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Climate shifts and coastal changes in a geological perspective. A contribution to integrated coastal zone management

Thomas A.M. de Groot
Netherlands Institute of Applied Geoscience TNO – National Geological Survey, PO Box 80015, 3508 TA Utrecht, the Netherlands (e-mail: t.degroot@nitg.tno.nl)

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Abstract

This Special Issue deals with the impact of climate change on western European coastal systems. Notwithstanding the inherent problems of studying geological data in terms of climate shifts, the results show that on the meso- and the macroscale of time, climatic forcing is a major drive for coastal change. However, its impact is largely influenced by other factors. Sediment availability plays a dominant role in the evolution of coastal systems and it can be considered one of the most important thresholds at the land-ocean interface. Sea-level changes are expected to have a significant impact on most European coasts. There is particular concern for the tidally influenced flats and marshes, and for those coastal areas known to have already a net sediment deficit and to be threatened by erosion. Areas where isostatic uplift has countered sea-level rise until now, are expected to become subject to coastal erosion in the near future under an accelerated sea-level rise scenario. The sensitivity and vulnerability of coastal systems to climate shifts is shown to be largely controlled by storm magnitude and fetch. A particular case of vulnerability is the impact of tsunamis. Finally, the consequences of human interference have been demonstrated in many cases. The implementation of geoscientific studies for rational, comprehensive and cost-effective strategies on a regional or national level of integrated coastal zone management is reviewed.

Introduction

Through most of Earth's history, the coastal system has always been dynamically forced by a variety of factors resulting in complex erosion and sedimentation patterns (Figure 1). Although coastlines and coastal environments rarely occupy the same areas over geological time, the processes that shape them have not changed. Those processes are already complex in themselves, but also interact with each other in a complex way (Figure 2).

Until recently, sea-level rise was the main forcing factor studied in relation to coastal changes (e.g. Tooley & Jelgersma 1992). An important, although often underexposed aspect in coastal studies, is the impact of climate changes. Throughout geological time, the Earth has undergone local or global climatic changes, triggered by a complex combination of astronomical, geological and environmental factors (Eddy & Oeschger 1993, Nkemdirim & Budikova 1996). The geological record is the net result of this complex combination acting upon the atmosphere, hydrosphere, lithosphere and biosphere, and thus includes information about climatic changes in the past (Frakes 1979). However, this information is not only difficult to extract and to interpret, the geological record itself is also far from complete, more often than not showing large gaps. In fact, the agents of change, e.g. geological processes, wind, water, ice, plants, and animals, have interacted to produce dynamic (eco)systems that are controlled by each other. Dynamic equilibrium within these systems is achieved by negative feedback loops, while changes from one equilibrium state to the next are achieved by positive feedback loops as well as by the crossing of geomorphic or biological thresholds. These changes by positive feedback are the major agents of environmental change (see discussion in Cowell & Thom 1994).

In order to recognise and interpret climatic changes from the geological record, and in particular from

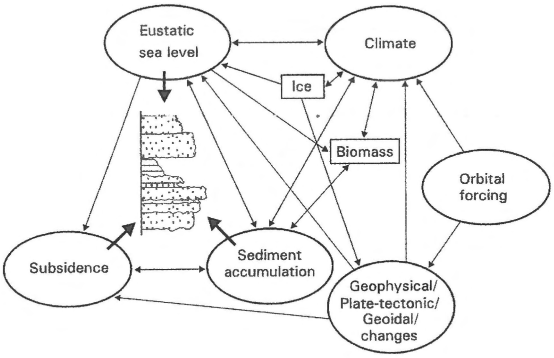

Figure 1. Interrelationships between parameters that determine the final sedimentary record. Periodicities vary greatly in this schematic diagram. Feedback effects may be rapid or slow, and their relative importance varies with geographic location and geological time (after Strasser, 1991).

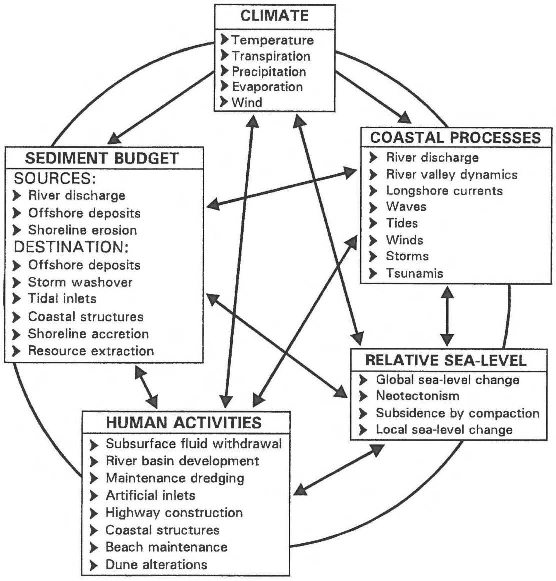

Figure 2. Processes and parameters affecting the coastal environment, and their mutual interactions (after Williams et al. 1991).

coastal sections, it is of paramount importance to recognise first of all the recorded changes in e.g. palaeo-environments, environmental thresholds, and rates of erosion and sedimentation, as well as the factors, or combinations of factors, directly related to climatic change. Inversely, it is also of paramount importance to understand in which way environmental changes resulting from geological processes are themselves triggers of climatic changes.

The set of papers in this issue, derived from the international research project ‘Climate Change and Coastal Evolution in Europe’, is concerned with the assessment of climate signals from coastal records on the western seaboard of the European Union (De Groot & Orford this issue), and contributes to the understanding of how climatic shifting in the recent geological past has influenced the coastal zone on different time scales (Table 1). After a review of the different problems identified and of the contribution of this project towards an answer to these problems, a brief overview is given of how these studies can contribute to a better understanding of the functioning of coastal systems, and thus to a better integrated coastal zone management (ICZM), taking into account, amongst other forcing parameters, future climate shifting triggered by the postulated accelerating global greenhouse effect (Houghton et al. 1990, 1992, 1996; UNCED 1993), as defined by the objectives of the project (De Groot & Orford this issue).

Table 1. Time-scale terminology (in years) used in this issue (after Orford & Carter 1995).

Microscale	Mesoscale			Macroscale	Megascale
	Inter-annual	Sub-decadal	Decadal		
< 1	1	1–10	10–100	100–1000	> 1000

Problem statement

The sensitivity of the climate system itself to e.g. astronomical forcing or plate tectonic processes (cf. Covey et al. 1996) is not discussed here. The sensitivity of coastal systems to climate shifting is the main issue. When considering the geological records of coastal sections, several pitfalls are to be avoided in interpreting palaeo-climate signals, in particular those concerning problems of erosion and sedimentation processes that are active in the coastal zone (De Groot 1996). In addition, several problems derive directly from the ways in which scientific research is conducted, since erroneous assessments and extrapolations of data can jeopardise predictions of future changes, especially in the case of ICZM. Of particular importance to coastal research are uniformitarianism, availability and usefulness of palaeo-climatological data, scales of time and space, completeness of the geological record, and the sensitivity of the coastal system to external forcing.

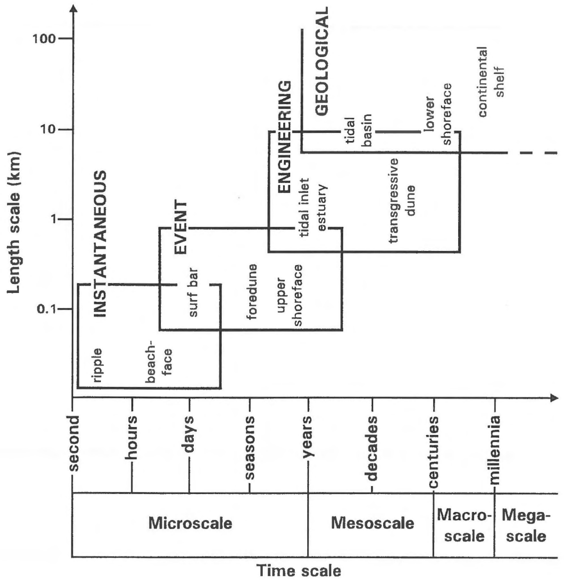

Figure 3. Spatial and temporal scales involved in coastal evolution, with typical classes of sedimentary features (after Cowell & Thom 1994).

Uniformitarianism: According to Frakes (1979), the problem of uniformitarianism relates to the researchers' degree of familiarity with the full range of possibilities for a given process, including those that may not be functioning under present climatic conditions.

Availability and usefulness of palaeo-climatological data: Frakes (1979) states that geological data are always insufficient for palaeo-climatological purposes. The shortage results from poor preservation, alteration, or dissolution, and many climatic parameters leave no discernible marks in the sediments. This results in controversial models, since assumptions about feedback mechanisms within the physical, chemical and biological components of the climate system are involved, e.g. translating human additions to global greenhouse gases into surface-atmosphere heating, and translating such heating into estimates of global surface temperature increases (Schneider 1993).

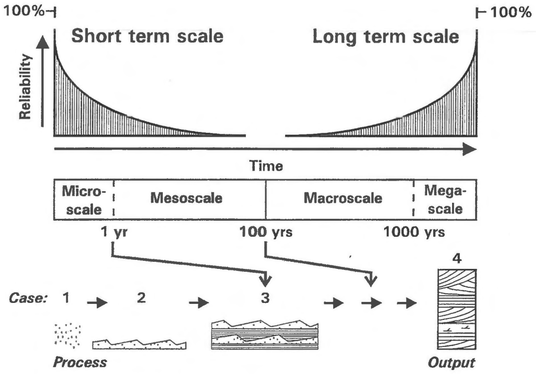

Figure 4. Reliability of research on short-term to long-term processes. Best reliabilities are achieved on the hour scale (microscale) at one end and on the geological scale (megascale) at the other. See explanation in text (courtesy A. van der Spek).

Scales of time and space: This has been critically reviewed by Schumm (1991) and particularly concerns the varying time spans over which physical systems operate in relation to space (Figure 3). There are two aspects to the time and space problem: 1) the temporal or scale resolution at which an object is viewed, and 2) the comparison between different durations and between large and small things. Thus, short-term results must be applied with care to the solution of long-term problems. Inversely, the history of geological systems can be of prime importance for interpretations and predictions of present-day processes (cf. Ricken 1991).

The problem of time in particular, is exemplified in Figure 4. The reliability of research results is highest at the two opposed ends of the time scale, i.e. at the micro- and the megascale. On the microscale, sediment movement on an hourly basis can readily be studied, e.g. fluid flow or fluid-flow structures and movement of individual particles or mass aggregates (Figure 4: case 1). Ripple generation and ripple-set movements (case 2) can be studied with a fair accuracy on a daily basis. Uncertainties start to occur when studying the evolution of ripple-train sets on a monthly to yearly basis (case 3) as the processes involved, e.g. variations in tides, storm incidence, erosion, sedimentation, and sediment budget, become more complex, and the preservation potential more important. At the megascale, the reliability of coastal-section analysis (case 4) becomes higher again as the net result of geological processes can be assessed, including the occurrence of hiatuses (see below). In between, and in particular on the time scale between circa 50 years to a couple of hundreds of years, there is a large gap in our understanding and interpretation of data, especially when these data are extrapolated to the future. Process interactions become too complex to be understood and validated in a satisfying way, and extrapolations from these interactions remain speculative. However, it is precisely this gap which covers the domain of ICZM as most, if not all ICZM problems are, in the end, meso- to macroscale and regional (Figures 3, 4). Such

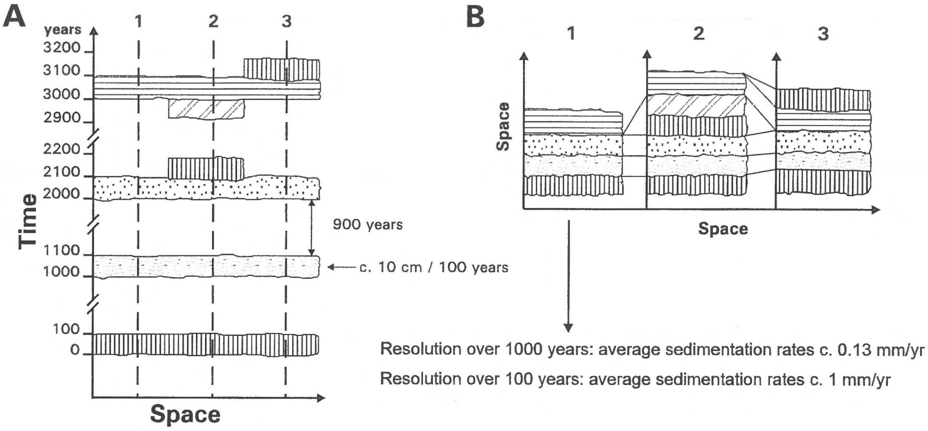

Figure 5. The completeness of the geological record. In A, sedimentation takes place during periods of 100 years, separated by three periods of 900 years of nondeposition in location 1, without visible sedimentation breaks but with a known time scale from the fossil record. In B, three different locations show different geological successions. At location 1, averaging of sedimentation rates with a 1000-years resolution will yield a low rate, and stratigraphic gaps are ignored. Averaging with a 100-years resolution will yield a higher rate. Some stratigraphic gaps will become visible when comparing different resolutions and different sites like location 2 or 3 (modified after McKinney 1991. See also Sadler 1981 and Schindel 1982).

problems are currently answered by micro- to mesoscale and local measures, e.g. beach nourishment and coastal defence works.

If time extrapolation is hazardous, extrapolation to different space scales is particularly problematic as site-specific conditions are rarely reproduced elsewhere. Trends derived from individual site studies can only be used as guidelines or rules for ICZM if they can be proven to be of more than only local value. This is often impossible, and the primary rule that can be defined is that each new ICZM site has to be studied in detail, in order to assess the local forcing conditions. This is an inherent weakness of coastal studies. The application of generic principles is difficult. Site-specific studies, however, do increase the understanding of coastal evolution under different forcing conditions.

Completeness of the geological record: With the exception of the human impact on the coastal zone which will not be discussed here, a last problem to be mentioned concerns the completeness of the geological record and the geological averaging occurring through time (Schick et al. 1987). The sedimentary record (Figure 1) is determined by two types of processes (cf. Strasser 1991), autogenic processes, i.e. erosion and sedimentation, and allogenic processes, i.e. processes external to the sedimentary system like eustatic sea-level variations, subsidence or climate change. The geological record contains large gaps that are difficult to reconstruct without precise datings or a thorough understanding of all processes involved. The recognition of erosional boundaries and periods of nondeposition, and hence the sedimentation rates within a section, are not always easy to assess and especially the time gaps involved are difficult to determine, even with the use of the whole range of palaeontological and other dating possibilities (Figure 5). According to Sadler (1981) and Schindel (1982), mean sedimentation rates averaged over long time spans include many gaps of nondeposition and erosion. As a result, these averages are relatively low. Short-time-span studies however will yield average rates that are relatively high because of a higher stratigraphic completeness. McKinney (1991) argues that, from the example at location 1 (Figure 5), 'the section would eventually be 100 per cent complete at the 1000-year level of resolution. But it would be only 10 per cent complete at the 100-year level of resolution, with deposition in only one in ten 100-year intervals'. The (in)completeness of the geological record can only be made visible by a high sampling density and the correlation between different sites (Figure 5: locations 2, 3).

Sensitivity of the coastal system: Due to the complex process interactions in the coastal zone (Figures 1, 2), it is extremely difficult to assess a 'coastal sensitivity response' (CSR) at each particular site. CSR can be defined as the rate of change occurring on a particular coast through autogenic or allogenic processes. This

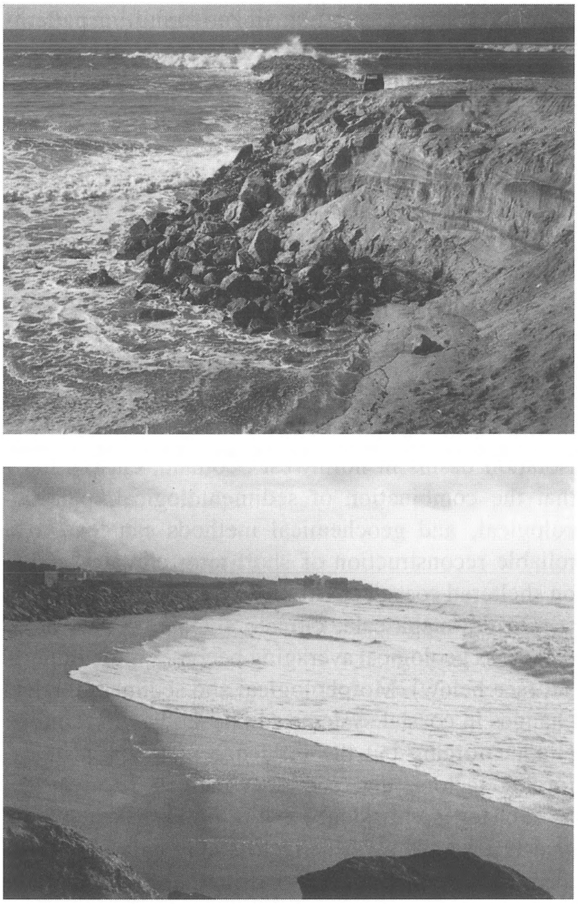

Figure 6. Examples of increased coastal erosion from engineering structures on the coastal zone of northwest Portugal, south of Porto. Above: Undercutting of the sandy cliffs at Maceda beach downdrift of a groyne intended to protect the beach (situation November 1993). Cliff height is about 5 m. Below: Despite protection measures at the base of the foredune, erosion downdrift of the groyne from where the photograph was taken, threatens the village of Cortegaça, sticking out like a cape in the background (situation February 1996).

includes some measure of 'coastal vulnerability' too. In fact, it is impossible to define a global CSR to be applied to all coastal systems in the world. One of the problems we should be aware of is the notion that we have to deal with two kinds of sensitivity: 1) a natural sensitivity, essentially a negative feedback related to autogenic and allogenic processes, and 2) an artificial sensitivity, essentially a positive feedback related to human interference, e.g. increased coastal erosion downdrift of engineering structures (Figure 6). In addition, the 'vulnerability' of the coastal system can be considered as a measure of the system's 'sensitivity', especially in relation to its interaction with human impacts. Vulnerability is mainly expressed through positive feedback while sensitivity feedback can be both positive and negative. The IPCC (1991) proposed a general methodology for vulnerability assessment in relation to sea-level rise. The methodology, however, was not applicable, as was shown by Kay et al. (1996) who concluded that '*The Common Methodology* has failed to meet two of its three main objectives, namely, 1) that of becoming a globally applicable method for assessing the potential future coastal impacts of greenhouse effects, and 2) that of enabling the development of a global picture of coastal zone vulnerability to greenhouse effects. The third objective, however, that of assisting coastal nations in planning to reduce the impact of future greenhouse effects has been partially met through the raising of awareness of the sea-level rise issue within coastal nations'. Although the third objective should not be slighted, the problems deriving from the two first objectives underscore the difficulties of the study of coastal sensitivity in a geological perspective.

Problem solving: the project's contribution

Within the context of the three objectives of investigation (De Groot & Orford this issue), problem solving has been addressed in the following ways.

Uniformitarianism: The problem of uniformitarianism appears as minimal on the microscale and the lower end of the mesoscale (Figure 4). Processes and process interactions are well-documented and can be fairly well studied within a framework of coastal changes under changing climate conditions (Duffy & Devoy, Freitas et al., Regnauld et al., Wheeler et al., all in this issue), although human impact during the last century in particular, should not be overlooked. Increasing the time scale from the mesoscale to the lower part of the megascale however, increases the uncertainties, especially those concerning climate. It may be assumed that autogenic coastal processes and responses have not changed drastically over the last few thousand years thus giving the opportunity to concentrate upon the allogenic impacts derived from climate and sea-level changes (Dabrio et al., Shennan et al., both in this issue). Beyond that duration, the allogenic influence becomes more uncertain, especially where climate is concerned, as in addition to important sea-level changes, tectonism becomes increasingly important (Dabrio et al., Dawson et al., Granja, Zazo et al., all in this issue). Uniformitarianism is especially challenged when 'events', e.g. tsunamis, are studied (Hindson et al. this issue).

Availability and usefulness of palaeo-climatological data: Solving the problem of availability and usefulness of palaeo-climatological data from the geological record has been one of the main goals of the project (De Groot & Orford this issue). Potentially, the assessment of climate-change forcing can be best obtained in microscale studies. Duffy & Devoy (this issue) show that in western Ireland sites, storms are dominant processes for winter accretion in the low-energy, silt-dominated, saltmarshes as well as in the higher-energy, sandy dunes and machairs. This operates on a threshold-response basis with accretion during minor and/or medium-scale storms, and erosion during major ones. The directional aspect of meteorological forcing is also underscored, particularly in the high-energy sites, where the longest westerly and south-westerly fetches have the largest erosional response to the wind and wave climate. Lower-energy coasts have a weaker relationship with environmental forcing factors and are more liable to local influences. However, Duffy & Devoy show considerable differences in accretion rates between the micro- and the mesoscale. They conclude therefore that it is difficult to make direct comparisons between factors acting on the sites in western Ireland at different time scales.

In Brittany (Regnauld et al. this issue), comparison between field data and modelling results of climate forcing on small sandy bays, shows that storm magnitude and fetch direction are the main factors influencing the erosional patterns on the microscale and the mesoscale, with emphasis on the local conditions of exposure to storm waves. However, the stability of the coast is primarily controlled by the availability of sediment from the cliffs that counters any effects from changes in sea-level or climate.

In northwest Ireland, Wheeler et al. (this issue) demonstrate annual and decadal superimposed time-scale controls on sedimentation in saltmarshes. The annual variation is related to frequency and magnitude of extreme storm-surge water levels as recorded for the south-western British Isles, and shows inverse variations of deposition rates in relation to storm-surge on the one hand, and the association of increasing amounts of coarser sediments in the saltmarshes with increasing annual surge activity on the other hand. The decadal control on deposition is related to trends in the strength of surge generation, linked to shifting patterns of storminess over the last century.

Increasing the time scale decreases the reliability of palaeo-climatological data. As discussed by Hindson et al. (this issue), the meso- to macroscale transition from marine to fluvial conditions in the Boca do Rio estuary in southern Portugal, seems to be related to changes in climate and/or ocean-current circulation during the Late Holocene, influencing the growth of a coastal barrier in front of the estuary (cf. Dabrio et al. this issue).

In contrast however, the macroscale work of Freitas et al. (this issue) on the Tagus estuary, and the megascale work of Shennan et al. (this issue) on isolation basins in northwest Scotland, clearly show that the combination of sedimentological, palaeoecological, and geochemical methods can lead to a reliable reconstruction of short-term climate forcing on sheltered coastal environments.

On the megascale, climate signals become more diffuse as geological averaging becomes more important (see below). Morphological and sedimentological changes in coastal systems can be studied in terms of climate forcing but the influence of other, primary, forcing factors, e.g. sediment budget, relative sea-level changes, subsidence and/or uplift, has then to be clearly assessed as these factors may hide or destroy the more diffuse climate signals in the sedimentary record. This has been attempted in several contributions to this Special Issue. Dabrio et al. show that changes in spit-growth orientation in estuaries of the Gulf of Cádiz are controlled by changes in prevailing wind directions and in aridity. In this same area, Zazo et al. come to the same conclusions in their study of the sandy cliffs of El Asperillo. The recorded wind directions in fossil dunes are here the most important proxy data available for climatic reconstruction.

Also on the megascale, the link between global climate change and coastal evolution is addressed by Dawson et al. (this issue). Their work shows a direct link between climate, sedimentation and erosion in the exposed coast of western Jura, Scotland. The temperate interstadial climate was associated with gravelly beach-ridge formation while cold climate conditions during the Younger Dryas were associated with rapid coastal erosion.

Scales of time and space: Time and space problems are difficult to resolve as the extrapolation from short to long and from small to large inherently involves considerable uncertainty. Unexpected results may even be obtained, as was shown by the macroscale modelling of the Westerscheldt estuary in the Netherlands within the framework of the project (Van der Spek 1997). Despite a significant sediment input and the accretion of the tidal flats and marshes to supratidal level, resulting in reduction of the total surface area of the intertidal flats over the last 300 years, flood dominance decreased since peak flood velocities declined more than peak ebb velocities, while the main channels of the estuary got deeper. These changes were not significantly influenced by an increasing tidal range and a rising mean sea-level.

The space (i.e. scale) problem is successfully addressed by Shennan et al. (this issue) in the isolation basins of northwest Scotland. The megascale evolution of these basins over the last 12 000 years, analysed at high resolution, shows that relative sea-level change controls the broad pattern of coastal evolution at each site, while local, site-specific, factors contribute to the short-term process changes.

Completeness of the geological record: Duffy & Devoy (this issue) show that the considerable differences in accretion rates between the micro- and the mesoscale are most probably due to the geological averaging of the record. Notwithstanding this, the results show that, in order to assess coastal changes forced by climate factors, studies should include short- and long-term evaluations at the same time. In this way, the averaging effect can be quantified, and accordingly translated to a higher degree of certainty.

The completeness is a particular problem in areas under tectonic control (Granja, Zazo et al., both in this issue). Erosional surfaces have to be defined clearly in order to assess the role climate change may have had in coastal evolution, especially in combination with sea-level changes. In areas subject to isostatic uplift, coastal history was preserved to some extent (Dawson et al., Shennan et al., both in this issue). Shennan et al. rightly stress that a future accelerated sea-level rise might endanger those areas that have not been exposed to coastal erosion yet.

Sensitivity of the coastal system: The sensitivity of the coastal system to climate change has been shown by Duffy & Devoy (this issue) to be mainly controlled by storm magnitude and fetch. In more sheltered areas, local factors like sediment budget, tides and human interference, may have a larger impact. This same conclusion is reached by Regnauld et al. (this issue) concerning the embayments of Brittany.

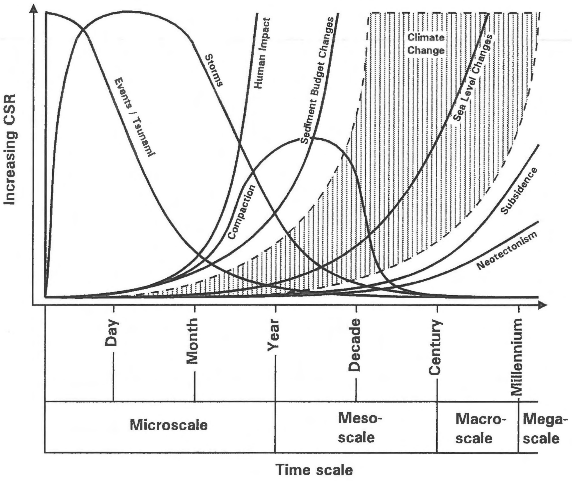

Figure 7. ‘Coastal Sensitivity Response’ (CSR) to different forcing parameters through time.

Sensitivity of the coastal system is a particular issue when ‘events’ are taking place. Earthquakes and associated tsunamis are important, though transient, forcing factors on coastal systems of the world (e.g. Young & Bryant 1992). In Europe, tsunami impacts have been recorded particularly in Scotland (e.g. Dawson et al. 1988, Long et al. 1989, Harbitz 1992). The Lisbon earthquake in 1755 caused a conspicuous fining-upward sandy to silty bed with a basal conglomerate of boulders and shells in the tsunami deposits studied in southern Portugal by Hindson et al. (this issue). Palaeo-ecological data proved invaluable to interpret the evolution of the site. The influence of co-seismic subsidence and subsequent tectonic uplift played a major role in the evolution of the area during the last two centuries.

Also, the work of Shennan et al. (this issue) demonstrates that within coastal systems in dynamic metastable equilibrium, the exact timing of system breakdown (i.e. positive feedback of the system responding to a threshold crossing) is determined by site-specific factors, superimposed on regional sea-level rise.

The sensitivity of coastal systems is particularly important in the case of neotectonic movements. Zazo et al. (this issue) demonstrate the importance of such movements on coastal evolution near Huelva, southern Spain, as does Granja (this issue) for northwest Portugal. This last author indicates furthermore that sediment availability on the shoreface and the shelf, and knowledge about sediment transport are a *sine qua non* in coastal studies. In many areas of the western

European seaboard, including most of the sites studied in this issue, this is still an incompletely answered question.

Last but not least, the sensitivity of coastal systems to accelerated sea-level rise has been the special concern of the authors concerned with the macro- to megascale approach (Dabrio et al., Dawson et al., Granja, Shennan et al., Zazo et al., all in this issue).

The time-scale relationships of the different forcing factors and their incidence on coastal sensitivity response (CSR) are shown in Figure 7. This shows in particular that the main time range of concern is the meso- and the macroscale. This is also the domain of current ICZM approaches. Especially regarding the sensitivity of coastal systems to sea-level or climate fluctuations, there is still much debate about the impacts of the Little Ice Age (e.g. Beltrami & Mareschal 1993). Dune development seems to be related to this in northwest Portugal (Granja this issue), and a 20 to 30 cm mean-high-water drop in the southern North Sea has been shown to correspond to the global cooling during that period (Jensen et al. 1993, Louters & Gerritsen 1994, Barth & Titus 1984).

ICZM implications: an assessment

The variety of geoscientific disciplines represented in this issue has established an important basis for conceptual ICZM models which will be needed in the next generation of physical coastal understanding. Decision Support Systems (DSS), created to help formulate coastal zone management issues, are mainly based on the geoscientific information for the sites at risk. In particular, the following observations can be derived from the work presented.

The nature of climate-shift forcing: ICZM should pay attention to:

- Coastal response to an accelerated sea-level rise due to the postulated greenhouse effect, as this response could very well become the dominant coastal problem on the mesoscale (see in particular Titus & Narayanan 1996). Particularly in coastal areas with a long-standing history of isostatic uplift, accelerated sea-level rise can be considered as a new factor in addition to storm-surge forcing, as its effects may no longer be offset by the rate of uplift.
- The important role of storms and tides on the mesoscale, especially when combined under mutually re-enforcing conditions under a scenario of changing storminess patterns (e.g. Mason et al. 1996; Kuemmel 1996).

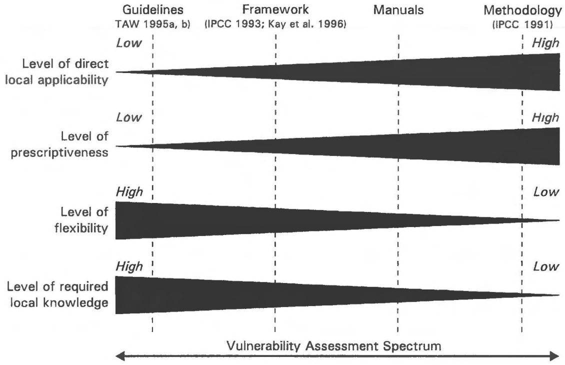

Figure 8. Schematic coastal 'vulnerability assessment guidance spectrum' for different types of measures (after Kay et al. 1996).

- The growing impact of increased storm frequencies and magnitudes on the higher-energy environments, not only on the open beach systems but also on the mudflats and degraded saltmarshes, and more so in macrotidal than in mesotidal environments. In contrast, the lower-energy or less exposed environments, e.g. mature and growing saltmarshes, show a weaker relationship with environmental forcing and thus might be, for the time being, free from direct climate shift forcing. However, these environments may be increasingly subject to local impacts of which the human ones are not the least.
- Detailed knowledge of local parameters like geomorphology, exposure to storms and tides, and sediment availability and delivery. In many cases, the availability of sufficient sediment on the shoreface or shelf may counter coastal erosion resulting from accelerated sea-level rise. However, this knowledge is often missing or not taken into account.

The time scales of activity and control: ICZM planners are recommended to be especially aware of the mesoscale (decadal) rates of coastal change. At this stage of knowledge, the macroscale is still out of reach for significant contributions to ICZM, except where an accelerated sea-level rise on the mesoscale is likely to occur and to continue.

The regional context of ICZM: The need for better environmental monitoring and better integration of existing environmental data is clear. Especially the extrapolation of results from site to site should be done with care. Site-specific forcing factors should be assessed. The regional context of ICZM is also clearly involved with human impacts. Here too, better monitoring of environmental changes is needed on a regular basis in order to integrate the effects of natural and artificial forcing on European coastal zones.

Sensitivity and /or vulnerability assessment strategies: It is hardly possible, nor recommended, to draw-up general management rules for the assessment of coastal sensitivity on the basis of present knowledge. Especially temporal and spatial extrapolations should be used with great care. To this end, future sensitivity and vulnerability assessment methodologies should not be as prescriptive and inflexible as the IPCC Methodology (IPCC 1991). Alternatively, broad, flexible, and non-prescriptive guidelines (e.g. TAW 1995a, b) may result in low levels of direct applicability (Figure 8). Therefore, the use of a 'Framework' for ICZM is recommended, in order to integrate vulnerability assessment within the national strategies anticipating and mitigating the impacts of climate change in coastal zones (Kay et al. 1996; IPCC 1993).

Conclusions

This Special Issue is concerned with the impacts of climate shifts on coastal evolution in western Europe. A large array of methodologies, coastal sites, and studied coastal forcing factors on different time scales has led to a better understanding of coastal processes influenced by climate shifts (especially storms), sea-level changes, tectonic movements, isostasy, and sudden events (tsunami).

Climate-shift forcing on the meso- and the macroscale, i.e. the important role of storms and tides, in combination with local site conditions, has been shown to be one of the major drives for coastal changes. Sediment availability, however, also plays a dominant role and can be considered one of the most important thresholds controlling coasts.

Sea-level changes, especially the postulated accelerated future sea-level rise, will have a significant impact on most western European coasts, particularly on the tidally influenced flats and marshes, and on the areas known to have a net sediment deficit which are already subject to erosion. Other areas at risk may be those where isostatic uplift has countered sea-level rise until now. They are expected to be vulnerable to coastal erosion in the near future under an accelerated sea-level rise scenario.

The sensitivity and vulnerability of coastal systems to climate shifts are largely controlled by storm magnitude, and direction and length of fetch. The sediment availability may play a dominant role in the autogenic and allogenic processes that control the sensitivity. A particular case of vulnerability is the impact of tsunamis.

Last but not least, the impact of human interference on coastal systems has been approached. It can be concluded that as long as the economic pressure for exploitation and use of the coastal zone plays a dominant role, very little can be achieved in terms of 'integrated' or 'sustainable' coastal-zone management (Sorensen 1997).

While global-change research has still a long way to go towards rational, comprehensive and cost-effective policy responses (e.g. Brunner 1996), 'There is a growing recognition that the unmanaged, increased use of coastal resources will have a devastating effect on the environment, with ensuing physical, social and economic consequences' (Preface in: Taussik & Mitchell 1996). In terms of an ICZM policy applicable for a variety of coastal zones, long-term, i.e. meso- to macroscale, geological coastal studies are needed in addition to knowledge about global-change issues from General Circulation Models of climate shifting on the one hand, and short-term, i.e. microscale, understanding of physical processes on the other hand. However, difficult the validation and extrapolation of geological data might be for ICZM, such data are considered of paramount importance for better regional or national policies. As such, this set of papers contributes to a more rational, comprehensive and cost-effective ICZM approach, and in particular to the creation of Decision Support Systems, in which the geological information and understanding of coastal-zone evolution are integrated in the assessment of management strategies and of sensitivity and/or vulnerability studies.

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