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Technological Options for Adaptation to Climate Change in Coastal Zones

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ABSTRACT

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Many different technologies exist to adapt to natural coastal hazards. These technologies can also play an important part in reducing vulnerability to climate change in coastal zones. Technologies are available to develop information and awareness for adaptation in coastal zones, to plan and design adaptation strategies, to implement them, and to monitor and evaluate their performance. This paper briefly describes these four steps and provides important examples of technologies that can be employed to accomplish them. In addition, it identifies three trends in coastal adaptation and associated technology use: (*i*) a growing recognition of the benefits of "soft" protection and of the adaptation strategies retreat and accommodate, (*ii*) an increasing reliance on technologies to develop and manage information, and (*iii*) an enhanced awareness of the need for coastal adaptation to be appropriate for local natural and socio-economic conditions.

ADDITIONAL INDEX WORDS: *Protect, retreat, accommodate, sea-level rise, coastal zone management.*

INTRODUCTION

The interface of land, sea and air features the most dynamic natural environments on Earth. A variety of coastal systems produce a large number of goods and services that are valuable to society. This diversity has attracted many people and major investments to coastal zones, even to places that are susceptible to hazards such as storm surges and coastal erosion. A large part of the global human population now lives in coastal areas: estimates range from 20.6 per cent within 30 km from the sea to 37 per cent in the nearest 100 km to the coast (COHEN *et al.,* 1997; GOMMES *et al.,* 1998). In addition, a considerable portion of global GDP is produced in coastal zones (TURNER *et al.,* 1996). Many coastal locations exhibit a growth in population and GDP higher than their national averages (CARTER, 1988; WCC'93, 1994), as well as significant urbanization (NICHOLLS, 1995).

In many places, technology (defined in its broadest possible sense as equipment, techniques, practical knowledge or skills for performing a particular activity) has been instrumental in reducing society's vulnerability to ever-present coastal hazards. There are three basic strategies to reduce hazard vulnerability in coastal zones and for each of these, a range of technological options are available (IPCC CZMS, 1990; BIJLSMA *et al.,* 1996). The three basic strategies, coined "protect", "retreat" and "accommodate", respectively, are:

- to reduce the risk of the event by decreasing its probability of occurrence;
- to reduce the risk of the event by limiting its potential effects;
- to increase society's ability to cope with the effects of the event.

Extensive research has shown that today's hazard potential for many coastal zones will increase because of climate change. Reducing coastal vulnerability to expected impacts of climate change requires following the same three strategies of protect, retreat and accommodate as for current coastal hazards, including application of the same technological options as are used today. However, the purpose and design of existing technologies may have to be adjusted.

"Adaptation" refers to the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial op-

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portunities. As such, reducing coastal vulnerability to natural hazards and climate change is a form of adaptation. This paper discusses the need for coastal societies to adapt to climate change and the importance of technological options for adaptation[1]. The purpose of the paper is to show that coastal adaptation comprises more than merely increasing the design level of existing coastal protection structures. Instead, adaptation is a policy process that involves making decisions and applying technologies in a number of successive stages. The paper presents a conceptual framework for adaptation, outlining four iterative steps. Based on this framework, available technologies to assist in executing these four steps are presented.

CURRENT AND FUTURE ADAPTATION NEEDS IN COASTAL ZONES

In the 21st century and beyond, climate change is expected to have important impacts on coastal zones. The magnitude of these impacts and hence the need for adaptation will depend on a variety of factors, including the magnitude of climate change and the interaction of climate change with other stresses (BIJLSMA *et al.,* 1996). This section discusses both these factors.

Potential Impacts of Climate Change on Coastal Zones

Many climate factors have relevance to the coast, most notably sea level and the frequency and intensity of extreme events such as cyclones and storm surges. Global sea levels are expected to rise in the order of 23 to 96 cm by 2100, with a mid-estimate of 55 cm, assuming the IS92a emissions scenario ("business as usual") without the cooling effect of aerosols (WARRICK *et al.,* 1996). Even if atmospheric greenhouse-gas concentrations are stabilized in the next few decades, a significant rise in global sea level would still occur, owing to the long lag between the temperature increase at the ocean surface and the warming of the deeper ocean (WIGLEY, 1995; RAPER *et al.,* 1996).

Sea-level rise produces a range of impacts (TSYBAN *et al.,* 1990), including:

- inundation and displacement of wetlands and lowlands;
- erosion and degradation of shorelines and coral reefs;
- increased coastal flooding during storms;
- salinization of estuaries and freshwater aquifers.

BIJLSMA *et al.* (1996) concluded that most coastal areas are vulnerable to such impacts to some degree and some form of adaptation will be necessary. However, deltaic areas, small islands—especially coral atolls—and coastal wetlands appear particularly vulnerable to climate change. In addition, developed sandy shores could be vulnerable because of the large investment and significant sand resources required to maintain beaches and adjoining infrastructure as sea level rises. Taking a regional perspective, WATSON *et al.* (1998) and NICHOLLS *et al.* (1999) concluded that the threat of increased coastal flooding will be most severe for South and South-East Asia, Africa, the southern Mediterranean coasts, the Caribbean and most islands in the Indian and Pacific Oceans.

Ongoing Developments in Coastal Zones

BIJLSMA *et al.* (1996) noted that climate-related change in coastal zones "represents potential additional stresses on systems that are already under intense and growing pressure". Climate change is one factor among many that affect coastal ecological systems and societies. Other factors that interact with climate change include overexploitation of resources, pollution, increasing nutrient fluxes, decreasing fresh-water availability, sediment starvation and urbanization (GOLDBERG, 1994; VILES and SPENCER, 1995). These non-climate stresses decrease the resilience of coastal systems to cope with natural climate variability and anticipated climate change (NICHOLLS and BRANSON, 1998; KLEIN and NICHOLLS, 1999). BIJLSMA *et al.* (1996) concluded that "although the potential impacts of climate change by itself may not always be the largest threat to natural coastal systems, in conjunction with other stresses they can become a serious issue for coastal societies, particularly in those places where the resilience of natural coastal systems has been reduced."

Policies and practices that are unrelated to climate but which do increase a system's vulnerability to climate change are termed "maladaptation" (BURTON, 1996, 1997). Examples of maladaptation in coastal zones include investments in hazardous zones, inappropriate coastal protection schemes, sand or coral mining and coastal habitat conversions. A common cause of maladaptation is a lack of information on the potential external effects of proposed developments on other sectors, or a lack of consideration thereof. More proactive and integrated planning and management of coastal zones is widely suggested as an effective mechanism for strengthening sustainable development (*e.g.,* CICIN-SAIN, 1993; CICIN-SAIN and KNECHT, 1998) and can be both environmentally sound and economically efficient (TOL *et al.,* 1996). The need to consider adaptation to climate change within the framework of integrated coastal zone management was discussed by WCC'93 (1994), BIJLSMA *et al.* (1996) and EHLER *et al.* (1997), among others.

To identify the most appropriate coastal adaptation strategy, one must consider this full context in which impacts of climate change arise, and realize that the three earlier-mentioned strategies—protect, retreat, accommodate—happen within a broader policy process, which includes consideration of the numerous non-climatic issues (HARVEY *et al.,* 1999). Within this process, increasing resilience by reversing mal-

[1] This paper is based on the chapter "Coastal Adaptation" of the Special Report on Methodological and Technological Issues in Technology Transfer of the Intergovernmental Panel on Climate Change (IPCC) (KLEIN *et al.,* 2000). In parallel with the preparation of the IPCC Special Report, the Secretariat of the United Nations Framework Convention on Climate Change produced a Technical Paper on coastal adaptation technologies (UNFCCC, 1999). Having a similar purpose, the UNFCCC Technical Paper has been based primarily on information provided directly by experts, while the IPCC chapter has relied predominantly on published, peer-reviewed literature. The fact that two important intergovernmental organizations in the field of climate change have assessed the potential for the use and transfer of coastal adaptation technologies illustrates the importance attached to this issue by the international climate change policy community.

adaptive trends could be an important option to reduce coastal vulnerability to climate variability and change. This approach will usually address more than climate issues alone and involve a change in adaptation strategy, for example, nourishing beaches instead of constructing seawalls, or introducing a building setback instead of allowing construction next to the coast.

TRENDS IN COASTAL TECHNOLOGY USE

The emphasis of adaptation to coastal hazards has traditionally been on protecting developed areas using hard structures. The skills and technologies required to plan, design and build these structures depend on their required scale and level of sophistication. At a small scale, local communities can use readily-available materials to build protective structures (MIMURA and NUNN, 1998). However, these communities often lack the information to know whether or not these structures are appropriate and whether or not their design standards are acceptable. For larger-scale, more sophisticated structures technical advice is required, as well as a contracting firm to build the structure.

Until recently, it was rarely questioned whether a country's coastline could be protected effectively if optimal management conditions prevail. It has become clear, however, that even with massive amounts of external funding, coastlines in the developing world (particularly of archipelagic countries) cannot be effectively protected by hard structures. In addition, increasing awareness of unwanted effects of hard structures on erosion and sedimentation patterns has led to growing recognition of the benefits of "soft" protection (*e.g.,* beach nourishment, wetland restoration and creation) and of the adaptation strategies retreat and accommodate (CAPOBIANCO and STIVE, 1997; LEAFE *et al.,* 1998). An increasing number of private companies in the industrialized world are now discovering market opportunities for implementing soft-protection options (DAVISON *et al.,* 1992; HAMM *et al.,* 1999). Interest in the retreat and accommodate strategies is also growing among coastal managers, but these strategies requires a more integrated approach to coastal management than is currently present in many countries, so application is still less developed.

In spite of this trend to consider adaptation technologies other than hard protection, many structures are still being built without a full evaluation of the alternatives (VILES and SPENCER, 1995; CEC, 1999). A reason could be that hard structures are more tangible and hence appeal more strongly to the imagination of decision-makers and stakeholders and—by their visibility—may be perceived to provide more safety and hold the sea at bay forever. In addition, it is generally felt that hard structures are less maintenance-intensive than soft structures. However, past experiences suggest that the design of soft structures is particularly important in determining the level of maintenance required, but that appropriate design and implementation often require good knowledge of coastal dynamics as well as effective coastal management institutions.

A second trend in coastal technology use is an increasing reliance on technologies to develop and manage information (WRIGHT and BARTLETT, 1999). This trend stems from the recognition that designing an appropriate technology to protect, retreat or accommodate requires a considerable amount of data on a range of coastal parameters, as well as a good understanding of the uncertainties involved in the impacts to be addressed (CAPOBIANCO, 1999). National, regional and global monitoring networks are being set up to help to assess technology needs and opportunities. In the Caribbean, for example, developing GIS information bases has been presented as the first phase of a regional adaptation process and as such has been found eligible for funding from the Global Environment Facility (the interim international entity entrusted with the operation of the financial mechanism of the United Nations Framework Convention on Climate Change).

Third, many efforts are now initiated to enhance awareness of the need for appropriate coastal technologies, often as maladaptive practices are becoming apparent. For example, before a new hospital was built in Kiribati in 1992, a substantial site-selection document had been prepared, examining numerous aspects of three alternative sites but without consideration of coastal processes. A serious shoreline erosion problem, advancing rapidly to within eight meters of the hospital, was discovered by 1995 (FORBES and HOSOI, 1995). Options to enhance awareness include national and international workshops and conferences, training programs, on-line courses and technical assistance and capacity-building as part of bilateral or multilateral projects. In view of the many sectoral interests in coastal zones, it will become increasingly important to involve decision-makers without direct responsibility for coastal issues and other stakeholders in this ongoing learning process (HUMPHREY and BURBRIDGE, 1999; KING, 1999).

THE PROCESS OF ADAPTATION TO CLIMATE CHANGE

Since climate change was recognized as a problem in the late 1980s, the major focus has been on mitigation (*i.e.,* reducing atmospheric greenhouse-gas emissions) rather than adaptation. However, interest in adaptation to climate change is growing as it is increasingly recognized that some climate change has become inevitable even with significant mitigation. Further, there can be important synergies between adaptation and management of existing problems (PARRY *et al.,* 1998; PIELKE, 1998).

In an integrated coastal policy that aims to address both climate and non-climate issues, the potential for conflict between development objectives and adaptation needs should be minimized. In view of the fact that coastal zones are usually host to a number of, often competing, sectoral activities, coastal technologies to date have been designed primarily to satisfy sectoral needs. Given the additional challenge of climate change in coastal zones, the purpose and design of coastal technologies may have to be revisited. In order to do so, it is important that all stakeholders—governments, universities and government-sponsored laboratories, the private sector, non-governmental organizations and local communities—are aware of the need to reduce coastal vulnerability to climate. In addition, successful coastal management requires

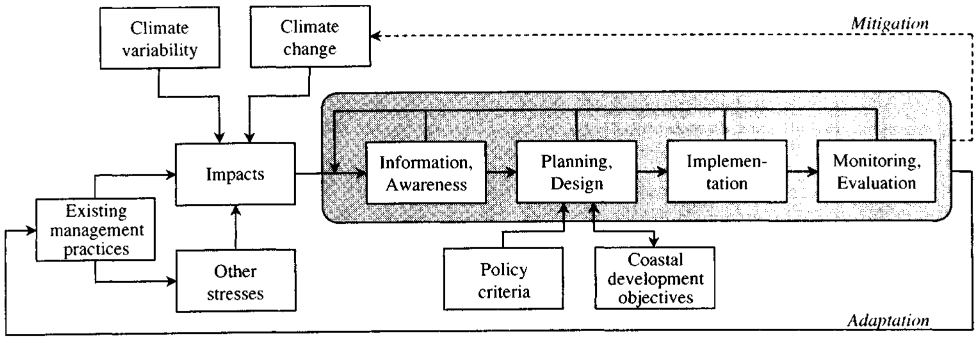

Figure 1. Conceptual framework showing in the shaded area the iterative steps involved in coastal adaptation to climate variability and change (KLEIN *et al.*, 1999).

that the planning, design and implementation of adaptation technologies be based on the best available information as well as on the regular monitoring and evaluation of their performance.

Accordingly, KLEIN *et al.* (1999) showed that coastal adaptation to climate change can be considered a multi-stage and iterative process, involving four basic steps:

- information development and awareness raising;
- planning and design;
- implementation;
- monitoring and evaluation.

The process of coastal adaptation to climate change can be conceptualized as depicted in Figure 1. Climate variability and/or climate change—together with other stresses on the coastal environment brought about by existing management practices—produce actual or potential impacts. These impacts trigger efforts of mitigation to remove the cause of the impacts, or adaptation to modify the impacts. The process of adaptation is conditioned by policy criteria and coastal development objectives and interacts with existing management practices.

Figure 1 is a schematic framework, based on the long-term coastal management experiences in The Netherlands, the United Kingdom and Japan, with an emphasis on coastal protection. In each of these countries, management approaches have been adjusted over the past decades to reflect new insights and priorities, including concerns about climate variability and, more recently, climate change. It is important to note that Figure 1 represents an idealized decision framework, which does not capture the multitude of actors involved in decision-making, the uncertainty with which these actors are faced, the other interests they have, nor the institutional and political environments in which they operate.

In addition, in many countries faced with the impacts of climate variability and change, information, capacity or resources will not suffice to warrant large-scale investments in coastal adaptation. However, extensive discussions at the IPCC Workshop on Adaptation to Climate Variability and Change (Costa Rica, 29 March–1 April 1998) and the IPCC Expert Meeting on Small Island States (Malta, 19–22 July 1999) have revealed that also in these countries decisions need to be and are being made, despite the constraints. It can thus be assumed that the framework shown in Figure 1 is also applicable in countries where coastal management is less developed.

It should be noted that adaptation in Figure 1 refers to planned adaptation, aimed at changing current management practices. Planned adaptation is the result of a deliberate policy decision, based on an awareness that climate conditions have changed or are about to change and that action is required to return to or maintain a desired state. Autonomous adaptation, which does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems, is implied in Figure 1 as it determines the manifestation of impacts (KLEIN *et al.*, 1999).

COASTAL ADAPTATION TECHNOLOGIES

This section provides important examples of technologies that can be employed to accomplish each of the four steps shown in Figure 1, and provides some contextual information on their application. It should be noted that no attempt has been made to provide all-inclusive lists of technologies. Rather, the technologies and references listed in this section are meant to be illustrative and to encourage the reader to consider as wide a spectrum of adaptation technologies as possible.

An important issue that is often overlooked in adaptation assessment is that adaptation strategies involve more than just technological options (CAPOBIANCO, 1999). Technological options only can be implemented effectively in an appropriate economic, institutional, legal and socio-cultural context (KLEIN and TOL, 1997). Thus, a successful adaptation strategy will comprise a mix of various adaptation approaches, tailored to the particular needs of the area at risk and aimed at reducing implementation constraints (BIJLSMA *et al.*, 1996).

Information Development and Awareness Raising

Data collection and information development are essential prerequisites for coastal adaptation, particularly to identify adaptation needs and priorities. The more relevant, accurate

Table 1. *Selected technologies that can be used to better understand coastal systems.*

Application	Technology	Additional Information
Coastal System Description		
• Coastal topography and bathymetry	— Mapping and surveying	— BIRKEMEIER *et al.* (1985, 1999); STAUBLE and GROSSKOPF (1993)
	— Videography	— DEBUSSCHERE *et al.* (1991); HOLMAN *et al.* (1994); PLANT and HOLMAN (1997)
	— Airborne laserscanning (lidar)	— LILLYCROP and ESTEP (1995); SALLENGER *et al.* (1999)
	— Satellite remote sensing	— LEU *et al.* (1999)
• Wind and wave regime	— Waverider buoys	— MORANG *et al.* (1997*a*)
	— Satellite remote sensing	— MARTINEZ-DIAZ-DE-LEON *et al.* (1999)
• Tidal and surge regime	— Tide gauges	— PUGH (1987); ZHANG *et al.* (1997)
• Relative sea level	— Tide gauges	— EMERY and AUBREY (1991); WOODWORTH (1991); GROĞER and PLAG (1993); NICHOLLS and LEATHERMAN (1996); NOAA (1998)
	— Historical and geological methods	— VAN DE PLASSCHE (1986)
• Absolute sea level	— Satellite remote sensing	— NEREM (1995); FU *et al.* (1996); NEREM *et al.* (1997); CAZENAVE *et al.* (1998)
	— Tide gauges, satellite altimetry and global positioning systems	— DOUGLAS (1991); BAKER (1993); MILLER *et al.* (1993); ZERBINI *et al.* (1996); NEILAN *et al.* (1997)
• Past shoreline positions	— Historical and geological methods	— CROWELL *et al.* (1991); BEETS *et al.* (1992); CROWELL *et al.* (1993); MOORE (2000)
• Land use	— Airborne and satellite remote sensing	— REDFERN and WILLIAMS (1996); CLARK *et al.* (1997); HENDERSON *et al.* (1999)
• Natural values	— Resource surveys	— LIPTON and WELLMAN (1995); TURNER and ADGER (1996)
• Socio-economic aspects	— Mapping and surveying	— PENNING-ROSWELL *et al.* (1992)
• Legal and institutional arrangements	— Interviews, questionnaires	— ENGLISH NATURE (1993)
• Socio-cultural factors	— Interviews, questionnaires	— TUNSTALL and PENNING-ROSWELL (1998); TUNSTALL (2000)
Climate Impact Assessment		
• Index-based methods	— Coastal vulnerability index	— HUGHES and BRUNDRIT (1992); GORNITZ *et al.* (1994); SHAW *et al.* (1998)
	— Sustainable capacity index	— KAY and HAY (1993); YAMADA *et al.* (1995); NUNN *et al.* (1994*a,b*)
• (Semi-) quantitative methods	— IPCC common methodology	— IPCC CZMS (1992); BIJLSMA *et al.* (1996)
	— Aerial-videotape assisted vulnerability assessment	— LEATHERMAN *et al.* (1995); NICHOLLS and LEATHERMAN (1995)
	— UNEP impact and adaptation assessment	— KLEIN and NICHOLLS (1998, 1999)
• Integrated assessment	— Coupled models	— ENGELEN *et al.* (1993); RUTH and PIEPER (1994); WEST and DOWLATABADI (1999)
Awareness Raising		
• Printed information	— Brochures, leaflets, newsletters	
• Audio-visual media	— Newspapers, radio, television, cinema	
• Interactive tools	— Board-games	
	— Internet, worldwide web	
	— Computerized simulation models	

and up-to-date the data and information available to the coastal manager, the more targeted and effective adaptation strategies can be. Coastal adaptation requires data and information on coastal characteristics and dynamics, patterns of human behavior as well as an understanding of the potential consequences of climate change. It is also essential that there is a general awareness among the public, coastal managers and decision-makers of these consequences and the need to take appropriate action (KLEIN *et al.,* 1999).

Large-scale global and regional data repositories have been established for a great number of climatic and socio-economic variables relevant to coastal zones. These sources of data may be accessed, displayed and downloaded from the Internet. Sea-level data, for example, may be obtained from the Permanent Service for Mean Sea Level (www.nbi.ac.uk/psmsl/index.html), the Global Sea Level Observing System (www.pol.ac.uk/psmsl/programmes/gloss.info.html) and the University of Hawai'i Sea Level Center (uhslc.soest.hawaii.edu). Additional global data sets can be accessed via the IRI/LDEO Climate Data Library (ingrid.ldeo.columbia.edu), the ICSU World Data Center (www.wdc.rl.ac.uk/wdcmain/), IGBP-LOICZ (www.nioz.nl/loicz/), the Center for International Earth Science Information Network (www.ciesin.org) and the IPCC Data Distribution Centre (ipcc-ddc.cru.uea.ac.uk). The latter center also provides climatic and socio-economic scenarios.

Useful as they may be, coastal adaptation to climate change will require more detailed information than these readily-available data sets can provide. Table 1 lists a number of relevant technologies that can serve to increase the understanding of the coastal system (which involves data collection and analysis), to conduct climate impact assessment in coastal zones (so that the severity of potential impacts can be quantified for given scenarios), and to raise public awareness (that some form of adaptation is necessary). Where appropriate, reference is made to publications that either describe the technology in detail or provide examples of its application. Further information on a broad range of technologies for coastal system description can be found in MORANG *et al.* (1997a), LARSON *et al.* (1997), MORANG *et al.* (1997b) and GORMAN *et al.* (1998). CAPOBIANCO (1999) discussed technologies in relation to integrated coastal zone management.

Planning and Design

When the available data and information point toward a potential problem that would justify taking action, the next stage is to decide which action could best be taken and where and when this could best be implemented. The answers to these questions depend on the prevailing criteria that guide local, national or regional policy preparation, as well as on existing coastal development and management plans that form the broader context for any adaptation initiative. Important policy criteria that could influence adaptation decisions include cost-effectiveness, environmental sustainability, cultural compatibility and social acceptability. In addition, countries may choose to take a precautionary approach when postponing action would involve substantial risks, even though uncertainty may still be considerable (CEC, 1999).

Coastal planners always will face a certain degree of uncertainty, not only because the future is by definition uncertain, but also because knowledge of natural and socio-economic coastal processes is and always will remain incomplete. This uncertainty requires planners to assess the environmental and societal risks of climate change with and without adaptation (CARTER *et al.,* 1994). The information thus obtained can help to determine the optimal adaptation strategy (*which action?*) and timing of implementation (*when?*) (*e.g.,* CHAO and HOBBS, 1997; YOHE and NEUMANN, 1997). There are a number of decision tools available to assist in this process. Examples of these tools include cost-benefit analysis, cost-effectiveness analysis, risk-effectiveness analysis and multi-criteria analysis (TURNER and ADGER, 1996). The latter technique is particularly relevant when great significance is attached to values that cannot be easily expressed in monetary terms.

Geographical information systems (GIS) are an important technology for spatial planning. GIS combines computer mapping and visualization techniques with spatial databases and statistical, modeling and analytical tools. It offers powerful methods to collect, manage, retrieve, integrate, manipulate, combine, visualize and analyze spatial data and to derive information from these data (BURROUGH and MCDONNELL, 1998; LONGLEY *et al.,* 1999; WRIGHT and BARTLETT, 1999). One simple, first-order application of GIS in coastal adaptation would be overlaying scenarios of sea-level rise with elevation and coastal development data to define impact zones. More sophisticated applications may include the modeling of morphodynamic and ecological responses to climate change (*e.g.,* CAPOBIANCO *et al.,* 1999). GIS technology and its application are evolving rapidly, and GIS can provide excellent support to coastal managers for making decisions about adaptation.

It is important to note that GIS is an example of a technology that can contribute to each of the four adaptation steps. Collected data can be stored in a GIS, combined to develop new insights and information, and visualized for interpretation and educational purposes. In combination with scenarios of relevant developments and models to assess and evaluate changes in important natural and socio-economic variables, GIS can assist planners to identify appropriate adaptation technologies as well as their optimal locations for implementation, depending on the criteria of the decision-maker. It allows for the non-invasive, reversible and refinable testing of specific adaptation technologies before these are implemented in the real world. After implementation, newly acquired data can be analyzed to evaluate technology performance. Once created, a GIS database will have further utility in other aspects of coastal management (O'REGAN, 1996; WRIGHT and BARTLETT, 1999).

The modeling of potential futures based on plausible scenarios is particularly pertinent for the planning and design of adaptation technologies, when relevant impacts are quantified, alternative adaptation options are evaluated, and one course of action is selected. Coastal management and climate impact assessment require models of relevant changes in morphological, ecological and human factors, as well as their interaction over appropriate time scales (*i.e.,* a decade or longer) (CAPOBIANCO *et al.,* 1999). The necessary modeling capabilities are increasing rapidly, including morphological models (*e.g.,* DE VRIEND *et al.,* 1993; DE VRIEND, 1998; CAPOBIANCO *et al.,* 1998), ecological and landscape models (see CAPOBIANCO *et al.,* 1999), model frameworks designed for management purposes (*e.g.,* PONTEE and TOWNEND, 1999), and integrated models that explicitly include the human system (*e.g.,* ENGELEN *et al.,* 1993). The rapid developments in information technology are facilitating the rapid transfer and application of these tools as they are developed. However, the limitations inherent in all models (*i.e.,* they are representations of a part of reality for a specific purpose) must not be overlooked. Human expertise and interpretation remain essential for the intelligent use of any model.

The quality and effectiveness of the planning and design process is affected by the context in which the decision is made. Coastal management in many countries used to be top-down by nature, but as public interest and involvement in coastal issues has grown so has resistance to top-down decision-making (*e.g.,* TAIEPA *et al.,* 1997). The successful implementation of many coastal policies, including adaptation to climate change, is now increasingly dependent on public acceptance at the community level (KING, 1999). Hence, in addition to informing the public so as to raise their awareness of the issues at stake (see above), it is also important to involve them throughout the planning process (CEC, 1999). Gaining public acceptance, for example by two-way interaction and partnerships, is an important prerequisite for identifying and transferring appropriate adaptation technologies. Further, local expertise will be required for successful tech-

Table 2. *Options and technologies for coastal adaptation.*

Application	Technology	Additional Information
Protect		
• Hard structural options	— Dikes, levees, floodwalls — Seawalls, revetments, bulkheads — Groynes — Detached breakwaters	— PILARCZYK (1990); SILVESTER and HSU (1993)
	— Floodgates and tidal barriers	— GILBERT and HORNER (1984); KELLY (1991); PENNING-ROWSELL *et al.* (1998)
	— Saltwater intrusion barriers	— SORENSEN *et al.* (1984)
• Soft structural options	— Periodic beach nourishment	— DELFT HYDRAULICS and RIJKSWATERSTAAT (1987); DAVISON *et al.* (1992); STAUBLE and KRAUS (1993); HAMM *et al.* (1999)
	— Dune restoration and creation	— DOODY (1985); VELLINGA (1986); NORDSTROM and ARENS (1998); NORDSTROM *et al.* (1998)
	— Wetland restoration and creation	— NRC (1992, 1994); BOESCH *et al.* (1994); TRI *et al.* (1998)
• Indigenous options	— Afforestation — Coconut leaf walls — Coconut fiber stone units — Wooden walls — Stone walls	— MCLEAN *et al.* (1998); MIMURA and NUNN (1998)
(Managed) Retreat		
• Increasing or establishing setback zones	— Limited technology required	— NRC (1990); KAY (1990); OWENS and COPE (1992); CATON and ELIOT (1993); OTA (1993)
• Relocating threatened buildings	— Various technologies	— ROGERS (1993)
• Phased-out or no development in susceptible areas	— Limited technology required	— OTA (1993); DETR (2000)
• Presumed mobility, rolling easements	— Limited technology required	— TITUS (1991, 1998)
• Managed realignment	— Various technologies, depending on location	— BURD (1995); ENGLISH NATURE (1997); FRENCH (1997, 1999)
• Creating upland buffers	— Limited technology required	— KALY and JONES (1998)
Accommodate		
• Emergency planning	— Early-warning systems	— PENNING-ROSWELL and FORDHAM (1994); HAQUE (1995, 1997); HANDMER (1997); ROSENTHAL and 'T HART (1998); ELLIOTT and STEWART (2000)
	— Evacuation systems	— PARKER and HANDMER (1997); ROSENTHAL and 'T HART (1998)
• Hazard insurance	— Limited technology required	— DAVISON (1993); OTA (1993); CRICHTON and MOUNSY (1997); CLARK (1998)
• Modification of land use and agricultural practice	— Various technologies (*e.g.*, aquaculture, saline-resistant crops), depending on location and purpose	
• Modification of building styles and codes	— Various technologies	— FEMA (1986, 1994, 1997)
• Strict regulation of hazard zones	— Limited technology required	— MAY *et al.* (1996)
• Improved drainage	— Increased diameter of pipes	— TITUS *et al.* (1987)
	— Increased pump capacity	— TITUS *et al.* (1987)
• Desalination	— Desalination plants	— RIBEIRO (1996)

nology implementation, application, maintenance and enforcement.

In some settings, however, public involvement can be difficult to accomplish. In situations where there is little truly private land, coastal inhabitants may have little long-term stake and therefore interest in the land they occupy (*e.g.*, in parts of Tonga; NUNN and WADDELL, 1992). Further, governments may have neither the resources to address country-wide coastal management (particularly in archipelagic nations) nor, compared to long-resident inhabitants, the local knowledge or experience that are essential for effective management (*e.g.*, in parts of Fiji; NUNN *et al.*, 1994a).

Implementation

Once all options for coastal adaptation have been considered and the most appropriate strategy has been selected and designed, implementation is the next stage. As indicated in Section 1, an adaptation strategy to sea-level rise can comprise one or more options that fall under the three broad categories protect, retreat and accommodate. Table 2 provides an overview of these options and the technologies that make them possible. It should be noted that, in addition to the subdivision between protect, retreat and accommodate, there are various other ways to classify or distinguish between different adaptation strategies, both in generic terms (*e.g.*, SMIT, 1993; BURTON, 1997; KLEIN and TOL, 1997; SMIT *et al.*, 2000) and for coastal zones (*e.g.*, KAY *et al.*, 1996; POPE, 1997).

Adaptation can be either reactive or anticipatory, depending on the timing, goal and motive of its implementation. Reactive adaptation occurs after the initial impacts of climate change have become manifest, while anticipatory (or proactive) adaptation takes place before impacts are apparent. Second, as already discussed, adaptation may be considered to be autonomous or planned. Autonomous adaptation is spontaneous, while planned adaptation (as shown in Figure 1) requires informed and strategic actions. KLEIN and NICHOLLS (1998) concluded that most of the options listed in Table 2 require strategic planning, while few will occur autonomously. Further, options to protect against sea-level rise can be implemented both reactively and proactively, while most retreat and accommodation options are best implemented in an anticipatory manner. FISCHER (1985) distinguished between preemptive, prescriptive, preventive and promotive coastal management, whereby only promotive management seeks the integration of management issues, such as impacts of climate change with coastal development pressures.

To date, the assessment of possible response strategies has mainly focused on protection. BIJLSMA *et al.* (1996) noted the need to identify and evaluate the full range of options listed in Table 2. The range of appropriate options will vary among and within countries, and different socio-economic sectors may prefer competing adaptation options for the same area. The existence of such a broad range of options is one of the reasons why adaptation to climate change is recommended to take place within the framework of integrated coastal zone management (see Section 2.2).

Monitoring and Evaluation

It is recommended practice in any field of policy that the performance of implemented measures is periodically or continuously evaluated against the original objectives (although regrettably, this stage is often ignored or underplayed in practice). Such evaluation can yield new insights and information, which could give rise to adjust the strategy as appropriate (NRC, 1995). This process is illustrated in Figure 1 by the feedback loop from evaluation within the shaded box. This post-implementation evaluation must be distinguished from the evaluation exercise that is done to identify the most appropriate technology. The latter can be considered pre-implementation evaluation and is part of the planning and design phase (see Section 5.2).

Effective evaluation requires a reliable set of data or indicators, to be collected at some regular interval by means of an appropriate monitoring system. Indicators are a tool for reporting and communicating with decision-makers and the general public. They should fulfill a range of properties, including (*i*) a relationship to functional concepts, (*ii*) be representative and responsive to relevant changes in conditions, and (*iii*) be easily integrated within a broader evaluation framework. Evaluation is an ongoing process and the monitoring should be planned accordingly. There is limited experience of such long-term monitoring, so in many situations it is unclear which are the most appropriate data or indicators (see also BASHER, 1999). For physical systems, experience can be drawn from countries where the coast has been monitored for long periods. In The Netherlands, for instance, the position of high water has been collected annually for nearly a century and cross-shore profiles have been measured annually since 1963 (VERHAGEN, 1989; WIJNBERG and TERWINDT, 1995). Observations of the "natural" evolution of the coast allow trends to be reliably estimated and hence the impact of human interventions on the coast (breakwaters, nourishment, *etc.*) to be evaluated.

In general, the technologies to be used for monitoring are the same as those used for initial description of the coastal system. They are therefore listed in the upper part of Table 1 and discussed by MORANG *et al.* (1997a), LARSON *et al.* (1997), MORANG *et al.* (1997b) and GORMAN *et al.* (1998). As the monitoring data build up, so the strengths and weaknesses of the chosen policies become increasingly apparent.

DISCUSSION AND CONCLUSIONS

Ever since humans have lived near the sea, they have increasingly developed and applied technologies to reduce their vulnerability to coastal hazards. The same technologies can be applied to adapt to anticipated impacts of climate change. The above sections show that many technologies are available to develop information and awareness for adaptation in coastal zones, to plan and design adaptation strategies, to implement them, and to monitor and evaluate their performance. However, many of the world's vulnerable coastal countries currently do not have access to these technologies, nor to the knowledge that is required to develop or implement them. Effective coastal adaptation by these countries could therefore benefit from increasing current efforts of technology transfer (KLEIN *et al.* 2000).

In spite of this paper's focus on technological options to adapt to climate change, it should be stressed that technology by itself is not a panacea. The effectiveness of coastal adaptation technologies depends strongly on the economic, institutional, legal and socio-cultural contexts in which they are implemented. Therefore, coastal adaptation technologies are most effective as part of a broader, integrated coastal management framework that recognizes immediate as well as longer-term sectoral needs. "Win-win" situations could be established when coastal adaptation technologies also provide benefits unrelated to climate change. Thus, technology can make an important contribution towards the sustainable development of coastal zones, provided they are implemented in an enabling economic, institutional, legal and socio-cultural environment.

Furthermore, climate change is but one of many interacting stresses in coastal zones. The importance of controlling non-climate stresses in the quest to reduce vulnerability to climate change must not be underestimated. Reducing maladaptation and increasing resilience will increase the ability of natural and human coastal systems to deal with and recover from perturbations and thus reduce vulnerability to impacts of climate change.

CAMPBELL and DE WET (2000) propose three strategies to facilitate the inclusion of adaptation technologies into development programs:

- to incorporate considerations of climate change and sea-level rise into new development proposals;
- to develop proposals that are specifically aimed at addressing the possible effects of climate change and sea-level rise;
- to develop proposals for strengthening institutional and technical capacity to facilitate the above two strategies and manage the effects of climate change and sea-level rise.

These strategies require an understanding of the potential effects of climate change on coastal zones and an iterative consultative process, involving all stakeholders, to ensure that all relevant interests are considered (see, for example, FISCHER, 1986, 1990).

An important barrier to the identification and use of appropriate coastal adaptation technologies is that empirical information on coastal adaptation to climate change is still scarce, so uncertainty about the appropriateness and generic applicability of adaptation technologies remains considerable. Continued impact and adaptation assessment, combined with fundamental research on coastal system response and economic, institutional, legal and socio-cultural aspects of adaptation, is required to understand which adaptation technologies might be most appropriate and most effectively transferred to similar coastal settings.

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