# ACACIA Project

# Chapter 14:
# COASTAL ZONES

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**SUMMARY**

1. During the 20th Century, sea levels have risen 10 to 20 cm around much of Europe, while storm frequency and track have shown significant interdecadal variability in north-western Europe. These ongoing factors are already important contributors to the problems of flood risk, coastal erosion and coastal squeeze.
2. By the 2080s, global sea levels could be 20 to 105 cm higher than the 1961 to 1990 mean climate. Storm frequency and intensity may increase in Northern Europe and the large interdecadal variability will continue. However, climate change and variability is just one of the pressures facing coastal zones and their management over the next few decades.
3. These climate change scenarios will result in an increase in flood risk for coastal lowlands and increased rates of coastal erosion for cliffs and beaches. Quantitative analysis suggests that while northern Europe presently has the largest exposure, the incidence of flooding will increase more in southern Europe assuming no human adjustment or adaptation to climate change. Increases in storminess (due to short-term climate variability and/or long-term changes) would also increase storm damage and flood risk.
4. These climate change scenarios would also result in the rapid degradation of saltmarsh and intertidal ecosystems. The Baltic and Mediterranean coasts are most vulnerable due to their low tidal range and such ecosystems could be largely eliminated in these areas by the 2080s, given the ACACIA A2-High sea-level rise scenario.
5. The actual impacts of climate change will depend both on the magnitude of climate change and the human adaptation to that change. Many of the impacts could be avoided or managed effectively given appropriate proactive measures. This suggests the need to increase the capacity to manage the coast at short, medium and long time scales, with a particular focus on long-term coastal planning. To compliment these efforts, continued research on the potential impacts and adaptation measures to climate change is required. This research would have to address appropriate proactive adaptation options given the large uncertainties that exist concerning future climate and many other relevant factors.
6. Losses and changes to coastal ecosystems are one problem where adaptation measures may conflict with human use of the coastal zone. The natural response of wetlands with rising sea levels is for onshore migration, but this is stopped by rigid sea defences producing ‘coastal squeeze’ and a decline in wetland area. Managed retreat or realignment is appropriate if low-grade agricultural land is situated landward of the defence, but it is more difficult when higher value development exists landward of the defence. Thus, there is often a conflict between sustaining socio-economic activity and the ecological functioning of the coastal zone in Europe under rising sea levels. This needs to be explicitly addressed and resolved by coastal planning and management.
7. Global sea levels are likely to continue to rise for many centuries after 2100 irrespective of future emission pathways, as the oceans take millennia to reach equilibrium. Therefore, sea-level rise will remain an important issue within coastal management far into the future.

## 1. BACKGROUND

The coastal zone is where the land, ocean and atmosphere meet and hence comprises a terrestrial and a marine component. It is one of the more dynamic areas on the Earth's surface, experiencing large energy inputs from waves, tides and winds and changes in sea level at a range of time scales. Hence, while people often have an image of the coast as unchanging, its form is always evolving and substantial coastal changes have and are occurring.

The coastal zone in Europe is varied with a range of distinct environments in terms of coastal geomorphology, wave energy and exposure and tides. It is also an important focus for important population and economic centres. Human activities within the coastal zone include industry, urban and residential, tourism and recreation, transport, fisheries/aquaculture and agriculture (Rigg et al., 1997). One third of the European Union population lives within 50 km of the coast, with the proportion being 100% in Denmark and 75% in the United Kingdom and the Netherlands. 120 million people live in coastal urban agglomerations (Papathanassiou et al., 1998) and urbanisation is a continuing trend due to coastward migration and tourism development, particularly around the Mediterranean. The coast is also an important habitat of international significance with freshwater, brackish and saline marshes and intertidal and shallow subtidal habitats and it supports important fishery resources.

As populations have grown and economic activity has intensified so a range of often inter-related and conflicting pressures have emerged in the coastal zone focussed around agricultural use, industrial and port use, residential use, tourism, coastal water quality and fisheries (French, 1997; Papathanassiou et al., 1998). These in term have caused pressure for coastal development and land reclamation around estuaries and lagoons. For example, from 1960 to 1990 it is estimated that 1 km of unspoilt coastline was developed every day and 30 Ha of dune habitat disappeared. Given erosional trends and flood risks, there has been a widespread demand for (usually hard) defences. Hard defences reduce sediment input to the coastal system, intensifying erosional pressures and hence increase the need for hard defences. This vicious cycle has lead to armouring of significant lengths of the European coast. Hard defences also lock the coastal position and hence contribute to a coastal squeeze on eroding and retreating shorelines (Bijlsma et al., 1996). Human changes outside the immediate coast have also had adverse consequences. In this century, deltaic areas such as the Ebro, Rhone and Po have become threatened because they have been sediment-starved due to changing catchment management, particularly dam construction (e.g., Sanchez-Arcilla et al., 1998). Sediment input to the coast from smaller catchments has been similarly reduced.

These widespread coastal impacts of human interventions were not foreseen, and only now are some of their implications being fully appreciated. Most human activities can be characterised as having acted to reduce the resilient properties of the coastal system (compensating increases in resistant properties are sometime evident). This is an undesirable trend in the face of an uncertain future, including climate change (Nicholls and Branson, 1998). Moves towards more soft engineering, sediment recycling and managed realignment indicates a widespread change in thinking at the management unit level. Mapping and using coastal cells as part of coastal management is providing a broader framework to place projects in the wider context. Increasing efforts towards integrating coastal management are likely to allow more flexibility in planning for a changing coastal zone.

For coastal zones, climate change will add to the above stresses. The impacts of climate change on the coastal areas of Europe are expected to be overwhelmingly negative (Rotmans et al., 1994). The major impacts are expected to be increased flooding, increased erosion and permanent inundation, particularly for coastal ecosystems. Coastal morphology and human utilisation will condition the nature of these impacts and their implications: in general, coastal lowlands with microtidal conditions are most susceptible.

Using this context, this chapter examines the implications of climate change for Europe's coastal zone. It examines the potential impacts and response options, identifies vulnerable settings and areas and identifies policy implications and recommendations for further research. Firstly, the sensitivity of the coastal zone to present conditions is considered.

## 2. CURRENT SENSITIVITIES

Most of the issues raised by climate change already present widespread problems around Europe's coasts, including episodic storm damage and coastal flooding, and slower more continuous coastal erosion and coastal squeeze. While these problems may be linked with long-term climate change and historic sea-level rise, climatic variability and storms combined with changing land use are the most important contributors to these problems, particularly for flooding.

Coastal lowlands have always been flood-prone areas, but global sea-level rise, land subsidence and human management of these areas have all increased this risk. Large coastal areas such as (1) the western Netherlands, (2) the fens in Eastern England, and (3) the northeastern Italian coastal plain, including the Po delta are already beneath mean sea level and only remain land due to extensive sea defences and drainage infrastructure. Many more low-lying coastal areas are vulnerable to flooding from storm surges. In the 20$^{th}$ Century there have been a number of major flood events, including the 1953 flood around the southern North Sea, the 1966 flood in the German Bight and the 1966 flood of the northern Adriatic which is the flood of record for Venice. These floods all caused serious damage and in some cases, significant loss of life (see Chapter 1).

The main response to floods and storms has been the progressive upgrade of hard defences combined with more innovative techniques such as the provision of moveable storm surge barriers on estuaries such as the Thames, the Eastern Scheldt and the Europort channel (Rotterdam) to prevent such flooding. Flood warning is an integral part of flood defence and forecast techniques for coastal flooding have been developed. These provide warnings of extreme events and inform when surge barriers should be closed. Due to this investment, there is a widespread feeling that the flood risk has been reduced to zero, rather than to a small residual risk. In England and Wales, the design standard varies from a 1 in 5 year event for low grade agricultural areas to 1 in 200 year event for most urban areas, and a 1 in 1,000 year event for London (Environment Agency, 1999). (Note that exceptionally the design standard for most of the Netherlands is a 1 in 10,000-year event). Occasional overtopping or failure of defences and real flood events are an inevitable indicator of this residual risk. As an example, the 1990 coastal flood at Towyn, North Wales flooded 2,200 homes and 5,000 mainly elderly people required evacuation. In addition to the expected government interest, the insurance industry in Britain is concerned about its exposure to an extreme coastal flood (as it provides widespread flood insurance) (Nicholls and Branson, 1998). Therefore, managing this residual risk is a key issue (see also Chapter 10).

Coastal erosion during storms can also be an important problem if it reduces the wave protection afforded to the coast or if it degrades beaches for the tourist season. However, short-term storm erosion is usually followed by accretion and hence little or no net change. As well as these episodic events, slower more continuous erosional changes are also presenting problems. Long-term coastal erosion appears to be a widespread problem in Europe (European Commission, 1999). However, the data on erosion rates needs to be improved to reflect the range of timescales being observed and better distinguish long-term trends from cyclical behaviour. Nonetheless, long-term erosion rates of 0.5 to 1 m/yr, and even up to 2 m/yr are widely reported for both cliffed coasts and beaches. Saltmarsh and other estuarine habitats are observed to change even more rapidly over decadal time scales, particularly in periods of increased storminess (see below). Coastal erosion is the result of a sediment deficit, and recent sea-level rise is one factor that can contribute to a regional deficit to the coastal sediment budget, particularly on coasts with open lagoons and estuaries which act as sediment sinks under rising sea levels (Stive et al., 1990). Changes in storm frequency and track also change patterns of coastal erosion. Increases in wave heights in north-west Europe over the last 30 years have increased erosional processes (Environment Agency, 1999), but looking over the last 100 years, it seems that this observed increase is part of long-term climate variability rather than a long-term trend (WASA, 1995).

Coastal squeeze is also increasingly recognised as an important problem, particularly around the North Sea. The slow but steady degradation of the coastal fringe around much of Europe has gone largely unnoticed until the last 15 years (see Box). Managed retreat and/or managed realignment on low-grade agricultural land are presently being considered as a response to coastal squeeze in most countries around the North Sea. This response will also be applicable to future climate change and accelerated sea-level rise (see Section 3).

[place Box on Coastal Squeeze here]

## 3. BIOPHYSICAL AND SOCIOECONOMIC IMPACTS OF CLIMATE CHANGE

Europe's coastal zones are sensitive to changes in climate as illustrated in Table 1. Even small rises of sea level or increases in storm frequency can contribute to an increased flood risk or a decline in coastal ecosystems, unless there is appropriate adjustment or planned adaptive response. Other climate change factors such as rising seawater temperatures could have negative effects, such as an increased possibility of algal blooms and their attendant aesthetic and health problems. There may also be important benefits such as extending the tourist season and increasing the attractiveness of northern Europe as a tourist destination (see also Chapter 12).

Climate change will first effect the biophysical environment and this in turn affects human activities and results in a cascade of impacts. In this section, we first examine the climate change scenarios, and then consider the first-order (biophysical) impacts, followed by the second-order (socio-economic) impacts.

### 3.1 Climate Change Scenarios

Sea-level rise is the best understood of the climate change impacts. For impact and adaptation analysis we require scenarios of relative sea-level change. This is the sum of three components: (1) global sea-level change (due to changes in ocean volume), (2) regional sea-level change (due to meteorological and oceanographic dynamical changes) (Gregory, 1993), and (3) land uplift and subsidence (due to natural and anthropogenic geological processes). While relative sea levels have fallen in many of the formerly glaciated areas such as Sweden and Finland, tide gauge data shows that most of Europe has experienced a long-term trend of relative sea-level rise over the $20^{th}$ century (Figure 1). This can be attributed to global sea-level rise of 10 to 25 cm/century during the $20^{th}$ Century (Warrick et al., 1996), often augmented by a broad tendency for slow subsidence away from areas directly affected by glaciations during the last Ice Age.

The ACACIA sea-level rise scenarios represent an acceleration in the rate of rise and encompass a global rise of 20 to 105 cm rise by the 2080s, relative to the 1961 to 1990 mean (see Table 3 in Chapter 3). Sea-level rise from the 1961 to 1990 mean to a 1986 to 2015 mean (centred on the year 2000) is assumed to be 4 to 5 cm (or about 1.8 mm/yr). The regional oceanographic effects are modelled for the Atlantic in the HadCM2 and HadCM3 climate change simulations, but the Mediterranean and Baltic Seas are excluded. These simulations suggest that any effects on European sea levels over the 21$^{st}$ Century are minor and this effect is not considered further here. However, further investigation of this effect for a range of forcing scenarios and climate sensitivities would be prudent.

In contrast, differential land uplift and subsidence is occurring across Europe and will have an important influence on relative sea levels as indicated by the variation in the trends shown in Figure 1. At nationally-averaged scales the differences are a 5 cm/century fall in land level to a 60cm/century rise in land level (see Table 4 in Chapter 3). Northern countries (e.g., Finland, Sweden and Denmark) are rising due to post-glacial rebound and many other countries (Ireland, France, Belgium, Netherlands, Germany, Spain, Portugal, Italy and Greece) are sinking. At sub-national and local scales there are greater variations. Certain areas such as deltas naturally subside, as shown in the Rhone delta, France (Suanez and Provansal, 1996): human activity often exacerbates this process. As two extreme examples of sea-level change, in the Gulf of Bothnia land levels are rising at up to 1 m/century while in the Po delta, anthropogenic fluid withdrawals have contributed to a maximum subsidence of 3 m over the last 30 years (Cecini, 1998). In many coastal lowlands oxidation and erosion of peat deposits is an additional process causing a steady decline in land elevation with significant long-term implications. For example, in the Fens, UK the decline in elevation is reported at about 1 to 2 cm/yr in large part due to this effect, although only limited data is available. Due to our incomplete knowledge of the local and regional components of sea level, relative sea-level rise scenarios are often difficult to develop and most existing impact assessments have applied uniform scenarios of relative sea-level rise across the study area or study country.

Many other climate factors could have significant coastal implications given global warming (e.g., Table 1). However, in many cases the future changes to these climate factors given global warming are less certain than sea level, with a possibility of increase or decrease. For this reason, most impact assessments have only considered sea-level rise. This chapter reflects this bias and the main focus is on sea-level rise with discussion of other climate factors, where appropriate.

Given the destruction and potential loss of life associated with coastal storms, this climate factor deserves particular attention. Changes in storminess could be produced by several factors, including changes in the strength and/or track of coastal storms. Storm occurrence and wave climate has displayed significant interannual and interdecadal variability over the 20$^{th}$ century, but unlike sea level, there is little evidence of long-term trends (WASA, 1995). Given global warming, the balance of evidence suggests an increase in storminess in northern Europe, while elsewhere changes are uncertain. This change implies the occurrence of bigger storm surges and more extreme waves around northern Europe. However, two models of storm surge around the British Isles driven by climate change simulations suggests limited changes in surge elevations given doubling of atmospheric $CO_2$ concentrations (Flather and Smith, 1998; Lowe and Gregory, 1998). Further research is recommended. The variability in storminess already noted will interact with sea-level rise.

Beyond 2100, global sea level are likely to continue to rise for many centuries, irrespective of future emissions scenarios (Wigley, 1995). This is because the heat from global warming takes millennia to penetrate the entire ocean depth. This effect has been termed ‘the commitment to sea-level rise’.

## 3.2 First Order Impacts of Climate Change

Climate change could have a range of direct effects on Europe's coastal zone. The three most serious physical impacts of sea-level rise are: (1) inundation and displacement of wetlands and lowlands; (2) coastal erosion; and (3) increased storm flooding and damage. Other impacts include salinisation and rising water tables and impeded drainage. All these problems are already evident on European coasts so climate change will exacerbate existing problems rather than create fundamentally new problems. The magnitude of impacts will vary from place-to-place and will depend on a variety of factors, including the magnitude of relative sea-level rise and other aspects of climate change, coastal morphology and human modifications. It is also important to note that climate change interacts with all other coastal processes. For instance, a sediment supply could counter erosion due to sea-level rise, and *vice versa*. Therefore, the reduction in sediment input into the coastal zone due to human management noted in Section 1 is exacerbating our vulnerability to sea-level rise and climate change in general.

The coastal environments found within Europe which are most threatened by climate change are deltas, low-lying coastal plains, islands, beaches, coastal wetlands, and estuaries (Beniston et al., 1998). Tidal range is a key factor -- in general, the smaller the tidal range, the greater the susceptibility to a given rise in sea level. The Mediterranean and Baltic coasts have a low tidal range (<1 m) which suggests they will be more vulnerable to sea-level rise than the Atlantic Ocean and North Sea coasts.

Using a combination of process-based studies, local and national assessments and regional/global models, the different impacts of climate change are discussed in turn.

### Inundation and displacement of lowlands and wetlands

In Europe, most inhabited coastal lowland areas are already protected from temporary or permanent marine incursion. While sea-level rise may cause problems of drainage and salinisation (see below), loss of these areas will be associated with planned abandonment of the defences, or storm-induced failure. Looking at three national assessments (Table 4), large and significant areas of land totalling about 18,000 $km^2$ are potentially threatened given a 1-m rise in sea level. Large areas are similarly threatened in other EU countries, although precise areas are less defined.

Seaward of the defended lowland areas are extensive marsh and bare intertidal sand and mud wetland areas, particularly around the estuaries and lagoons on the Atlantic and North Sea coasts (Table 2). Such wetlands were formerly much more extensive and have been reduced by reclamation (i.e. land claim). While direct destruction of these wetlands by reclamation is now less common, they are still experiencing active losses due to present sea-level rise and coastal squeeze.

The wetland loss model described by Nicholls et al. (1999) was used to assess the potential decline of these systems given the ACACIA scenarios. The potential for vertical accretion and horizontal migration in the face of sea-level rise is assessed based on present conditions. ($CO_2$ fertilisation is expected to increase the growth of wetland plants, which could help to counter some of the impacts described below, but this effect has not been investigated). Given a range of uncertainties, a low and a high loss estimate are determined. The potential for vertical accretion is partly controlled by tidal range – i.e., the smaller the tidal range the more susceptible the wetland to loss. The potential for horizontal migration is assessed based on coastal geomorphology and human population density (it is assumed that wetland migration will not occur if population density $\geq$10 people/$km^2$). Under these assumptions, hardly any wetlands in the EU can migrate onshore, producing a coastal squeeze (see Box).

Figure 2 shows wetland losses due to sea-level rise by the 2080s. Losses due to other causes such as reclamation are additional to those shown, but are expected to be small due to legislative protection and increasing recognition of the value of these systems. By the 2080s, the losses for the EU range from 5 to 25% of the stock in the 1980s. However, the Baltic and the Mediterranean stand out with near-total losses of the wetlands in these areas given the ACACIA A2-high climate scenario. This high vulnerability reflects the low tidal range of these two areas. For the Baltic, the lower rate of relative sea-level rise for Finland and Sweden due to post-glacial rebound is of little practical benefit, as most of the threatened wetlands are in Germany. While the Atlantic and North Sea coasts have a lower vulnerability, the characteristics of the surviving saltmarsh and intertidal areas may be greatly altered compared with today. This has not been evaluated. Such losses (and changes) could have serious consequences for biodiversity in Europe, particularly for migratory shorebird populations that depend on these wetlands, particularly during the winter (see Chapter 6). Wetland decline may also have adverse impacts on coastal fisheries (see Chapter 9).

The available national results also indicate that large areas of coastal wetlands could be lost given a 1-m sea-level rise and no human response (Table 4). Assessments in England and Wales show that substantial losses of saltmarsh and intertidal habitat have occurred over the last few years (Pye and French, 1993). However, long-term proposals for managed retreat and realignment are being recommended in the current first generation of Shoreline Management Plans (see Section 5). If these are implemented, it is forecast that by 2050 there will be a gain in saltmarsh and intertidal habitat at the expense of coastal freshwater habitats under sea-level scenarios between the B1-low and B2-mid scenarios(Lee, 1998). These coastal freshwater habitats are largely artificial in origin and the proposed retreat and realignment is simply allowing the coast to revert to a more natural form. However, creation of new freshwater habitats in more sustainable inland locations to replace the losses in coastal locations could be costly.

Deltas provide some important coastal lowland areas that are particularly vulnerable to climate change. Deltaic systems such as those at the mouths of the Ebro, Rhone and Po rivers are important sites for human occupation, agriculture and coastal wetlands (Capobianco, 1996). Climate change will modify both the processes which act to maintain (or create) deltas and those which act to destroy them (Sanchez-Arcilla and Jimenez, 1997). Creational processes are primarily related to sediment supply by rivers, which is controlled by run-off and land cover. Chapter 4 suggests that run-off may decline in southern Europe under the ACACIA scenarios. Destructive processes are related to sea-level rise, storms and wave climate. Under the ACACIA scenarios, the increase in sea-level rise seems the most serious climate factor, compounded by reduced run-off for some of the Mediterranean deltas. Therefore, deltas are particularly threatened by climate change. Understanding the influence of catchment management on recent and future deltaic evolution is also fundamental to any realistic assessment.

**Coastal erosion**

Coastal erosion of beaches and cliffs is already a pervasive problem on European coasts. While it is agreed that if a coast is already eroding then an acceleration in sea-level rise will exacerbate the erosion, the precise causal link between sea-level rise and coastal erosion is controversial. The Bruun Rule suggests that shoreline retreat will be about 100 times the rise in sea level. In the case of the ACACIA scenarios this would amount to 25 to 110 m of shoreline recession in most EU countries by the 2080s. Given that human infrastructure is often built within 50 to 100 m of the present shoreline, changes of this magnitude would have important human impacts. Near inlets, the changes induced by sea-level rise may be much greater as the associated lagoons and estuaries become large sinks for sand as their equilibrium response is to rise with sea level (Stive et al., 1990).

Cliff retreat will also increase in response to accelerated sea-level rise, although it is likely that the response will be less than for beaches. Bray and Hooke (1997) have argued that low cliffs composed largely of silt and clay will be most sensitive to sea-level rise. While cliff erosion leads to land loss, it should be noted that it will also increase the sediment supply available to beaches and coastal wetlands, and hence help them respond to sea-level rise.

The increased storminess that is likely in northern Europe will also enhance coastal erosion and increase the back and forth movement of the shoreline. Natural features such as sand dunes and shingle ridges will be more prone to breaching and overtopping, exposing the areas to landward to flooding and destructive waves (see Increased storm flooding and damage, below). There is likely to be other changes to the cross-shore sediment budget, which may increase erosional trends such as increased storage of sand below low water. Rates of longshore transport are also likely to change, but the consequences of this are uncertain and it is likely to benefit some areas and impact others. To emphasise the potential of such effects, Peerbolte et al (1991) calculated that the response costs to an adverse 5% change in wind direction (and hence wave climate), would be equivalent to a 60-cm rise in sea level for the Netherlands.

As already noted for deltas, changes in run-off will also influence the sediment supply to the coast and hence influence erosion rates. Chapter 4 suggests a broad increase in run-off in northern Europe and a decrease in run-off in southern Europe, although there is variation between the ACACIA scenarios. This suggests a general decline in sediment supply to the coast in parts of the Mediterranean that might exacerbate coastal erosion from other causes.

### Increased storm flooding and damage

Sea-level rise raises surge elevations and allows floods and destructive waves to penetrate further inland. However, most low-lying coastal areas in Europe are already protected from flooding, so a rise in sea level will not automatically cause serious inundation of human-occupied areas (Beniston et al., 1998), with the exception of unusual locations such as Venice (see Box). However, assuming other climatic factors remain constant, the protection offered by the flood defence will decline as sea level rises. Changes in storminess and the frequency of storm surges will also influence the frequency of flooding. This is due to a direct increase in flood levels and also due to the effects of erosion which increase the likelihood of failure of the natural and human protection from flooding.

### Salinisation

As sea level rises or freshwater flows diminish, so seawater can push further inland along rivers and into aquifers (see Chapter 4). Freshwater flows might be reduced due to climate change, or increased exploitation of water resources. In general, increased catchment management has lead to reduced water (and sediment) fluxes to the coast. In southern Europe, this trend will be exacerbated by climate change as a significant decrease in run-off is projected, while in northern Europe, increased run-off is expected (Chapter 4).

Certain aquifers such as the sand dunes of the western Netherlands and surface waters near the heads of estuaries are potentially vulnerable to salinisation. However, this factor remains relatively unstudied in Europe and is probably of less significance than the other impacts considered previously, although there are likely to be local exceptions.

### Rising Water Tables and Impeded Drainage

Rising sea levels cause a rise in water tables in coastal areas and reduces the efficiency of drainage. These hydrological changes lead to an increased likelihood of flooding during major rainfall or run-off events, and may promote wetland formation. Precipitation intensity is expected to increase with global warming which may exacerbate these effects.

### Other Impacts

Sea-level rise could have many other impacts on coastal areas, including (1) changes in tidal range, (2) changes in sedimentation patterns and water depths, and (3) decreases in the amount of water reaching the sea bottom. These impacts could be significant on issues such as navigation, or the functioning of shallow water ecosystems. Other aspects of climate change may also be important and they will interact with these changes. For instance, rising sea water temperatures may allow more southerly species to migrate northwards, which would interact with other ecosystem changes. However, these effects have not been widely quantified in impact assessments to date.

## 3.3. Second-Order (and Higher) Impacts of Climate Change

The biogeophysical impacts of climate change will in turn potentially impact many human activities in the coastal zone such as tourism, coastal industries, oil refineries and power stations, agriculture and human habitation. The available national results all emphasise the large human values that could be impacted by climate change without any human response (Table 4). Tens of millions of people live in the zone potentially affected and the increase in flood risk for coastal populations and the loss of capital assets (represented by GDP at risk) could be large. Sub-national and local studies from East Anglia, UK (Turner et al., 1995), South Coast, UK (Ball et al., 1991), Rochefort sur Mer, France (Auger, 1994), and the Ebro delta, Spain, the Rhone delta, France, and the Po delta, Italy (Capobianco, 1996), as well as regional reviews (Tooley and Jelgersma, 1992, Nicholls and Hoozemans, 1996) produce similar results. Many of Europe's largest cities– such as Athens, Naples, Marseilles, Barcelona, Lisbon, London, the Randstad (Holland), Hamburg, Copenhagen and Stockholm – are built in coastal locations. In all cases, climate change could have important impacts and it is an important factor to consider for long-term coastal planning and development (Frasetto, 1991). The Dutch economy has a particularly high exposure to these risks as might be expected.

Other human values that may be impacted by climate change at the coast include cultural and archaeological resources; resources that are sometimes only now being fully recognised (Fulford et al., 1997; Pye and Allen, 2000; see Box on Venice).

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To quantitatively assess how flood risk to human populations might change under the ACACIA sea-level rise scenarios, the regional/global model of flooding described by Nicholls et al (1999) is used. This considers the incidence of flooding in response to the interacting effects of sea-level rise, population change and improving protection standards (as living standards rise). All other climate factors are assumed to be constant. Calculations are made by country, and take the estimates of mean land uplift/subsidence in Table 4 (Chapter 3) to transform the *global* scenarios into *national* relative sea-level scenarios. The population scenarios are taken from the World Bank and the protection standards are inferred using GDP/capita as an "ability to pay" parameter. For the EU countries, coastal population and protection standard show little change, so the major changes are due to the sea-level rise scenarios. For the purposes of the analysis, it is assumed that the protection standard is not upgraded to allow for any sea-level rise.

In 1990, 24 million people were estimated to live beneath the 1 in 1,000 year storm surge within the European Union with the largest exposure in northern Europe. However, these people are generally well protected from flooding and only about 20,000 people are estimated to experience flooding every year (Table 3). The evolving baseline for the 2020s through to the 2080s without any sea-level rise is also shown in Table 3. The average annual people flooded decreases slightly, reflecting a projected decline in the EU population. This may underestimate the actual flood risk as coastal populations may still increase under the scenario of falling national populations due to migration to the coast. Figure 3 shows the relative increase in the number of people flooded per year and for the entire EU and the southern and northern EU. Firstly, it is important to note that there is a large range for each estimate, reflecting the wide range of uncertainty for the climate scenarios. By the 2080s, the EU would see at least a doubling of the incidence of flooding, and possibly more than a 100-fold increase in the incidence of flooding (the estimates are very sensitive to the standards assumed for the existing flood protection). (As a reference, aggregated results from national studies of Germany, the Netherlands, and Poland (Table 4) show about a 10-fold increase with a 1-m rise scenario). The southern EU is much more vulnerable to these changes than the northern EU. This reflects that the storm surge curves in southern Europe are flatter than those in northern Europe and hence the same rise in sea level causes a larger increase in flood frequency.

In addition to people flooded, the projected increases in the frequency of flooding would have a range of direct and indirect, tangible and intangible impacts on human activity in the coastal zone. This would include industrial and port activity (see Chapter 11), tourism (see Chapter 12), locally on agriculture (Chapter 8) and human health (Chapter 13), to give some of the important impacts. Such an increases in the incidence of flooding would be unacceptable to coastal populations, and some proactive planning to manage the flood risk is required (Section 5). While the second-order and higher impacts of climate change on coastal zones need to be better understood, even with the present level of knowledge it is clear that the ACACIA scenarios would result in significant impacts without appropriate adjustments and adaptation.

The impacts of increasing storminess in northern Europe on the oil and gas industry is one area of concern which warrants further investigation.

## 4. KEY PRESSURE POINTS AND IMPACTED DOMAINS

Although the impacts of climate change on the coastal zone in Europe are only partly understood, some key issues can already be identified. The impacts of climate change will vary within Europe and this conditions a variation in vulnerability. We can distinguish between regional differences in vulnerability such as for flood risk and wetland loss, and vulnerable coastal settings such as coastal ecosystems, deltas, islands, and developed coasts (Bijlsma et al., 1996; Nicholls and Mimura, 1998). Biophysically, the Mediterranean and the Baltic coasts are more vulnerable to climate change than the Atlantic and North Sea coasts. The former areas are both microtidal with a spring tidal range of <1 m. This result is manifest in the results for coastal wetland loss which noted the possibility of near-total loss of coastal wetlands in both regions. Rates of relative sea-level rise tend to be higher in the Mediterranean than the

Baltic, making the Mediterranean the more vulnerable area. The greater increase in flood incidence shown for the southern EU in Section 3.3 is also related to the low tidal range in the Mediterranean. Other factors such as declining sediment supply to parts of the Mediterranean coast by rivers would exacerbate these problems. As a comparison, within the ESCAPE model, France, Italy and Denmark appear to be the three most vulnerable countries to sea-level rise, while northern Spain, Ireland and northern Britain appear least vulnerable (Rotmans et al., 1994). (Note that Sweden and Finland were not considered).

Coastal wetland ecosystems and deltas are highly vulnerable to climate change as their location is intimately linked with present sea level. Any rise or fall of sea level, necessitates a horizontal or lateral shift in their location if they are to survive. They are also sensitive to wider human management such as changes in catchment management, or the provision of hard defences. Deltas have been most dramatically effected and catchment management, and dam construction in particular, has generally reduced sediment (and freshwater) fluxes, increasing their vulnerability to sea-level rise and other climate change.

Most islands appear vulnerable to climate change due to their more limited resources. Considerable attention has been focused on island nation states external to Europe such as the Maldives, or the Marshall Islands. However, islands within nations may have similar problems. In the case of the Mediterranean islands, they have a low resource base and have often been extensively developed for tourist purposes. Climate change would exacerbate problems of beach erosion and degrade the primary resource for coastal tourism. To sustain a beach, and hence a tourist industry, beach nourishment (artificially adding sand to the beach) will be essential and this may require (the costly) shipment of sand external to the island as internal sources are often not available, or becoming exhausted. Declines in rainfall also threaten the islands drinking water supply. This suggests a continued move towards desalinisation as an important element in the water supply of coastal islands in the Mediterranean (see Chapter 4). The implications of climate change for other islands within the European Union is less clear, but worthy of further investigation.

In addition to beaches on islands, all developed coasts with beaches and the activities that are associated with them face important choices in all locations. Generally development is close to the shoreline so natural dynamics cannot be allowed. Any decline or loss of the beach will undermine any hard defences and necessitate an upgrade or beach nourishment. The long-term demand for nourishment needs to quantified so that more strategic planning can occur.

All human activities in the coastal zone will be affected by climate change. Activities which appear most vulnerable to climate change include tourism (as already discussed), ports and harbours and the offshore oil and gas industry. The implications of climate change should be investigated in each case.

## 5. POTENTIAL ADAPTATION

People will tend to respond to the threat of climate change on coastal zones and hence reduce the actual impacts. It is useful to distinguish spontaneous adjustments which are happening continuously from planned adaptation which involves both policy changes and more co-ordinated actions. While many adjustments are possible to climate change, such as using the renewal cycle to upgrade infrastructure, or changes in prices to reflect improving knowledge, in general it appears that most responses will require large-scale planned adaptation to be effective (Klein et al., 2000). Three broad response strategies are distinguished:

- reduce the risk of the event by decreasing its probability of occurrence
- reduce the risk of the event by limiting its potential effects

- increase society's ability to cope with the effects of the event

These strategies have been termed "protect", "retreat", and "accommodate", respectively. Protection is usually associated with coastal squeeze and hence a decline in natural functions and values, although soft protection approaches may not raise this problem.

More broadly, improving coastal planning and management and working towards enhancing the resilience of the coastal system to respond to the uncertain changes in the future could be an effective strategy to manage climate change (Nicholls and Branson, 1998). Coastal systems have a great capacity to respond to climate change if given sufficient space and/or sufficient sediment supply to adjust their form. Given that Europe's coastal zones are heavily used we cannot just let nature take its course, but working with nature as much as possible should help to sustain coastal ecosystems and minimise response costs.

The actual strategy chosen will depend on local and national circumstances, including the economic and ecological importance of the coastline, the technical and financial capabilities, and the legislative and political structure of the countries concerned. While optimum response strategies have yet to be developed, it is likely that a range of responses will be the norm within any country (Bijlsma et al., 1996). Some published analyses show that protection can be justified for most of Europe's coast given present uses and land values (Fankhauser, 1995). However, the results are dependent of the scale of analysis. Turner et al (1995) analysed protection in East Anglia, England. At an aggregated scale that considers East Anglia as one management unit, protection can be justified for the entire coast given a 50-cm rise in sea level by 2050. However, this is not the scale at which coastal management decisions are made. When the 113 individual flood compartments are evaluated independently, 20% would optimally be abandoned even for present rates of relative sea-level rise (10-cm rise in sea level by 2050). (Note that this analysis assumes that there is no interaction between flood compartments, so abandoning one will not affect its neighbours – in many cases this will be an invalid assumption). However, it reinforces the conclusion that a range of responses will be appropriate.

Protection options may also be influenced by the availability of suitable materials such as sand for beach nourishment. In Cyprus, the coast is no longer receiving new supplies of sand as a result of catchment regulation and management (Nicholls and Hoozemans, 1996). Erosion is expected in response to sea-level rise, but there are no ready sources of sand available for beach nourishment. Yet maintaining the beach is critical to the tourist industry. While this problem has not been analysed in detail, external (and hence costly) sources of sand may be required for beach nourishment. Many other Mediterranean islands appear to have similar problems, and in the absence of appropriate assessments, these problems may be widespread.

Some national estimates of protection costs assuming that all developed areas are protected are given in Table 4, primarily for a 1-m rise in sea level. In terms of adaptation costs, Poland appears more vulnerable than Germany and the Netherlands (Table 2). The absolute response costs for Germany are larger than for the Netherlands, reflecting the relatively long German coastline.

Some adaptation that anticipates climate change is already being implemented and this seems to be raising important questions about long-term coastal management (Klein et al., 1999). The Netherlands is highly threatened by sea-level rise (Table 4), with about 60% of the country (23,600 $km^2$) being in the potential impact zone (Baarse et al., 1994). A new national law "outlaws" erosion and mandates maintenance of the present shoreline position via ongoing beach nourishment (Koster and Hillen, 1995). However, a debate about the optimum response continues with some advocating a more dynamic response, including a mixture of holding the line, allowing some retreat, and coastal advancement in areas where more land is required (Klein et al., 1998). This debate includes an explicit consideration of maintaining and enhancing coastal resilience to compliment protection.

In Britain, coastal cells have become the basis of shoreline management and about 40 shoreline management plans which cover the entire coastline of England and Wales are finished or nearing completion (U.K. Ministry of Agriculture, Fisheries and Food et al., 1995; Leafe et al., 1998). One outcome of the approach will be maintaining the natural supply of sediment to the coast. As part of these efforts, managed realignment of sea defences in estuaries is attracting increasing attention, including trial experiments (Klein et al., 1999). Low grade agricultural land (which is often more valued as freshwater wetlands) is given up to the sea as flood defences are abandoned or relocated inland. If managed realignment is practise at a large scale, it will help to maintain natural values and the flood protection benefits of coastal wetlands under a rising sea level. However, there will be a net loss of freshwater ecosystems (Lee, 1998). In Britain, about 100 ha of land would need to be released every year just to counter present rates of saltmarsh loss due to sea-level rise. While the economic analysis of Turner et al (1995) would suggest that there are many suitable sites available, this requires strategic planning which is consistent with the shoreline management planning already described. Nonetheless, it remains unclear if managed realignment at the scale necessary to sustain the existing stock of saltmarsh will be both technically and politically acceptable. Given the similar problems on other European coasts, the possibility of managed realignment is likely to be widely explored in Europe.

Around the Mediterranean, models of deltaic response to climate change and frameworks to analyse vulnerability and sustainability are being developed (Capobianco, 1996; Sanchez-Arcilla et al., 1998). This raises the prospect of a dynamic management approach which more effectively harnesses the natural inputs and processes within deltas to counter global and local (due to subsidence) sea-level rise, rather than moving to hard defences.

One pertinent issue is cross-border transport of sediment, which has costs within the country of origin, but reduces the vulnerability of the receiving country to climate change. For instance, coastal erosion of Holderness in eastern England helps to sustain saltmarshes in the Wadden Sea in the Netherlands and Germany (Nicholls and Mimura, 1998). This suggests a need for some management at a regional scale for the coastal impacts of climate change.

In conclusion, adaptation to climate change is likely to lead to a range of reseponse options. One common problem across Europe for coastal management is developing strategic management approaches, which both allow continued human utilisation of the coastal zone and preserve coastal ecosystems given sea-level rise (Nicholls and Mimura, 1998). Given the commitment to sea-level rise (Section 3), it would also be prudent to consider the impacts of climate change beyond 2100. Sustaining coastal ecosystems under a rising sea level will be a coastal management issue long into the future.

## 6. IMPLICATIONS FOR RELATED SECTORS

The changes to the coastal zone that may be induced by climate change will have important implications for many human activities. While many of these implications are negative, there will also be some beneficial changes such as increased demand for civil engineering and construction services in coastal areas.

**Coastal ecosystems and biodiversity:** Climate change and sea-level rise in particular has significant implications for coastal ecosystems (see Chapter 6). These systems are often already stressed by human activities, including direct destruction in some cases, so climate change will exacerbate an already adverse trend. Coastal wetlands are predicted to decline, particularly around the Baltic and Mediterranean, while habitats such as beaches and dunes will experience erosion and a likely decline in area and pressures to protect previously "natural" coastal areas may emerge. However, these changes are highly sensitive to coastal management policy. In England and Wales, a policy of hold the line everywhere will lead to a significant decline in saltmarsh and intertidal habitats (and a large rise in the cost of coastal defences). In contrast, managed retreat and realignment as recommended in a series of recently completed Shoreline Management Plans could result in a large net gain in saltmarsh and associated habitats, but at the expense of coastal freshwater marshes (Lee, 1998). Similar (but non-coastal) freshwater habitats can be recreated further inland in more sustainable locations than the existing freshwater marshes, so changes at the coast may have land use policy implications elsewhere. It is likely that all the other countries bordering the North Sea will face similar choices. Considering coastal dunes, dynamic preservation of the 1990 shoreline using beach nourishment has been selected as the response to erosion on the coast of the Netherlands, whatever the cause. Therefore, given the sand resources necessary, the survival of the national dune stock is assured irrespective of future climate (see Section 5).

Trends for biodiversity are less clear, but a decline in coastal ecosystems would be an adverse trend.

**Insurance:** it is estimated that a repeat of the 1953 coastal floods in England would cost about 7 to 8 billion Euros today, while a flood of London alone would exceed 10 billion Euros. While these losses are unlikely to be fully insured, this sum gives an indication of the potential losses which coastal flooding could impose on the insurance industry. Increases in flood risk due to climate change are a threat to the insurance industry in areas where flood insurance is available (presently the United Kingdom and Ireland, although future availability is likely to change (see Chapter 10))

**Tourism:** The shoreline is the single most important tourist resource in Europe so losses and changes due to climate change threaten the tourist industry (Chapter 12). Beach erosion is already a widespread problem in Europe that will be exacerbated by sea-level rise. Beach nourishment is being increasingly used within the European Union as a response to such erosion problems to maintain the protection and recreational functions of the beach (Penning-Rowsell et al., 1992; Hamm et al., 1998). As already noted above, the Netherlands has selected dynamic preservation of the 1990 shoreline using beach nourishment as its primary response to future erosion from whatever cause. While beaches can be sustained with this approach under scenarios of rising sea levels, the long-term benefits versus costs need to be evaluated. This will include the availability of sources of suitable sediment and the long-term implications of their exploitation on other coastal resources such as fisheries. Given the growing demand for nourishment it is likely that sand will be moved over greater distances than has been the norm to now. The cost implications of these trends and their consequent implications for the sustainability of beach-based tourism have not been evaluated.

**Health:** Human health is adversely affected by flood events (see Chapter 13). Therefore, increased coastal flooding would have important health implications. Changes to coastal ecosystems may also have important implications for human health in terms of increased incidence of hazardous agents such as algal blooms, but this is much less certain (see Chapter 13). Such changes are occurring independently of climate change due to changes in factors such as nutrient inputs, overfishing, etc. However, climate change reinforces and exacerbates such changes by allowing more southerly species to move north, and influencing primary productivity.

**Ports and Harbours:** This sector may benefit from climate change. Higher sea levels will lead to greater water depths and hence a small decline in dredging requirements. However, the draft of ships has increased substantially and harbour channels have often been enlarged and deepened by several metres over the last few decades. This trend seems set to continue, so the benefits from climate change may be negligible compared to other dredging requirements. Other uncertain effects include changes in storminess, with uncertain impacts, and changes in rates of littoral drift that may necessitate changes in dredging and modification to harbour entrances. Adverse impacts include the increased flooding of dockside areas that may necessitate progressive raising. However, with suitable proactive planning, this could be incorporated within the renewal cycle (cf. Bijlsma et al., 1996). In high latitudes, rising temperatures will reduce the extent of sea ice and hence reduce the operational costs of ports and harbours in these areas.

**Civil engineering and construction industry:** The increased rate of coastal change induced by climate change will provide increased work for the coastal engineering and construction industry. Historically, this has provided hard coast and flood protection for eroding coastal areas and infrastructure and dredging around ports and harbours. However, there has been increasing interest in soft approaches to protection and more broadly a transformation of coastal engineering to coastal management services. This leads to more strategic approaches that consider the full range of adaptation options. These trends are expected to continue and see increased workloads due to direct human pressures on the coast. Climate change, particularly sea-level rise, will require substantial additional investment in coastal engineering and construction services, and encourage strategic planning and efforts towards integrated coastal zone management (European Union, 1999a; 1999b).

## 7. IMPLICATIONS FOR OTHER TRENDS

Coastal zones in the European Union are experiencing rapid changes, particularly increasing population (largely due to migration), development and urbanisation (Section 1). These trends are most pronounced around the Mediterranean and in vulnerable low-lying regions such as the Netherlands and East Anglia, UK. Land use decisions made centuries ago such as the location of major port cities reduces our response options for climate change today. There is little choice but to protect these areas. Similarly land use decisions being made today are locking us and future generations into protection options, or costly coastal abandonment.

Therefore, climate change provides an additional reason for strategic planning. The erosion and flood hazards associated with present conditions and climate change scenarios need to be defined and mapped for this purpose. For cliff erosion, cliff-top building setbacks are a useful planning mechanism (e.g., Brady Shipman Martin, 1992), ideally based on long-term erosion rates (e.g., Nicholls et al., 2000). Leafe et al (1998) have suggested that erosion could be allowed to recommence in some protected cliff-top communities in England and Wales, particularly if erosion rates are predicted. Flood-prone areas are more difficult to avoid as they cover extensive areas along much of the European coast and they are often highly developed already. However, use of these areas can be planned more strategically so that developed areas can be most easily defended, and some low-lying areas can be left for managed retreat and realignment to counter coastal squeeze. Long-term planning of the appropriate safety levels, taking into account potential climate change, is required for all protected flood-prone areas.

## 8. MAIN UNCERTAINTIES AND UNKNOWNS

There is a cascade of uncertainty when considering the impacts of climate change on coastal areas and activities from the scenario, through the biophysical effects, to the impacts and finally the responses. Each stage has its own set of uncertainties. It is important to distinguish that some uncertainties are inherent. These uncertainties arise because we do not know the future, including unforeseeable social, economic and cultural factors such as the changing demand for coastal recreation. Other uncertainties arise from our ignorance or lack of understanding of the processes that link climate change to impacts and responses. Scientific advances can reduce these uncertainties.

### 8.1 Uncertainties associated with scenarios

Future emission pathways are inherently uncertain, and the subject of ongoing international discussion and negotiation. There will also be a spread of possible futures, and the range of uncertainty will increase as we move further into the future (as illustrated by the four ACACIA scenarios considered here). Therefore, coastal managers and planners will always need to examine an appropriate range of scenarios. The range of climate scenarios available for coastal impact and adaptation assessment could be greatly refined as for many important factors, even the direction of change remains uncertain (see Table 1). Of particular interest would be scenarios of the change in the occurrence of extreme events due to climate change (and variability).

In this review, we have focussed on global mean sea-level rise scenarios, converted to relative sea-level rise scenarios for Europe using national aggregates of land uplift and subsidence. There is uncertainty concerning scenarios of change at the sub-national level. Planning for climate change requires such scenarios of relative sea-level rise, including global, regional and local effects due to climate change and geological processes. The appropriate scale of scenario required will depend upon the factor being considered. Considerable information already exists at the scale of the coastal cell, estuary or delta which is pertinent to many coastal management issues (e.g. Hulme and Jenkins, 1998). However, it needs to be collated, organised and upgraded with new research as appropriate.

### 8.2 Uncertainties in estimating first-order biophysical effects of climate change

The first-order impact models add significant uncertainties to the scenarios, as our understanding of large-scale coastal dynamics and behaviour is far from complete and the necessary data is generally only partly available. Importantly, models of coastal dynamics that are applicable for storm events or annual cycles may be invalid over the decadal timescales appropriate to climate change. Many studies necessarily take a static (or “bath-tub”) view of the coastal zone. Using this approach, coastal wetlands are always assumed to be partly or wholly submerged by sea-level rise. However, coastal wetlands respond to sea-level rise by increased vertical accretion so actual losses may be smaller than a static approach would predict.

There has also been a focus on sea-level rise at the expense of other climate change. For coastal ecosystems, the impacts of sea-level rise alone are generally neutral to negative. However, the integrated impacts of sea-level rise, rising temperature and increasing $CO_2$

concentrations, with changing salinity (due to varying freshwater inputs) and changing nutrient fluxes remains uncertain. While it is almost certain that these factors could counter the impact of sea-level rise, the net magnitude of climate change remains uncertain.

Lastly, many of the biophysical models are imprecise about details such as where losses will occur.

### 8.3 Uncertainties in estimating the higher-order impacts of climate change

The biophysical impacts of climate change can be translated into higher order impacts such as people flooded, or assets damaged or destroyed. At the level of an inventory of impacts, the translation of an effect into a net impact has few uncertainties. However, determining the timing of impacts has greater uncertainty and only a probabalistic answer is possible. Another uncertainty is the appropriate discount rate for economic losses. This is a controversial issue and the selected discount rate greatly influences the present value of any losses

### 8.4 Uncertainties in estimating the response to climate change

Human response to climate change will have a large effect on the actual impacts of climate change on the coastal zone. These will vary from spontaneous adjustments, such as falling property prices in areas known to be flood prone, to planned actions such as building storm surge barriers, or regional, national, or EU-wide policies to allow onshore wetland migration to counter coastal squeeze. The available results tend to look at the extremes of do nothing or protect all developed areas. As already noted, the optimum response is probably an intermediate mixture of responses. More detailed adaptation assessments are required to fill this gap. Another factor that is difficult to consider is evolving requirements of the coastal zone from European citizens. This is inherently uncertain, but it will have a fundamental influence on the progressive evolution of policy.

## 9. MAIN POLICY IMPLICATIONS

Climate change raises some important policy issues concerning the management of coastal areas. In contrast with most other world regions (see reviews in Watson et al., 1998), Europe's vulnerability (or "inability to cope") to climate change is relatively low. This is due to its high wealth, its historic investment and experience in coast and flood protection, and the ongoing evaluation of coastal management approaches, including anticipation of climate change and variability. However, the impacts of climate change depend both on the magnitude of climate change and the human response to those changes. Based on this review, the potential adverse effects are of sufficient magnitude to warrant proactive adaptation measures that anticipate and hopefully avoid many of the problems generated by climate change and sea-level rise. The increasing interest in sustainable development also mandates considering the implications of climate change.

However, such proactive policies are difficult to develop and implement. The time scale of climate change is beyond many existing institutional efforts to manage the coast, which have traditionally been short-term, fragmented and sectoral in nature. In contrast, there are developing local, national and EU-wide efforts to prompt Integrated Coastal Zone Management (ICZM) (European Commission, 1999a; 1999b). These need to be encouraged as they provide an appropriate framework for the proactive measures considered necessary, including managing the full range of coastal problems, from immediate to long-term (some decades away) issues. Climate change needs to be an explicit element of all ICZM planning.

Climate change impacts the entire coastal zone and adaptive responses have to be at a similar scale. On open coasts, coastal cells and sub-cells provide natural units for coastal management and they have been used for coastal management in England and Wales (MAFF et al., 1995; Leafe et al., 1998) and in Ireland (Brady Shipman Martin, 1997). A similar approach is implicit in the management of the Dutch coastline. To be effective, ICZM needs to recognise and use natural geomorphic units. Where cross-border sediment transport occurs, this may necessitate management units crossing frontiers.

The trade-off between conserving coastal ecosystems and protecting human activity also needs to be addressed. The slow but steady degradation of the coastal fringe in much of Europe has gone largely unnoticed until recently, and this will continue and accelerate with climate change. Following the historic pattern of hard defence and viewing the coast as a fixed unmoving line on a map would lead to an increasingly armoured shoreline and a continued loss of intertidal area. The endpoint for this trend is a seawall around all the soft (i.e. erodible) coasts of the European Union: a situation which would be both environmental undesirable and economically inefficient as current trends in coastal management illustrate.

Therefore, a common problem across Europe is developing strategic management policies that allow both continued human utilisation of the coastal zone and preserve coastal ecosystems under the situation of a rising sea level. This is a complex question embracing the natural, engineering and social sciences, together with public policy. Wherever possible, we could give space for coastal processes to occur, including sediment input and transport. This should include consideration of effects distant from the coast such as catchment management. In situations where this is not possible such as around a coastal city, the coastal fringe can be maintained artificially or we can just accept its loss.  The dynamic nature of changing location of coastal ecosystems in response to climate change should be explicitly considered when developing conservation policies.

## 10. MAIN RESEARCH IMPLICATIONS

To develop methods to balance the protection of people and the economy against the costs of degradation of the coastal environment will require multidisciplinary research.

To achieve sustainable management of coastal zones under a scenario of sea-level rise and other climate change will require vastly improved knowledge and understanding of the European coastal system. The following six areas need particular attention.

### 10.1 Coastal Typology of Europe

The coastline of Europe is large and varied. Development of an appropriate typology of coastal factors and an associated database in GIS format would greatly facilitate a range of analyses that would improve our understanding of the impacts of climate change. In particular, it would be useful to (1) define coastal assets and activities in a more objective manner, (2) provide a basis for sampling the coast for the process-based, impact and adaptation studies discussed below, and (3) provide a logical basis for up- and down-scaling results, as required. This effort is consistent with the IGBP-LOICZ (Land-Ocean Interaction in the Coastal Zone) project (Holligan and deBoois, 1993; Pernetta and Milliman, 1995).

### 10.2 Scenario Development

Many of the studies discussed below require consistent climate and non-climate scenarios for the relevant environmental and socio-economic factors (Klein and Nicholls, 1999). These are fundamental for comprehensive impact and adaptation assessments. The scenarios will need to reflect the uncertainty for many of the climate factors that are poorly defined, including the direction of future changes. Socio-economic scenarios are also required, including factors such as coastal populations. This could build on the SRES story-lines presented in Chapters (Chapters 2 and 3). For coastal zone management purposes, this information should be available at a high spatial resolution (say 50-km pixels, or other suitable form).

In addition to long-term change, variability is also of interest as it may be of great importance – e.g., scenarios of a decade characterised by large storms versus scenarios of a decade characterised by small storms. The issue of storminess raises two distinct questions: (1) do we know appropriate wave conditions for long-term coastal modelling and engineering design?, and (2) could we predict more and less stormy decades in advance?

### 10.3 Continued Biophysical Process Studies and Model Development

Our understanding of the biophysical impacts of sea-level rise on the coastal zone remains poor. There is a continued need for process-based studies to better understand how different coastal types might respond to climate change (and other changes such as a failing sediment supply). In addition, there is the need to integrate the interactions between physical and biological systems (e.g., Capobianco et al., 1999). The long-term goal is the ability to forecast coastal evolution of the next 50 years for a range of climate and other scenarios. This should include all the coastal types found in Europe: sandy shores with and without inlets, shingle beaches, lagoons, deltas, coastal ecosystems, including saltmarshes, etc. Exchange of research and experience will be beneficial based on similar biophysical characteristics: (1), the Mediterranean, (2) the Baltic, and (3) the North Sea/Atlantic.

### 10.4 Continued Impact Analyses

Impact analyses should continue at the local, national, EU and global level to inform efforts towards mitigation and adaptation on the likely impacts of climate change on the coastal zone. There is a need to look at a wider range of climate change factors than in earlier studies (see 10.2) and use and test the improving biophysical models as they emerge (see 10.3). Higher order impacts also need to be explored and methodological developments are best conducted within the impact analyses themselves. The more detailed studies can also be used to calibrate and test the more geographically-spread studies.

### 10.5 Adaptation Assessments

While we have a good understanding of some adaptation options (e.g., dykes), we have a poor understanding of the full range of available adaptation options (Bijlsma et al., 1996). Coastal adaptation needs to be widely investigated, including case studies that could be linked to impact assessments. Improving our understanding of the implications of uncertainty on proactive adaptation measures is a key issue, as large uncertainties will remain for the foreseeable future. Other important topics include (1) adaptation to coastal squeeze, including managed realignment, (2) shoreline management based on cells and sub-cells, (3) improved catchment management related to sustaining the sediment supply to deltas (and the wetlands they contain), and (4) the sustainability of artificial beach nourishment.

### 10.6 Will Sea-Level Rise Produce Dangerous Climate Change?

The Framework Convention on Climate Change talks about avoiding dangerous climate change. In the context of Europe, it is unclear what exactly dangerous climate change might mean. One possible example might be the near-total loss of coastal wetlands around the Mediterranean and the Baltic due to sea-level rise. It would be useful to explore the impacts of climate change from this perspective with a particular focus on the implications for coastal ecosystems and biodiversity.

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## FIGURES

Figure 1. Selected mean sea-level records from 1900 to the present for the European Union coast: Trieste, Marseille, Lagos, Brest, Aberdeen and Helsinki.

Figure 2. The range of wetland losses due to sea-level rise by the 2080s for the entire European Union, the Atlantic and North Sea Coast, the Baltic coast, and the Mediterranean coast (see Table 2).

Figure 3. Increase in average annual people flooded for the northern EU countries, the southern EU countries and the total EU relative to the evolving baseline values in Table 3.

**TABLES**

Table 1. Some climate change and related factors relevant to European coasts and their potential biophysical effects.

| CLIMATE FACTOR | DIRECTION OF CHANGE | POTENTIAL BIOPHYSICAL EFFECTS | COMMENTS |
|---|---|---|---|
| Global and regional sea level | +ve Accelerating | Inundation and displacement of wetlands and lowlands; coastal erosion; increased storm flooding and damage; salinisation; rising water tables and impeded drainage. | Also consider uplift/ subsidence |
| Sea water temperature | +ve | Increased algal blooms; northerly migration of coastal species; decreased incidence of sea ice at higher latitudes | |
| Precipitation intensity | +ve | Increased flood risk in coastal lowlands | Reinforces sea-level rise effects |
| Wave climate | Unknown | Changed cross-shore and longshore sediment transport, and hence patterns of erosion and accretion | Significant variability |
| Storm frequency | Regional variation (possible increase in N. Europe, elsewhere unknown) | Changed occurrence of storm flooding and damage | Significant variability |
| Run-off | Regional variation (increase in N. Europe, decrease in S. Europe) | Changed sediment supply from rivers to the coast | Consider catchment management |
| Atmospheric CO2 | +ve | Increased productivity in coastal ecosystems. | |

Table 2. Saltmarsh and unvegetated intertidal habitat stock in the late 1980s in different areas of the European Union (Hoozemans et al., 1993). Atlantic/North Sea EU comprises Portugal, Atlantic Spain, Atlantic France, Belgium, Netherlands, North Sea German coast, Denmark, United Kingdom and Ireland. Baltic EU comprises Baltic German coast, Sweden and Finland. Mediterranean EU comprises Mediterranean Spain, Mediterranean France, Italy and Greece.

| Region | Saltmarsh | Intertidal |
|---|---|---|
| | Area ($km^2$) | |
| Atlantic/North Sea EU | 2,305 | 5,538 |
| Baltic EU | 226 | 271 |
| Mediterranean EU | 346 | 135 |
| Total EU | 2876 | 5944 |

Table 3. Baseline changes (i.e. no climate change) in the average annual number of people who experience flooding due to storm surge each year in the European Union. Results based on the flood model of Nicholls et al. (1999). Northern Europe comprises Finland, Sweden, Denmark, Germany, Netherlands, Belgium, United Kingdom, Ireland and Atlantic France. Southern Europe comprises Portugal, Spain, Mediterranean France, Italy and Greece.

| | Average Annual People Flooded (thousands/year) | | |
|---|---|---|---|
| Year | Northern Europe | Southern Europe | Total EU |
| 1990 | 19 | 6 | 24 |
| 2020s | 21 | 5 | 26 |
| 2050s | 19 | 4 | 23 |
| 2080s | 18 | 4 | 22 |

Table 4. Europe: Some national impacts of sea-level rise (SLR) as summarised by Nicholls and Mimura (1998). Results are for existing development and all costs have been adjusted to 1990 US$. People Living in the Coastal Flood Plain, Average Annual People Flooded, Capital Loss, Land Loss and Wetland Loss assumes no human response, whereas Adaptation assumes protection except in areas with low population density. Average Annual People Flooded is the number of people flooded by storm surge in an average year. Adaptation/Protection costs for Poland include capital and annual running costs, while %GNP assumes that capital costs are all incurred in one year. A national study of the impacts of climate change on Finland is excluded because it does not consider coastal impacts.

| Country | SLR scenario (m) | People Living in the Coastal Flood Plain | | Average Annual People Flooded | | Capital Value Loss | | Land Loss | | Wetland Loss | Adaptation/ Protection Costs | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | #people (1000s) | % Total | #people (1000s) | % Total | Million US$ | %GNP | $km^2$ | % Total | $km^2$ | Million US$ | %GNP |
| Netherlands | 1.0 | 10,000 | 67 | 3,600 | 24 | 186,000 | 69 | 2,165 | 6.7 | 642 | 12,300 | 5.5 |
| Germany | 1.0 | 3,200 | 3.9 | 309 | 0.3 | 7,500 | 0.05 | 13,900 | 3.9 | 2,000 | 23,500 | 2.2 |
| Poland | 0.1 | n.a. | n.a. | 25 | 0.1 | 1,800 | 2 | n.a. | n.a. | n.a. | 700+4 | 2.1+0.01 |
| Poland | 0.3 | n.a. | n.a. | 58 | 0.1 | 4,700 | 5 | 845 | 0.25 | n.a. | 1,800+8 | 5.4+0.02 |
| Poland | 1.0 | 235 | 0.6 | 196 | 0.5 | 22,000 | 24 | 1,700 | 0.5 | n.a. | 4,800+400 | 14.5+1.2 |

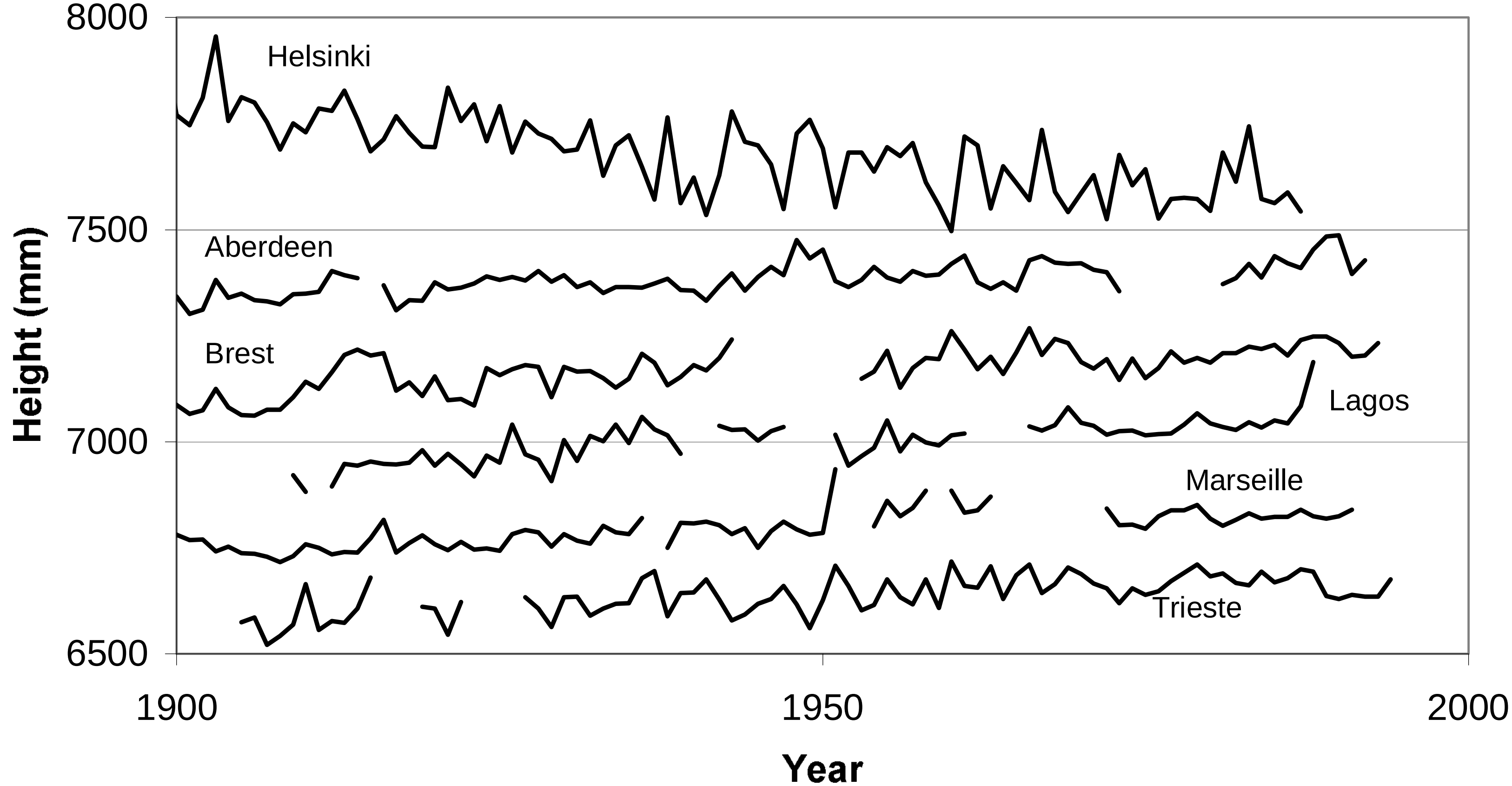
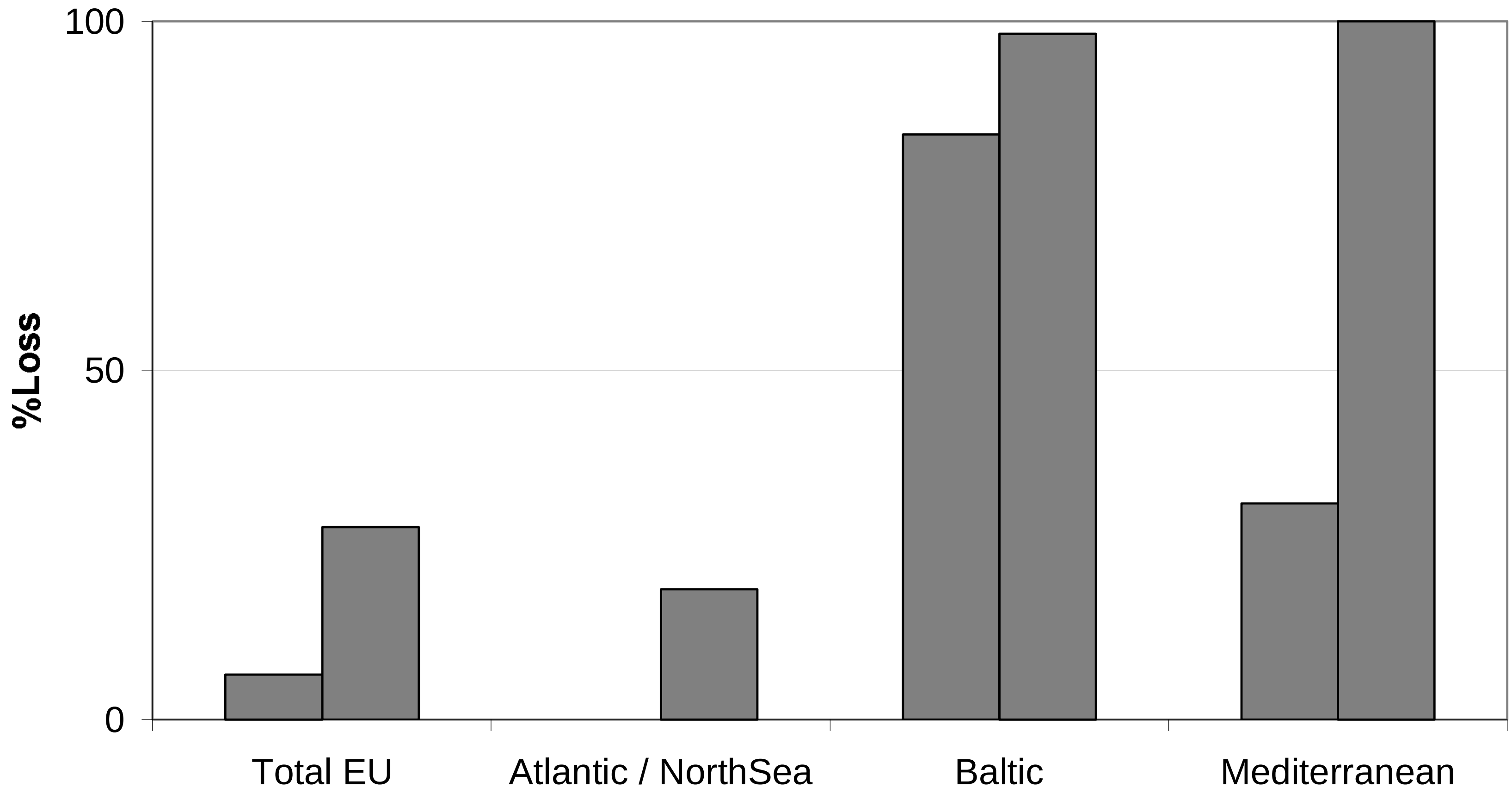



Figure 1. Selected mean sea-level records from 1900 to the present for the European Union coast: Trieste, Marseille, Lagos, Brest, Aberdeen and Helsinki.

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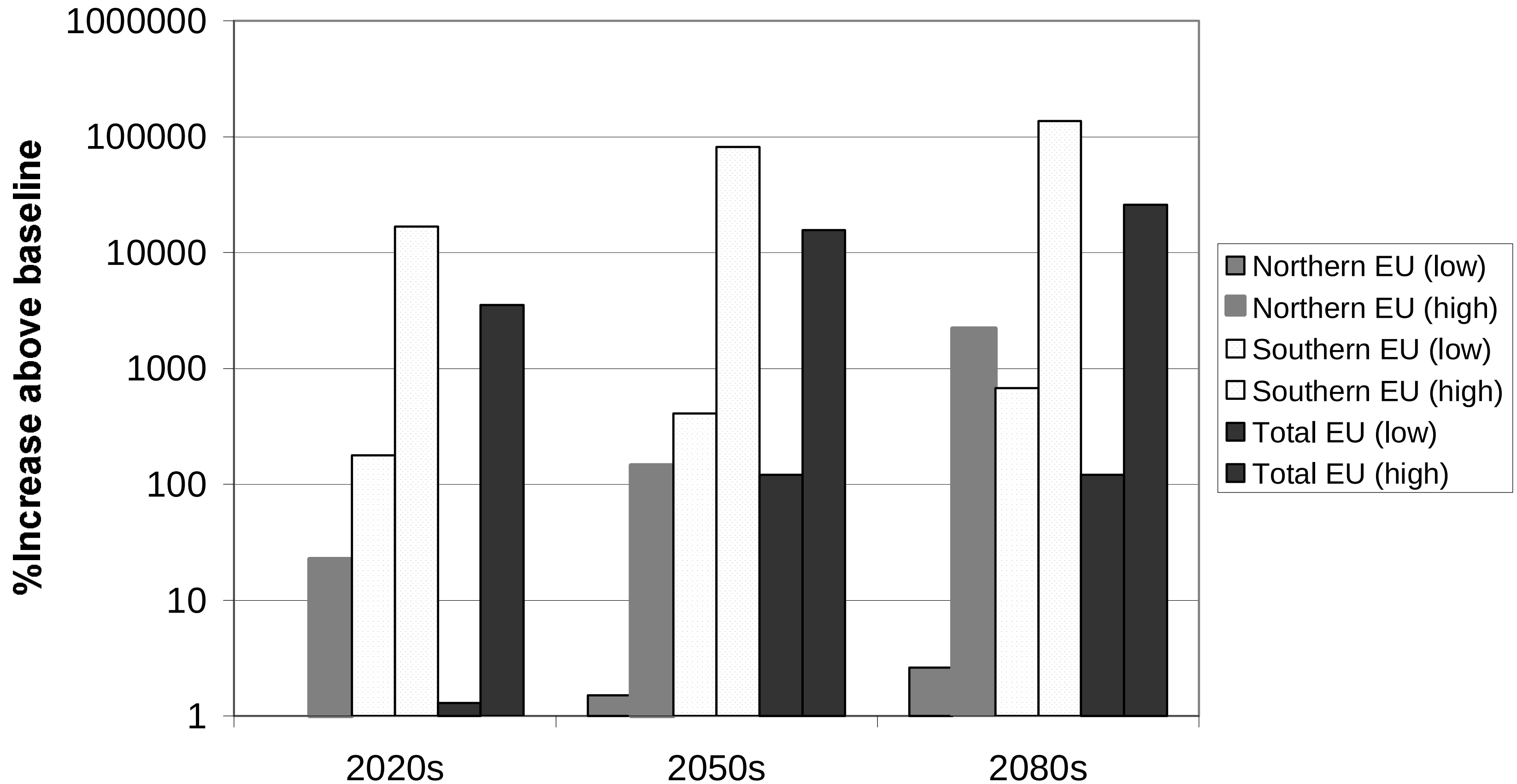


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TEXT FOR VENICE BOX

Venice – A Historic City Threatened by Climate Change

Venice is a unique medieval city in a lagoon setting and a cultural icon to Italy, Europe and the world. Venice has experienced a 30-cm relative rise in sea level during the 20th century, which has greatly increased the frequency of flooding and damage. Flooding in San Marco Square increased from 7- to 40-events per year. After the 1966 flood, a permanent solution was sought which focussed on barriers to isolate the Venice lagoon from the Adriatic during floods. However, the merits and dismerits of this approach are still being debated. Alternative low-cost solutions can be found in the short-term, including small-scale defences and allowing the hydrography of the Venice lagoon and its entrances to return to a more natural (shallower) configuration (Penning-Rowsell et al., 1998). The additional friction within the lagoon will reduce surge heights. However, longer term solutions have to address global sea-level rise and local subsidence as only a 30-cm rise in sea level could lead to daily flooding of San Marco Square (Nicholls and Hoozemans, 1996). Such a rise in sea level would occur before the 2020s under the A2-high ACACIA scenario, before the 2050s under the A1-mid and B2-mid ACACIA scenario, and likely by the 2080s under the B1-mid scenario if future subsidence is taken into account. Therefore, Venice is highly threatened by climate change.

TEXT FOR COASTAL SQUEEZE

Coastal Squeeze

Coastal environments and their ecosystems tend to move onshore in response to a rising sea level. While the area covered by the environment may change, the ecosystem will survive. However, if this onshore movement is hindered by natural or unnatural barriers, a ‘coastal squeeze’ results and the environment will decline and ultimately may be completely lost. The combination of slowly rising sea levels and the construction of hard defences around much of Europe’s open and sheltered coasts has resulted in significant coastal squeeze during the $20^{th}$ Century. However, this slow progressive degradation of the coastal fringe has gone largely unnoticed until human infrastructure becomes threatened. The increased rate of coastal squeeze that will occur under accelerated sea-level rise raises the profile of the issue. It focuses attention on the choices that society faces between protection options which would exacerbate coastal squeeze and the retreat and accommodate options which would stabilise or even reverse the existing situation.