and adaptation is required in the coastal zone as these policies are intertwined. Such assessments must continue beyond 2100 to provide the full implications of the different policy choices. Further, policymakers should note that the results of any assessment of sea-level rise and climate change depends on the scale of assessment and the detailed methods utilised. For instance, choices on adaptation are sensitive to spatial scale. Hence, there is a critical need to match policy questions and formulation to the appropriate level of assessment.

Despite the concerns about sea-level rise, most countries appear to be ignoring changes in sea level in coastal planning at the present time. There is a need to develop adaptive capacity of vulnerable coastal areas such as small island states. The following research would assist in identifying such areas and improve climate policy formulation for coastal areas:

- More complete assessment of the range of possible impacts in the 21st Century and beyond, including the consequences of low probability/high impact events such as the collapse of the West Antarctic Ice Shelf;

- Improved regional and global integrated models to quantify and explore the impacts of sea-level rise and other changes, conducted in conjunction with more detailed local and national assessments which will provide more detailed information and allow for validation. This would assist identification of vulnerable coastal areas (or 'hotspots');

- Continued assessment of the adaptation process in coastal zones as the actual impacts depend on the potential to adapt, which remains a major gap in our understanding.

1. INTRODUCTION

Global-mean sea level rose at least 10 cm during the 20th Century, and this rise is expected to continue and most likely accelerate due to human-induced warming during the 21st Century. In the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) the projected rise from 1990 to 2100 was 9 to 88 cm with a mid estimate of 48 cm (Church et al., 2001). Beyond the 21st Century, substantial ***additional*** rises of sea level appear to be inevitable, and if climate change is not controlled both Greenland and Antarctica could become significant sources of sea-level rise (Church et al., 2001). While the possibility of significant rises in sea level due to the instability of the West Antarctic Ice Shelf (WAIS) is presently considered very low, it becomes more likely if global warming continues (Church et al., 2001; Vaughan and Sponge, 2002).

While sea-level rise will only directly impact the coastal zone, such changes raise significant concern due to the high concentration of natural and socio-economic values located there. The coastal zone is a major focus of human habitation and economic activity, as well as being important ecologically (Holligan and deBoois, 1993; Turner et al., 1996; Sachs et al., 2001). For 1990, it is estimated that 1.2 billion (or 23%) of the world's population lived in the near-coastal zone[1], at densities about three times higher than the global mean (Nicholls and Small, 2002; Small and Nicholls, 2003). The population density also increases seaward across the near-coastal zone, with the highest densities occurring below 20-m elevation. Furthermore, coastal populations are widely reported to be growing more rapidly than the global mean, due to net coastal migration. Urbanisation is an important trend and 20 large coastal cities (>8 million people) are projected for 2010, together with many more smaller cities and towns clustered close to the coastline (Nicholls, 1995a; Small and Nicholls, 2003). Therefore, human exposure to sea-level rise is significant and growing.

In addition to se-level rise, human-induced changes in coastal zones are widespread and often profound. These include declining sediment and freshwater inputs due to increased catchment regulation, direct and indirect destruction of mangroves, coral degradation due to a range of causes, and increasing inputs of nitrates and phosphates leading to eutrophication of coastal and shelf sea waters. Management of coastal zones is already perceived as a significant problem at the global scale (e.g., WCC'93, 1994; IGBP-LOICZ, 2002). Therefore, sea-level rise represents *one* of a number of stresses on the coastal zone (Bijlsma et al., 1996). This multiple stress situation will often amplify the impacts of sea-level rise when compared to an 'unstressed' coastal system.

This paper examines the potential impacts of human-induced sea-level rise in the context of the evolving coastal system, rather than simply imposing sea-level rise on today's coastal zone and its activities. First, the observed and likely changes in sea level are considered over the 20th and 21st Century and beyond to illustrate the long time scales associated with this issue. This includes a consideration of the effects of mitigation on sea-level rise. Then an appropriate conceptual framework for considering the impacts of sea-level rise is presented and discussed. This is followed by a review of the impacts of sea-level rise, including the potential for adaptation which strongly controls the actual impacts that might be experienced. Finally, the key issues are developed, including defining the research needs to better inform climate policy on coastal issues.

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[1] The area both within 100 km horizontally and 100 m vertically of the coastline.

2. SEA-LEVEL AND CLIMATE CHANGE IN COASTAL AREAS

2.1 Sea-level change components

The local change in sea level at any coastal location depends on the sum of global, regional and local factors and is termed relative sea-level change (Nicholls and Leatherman, 1996; Nicholls, 2002a). Therefore, global-mean sea-level rise does not translate into a uniform rise in sea level around the world. The relative (or local) level of the sea to the land can change for a number of reasons and over a range of time scales. Over the main time scale of human concerns (10^2 to 10^3 years), relative sea level is the sum of the following components (Church et al., 2001):

- *Global-mean sea-level rise* which is an increase in the global volume of the ocean. In the 20th/21st Century, this is primarily due to thermal expansion of upper ocean as it warms and the melting of small ice caps due to human-induced global warming (Church et al., 2001). The contribution of Greenland is less certain, and Antarctica is expected to grow in size producing a sea-level *fall*, offsetting any positive contribution from Greenland. Direct human influence is also possible due to modifications to the hydrological cycle (*e.g*., increased terrestrial storage of water (causing sea-level fall), versus increased groundwater mining (causing sea-level rise)), although this balance is most uncertain.

- *Regional meteo-oceanographic factors* such as spatial variation in thermal expansion effects, changes to long-term wind fields and atmospheric pressure, and changes in ocean circulation such as the Gulf Stream (e.g. Gregory, 1993). These effects could be significant with regional effects equal to the magnitude of the global-mean thermal expansion term. Models of these effects under global warming show little agreement (Gregory *et al*., 2001), and this component has been largely ignored in impact assessments to date.

- *Vertical land movement* (subsidence/uplift) due to various geological processes such as tectonics, neotectonics, glacial-isostatic adjustment (GIA[2]), and consolidation (Emery and Aubrey, 1991). In addition to natural changes, groundwater withdrawal and improved drainage has enhanced subsidence (and peat destruction by oxidation and erosion) in many coastal lowlands, producing several metres subsidence in susceptible areas over the 20th Century, including within some major coastal cities such as Tokyo and Shanghai (e.g., Nicholls, 1995a).

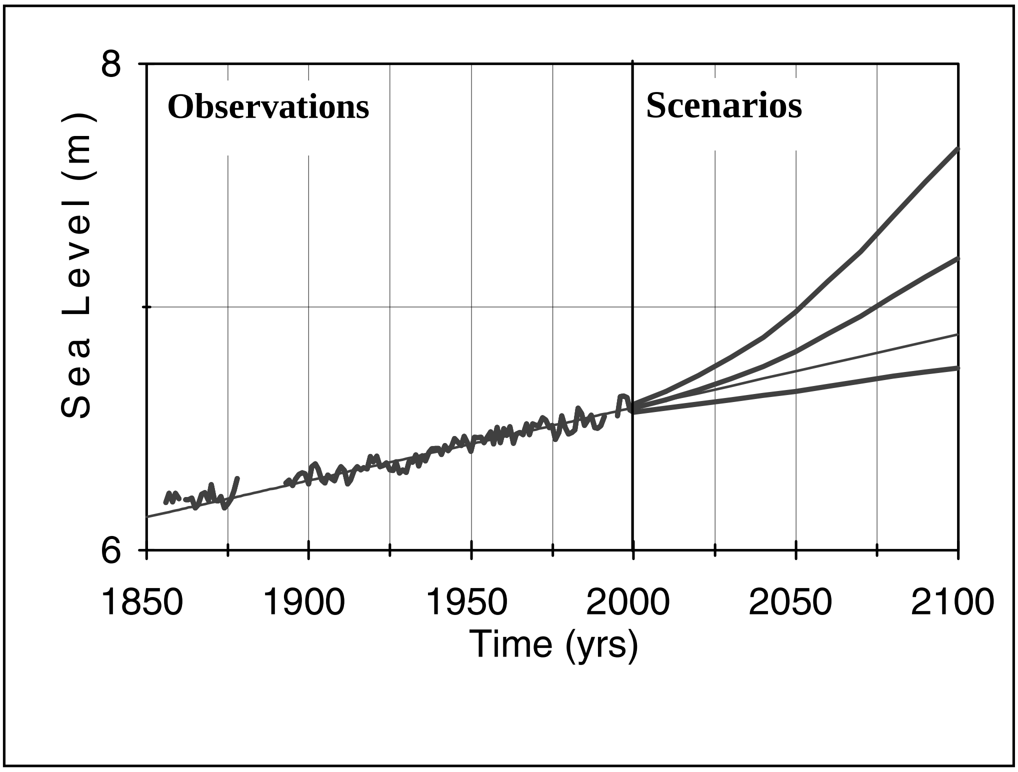
2.2 Recent sea-level trends

Sea-level rise during the 20th Century was faster than during the 18th and 19th Century (Woodworth, 1999; Church et al., 2001), as suggested by the 19th Century data in Figure 1. The timing of this small acceleration suggests that it is probably related to the end of the 'Little Ice Age' and that it has nothing to do with human-induced changes. Global sea levels are estimated to have risen 10 to 20 cm during the 20th Century, but with no evidence of acceleration (Church et al., 2001). It has since been argued that an estimate centred on a 20-cm rise during the 20th Century is most consistent with the

[2] GIA is still occurring due to the unloading of melting ice sheets from 18,000 to 6,000 years ago, producing vertical changes comparable to global-mean sea-level rise in many locations (Douglas, 2000).

available data (Douglas and Peltier, 2002). Thus, we experienced a significant sea-level rise during the 20th Century, which has arguably been one stress factor contributing to many of the existing coastal problems.

Figure 1. Relative sea-level rise observations and the SRES sea-level scenarios at New York City: 1850 to 2100.



Notes: The straight dashed line shows the observed trend for the 20th Century.

2.3 Future sea-level scenarios

Taking the greenhouse gas emission scenarios from the Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000), it is estimated that the global rise in sea level from 1990 to 2100 would be between 9 and 88 cm, with a mid estimate of 48 cm[3] (Church et al., 2001). This is a slightly lower estimate than the second IPCC assessment (Warrick et al., 1996), but the large range of uncertainty for future global-mean rise remains. These uncertainties can be attributed to two distinct reasons:

- uncertainties about future greenhouse gas concentrations; and
- uncertainties about the climate response to a greenhouse forcing (the climate and the sea-level rise sensitivity).

After 2100, detailed sea-level rise scenarios are less developed, but a significant *additional* rise would be expected depending on the magnitude of global warming.

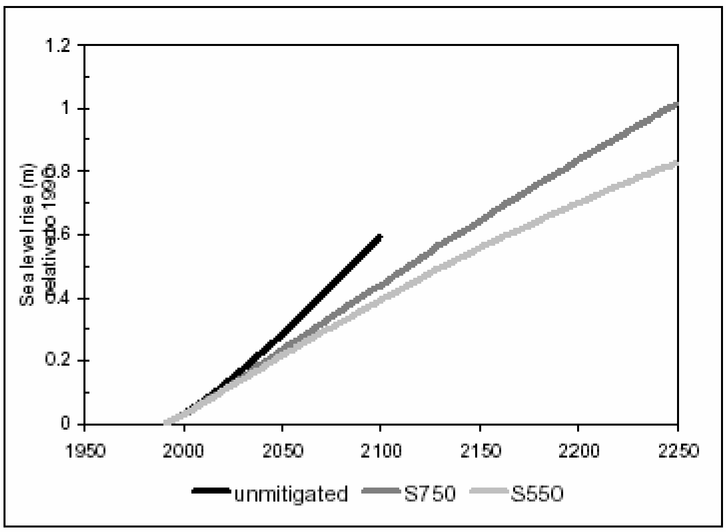
An example of relative sea-level observations and relative sea-level rise scenarios to 2100 based on the conclusions of Church et al. (2001) are shown for New York City in Figure 1. The rise during the

[3] These global-mean sea-level rise scenarios do not include any contribution from Antarctica (Church et al., 2001).

20th Century (30 cm/century) is 10 to 20 cm/century larger than the global-mean trend reported by Church et al. (2001), reflecting that New York is slowly subsiding due to GIA (Douglas, 1991). The relative mid scenario shows a 2-fold acceleration relative to the 20th Century. However, the possible range is more than a 3-fold acceleration to a slight deceleration. Note that the scenarios assume no meteo-oceanographic effects at New York, but they do take account of the uncertainty in the rate of subsidence. These large uncertainties need to be considered when assessing impacts and adaptation needs (see later).

Mitigation of greenhouse gas emissions or enhancement of greenhouse sinks will reduce future global warming and hence sea-level rise. Recent analyses suggest that global-mean sea-level rise is almost independent of future emissions to 2050, and future emissions become most important in controlling sea-level rise after 2100 (Church et al., 2001). This means that during the 21st Century, the main source of uncertainty concerning global-mean sea-level rise is the sensitivity of climate and sea-level rise to greenhouse forcing. Even if atmospheric greenhouse-gas concentrations are stabilised by a substantial mitigation effort, as is implied in the stabilisation experiments of Mitchell et al. (2000), the rise in global sea level is only delayed at most by a few decades during the 21st Century (Figure 2). These results are due to what has been termed "*the commitment to sea-level rise*", which reflects the slow penetration of heat into the deeper ocean. It may take thousands of years for the ocean temperature to reach equilibrium with a new stable climate (Wigley and Raper, 1993; Church et al., 2001). Thus, in the case of sea-level rise, mitigation has the slowest effects on the future change compared to other climate change factors (e.g., precipitation, air temperature, etc.). However, both the ultimate maximum rise and also the rate of sea-level rise can be significantly reduced, as illustrated in Figure 2. Therefore, global-mean sea-level rise appears inevitable during the 21st Century and beyond even given substantial mitigation of climate change, but we can influence the amount and rate of sea-level rise by mitigation. This illustrates the long time scales associated with sea-level rise and this has important implications for climate policy (Watson et al., 2001).

Figure 2. Global-mean rise in sea level (relative to 1990)



Notes: Under unmitigated emissions (top line), S750 (middle line) and S550 (bottom line) as simulated with the HadCM2 atmosphere-ocean coupled model

Source: Mitchell et al. (2000)

These scenarios do not include the possibility of large changes, particularly the collapse of the West Antarctic Ice Sheet (WAIS). This could raise global sea levels by up to 6 m (Mercer, 1978;

Oppenheimer, 1998), causing potentially catastrophic impacts, although the potential impacts have not been investigated in detail since Schneider and Chen (1980). This lack of analysis reflects that collapse is considered highly unlikely during the 21st Century, and the timescale of the change is uncertain. For instance, Vaughan and Sponge (2002) concluded that the probability of a sea-level rise contribution from the WAIS of more than 0.5 m during the 21st Century was 5%. Going beyond 2100, this probability increases. Thus, WAIS collapse remains a plausible, albeit unlikely scenario, and from an impacts perspective it is worthy of consideration as a low probability/high consequence scenario. Climate mitigation would reduce the risk of this occurrence, as well as other large rises in sea level (e.g., the melting of the Greenland ice sheet), but this benefit of mitigation has not been evaluated.

2.4 Other climate change

Many other aspects of climate change will also have coastal implications that will interact with sea-level rise , although the details will vary from place-to-place (Nicholls, 2002a). A major concern is changes in the frequency, magnitude and location of the tracks of tropical and extra-tropical storms (e.g., Knutson et al., 1998; Warrick et al., 2000), and this issue often excites more attention than sea-level rise (e.g., Henderson-Sellers et al., 1998). It is noteworthy that historical analyses of north-west Europe and eastern North America have found evidence of significant inter-annual and inter-decadal variability of storminess, but no evidence of long-term trends during the 20th Century (WASA Group, 1998; Zhang et al., 2000). The IPCC TAR was uncertain about the future magnitude of storminess, although some recent national and regional scenarios in Europe do suggest an increase in storminess, which will interact unfavourably with sea-level rise (Hulme et al., 2000; 2002). Given the damage potential of coastal storms this is a high priority for further research and careful scenario development for impact assessment.

3. FRAMEWORK FOR THE ANALYSIS OF SEA-LEVEL RISE IMPACTS

Following the uncertainties about other climate change factors, the main focus of most assessments has been the impacts and responses to sea-level rise. To make the most of these studies, a common framework as shown in Figure 3 provides a useful basis for interpretation and comparison. In particular, it highlights the varying implicit and explicit assumptions and simplifications that are made within all the available studies and hence helps to establish common issues as well as making limitations more explicit.

Relative sea-level rise, due to whatever cause, has a number of biogeophysical impacts such as increased erosion and flood potential. In turn, these can have direct and indirect socio-economic impacts depending on the human exposure to these changes. There are also important feedbacks as the impacted systems adjust and adapt to these changes, including the human exploitation of beneficial changes and adaptation to adverse changes. Hence, the coastal system is best defined in terms of interacting natural and socio-economic systems. The terminology in Figure 3 has been modified slightly from the original in Klein and Nicholls (1999) to reflect the terms used by Smit et al. (2001), but the underlying meanings remain the same. Both systems may be characterized by their *exposure*[4], *sensitivity*[5] and *adaptive capacity*[6] to change, both from sea-level rise and related climate change, and this may be modified by *other non-climate stresses* (as discussed in Section 2). Collectively, sensitivity and adaptive capacity, combined with exposure, determine each system's *vulnerability* to sea-level rise and other changes.

Both systems are dynamic and different types of adaptation and adjustment can be distinguished (Smit et al., 2001). *Autonomous adaptation* (or spontaneous adjustments) represent the natural adaptive response to sea-level rise (*e.g*., increased vertical accretion of coastal wetlands within the natural system, or market price adjustments within the socio-economic system). Autonomous processes are often poorly understood and yet have a significant influence on the magnitude of many impacts. Further, autonomous natural processes are often being reduced or stopped by the human-induced non-climatic stresses as shown in Figure 3 (Bijlsma et al., 1996). *Planned adaptation* (which must emerge from the socio-economic system) can serve to reduce vulnerability by a range of measures.

Dynamic interaction occurs between the natural and socio-economic systems in the coastal zone, including the natural system impacts on the socio-economic system and planned adaptation by the socio-economic system influencing the natural system (see Section 6). This results in the natural and socio-economic systems interacting in a complex manner. The constant adaptations and adjustments that occur both within and between the systems normally act to reduce the magnitude of the potential impacts that would occur in their absence. Hence, actual impacts are normally much less than the potential impacts that are estimated in the absence of adaptation (except in the case of maladaptation (Smit et al., 2001)). Impact

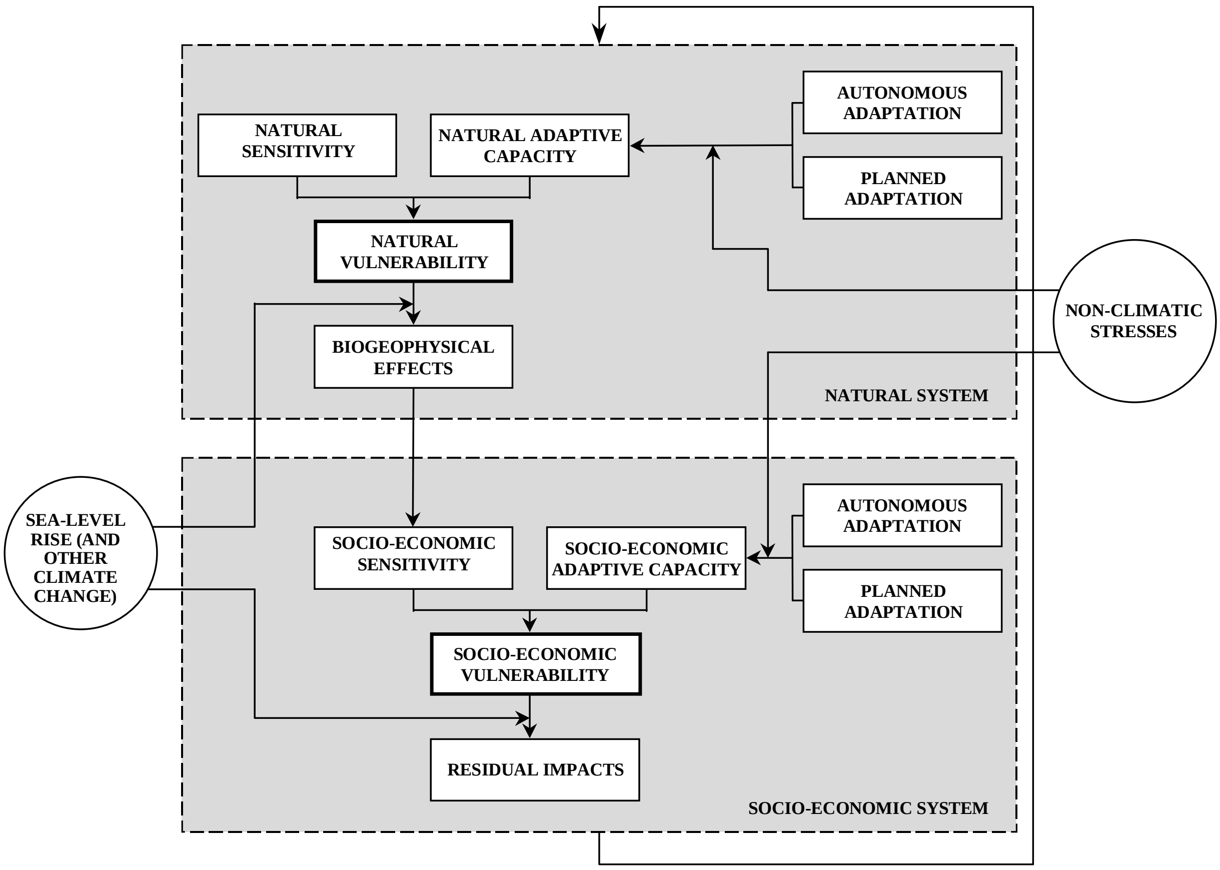
[4] Exposure is defined as the nature and degree to which a system is exposed to significant climatic variations (McCarthy et al., 2001). Exposure is not indicated in Figure 3.

[5] Sensitivity is the degree to which a system is affected, either adversely of beneficially by climate-related stimuli such as sea-level rise (McCarthy et al., 2001).

[6] Adaptive capacity is the ability of a system to adjust to sea-level rise and climate change (including cliamte variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (McCarthy et al., 2001).

assessments that do not take adaptation into account will generally overestimate impacts (determining *potential impacts* rather than *actual impacts*).

Figure 3. A conceptual framework for coastal impact and vulnerability assessment of sea-level rise



Source: Nicholls (2002a)

4. IMPACTS OF SEA-LEVEL RISE

The most significant biogeophysical effects of sea-level rise are summarised in Table 1, including relevant interacting factors. Most of these impacts are broadly linear functions of sea-level rise, although some processes such as wetland loss show a threshold response and are more related to the rate of sea-level rise, rather than the absolute change. Most existing studies have focused on one or more of the first three factors: (1) inundation, flood and storm damage, (2) erosion and (3) wetland loss (Nicholls, 1995b). These studies are often based on very simple assumptions and ignore most landscape dynamics: wetlands are treated as passive elements of the landscape and are simply submerged as sea levels rise. In addition, interacting factors are often ignored. The main reason that salinisation and rising water tables have not been considered is that they are methodologically more difficult to analyse. Hence, most assessments of the biophysical impacts of sea-level rise are incomplete in some aspect.

Table 1. The main effects of relative sea-level rise

BIOGEOPHYSICAL EFFECT		OTHER RELEVANT FACTORS	
		CLIMATE	NON-CLIMATE
Inundation, flood and storm damage	Surge	Wave and storm climate, morphological changes, sediment supply	Sediment supply, flood management, morphological changes, land claim
	Backwater effect (river)	Run-off	Catchment management and land use
Wetland loss (and change)		CO_2 fertilisation Sediment supply	Sediment supply, migration space, direct destruction
Erosion		Sediment supply, wave and storm climate	Sediment supply
Saltwater Intrusion	Surface Waters	Run-off	Catchment management and land use
	Ground-water	Rainfall	Land use, aquifer use
Rising water tables/ impeded drainage		Rainfall	Land use, aquifer use

Notes: Including relevant interacting factors as described by Nicholls (2002a). Some factors (e.g., sediment supply) appear twice as they may be influenced both by climate and non-climate factors.

The natural-system effects of sea-level rise in Table 1 have a range of potential socio-economic impacts (Nicholls, 2002a), including the following identified by McLean et al (2001):

- Increased loss of property and coastal habitats
- Increased flood risk and potential loss of life
- Damage to coastal protection works and other infrastructure

- Loss of renewable and subsistence resources
- Loss of tourism, recreation, and transportation functions
- Loss of non-monetary cultural resources and values
- Impacts on agriculture and aquaculture through decline in soil and water quality

The indirect impacts of sea-level rise are more difficult to analyze, but they have the potential to be important in many sectors, such as fisheries. Coastal wetlands play an important role in the life cycles of many important fisheries species. Therefore, if sea-level rise causes a decline in wetlands, this would impact fisheries (McLean et al., 2001, Kennedy et al., 2002). Dramatic non-linear effects are possible as illustrated by the rapid decline in the Mississippi delta wetlands, USA[7]. Browder et al. (1989) found that the Louisiana brown shrimp fishery improved as these marshes have declined due to an increase in the length of the marsh-water interface as the marshes broke up. Clearly, this process cannot continue indefinitely, and a crash in this fishery is predicted for the 21st Century unless substantial new areas of wetlands are created. Human health is another sector where the indirect effects of sea-level rise could be significant. Hence, sea-level rise could produce a cascade of impacts through the coastal system, although analysis to date has focussed mainly on the direct impacts.

The impacts of sea-level rise have been investigated in a range of policy-driven sub-national, national and regional/global case studies (e.g., Nicholls and Mimura, 1998; Mimura, 2000; de la Vega-Leinert and Nicholls, 2001), as well as in more science-orientated studies which examine the biogeophysical processes of sea-level rise (e.g., Cahoon et al., 1999; Leatherman et al., 2000) and methodological studies that transfer scientific knowledge into policy relevant tools (e.g., Stive et al., 1990; Capobianco et al., 1999). A range of socio-economic analyses have also been undertaken in the broad realm of integrated assessment (e.g., Fankhauser, 1995a; Tol, 2002a; 2002b). While these studies are often seen as policy relevant as they discuss issues such as the costs of sea-level rise in monetary terms, they are also often experimental in terms of exploring the socio-economic dynamics of the coastal zone. Here the main focus is on the policy-driven studies.

4.1 National-scale assessments

The available national-scale assessments generally comprise inventories of the potential impacts to a 1-m rise in sea level, with limited consideration of adaptation (Nicholls, 1995b; Nicholls and Mimura, 1998). In this regard they confirm what has already been stated about the importance of the coastal zone. Table 2 suggests that almost 180 million people would be affected by a 1-m rise in sea level and assuming no human response in terms of adaptation. The term '*people affected*' integrates a wide range and magnitude of impacts. As one might expect, low-lying coastal areas are most sensitive to sea-level rise, particularly deltaic and small island settings. Coastal wetlands also appear highly threatened, although this may partly reflect the simple impact assumptions made in the studies, rather than the real vulnerability which could be much less if the wetlands are able to respond to sea-level rise (Cahoon et al., 1999).

[7] The decline in this wetlands is due to natural subsidence of the delta plain (i.e. relative sea-level rise) compounded by reduced hydrological and sediment inputs due to human management – recent losses are 50 km^2/yr (Boesch et al., 1994).

Table 2. Aggregated results of country studies

Country	People Affected		Capital Value at Loss		Land At Loss		Wetland At Loss	Adaptation/ Protection Costs	
	#People (1000s)	% Total	Mil US$	% GNP	Km^2	% Total	Km^2	Mil US$	% GNP
Antigua	38	50	-	-	5	1.0	3	71	0.32
Argentina	-	-	5000	>5	3400	0.1	1100	>1800	>0.02
Bangladesh	71000	60	-	-	25000	17.5	5800	>1000	>0.06
Belize	70	35	-	-	1900	8.4	-	-	-
Benin	1350	25	118	12	230	0.2	85	>400	>0.41
China	72000	7	-	-	35000	-	-	-	-
Egypt	4700	9	59000	204	5800	1.0	-	13100	0.45
Guyana	600	80	4000	1115	2400	1.1	500	200	0.26
Japan	15400	15	849000	72	2300	2.4	-	>156000	>0.12
Kiribati	9	100	2	8	4	12.5	-	3	0.10
Malaysia	-	-	-	-	7000	2.1	6,000	-	-
Marshall I.	20	100	160	324	9	80	-	>360	>7.04
Mauritius	3	<1	-	-	5	0.3	-	-	-
Netherlands	10000	67	186000	69	2165	5.9	642	12300	0.05
Nigeria	3200	4	17000	52	18600	2.0	16000	>1400	>0.04
Poland	235	1	24000	24	1700	0.5	36	1400	0.02
Senegal	110	>1	>500	>12	6100	3.1	6000	>1000	>0.21
St Kitts	-	-	-	-	1	1.4	1	50	2.65
Tonga	30	47	-	-	7	2.9	-	-	-
Uruguay	13	<1	1700	26	96	0.1	23	>1000	>0.12
U.S.A.	-	-	-	-	31600	0.3	17000	>156000[8]	>0.03
Venezuela	56	<1	330	1	5700	0.6	5600	>1600	>0.03
TOTAL	178834		1146310		149022		58790	27124	

Notes: Assuming Existing Development and a 1-m Rise in Sea level. All impacts assumed no adaptation, while adaptation assumes protection, except in areas of low population density. Costs are 1990 US$

Source: Bijlsma et al. (1996)

In terms of adaptation, these studies have usually made very simple assumptions that are consistent with the inventory approach, such as costing protection for all areas, except those with a low population (a common threshold is <10 people/km^2). These results suggest that the costs of adaptation will pose a varying burden in relation to the present size of the national economies, particularly for many small island nations (Table 2). However, the issues of the adaptation process and the capacity of the coastal communities to adapt are not usually considered. It is now widely recognised that this is grossly inadequate and future studies have been recommended to address this issue as a priority (e.g., de la Vega-Leinert and Nicholls, 2001).

One important result is the importance of the scale of assessment. Sterr (2003) has investigated the vulnerability of Germany to sea-level rise, at national, state (Schlesweig-Holstein) and case studies (within Schlesweig-Holstein) levels. As the scale of study increases, so the size of the hazard zones declined due to the use of higher resolution data. However, the potential impacts do not change significantly as the human values remain concentrated in the (smaller) hazard zones. Turner et al. (1995) examine the optimum response to sea-level rise in East Anglia, UK, using cost-benefit analysis. At the regional scale, it was worth protecting the entire coastal length. In contrast, at the scale of individual flood compartments, 20% of flood compartments should be abandoned even for the present rates of sea-level rise. This conclusion is consistent with current trends in coastal management policy for this region. This shows that realistic assessment of adaptation options requires quite detailed analysis to capture the potential variation in responses within a region, rather than assuming a uniform adaptation response.

8 See also Table 4 and discussion in main text

The potential cost of sea-level rise on the United States has received continuing analysis as summarized in Table 3 for a 1-m global sea-level rise scenario. The early studies had much higher cost estimates as they either ignored adaptation, or considered it in very simple terms and rather inflexibility, which imposed costs that are unrealistic on the ground. These studies show that our understanding of adaptation remains poor. Given the influence of our assumptions about adaptation on the costs of sea-level rise, it must be a main priority to improve this understanding.

Table 3. Potential cost of sea-level rise along the developed coastline of the United States (billions of 1990 dollars)

Source	Measurement	Annualised Estimate	Cumulative Estimate	Annual Estimate in 2065
Yohe (1989)	Property at risk of inundation	N/A	321	1.37
Smith and Tirpak (1989)	Protection	N/A	73-111	N/A
Titus et al (1991)	Protection	N/A	156	N/A
Nordhaus (1991)	Protection	4.9	N/A	N/A
Fankhauser (1995a)	Protection	1.0	62.6	N/A
Yohe et al. (1996)	Protection and abandonment	0.16	36.1	0.33
Yohe and Schlesinger (1998)	Expected protection and abandonment	0.38	N/A	0.4

Notes: For a 1-m Global Sea-Level Rise

Source: Adapted from Neumann et al. (2001)

4.2 Regional and global scale assessments

Regional and global assessments provide a more consistent basis to assess the impacts of sea-level rise. A range of impact estimates are available for coastal flooding (Section 5.2.1) and wetland loss (Section 5.2.2) conducted as part of the 'Fast Track' assessments (Parry and Livermore, 1999; Arnell et al., 2002). Collectively, these studies looked at a range of impacts given common climate and socio-economic scenarios. The coastal analysis is based on the Global Vulnerability Analysis of Hoozemans et al. (1993) and its updates (e.g., Nicholls, 2002b; Nicholls et al., 1999). The issue of impact and adaptation costs was not directly explored within the Fast Track work, but if has been explored in a range of other studies, some of which are reviewed in Section 5.2.3).

4.2.1 Coastal flooding

Globally, it is estimated that about 200 million people lived in the coastal flood plain (below the 1 in 1,000 year surge-flood elevation) in 1990, or about 4% of the world's population (Nicholls et al., 1999). Based on this data, it is estimated that on average 10 million people/year experienced coastal flooding in 1990 (Table 4).

Table 4. People within the 1,000-year flood plain (PHZ)

Time (years)	Sea-Level Scenario	PHZ	AAPF	PTR
1990		197	10	0
2020s	No Rise	399	22	0
	Low	403	23	0
	Mid	411	24	0
	High	423	30	5
2050s	No Rise	511	27	0
	Low	525	28	0
	Mid	550	64	34
	High	581	176	149
2080s	No Rise	575	13	0
	Low	605	17	1
	Mid	647	133	107
	High	702	353	332

Notes: The average annual number of people estimated to be flooded per year (AAPF) and number of people who experience flooding annually or more frequently (PTR) for the IS92a sea-level rise scenarios. These results assume sea-level rise, changing coastal populations and rising protection standards, but adaptation to sea-level rise is not considered – see text (adapted from Nicholls, 2002b). The population scenario assumes that population change within the coastal flood plain is double national trends.

Source: Adapted from Nicholls (2002b)

A dynamic analysis has been conducted which looks at the competing influences of relative sea-level rise (due to local subsidence and global changes), coastal population (assuming coastal changes are twice national population change to reflect a coastal migration) and improving defence standards in phase with rising GDP/capita (Nicholls et al., 1999; Nicholls, 2002b). The effect of sea-level rise on extreme water levels (i.e., storm surges) is an explicit part of the analysis. It is assumed that surge characteristics are constant over time and relative sea-level rise simply displaces these extreme water levels upwards. These analyses were designed to explore if global-mean sea-level rise was a serious issue. Therefore, the increasing protection standards only take account of existing climate variability (i.e. surges in 1990) and the analysis is considering a world that is completely ignoring the issue of global-mean (and relative) sea-level rise. Outputs include:

- people in the hazard zone (PHZ) – the population living below the 1 in 1,000 year flood plain (or the exposed population);
- average annual people flooded (AAPF) – the average number of people who experience flooding per year (a measure of risk that takes account of flood protection);
- people to respond (PTR) --- the number of people who are flooded annually or more frequently (indicating those people for whom flooding will be a severe problem, and hence a response would be likely).

Note that PHZ > AAPF > PTR.

Table 3 estimates the impacts of no global-mean sea-level rise and the IS92a global-mean sea-level rise scenarios on flooding (a global-mean rise in the range 19 to 80 cm from 1990 to the 2080s) (Warrick et al.,1996). Thus, Table 3 captures the full range of uncertainty in the global scenarios, including the wide uncertainty of climate sensitivity. The results illustrate a number of issues:

- Even without sea-level rise, the number of people flooded each year will increase significantly due to increasing coastal populations (i.e., exposure) to the 2050s, and then diminish to the 2080s as increasing protection standards due to rising GDP/capita become the most important factor.
- Significant impacts of sea-level rise are not apparent until the 2050s.
- However, the uncertainty is large with relatively minor impacts for the low rise scenario in the 2080s, a 10-fold increase in AAPF under the mid rise scenario and a 27-fold increase in AAPF under the high rise scenario for the 2080s.

Hence, global-mean sea-level rise is worthy of concern. Mitigation of climate change is one way to respond to the problem. Taking the sea-level rise scenarios in Figure 2 which represent unmitigated emissions, and stabilisation of atmospheric CO_2 at concentrations of 750 and 550 ppm, respectively (termed S750 and S550) the modelling experiments above were repeated (Table 5).

Table 5. Average annual number of people flooded in coastal storm surges (millions)

	No Climate Change	Unmitigated	S750	S550
1990	10			
2020s	22	24	23	23
2050s	27	50	40	38
2080s	13	94	35	18

Based on climate scenarios from the HadCM2 model and the same assumptions as the results in Table 4.

Source: Arnell et al. (2002)

Note that these results only represent one climate model and hence one estimate of climate sensitivity, and smaller or larger rises in sea level could emerge with other climate models. The S750 and S550 scenarios do reduce the number of people flooded, particularly the S550 emissions scenario. However, in all cases additional impacts due to sea-level rise are observed and given that sea levels will continue to rise after the 2080s, we may simply be delaying rather than avoiding the unmitigated impacts as observed in the 21st Century.

All regions see an increase in the incidence of flooding compared to the baseline, with this effect increasing with the magnitude of sea-level rise. In all cases, the most vulnerable regions in relative terms are the small island regions of the Caribbean, Indian Ocean and Pacific Ocean (Table 6). Absolute increases are largest in the southern Mediterranean, West Africa, East Africa, South Asia and South-East Asia – these five regions contain about 90% of the people flooded in all cases for the 2080s. This reflects the large populations of low-lying deltas in parts of Asia, and projections of rapid population growth around Africa's coastal areas. While developed country regions have relatively low impacts, sea-level rise still produces a significant increase in the number of people who would be flooded. These results show that sea-level rise could have a profound impact on the incidence of flooding – the higher the total rise, the greater the increase in flood risk, all other factors being equal. Any increase in storminess would further exacerbate the predicted increase in coastal flooding. They suggest that it would be prudent to start planning for coastal adaptation to climate change. Small island states are of particular concern as they have the most limited capacity for such adaptation.

Table 6. Average annual number of people flooded in coastal storm surge in three island regions (thousands)

	No Climate Change	Unmitigated	S750	S550
Caribbean				
1990	10			
2020s	4	15	12	12
2050s	3	40	23	19
2080s	3	613	129	11
Indian Ocean Island States				
1990	9			
2020s	4	20	16	15
2050s	7	69	49	44
2080s	1	509	108	10
Pacific Ocean Island States				
1990	3			
2020s	2	5	4	4
2050s	1	80	39	29
2080s	0	171	44	12

Notes: Based on climate scenarios from the HadCM2 model and the same assumptions as the results in Table 4.

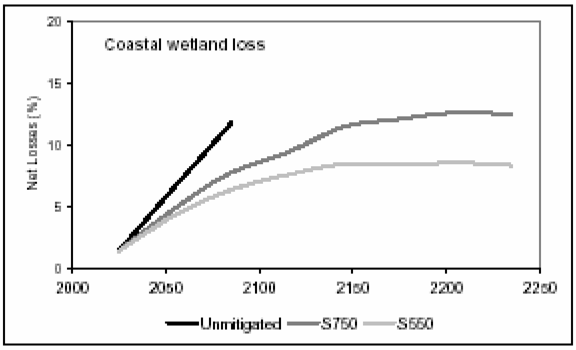
Source: Arnell et al. (2002)

4.2.2 Coastal wetlands

Coastal wetlands are already declining at 1%/year, largely due to indirect and direct human activities, with sea-level rise only playing a minor role in these losses (Hoozemans et al., 1993). Wetland losses are driven more by the rate of sea-level rise, rather than the total rise, as they have capacity to respond to inundation (Cahoon et al., 1999). Given a 1-m rise in sea level, wetland losses could approach 46% of the present stock (Nicholls et al., 1999). Taking a 38-cm global scenario by the 2080s, between 6% and 22% of the world's wetlands could be lost due to sea-level rise. When added to existing trends of indirect and direct human destruction, the net effect could be the loss of 36% to 70% of the world's coastal wetlands of international importance, or an area of up to 210,000 km^2. Therefore, sea-level rise is a significant additional stress which worsens the already poor prognosis for coastal wetlands worldwide. Regional losses would be most severe on the Atlantic coast of North and Central America, the Caribbean, the Mediterranean, the Baltic, and all small island regions. It is noteworthy that coastal wetlands in many developed countries appear threatened by sea-level rise.

Stabilisation could significantly reduce the losses of coastal wetlands as they are sensitive to the rate of sea-level rise, rather than the absolute change. In Figure 4, wetland losses have been simulated to the 2230s for the mitigated scenarios. In these cases, losses stabilise at levels similar to or below those under unmitigated climate change in the 2080s. Thus mitigation could be an important contribution to global conservation of coastal wetlands. However, for wetland conservation to be successful, the other factors causing wetland decline in many parts of the world also need to be addressed promptly to ensure that coastal wetlands survive to be able to benefit from climate policy.

Figure 4. Net wetland losses relative to 1990



Notes: Under unmitigated emissions (top line), S750 (middle line) and S550 (bottom line). Note that these losses are in addition to losses due to direct and indirect human destruction

Source: Arnell et al. (2002)

4.2.3 Global costs of sea-level rise

The preceding discussion has emphasised the importance of considering adaptation, and how the results of any analysis will depend strongly on how adaptation is considered. Top-down and integrated analyses have addressed these issues and illustrate some important points. Tol (2002a; 2002b) has examined a range of climate change impacts including sea-level rise. The underlying data source is primarily Hoozemans et al. (1993), supplemented by other data sources. It assesses the optimum protection response and then costs the consequences of the option, including protection costs, dryland and wetland losses and displaced people. While the author notes that the results are crude, the annual costs are only $13 billion/year for a 1-m global rise in sea level, as opposed to $47 billion/year by Fankhauser (1995b). The difference primarily reflects different assumptions concerning adaptation – Tol is assuming an optimum adaptation response within the constraints of the available data.

These results raise important questions about the potential and process of adaptation. In particular, there is a need to better define realistic adaptation processes. Further the underlying data and impact methods need to be improved as is being explore in the DINAS-COAST project (McFadden et al., 2003) (http://www.pik-potsdam.de/~richardk/dinas-coast/).

5. ADAPTING TO SEA-LEVEL RISE

While adaptation has already been discussed, it is useful to consider the available adaptation options in coastal zones. Adaptation acts to reduce the impacts of sea-level rise and climate change, as well as other changes (as well as exploiting benefits). These decisions need to be made in the face of the large uncertainty about future climate (and many other factors), so there is a need to think in a risk- and uncertainty-based manner rather than looking for deterministic solutions.

Given the large and growing concentration of people and activity in the coastal zone, autonomous adaptation processes are unlikely to be sufficient to respond to sea-level rise as already shown for flood and ecosystem impacts in Section 5. 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 planned adaptation measures. Planned adaptation options to sea-level rise are usually presented as one of three generic approaches (e.g., Bijlsma et al., 1996; Klein et al, 2001):

- *(Planned) Retreat* – all natural system effects are allowed to occur and human impacts are minimised by pulling back from the coast;

- *Accommodation* – all natural system effects are allowed to occur and human impacts are minimised by adjusting human use of the coastal zone;

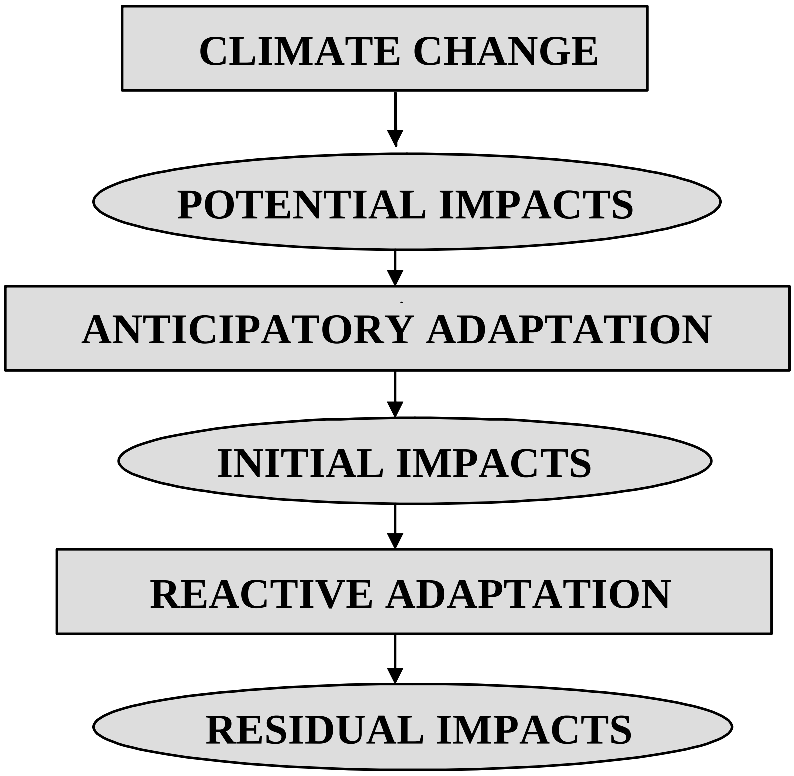
- *Protection* – natural system effects are controlled by soft or hard engineering, reducing human impacts in the zone that would be impacted without protection.

In practise, many responses will be hybrid and combine elements of more than one approach. It is also noteworthy that most assessments of adaptation only consider mixtures of retreat (or 'do nothing') and protection, and the accommodation option remains largely un assessed.

Given that adverse actual impacts of climate change are expected, the most appropriate timing of the response needs to be considered in terms of anticipatory versus reactive planned adaptation (or in practical terms -- What should we do today, versus wait and see until tomorrow?). Anticipatory decisions are made with more uncertainty than reactive decisions which will have the benefit of future knowledge. However, wait and see may lock in an adverse direction of development which increase exposure to sea-level rise. In terms of impacts, sea-level rise has *potential impacts* (Figure 5). Anticipatory planned adaptation can reduce these potential impacts to the *initial impacts*. Reactive adaptation (including autonomous adaptation) in response to the initial impacts further reduces the impacts to the *residual impacts*. The realistic magnitude of the initial and residual impacts is a key measure of vulnerability.

Given that many decisions at the coast have long-term implications, the coastal zone is an area where anticipatory adaptation needs to be carefully considered (cf. Smith, 1997; Fankhauser et al. 1999). Examples of anticipatory adaptation in coastal zones include upgraded flood defences and waste water discharges, higher levels for areas of land claim and new bridges, and building setbacks to prevent development (Bijlsma et al., 1996; McLean et al., 2001).

Figure 5. Definition of impacts of sea-level rise and climate change



Source: Nicholls (2002a)

While there is still limited experience of adaptation to climate change, there is abundant experience of adapting to climate 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. These stages were embedded within multiple policy cycles, and the adaptation processes was constrained by broader policy and development goals. Green et al (2000) argue along consistent lines that an adaptive management approach to climate change is clearly appropriate given all the climate and other uncertainties (see also National Research Council, 1995; Willows and Connell, 2002). An explicit "learning by doing" approach accepts these uncertainties and sees any intervention in the environment as an educated experiment and an opportunity to learn via careful monitoring and evaluation. It also recognises that the criteria for assessing the suitability of an adaptation approach is 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 problems (Pielke, 1998). In some cases, the focus of sea-level rise and climate change may help identify "win-win" situations that are worthy of implementation without any climate change. Other adaptation measures may offer immediate benefits in reducing impacts of short-term climate variability as well as long-term climate change.

Lastly, broader measures in terms of enhancing adaptive capacity and creating an environment where adaptation can more easily occur are also vital (cf. Smit et al., 2001). Such capacity building could focus on developing coastal management (WCC'93, 1994; Cicin-Sain et al., 1997; Cicin-Sain and Knecht , 1998). In most countries present rises in sea level are not addressed in coastal management even though we can observe sea-level rise on most of the world's coasts, illustrating the poor basis to plan for future rise. New coastal management efforts should be focussed on the most vulnerable locations, such as small island states.

6. DISCUSSION/CONCLUSIONS

Global-mean sea-level rise is one of the more certain impacts of global warming. This will result in a range of impacts including (1) increased flood risk and submergence, (2) salinisation of surface and ground waters, and (3) morphological change, such as erosion and wetland loss. All these impacts have been assessed in various ways, but the integrated assessments that are most useful to policymakers are less developed. Importantly, policymakers should note that the results of any assessment depends on the scale of assessment and the detailed methods utilised, as illustrated in the analysis of Turner et al. (1995) and Sterr (2003). Hence, there is a need to match policy questions and formulation to the appropriate level of assessment (Klein and Nicholls, 1999).

The challenge of modelling the impacts of sea-level rise and climate change in the future is the range of knowledge required to assess their consequences and impacts in the context of a coastal zone which is already experiencing multiple stresses due to other causes. More comprehensive studies that better communicate the full range of uncertainty would assess the full range of change scenarios rather than just a 1-m rise scenario on today's world. They would also assess the adaptive capacity and the range of adaptation options and their interactions, such as coastal squeeze of coastal ecosystems if hard flood defences are used. Better information on adaptation is critical for these studies to connect to the formulation of coastal management policy.

The preceding material has shown that there is a high impact potential, both in terms of human and natural systems (e.g., flooding and wetland loss). Climate mitigation will only reduce the amount and rate of sea-level rise, which will continue for hundreds if not thousands of years given a stable climate (the commitment to sea-level rise). Hence, while significant climate mitigation would reduce many impacts of sea-level rise in the second half of the 21st Century, for some impacts we may only be buying time to adapt, as the impacts will still occur in the 22nd Century. This is most important for those impacts that depend on the absolute rise in sea level (such as flooding), as opposed to those impacts that depend on the rate of sea-level rise (such as wetland change and loss). Based on the available knowledge, a combination of adaptation and mitigation would be the most prudent response to climate change for coastal areas. Hence, mitigation and adaptation policies are intertwined in the coastal zone and they need to be assessed together in an integrated manner to develop the best policy combinations for climate change in coastal areas.

The time and space scales of all aspects of climate change are highly challenging for human institutions and policy development given their global scale and potential impacts generations into the future. This effect is most extreme for coastal areas as the commitment to sea-level rise may commit coastal inhabitants to adapt to sea-level rise for hundreds if not thousands of years into the future (Watson et al., 2001). More focus on these impacts over long time scales, including methods for meaningfully evaluation of their significance would be useful, rather than treating the world like it ends in 2100 as is implicit in most existing analysis. As an example, a potential benefit of mitigation which is not often discussed is avoidance of large amounts of sea-level rise, such as collapse of the West Antarctic Ice Shelf. A more detailed analysis of sea levels over the next millennium (and their possible impacts) would be useful to formulate better climate policy in this regard, including developing worst-case scenarios for high impact/low probability events.

The high vulnerability of deltaic and especially small island settings is noteworthy. The analysis of flooding also suggests that Africa is vulnerable to increased flooding. More detailed assessment would identify the more vulnerable areas (or 'hotspots') within Africa and elsewhere. Detailed vulnerability assessment and the development of adaptation capacity should be focussed on these vulnerable areas. The small islands would seem to be the most needy regions. Existing efforts such as Caribbean: Planning for Climate Change (CPACC) and Mainstreaming Adaptation to Climate Change (MACC) in the Caribbean and PICCAP in the Pacific are good beginnings in this regard, although it is noteworthy that there is no similar effort for the Indian Ocean islands.

A range of further work that would be particularly useful to climate policymakers can be identified, including:

- More complete assessment of the range of possible impacts, including the consequences of low probability/high impact events such as the collapse of the WAIS;

- Continued development of local, national, regional and global impact and vulnerability assessments of coastal areas[9]. The local and national studies will provide detailed knowledge and allow validation of regional and global integrated assessment models. This will allow further quantification of the impacts of sea-level rise, including more consistent identification and mapping of vulnerable 'hotspots' at a national or sub-national level (for large countries);

- Consideration of the impacts of other climate change, as well as the wider implications of global change for the coastal zone;

- Continued assessment of the adaptation process in coastal zones, as this remains a major gap in our understanding. This can be linked to the more detailed assessments above.

All these studies would be supported by:

- Developing existing guidance on impact and vulnerability assessment, especially for the local and national studies;

- Developing better datasets on the world's coastal zones, as existing global coverages are far from ideal for integrated assessment.

Collectively, these efforts would improve identification of vulnerable areas to sea-level rise and climate change and the formulation of the best policies to manage and reduce this vulnerability.

[9] See www.survas.mdx.ac.uk, and www.pik-potsdam.de/~richardk/dinas-coast/.

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