Chapter 1

The Coastal Zone – a Domain of Global Interactions

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1.1 Introduction

The coastal zone is a zone of transition between the purely terrestrial and purely marine components on Earth's surface. It is widely recognised as being an important element of the biosphere – as a place of diverse natural systems and resources.

Intense interaction characterises the coastal zone. Here, land-dominated global processes and ocean-dominated global processes coalesce and interact, characterised by multiple biogeochemical environmental gradients. The balance of these interactions provides a unique domain of gradient-dependent ecosystems, climate, geomorphology, human habitation and, importantly, regimes of highly dynamic physical, chemical and biological processes.

Coastal processes and natural ecosystems are subject to changes that vary greatly in geographic scale, timing and duration and that combine to create dynamic and biologically productive coastal systems vulnerable to additional pressures resulting from human activities. In turn, the sustainability of human economic and social development is vulnerable to natural and human-induced hazards as a result of our poor understanding of the dynamics of land-ocean interactions, coastal processes and the influence of poorly planned and managed human interventions.

Terrestrial processes are dominated by hydrological regimes and horizontal flows that sustain mechanisms for energy gradients and transfer of materials (nutrients, contaminants, sediments), providing a variety of conditions for material transformations and biological sustenance. Oceanic processes are similarly dominated by hydrological and physical factors that control transport of materials and energy regimes, often in contrast with the land-dominated factors. The resultant balance of terrestrial and oceanic processes yields regional and local heterogeneity in physical and ecological structure, and sustains the dynamics of ecosystem function and biogeochemical cycling in the coastal domain.

The interactions that sustain this balance of processes are in turn influenced by the temporal variability of large-scale phenomena such as CO_2 concentrations in the atmosphere and in seawater and allied temperature changes. Increasingly, humans are influencing these processes and phenomena, resulting in measurable changes directly within the coastal domain and, through feedback, indirectly within the terrestrial, oceanic and atmospheric compartments of the Earth system (Steffen et al. 2004). The result is a diversity of habitats, habitation and areas that are undergoing structural and process changes with significant implications for human society and for the integrity of the coastal zone.

The richness and diversity of resources found in coastal areas have led to a corresponding concentration of human activities and settlement along coasts and estuaries throughout the world. It is estimated that about half of the world's human population lives near the coast and, while the density of coastal populations varies dramatically among regions, there is a general trend of people moving from inland regions to the coast. Clearly the coastal zone will be expected to sustain the livelihoods of a very large proportion of the human population and will remain an important asset to people worldwide, for the foreseeable future.

The coastal zone is also one of the most perturbed areas in the world. Pollution, eutrophication, industrialisation, urban developments, land reclamation, agricultural production, overfishing and exploitation continuously impact on the sustainability of the coastal environment. The major challenge that humans face today is how to manage the use of this area so that future generations can also enjoy its visual, cultural and societal resources. A recent evaluation of the impacts of marine pollution from land-based sources found that marine environmental degradation is continuing and in many places has intensified (GESAMP 2001). The Intergovernmental Panel on Climate Change (IPCC) in 2001 projected increased global atmospheric CO_2 concentrations and temperature elevations that will increasingly, although differentially, influence the coastal zone across regions (Houghton et al. 2001). Global assessment of the environment (OECD 2001), of world resources (WRI 2000, Burke et al. 2001), of oceans and coastal seas (Field et al. 2002), and of global change (Steffen et al. 2002, 2004) describe a tapestry of pressures, impacts and predictions of changes in the coastal zone.

The resources and amenities of the coastal zone are crucial to our societal needs. While it represents about 12% of the world's surface (< 20% of the land surface area and < 9% of the global marine surface area: Costanza et al. 1997), the coastal zone presently is:

- a major food source including major crops and most of the global fisheries,
- a focus of transport and industrial development,
- a source of minerals and geological products including oil and gas,
- a location for most tourism, and
- an important repository of biodiversity and ecosystems that support the function of Earth's systems.

New commercial and socio-economic benefits and opportunities continue to be developed from use of coastal resources, while products and amenities and the issues of environmental management and sustainability challenge planners, managers and policy-makers (Cicin-Sain and Knecht 1998, WRI 2000, von Bodungen and Turner 2001).

A major problem for coastal management is the constant changing of coastal systems, from both "natural" and human causes. Changing wave and current regimes, climate, morphological processes and fluxes of materials from land, atmosphere and oceans are causes of high natural variability, which is still imperfectly understood. Over the last century, humans with their improving technological capabilities have accelerated the rate of change, increasing their influence on the dynamics of already highly variable ecosystems. Our understanding of these impacts, and any decisions for remedial or ameliorating actions, needs to be couched within a wider appreciation of the dynamics of global change, including climate change.

Political, institutional and coastal management initiatives have moved slowly to encapsulate three major conceptual advances embraced by coastal science researchers: (*a*) that humans are an integral component of the ecology and function of ecosystems (for example, von Bodungen and Turner 2001, Smith and Maltby 2003); (*b*) that the water continuum of a river basin catchment (or watershed) and its receiving coastal ocean is a fundamental unit for coastal assessment and management (for example, Salomons et al. 1999); and (*c*) that an ecosystems approach is required for coastal zone management (for example, Wulff et al. 2001).

New tools and techniques have been developed with applications to the coastal zone for scientific inquiry, concept-building, assessment and monitoring (see, for example, Sylvand and Ducrotoy 1998, Sala et al. 2000, UNESCO 2003). These range across observational scales from molecular level assay to measurements from space.

Extended global communications and regional capacity-building have increased public awareness and understanding of coastal zone issues. However, the resolution of problems in the coastal zone remains an enormous challenge if we are to meet the often-stated goals of sustainable resource use and maintenance of Earth system function.

In this chapter, we provide a contextual framework for the coastal zone and its vital interactions, including information about its resources, societal and environmental benefits and values, and an overview of the natural and human pressures and threats that affect the significant changes and dynamics of the global coastal zone. A synopsis is provided of key methodologies and approaches developed and used by LOICZ to assess issues about material fluxes and the interactions between pressures and system responses in this dynamic domain.

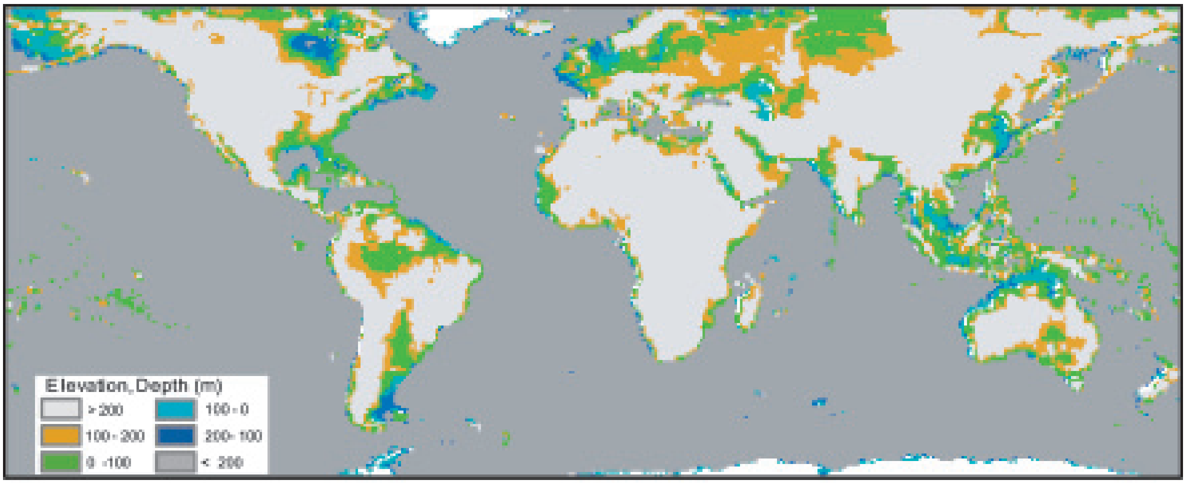


Fig. 1.1. The coastal zone. The LOICZ domain (terrestrial areas: *yellow* 100–200 m elevation, *green* < 100 m elevation; marine areas: *light blue* 100 m depth, *blue* 100–200 m depth)

1.2 What is the Coastal Zone?

The coastal zone comprises a suite of unique ecosystems adapted to high concentrations of energy, sediments and nutrients that stimulate both high biological productivity and a diversity of habitats and species. The variety of ecosystems in the coastal zone encompasses distinctive communities of plants and animals. Powerful and dynamic physical forces continuously shape the coastal zone and its ecosystems and also pose risks to human activities.

The coastal zone (Fig. 1.1) includes river basins and catchments, estuaries and coastal seas and extends to the continental shelf. This relatively narrow transition zone between land and ocean is coupled to phenomena and processes in more distant uplands and offshore waters. Both biogeochemical and socio-economic linkages are included.

There is no single, consistent definition for the coastal zone. Definitions to constrain the spatial boundaries of the coastal zone have ranged from very broad (e.g., extending to the landward and seaward limits of marine and terrestrial influences) to highly restricted (e.g., the coastline and adjacent geomorphological features determined by the action of the sea on the land margin). However, there is now general adoption of the OECD Environment Directorate's approach, wherein the definition of the coastal zone needs to vary according to the type of problem or issue being addressed and the objectives of management (see, for example, Harvey and Caton 2003).

A common rule of thumb is to include the landward area to 100 km from the land-sea interface (WRI 2000, Burke et al. 2001). While this is convenient for generic mapping purposes and captures most of the landward area of the coastal zone, it does not fully embrace vital river catchments and their processes. Recent estimates of coastal population and human exposure to hazards have considered the "near-coastal zone" to include the landward area contained within 100 m elevation of sea level and 100 km of the shoreline (Nicholls and Small

Text Box 1.1. Length of the global coastal zone

Stephen V. Smith

The length of the coastline is dependent upon how it is measured. Mandelbrot (1967) expressed this as a problem in fractals in a classical paper entitled "How long is the coast of Britain?" The answer to the question becomes a matter of both scale and methodology. As long as an internally consistent methodology is used, the question can be answered in an internally consistent and useful fashion. Further, the difference among methods (and scales) can provide information about coastline tortuosity, hence statistical information related to coastal features (e.g., bays, estuaries).

The 2002 CIA World Factbook (*http://www.cia.gov/cia/publications/factbook/*) reports a world coastline length of 356 000 km, based on analysis of a 1 : 35 000 000 map. A summation in the same publication for the coastlines of the world's oceans (at variable scales) gives about 377 000 km, while a summation for the world's countries (with even more variable scales and, probably, variable methodologies) gives a total length of about 842 000 km. Various estimates for the length of the world coastline are provided below, each reasonably well defined.

One approach is based on simple geometry. Consider the coastal zone as a rectangle of known area and width, and calculate the length. The area of the ocean shallower than 200 m is approximately 27×10^6 km² and generally the shelf break lies between 110 m and 146 m depth (Sverdrup et al. 1942). This implies that the area to 200 m overestimates the shelf area slightly, so we use a nominal area of 25×10^6 km². This is also consistent with estimates derived from the World Vector Shoreline (WVS) ETOPO2 (see below). Hayes (1964) measured the width of the inner continental shelf (< 60 m depth) along 2 136 transects and estimated the average width to be about 17 km. The primary uncertainty in this calculation is that Hayes' transects excluded some areas: much of the Arctic and Antarctic, and also small island shelves. If we assume that the shelf width to ~130 m depth is twice this inner shelf width, then the average shelf width is about 34 km. By this calculation, the estimated length of the coastal zone is $25 \times 10^6/34$, or about 740 000 km. This calculation approximates the world coastline as a long rectangle with a length : width ratio of about 20 000 : 1. The length is about twice the global value reported in the CIA World Factbook and 12% below its country sum.

A second approach is to use a globally consistent high-resolution shoreline available as a GIS layer. The 1 : 250 000 World Vector Shoreline (WVS, *http://rimmer.ngdc.noaa.gov/coast/wvs.html*) has high enough resolution to distinguish most (although not all) of the small lagoonal features. In using equidistant azimuthal projections of the globe (30° latitude zones; polar projections above 60° latitude and geographically centered 30° × 90° boxes at lower latitudes), a coastline length of 1.2×10^6 km is derived. Similar analysis using a 1 : 5 000 000 shoreline (same web-site) gives a length of 600 000 km.

Finally, using gridded data from ETOPO2 (2-minute grid resolution, a length scale varying between about 0 and 3 km, which is latitude-dependent; see Text Box 1.7), yielded a shoreline length of about 1.1×10^6 km.

It is useful to consider these estimates in the context of Mandelbrot's (1967) characteristic length. We assign the WVS a characteristic length (l) of 1 km, based on ability to discern features to about this scale. The 1 : 5 000 000 shoreline is assigned l of 20 times the WVS, or 20 km; the 1 : 35 000 000 is similarly scaled ($l = 140$). The three scales show the following relationship:

$$\text{(coastline length)} = 0.78\, l^{-0.24}$$

From this equation a fractal dimension of 1.24 can be calculated, virtually identical to the value for Britain, which Mandelbrot considered "one of the most irregular in the world." We can then use the regression equation to estimate l for both the ETOPO2 and "simple geometry" cases. ETOPO2 has an apparent l of 1.5, consistent with expectation based on grid spacing; the simple geometry has an apparent l of 7.2 (or a scale of about 1 : 2 000 000). This also seems reasonable.

These calculations are relevant for several reasons. The average width, 34 km, is narrower than the 0.5 degree (~50 km) grid-spacing used in the LOICZ typology. This is a reminder that it is difficult to represent the characteristics of the shelf with even this relatively high resolution grid. Further, for every kilometre of smooth, "simple-geometry" coastline, there are 2 km of coastline irregularities at scales > 1 km. The irregularities include both embayments and promontories.

2002). The seaward boundary of the coastal zone has been subject to a variety of determinants, most of them based on depth bathymetry limits (see also Chap. 3). Reported estimates for the global coastal area and coastline length are also highly variable and the cited metrics depend on the scale and methodology used for the estimation (see Text Box 1.1).

For the purposes of the LOICZ programme, the broad domain of the coastal zone as a global compartment was defined in the LOICZ Science Plan as:

> "extending from the coastal plains to the outer edge of the continental shelves, approximately matching the region that has been alternatively flooded and exposed during the sea level fluctuations of the late Quaternary period" (Holligan and de Boois 1993).

As a general metric, the coastal zone for LOICZ purposes nominally extends from the 200 m land elevation contour seaward to the 200 m depth isopleth (Pernetta and Milliman 1995). This region is viewed as encapsulating most of the material fluxes and processes of transformation, storage and interaction of materials, including human dimensions of the coastal zone. However, operationally in LOICZ and in keeping with the general acceptance of the OECD approach, the setting of the spatial or geographical dimensions of the coastal zone has been determined by the particular issues of land-ocean interaction being addressed.

In the LOICZ Typology approach used to integrate biogeochemical processes and interactions in the global coastal zone (see Sect. 1.5.2 below, and Chap. 3), the coastal domain is described by about 47 000 cells of half-degree resolution, generally extending inland 70–100 km and offshore to the edge of the continental shelf (*http://www.kgs.ukans.edu/Hexacoral*). Assessments of nutrient discharges from land to the coastal sea require consideration of entire catchment (or watershed) areas that often extend beyond the 100 km planar boundary (see Chap. 3). Similarly, the LOICZ assessments of regional and global sediment and water fluxes (see Chap. 2) and of socio-economic inter-relationships with material flows in river basins (see Chap. 4) generally deal with entire river catchments as the vital spatial elements of the coastal zone.

The coastal zone is a relatively small area of Earth's surface. It contains an array of natural ecosystems and habitats, functions as a significant and complex region for biogeochemical transformation, houses more than 45% of the human population and provides wide societal benefits (Table 1.1). Its heterogeneity in physical, chemical, biological and human dimensions and the allied spatial scaling implications ensures that the coastal zone remains a challenge to measure, model and manage.

Biogeochemically, the coastal zone can be considered as a region of dominantly horizontal gradients, exchanges and fluxes. However, vertical flux interactions with atmosphere, soil and groundwater sustain and influence vital processes in Earth's system (Steffen et al. 2004). Temporal dimensions and variability are crucial to the dynamics and natural functioning of the coastal zone. It is not in a steady state, but changes through time in response to different forcings, ranging from daily (e.g., tides and precipitation/river flow) to seasonal (e.g., climatic patterns), annual (e.g., fisheries yield), decadal (e.g., El Niño-Southern Oscillation) and millennial (e.g., sea level was about 100 m lower 8 000 years ago in many parts of the world and considerably higher in Scandinavia than present levels).

A multiplicity of human uses and benefits is derived from the coastal zone (Table 1.2). Resources, products and amenities are as heterogeneously dispersed at local and

Table 1.1. The coastal zone. Global characteristics

The coastal zone:
▪ comprises <20% of the Earth's surface
▪ contains >45% of the human population
▪ is the location of 75% of cities (megacities) with >10 million inhabitants
▪ yields 90% of the global fisheries
▪ produces about 25% of global biological productivity
▪ is the major sink for sediments
▪ is a major site of nutrient-sediment biogeochemical processes
▪ is a heterogeneous domain, dynamic in space and time
▪ has high gradients, high variability, high diversity

Table 1.2. The coastal zone. Resources, products and amenities

Resource – natural materials
▪ Water – surface, ground
▪ Forests and timber
▪ Arable land
▪ Food
▪ Geological ores and deposits
▪ Ecosystems and biodiversity
Products – natural and human derived commodities include
▪ Food
▪ Fisheries
▪ Habitation
▪ Industrial goods and processes
▪ Oil, gas and minerals
Amenities – natural and human-derived services include
▪ Transport and infrastructure
▪ Tourism
▪ Recreation and culture
▪ Biodiversity
▪ Ecosystem services

regional scales as are natural settings and processes, and are subject to changing patterns of availability, quality, limitations and pressures.

The human dimension is crucial in directly and indirectly modifying the entire fabric of the coastal zone through exploitation of living and non-living resources (Vitousek et al. 1997). Urbanisation and land-use changes continue to result in degraded water and soil quality, pollution and contamination, eutrophication, overfishing, alienation of wetlands, habitat destruction and species extinction (Burke et al. 2001). Current research by LOICZ on C-N-P nutrient processes in estuarine systems suggests that there are few, if any, regional examples of unimpacted coastal environments (see Chap. 3).

1.3 System and Human Attributes of the Coastal Zone

Coastal ecosystems are diverse in their living and non-living components; most of them are highly productive, have high degrees of biocomplexity, and provide food and shelter for a myriad of species, including humans. Despite their diversity and structural differences, the ecosystems all have common functional characteristics such as the flow of energy through them and the recycling of the macro- and micro-elements essential for life.

1.3.1 Coastal Ecosystems

The coastal zone contains a number of distinctive biological assemblages including coral reefs, mangroves, saltmarshes and other wetlands, seagrass and seaweed beds, beaches and sand dune habitats, estuarine assemblages and coastal lagoons, forests and grasslands. The ecosystems and habitat assemblages are constrained by their adaptation to a number of dynamic environmental settings: shallow marine environments, marine-freshwater fluctuations and aquatic-terrestrial conditions imposed by the interaction of atmospheric, marine, freshwater and terrestrial elements across the land-ocean boundary (Ibanez and Ducrotoy 2002). These conditions determine a vital mixture of habitats subject to regimes that are too extreme for many purely terrestrial or aquatic plants and animals, including strong salinity gradients, conditions of aquatic emergence-submergence, patterns of hydrological fluctuation and a diversity of energy regimes. Like the flora and fauna, the underpinning biogeochemical cycles and ecological processes of the coastal ecosystems interlink in special ways that are characteristic of both the various ecosystems and the coastal zone itself.

Assessment of the status of coastal ecosystems has been the subject of many efforts and publications, across local to regional scales. However, datasets describing the extent of different coastal habitats remain incomplete and often inconsistent (see Burke et al. 2001). Generally, the data encompass only local areas, so that a limited patchwork of information is available at local and sometimes regional scales (Sheppard 2002). Historical records are rarely available and, when present, the reliability of data and geo-referencing is often questionable. These limitations are being addressed by an increasing number of nations, as efforts are being made to assess national resources, to meet legislative requirements for state of environment reporting, and in the course of academic and applied management studies (e.g., in Australia, Wakenfeld et al. 1998, SOER 2002; in North America, UNEP 2002).

At a global scale, a recent report on world resources 2000–2001 (WRI 2000) provided a score-card that painted a less than desirable picture of the state of the global coastal zone. The Intergovernmental Oceanographic Commission (IOC) program of coral reef assessment considered that human activities continue to threaten their stability and existence, with 11% of global reefs lost and 16% not fully functional (Wilkinson 2000). Regional differences in the level of impacts on coral reefs are exemplified by the Southeast Asian region where 86% of reefs are under medium to high anthropogenic threat, particularly from over-fishing, coastal development and sedimentation (Talaue-McManus 2002).

Globally, mangroves are considered to have been reduced by more than half (Kelleher 1995); in Southeast Asia more than two-thirds of mangrove forests have been destroyed since the early 1900s, with current loss rates ranging between 1–4% per year (McManus et al. 2000). While some re-forestation of mangroves is occurring (by planting at local scales and as a result of changes in sedimentation processes), the net global trend in areal distribution and ecosystem quality is downwards (Burke et al. 2001). Direct loss of other wetlands and seagrass meadows near the coastal interface has been documented at regional and local scales but a comprehensive global assessment has yet to be achieved. In all cases, the changes in the extent of coastal habitats around the world result from a mosaic of local and regional differences in the intensity of societal and climatic pressures (see Fig. 1.3) operating across various spatial and temporal scales.

The diverse chemical, physical and biological processes integrated within habitats or coastal ecosystems are crucial in providing socio-economic goods and services for humankind (Costanza et al. 1997, also see Sect. 1.4.3). Scientifically, our understanding of the key processes dominating in any specified ecosystem has improved greatly over the last few decades. Concepts and methods for studying integrated processes within coastal ecosystems continue to be developed and extended (e.g., Alongi 1999, Black and Shimmield 2003, Lakhan 2003). Similarly, there have been advances in our understanding of the integrated processes and regimes of feedbacks between the fluxes of physical, chemical and biological materials between ecosystems; for example, between UK rivers and the North Sea, by the Land Ocean Interaction Study (LOIS: Neal et al. 1998, Huntley et al. 2001) and between the Great Barrier Reef and adjacent land catchments (Wolanski 2001).

However, we are still grappling with ways to measure and assess changes in coastal ecosystem processes across spatial scales to allow an understanding of regional and global changes in the functioning of coastal ecosystems.

A recent expert workshop (Buddemeier et al. 2002) addressing disturbed and undisturbed nutrient systems in estuaries and coastal seas examined a number of typological databases of the global coastal zone in an effort to partition different variables influencing coastal systems: the biophysical (indicative of the system dynamics) and the anthropogenic (indicative of a strong river-basin influence). Because sea temperature is known to play a major role in structuring ecological patterns in the ocean, influencing the distribution of ecosystems (coral reefs, salt-marshes and mangroves, seagrasses and kelp beds) and indicating sites of major coastal upwelling, the globe was partitioned on the basis of sea-surface temperature into polar (< 4 °C), temperate (4–24 °C) and tropical (> 24 °C) zones to represent major coastal climatic regions (Fig. 1.2). Increasing evidence suggests that anthropogenic influences in small to medium catchments may have a much greater influence on the changes in material flows to the immediate coastal seas than large catchment (see Chapters 2 and 3).

Further expert judgement yielded separate concept diagrams for the processes and conditions affecting biogeochemical fluxes in each coastal region (Fig. 1.3). These diagrams demonstrate clear latitudinal differences in the dominant material fluxes, as well as the key processes and their susceptibilities for change in each climatic region. Further, the expert workshop considered that the major phenomena and processes impacting on coastal ecosystems differed among regions, viz., soil erosion in tropical regions, eutrophication (*sensu* Richardson and Jørgensen 1996) in temperate regions, climate change in polar regions. At a global scale, direct alteration of coastal ecosystems was considered the major factor forcing change (e.g., altered hydrological conditions, altered landscape, sea-level rise).

1.3.2 Variability in Coastal Ecosystems

Environmental conditions in coastal ecosystems are not constant. They vary seasonally and annually, and such changes are difficult to predict through time. On a geographical scale, coastal ecosystems differ greatly in size, from a small estuary to a fjord or a bay. Estuaries themselves differ by orders of magnitude, yet they all have common properties and processes (see Chap. 3). The same system may vary in a number of ways (e.g., rates of production, diversity) on seasonal or decadal scales.

Changing wave and current regimes, climate, geomorphological processes and fluxes of chemicals and nutrients from land, atmosphere and ocean result in a highly variable environment in which interactions are still imperfectly understood. In recent years humans have accelerated the rate of change (Lindeboom 2002b, in press). Impacts originate locally and regionally, but influence globally, so that the climate of the planet is changing dramatically (Tyson et al. 2001, Steffen et al. 2004).

1.3.2.1 *Temporal and Spatial Scales of Variability*

Coastal marine ecosystems undergo continuous changes in rates of production, species abundance and community composition. A holistic understanding of the full effects of human impacts on natural process variability is still lacking (Lindeboom 2002b).

Long-term datasets on phytoplankton, zooplankton, macrofauna, fish and birds have been collected around the world, and have been used to demonstrate the effects of anthropogenic impacts on ecosystems. These datasets show that fluctuations in abundance or in productivity are in some cases very sudden and unpredictable, not

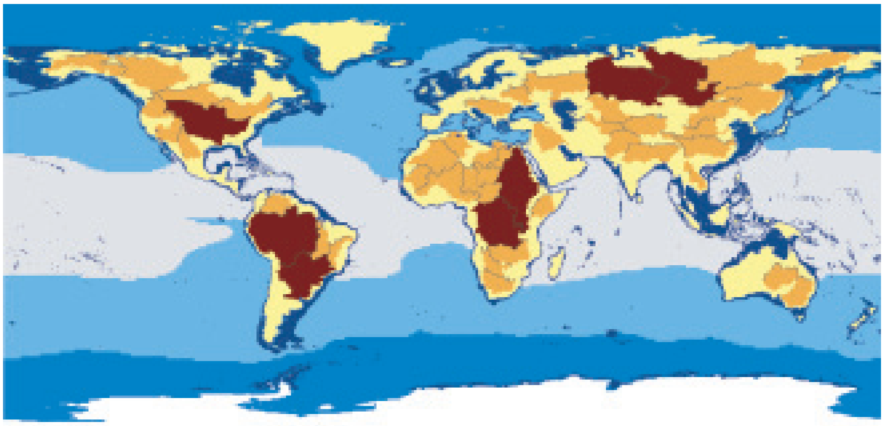


Fig. 1.2.
The coastal zone. Latitudinal relationships between the broad coastal domain (landward from the 200 m isobath, *dark blue*) and polar (< 4 °C, *light blue*), temperate (4–24 °C, *pale blue*) and tropical (> 24 °C, *grey*) regions defined by sea surface temperature. The *brown and orange areas* are major river basins; the *yellow zone* merges the small and medium-small river basins ($< 5 \times 10^5$ km^2) that dominate the coastal zone (see Chap. 3; modified from Buddemeier et al. 2002)

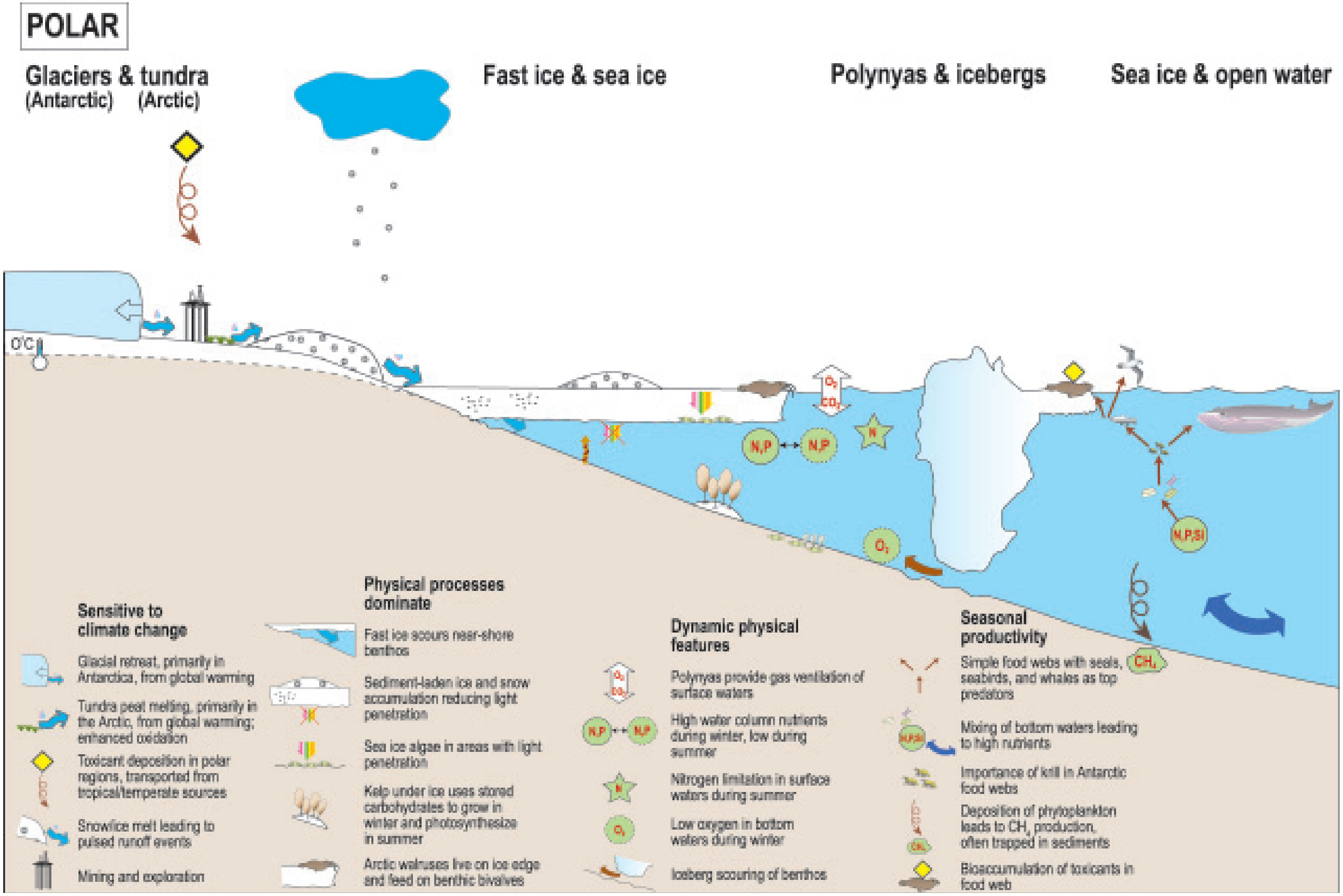


Fig. 1.3a. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in polar coastal zones

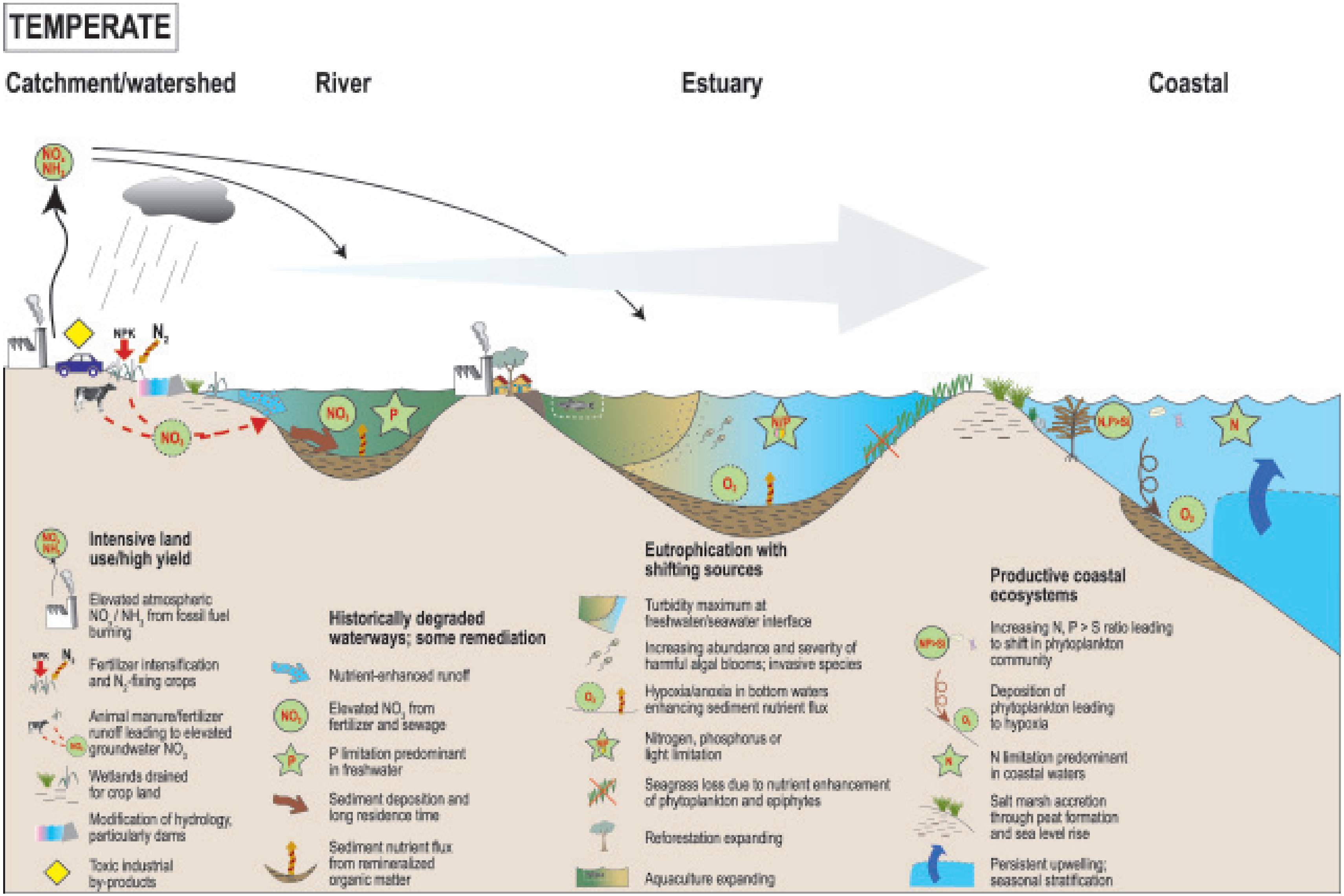


Fig. 1.3b. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in temperate coastal zones

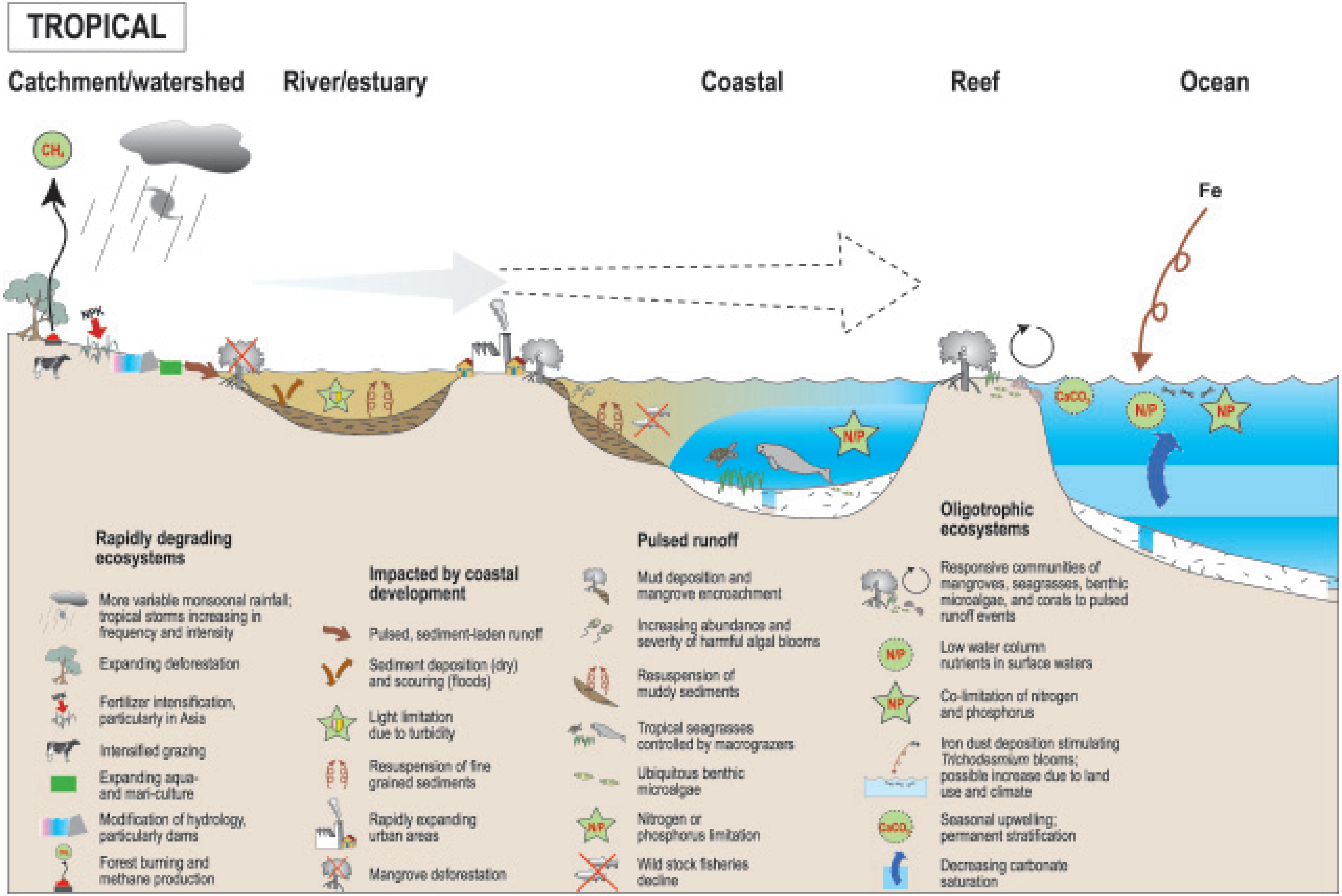


Fig. 1.3c. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in tropical coastal zones

gradual if due to a steady increase in human impacts (Lindeboom 2002a). Variability in ecosystem processes and in their biotic components can also vary dramatically over spatial scales. For example, at a global level, the El Niño-Southern Oscillation (ENSO) cycle in the Pacific basin is known to result in the almost complete failure of fisheries in South American waters and in many other ecological deviations worldwide every 4–7 years. Similarly, the North Atlantic Oscillation (NAO), a response to periodic changes in atmospheric pressure differences in the North Atlantic, has increased in the past few decades, causing changes in water and air circulation and influencing the distribution and diversity of key zooplankton that support coastal and regional fisheries (Text Box 1.2).

Spatial variability in ecosystem behaviour is determined to a large degree by biological dynamics, or the scales over which individual components interact, and by internal and external forcing functions. Recent work on the measurement of material and energy flows among ecosystem components has shown that the efficiency with which energy is transferred, assimilated and dissipated not only influences the fundamental structure and function of the system as a whole, but also causes differences and similarities in the way systems operate.

Comparative studies among systems which differ in size and shape over spatial scales have made use of network analysis and ECOPATH modelling approaches, from which common system properties such as the magnitude of recycling, ascendancy, development capacity and flow diversity can be derived (Wulff et al. 1989, Baird and Ulanowicz 1989). These studies showed that the magnitude of C, N and P recycling is higher in detritus-based systems such as estuaries, compared with plankton-dominated upwelling systems. The structure of recycling is relatively simple (i.e., short cycles) in chemically-stressed systems compared with those more "pristine" systems where longer cycles and more complex cycle structures prevail. Further, the ratio between the development capacity and ascendancy is higher in less disturbed (e.g., upwelling systems) than in eutrophied or chemically-impacted systems (for example, Baird 1998, 1999; Baird et al. 1991, 1998; Baird and Ulanowicz 1993, Christensen 1995, Christian et al. 1996). These analytical methodologies are most useful in the assessment of ecosystem function by comparing system properties. However, the required quantitative data describing standing stocks and flows between the components are not available for many coastal ecosystems (Baird 1998).

Seuront et al. (2002) studied ecosystem patterns arising in relation to prevailing local conditions. They showed that nutrient patches in tidally-mixed coastal waters in the eastern English Channel are caused by its megatidal regime and the resultant high turbulence. While purely passive factors, such as temperature and salinity, are generally regarded as being homogenised by turbulent fluid motions, recent studies have demonstrated that these parameters are also heterogeneously distributed at smaller scales than predicted; associated delimiting fronts or boundaries between different water patches are characterised by high phytoplankton production and high numbers of associated zooplankton (Mann and Lazier 1996). Links have been suggested with changes of short-term or large-scale weather patterns, wind, winter and/or summer temperatures or rainfall (Lindeboom 2002a), emphasising the interaction between local and global influences.

Temporal variability in coastal ecosystem properties and rates is well documented. In the long term, a shift in storm frequencies or wind directions may cause changes in the mixing of water masses and the deposition of sediments (Lindeboom 2002a). In temperate regions the occurrence of cold winters strongly influences the species composition of intertidal benthic communities (Beukema et al. 1996, Ibanez and Ducrotoy 2002). Possible causes of these observed phenomena include changes in water or nutrient fluxes from the land or sea, and internal processes in the marine ecosystem.

Different impacts can yield similar effects in ecosystems, while local human disturbances often further complicate the analyses. A substantial body of literature exists on changes in ecosystem properties across temporal scales. The studies reported clearly illustrate the dynamic and variable nature of ecosystem processes over time; for example, Warwick (1989) on seasonal changes in estuarine benthic communities, Gaedke and Straile (1994) on seasonal changes and trophic transfer efficiencies in planktonic food webs, Field et al. (1989) on the successional development of planktonic communities during upwelling, Baird and Ulanowicz (1989) on the seasonal dynamics of carbon and nitrogen, Fores and Christian (1993) and Christian et al. (1996) on nitrogen cycling in coastal ecosystems, Baird and Heymans (1996) on changes in system properties of an estuary over decades due to reduced freshwater inflows, Baird et al. (1998) on spatial and temporal variability in ecosystem attributes of seagrass beds, and Rabelais et al. (1996, 2002) on a river-influenced coastal system response to changing nutrient loads (see Text Box 5.1, Chap. 5).

There is growing evidence that the cycles long recognised in freshwater systems and trees occur in marine sediments (Pike and Kemp 1997), corals (Barnes and Taylor 2001), shellfish (Witbaard 1996) and coastal marine systems (Bergman and Lindeboom 1999). However, despite an increasing number of examples for many types of biota around the world, cyclical behaviour (e.g., in numbers of organisms in coastal seas) remains disputed. Until lasting and predictable cycles with clear cause-ef-

Text Box 1.2. North Atlantic Oscillation influences copepod abundance and distribution

Jean-Paul Ducrotoy

The North Atlantic Oscillation (NAO) is defined as the pressure difference between the Icelandic Low and the Azores High (Fig. TB1.2.1). It determines the strength of the prevailing westerlies and other wind patterns in the North Atlantic which in turn affects the ocean surface currents there and the movement of water towards north-western Europe, in particular into the North Sea.

The influence of this phenomenon on the physical and biological functioning of the North Sea requires further study (Ducrotoy et al. 2000), but it is predicted that the flows of the North Atlantic Current and the Continental Slope Current along the European Shelf Break, which determine the rate of heat transfer towards Europe, have a large influence on biodiversity. Present-day patterns in pelagic biodiversity are the result of the interaction of many factors acting at different scales. Temperature, hydrodynamics, stratification and seasonal variability of the environment are likely to be main factors contributing to the ecological regulation of the diversity of planktonic organisms.

The similar geographical patterns evident between currents/water masses and species associations suggest that the species groups may be used as environmental indicators to evaluate long-term changes in the marine environment related to climate change and other increasing human-induced influences (Beaugrand et al. 2002).

Changes are visible in biologically distinct areas of seawater and coasts, recognised by scientists as large marine ecosystems. Geographical changes in the diversity of planktonic calanoid copepods have been studied in the North Atlantic and the North Sea based on historic data collected by Continuous Plankton Recorder (CPR) surveys (Warner and Hays 1994). Detectable year-to-year or decadal changes in the diversity of pelagic communities of this region may be expected to have already occurred, or may change in the future due to climate change. Over the last decade there has been an increase in the abundance of a number of arctic-boreal plankton species (Fig. TB1.2.2), notably *Calanus hyperboreus, Calanus glacialis* and *Ceratium arcticum*, and a southerly shift of the copepods *C. hyperboreus* and *C. heligolandicus* in these areas.

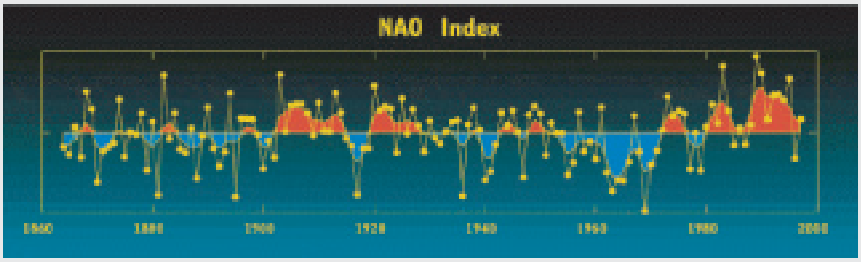


Fig. TB1.2.1. The anomalous difference between the polar low and the subtropical high during the winter season (December-March) measured using NAO index variations

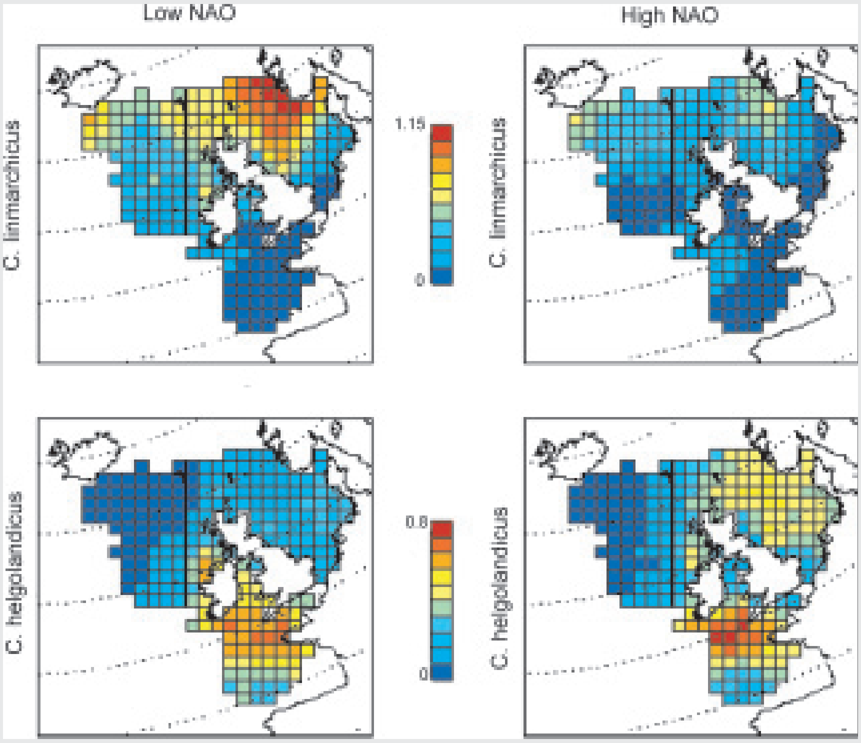


Fig. TB1.2.2. Distribution of copepods (*Calanus helgolandicus*, *C. linmarchicus*) and NAO state, 1986–1996 (from Reid et al. 1998) fect relationships are proven, it remains questionable whether this is really the result of complex physical-biological interactions or just a coincidental, statistical feature of datasets. The number of papers suggesting links between observed cyclical events and solar activity is increasing. Very long datasets also indicate alternations of cyclical periods with periods without cyclical patterns (Lindeboom 2002a). Long-term data-series, in combination with the results of experimental laboratory and field studies, are necessary to provide insights and understanding of trends in coastal ecosystems and whether they are due to local-scale disturbances and/or to global climatic changes.

1.3.2.2 *Climate Change and Variability*

Earth's climate is subject to natural cycles (Petit et al. 1999, Rial 2004, Steffen et al. 2004). Cycles may occur over short time-scales or may span decades, centuries or millennia, so that change rather than stability characterises the global system and subsequently the coastal environment.

Climate change is not climate variability. Scientists have struggled to gain an understanding of coastal ecosystem responses to seasonal, inter-annual and, to a degree, decadal time scales, but prediction of responses to climate change opens up new and larger challenges. As Busalacchi (2002) stated: "*Detection of climate change is the process of demonstrating that an observed variation in climate is highly unusual in a statistical sense. Detection of climate change requires demonstrating that the observed change is larger than would be expected to occur by natural internal fluctuations.*"

There is a large weight of evidence that Earth systems are now subject to a regime of significant climate change, driven especially by a continuing increase in atmospheric CO_2 concentrations in response to anthropogenic actions (Fig. 1.4; Houghton et al. 2001, Steffen et al. 2002, Walther et al. 2002). Direct CO_2 effects and allied temperature increases have a number of ramifications for the functioning of the Earth systems including the ecosystems of the coastal zone (Steffen et al. 2004).

The rate and duration of warming in the 20th century was greater than in any of the previous centuries – and humans are modifying the rate of change (Moore 2002). The global average surface temperature has increased by 0.6 °C since 1900 and, from modelling projections, is expected to increase by about 2.5 °C (1.5 to 4.5 °C modelled range) over the next 100 years. Such climate changes are a response mainly to increases in "greenhouse gases" and are part of a global change affecting Earth's energy balance, which in turn influences the atmospheric and oceanic circulation patterns and, hence, weather systems. However, there are large regional variations in the spatial manifestation of these temperature patterns, including cooling in some areas.

Changes in response to natural or anthropogenic forcing have the potential to push ecological systems beyond

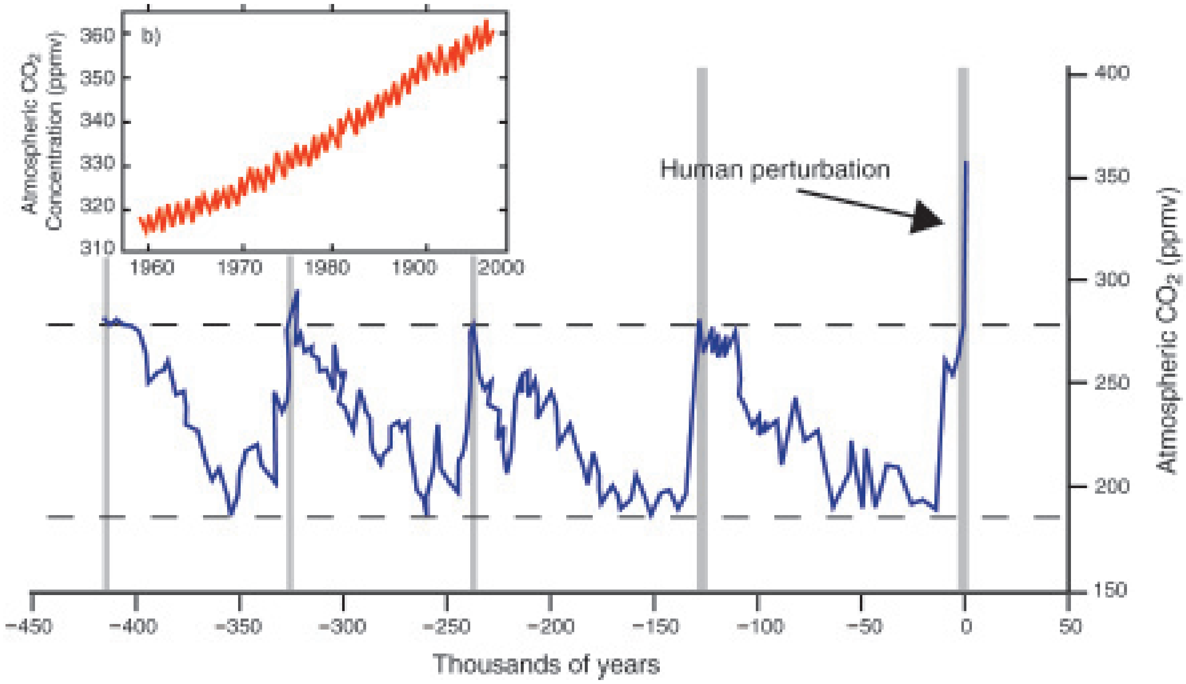


Fig. 1.4. The coastal zone. Atmospheric CO_2 concentration from the Vostok ice core data, with human perturbations superimposed (from Steffen et al. 2002, derived from Petit et al. 1999 and NOAA)

their limits of sustainability and to increase variability in environmental conditions. For example, calcification rates in coral reef systems continue to decline in response to increasing levels of atmospheric CO_2 (see Text Box 3.2, Chap. 3), and elevated sea-surface temperatures are firmly associated with widespread coral bleaching events (Hughes et al. 2003, Buddemeier et al. 2004). Changes in temperature and precipitation patterns already affect runoff and flow in rivers. In Southeast Asia, low-lying areas are experiencing an increased frequency of typhoons and flooding, while monsoonal shifts are influencing patterns of sedimentation and nutrient delivery from the land; these can lead to changes in coastal ecosystem structure and function (Talaue-McManus 2002).

The physical responses of estuaries and coasts to sea-level rise at local scales will depend on a combination of eustatic movements (reflecting the increase of seawater in the oceans) and isostatic movements (due to the tilting of land masses in relation to the melting of the ice cap; also see Sect. 2.2, Chap. 2.2). Estimates of the magnitude of the sea-level rise have been based on a doubling of atmospheric CO_2 resulting in an overall sea-level rise of about 48 cm by 2100, which is 2–4 times the rate observed through the 20th century (Houghton et al. 2001).

Along the open coast, an increase in wave occurrence linked to an increase in high-tide level will lead to widespread erosion with a landward migration of the high-tide mark and a flattening of the shore slope. In the Atlantic Ocean, wave heights have increased by 2–3 cm per year over the last 30 years (von Storch and Rheinhardt 1996). If the shore is protected by embankments, the intertidal profile will probably steepen, with a concomitant reduction in the areas occupied by intertidal communities. Associated with such sea-level rise, estuaries will simply become "arms of the sea", with dramatic impacts on their unique biodiversity, system function and habitats (Ducrotoy 1999). Possible consequences of climate change on the biology of coasts and estuaries include a shift of high-energy habitats towards the outer parts of the coast and a change in the rates of biogeochemical cycles.

The possible effects of predicted climate changes need to be considered (for example, Walther et al. 2002). The direct effects of increased CO_2 on living organisms will have a bearing on carbon fixation pathways, in particular photosynthesis. An increase in primary production could be expected but a change in cloud albedo may have a negative effect on the metabolism of plankton. A decrease in seawater pH could lead to shell dissolution in molluscs and corals, while a lack of availability of essential metal ions would have a negative effect on the growth and morphology of coastal organisms. Recent experiments have shown certain algal species (in particular the red algae, Phylum Rhodophyta) to be sensitive to changes in temperature, length of photoperiod and solar radiation intensity (see for example, Molenaar and Breeman 1997).

Variability of ecosystems is a major feature of all domains and knowledge of the fundamental mechanisms and their response to local climates is essential for the establishment of appropriate management strategies for the coastal zone. Variability of coastal systems depends on two major forcing factors: the climate/meteorology and, directly or indirectly, anthropogenic activities. Both factors have an impact on the ecology and physical structure of the coastal environment and on its dynamics and biogeochemistry, thus influencing the biological performance of the coastal systems. The structure and organisation of communities, conditioned in each coastal environment by a combination of abiotic factors, also depend upon biological characteristics such as recruitment and productivity rates. Keystone species may control local biodiversity through indirect effects, disproportionately larger than their relative abundance, and hence have an impact on the local natural variability, notably by changing local habitats (Piraino et al. 2002) and the biogeochemical cycles involved in their maintenance (Ducrotoy et al. 2000).

Historically, humans have been closely associated with the coast, in part reflecting the evolution of trade and commerce and access to resources. The industrial revolution led to marked increases in coastal transport and population impacts such as human and industrial waste discharge and food extraction. In recent times, the growing popularity of recreation and leisure pursuits is significantly increasing direct human activities.

The impact and influence of humans in the coastal zone is widely recognised locally and is increasingly apparent across most regional scales (Fig. 1.5). However, information about human (or anthropogenic) impacts is poorly described at global scales. Even reported estimates for population numbers and densities are quite disparate. Much depends on:

a the source and quality of the population database (usually derived by modelling of census data from global administrative units which often have different census dates and resolution),
b the year to which the modelled population date is standardised, and
c the definition and methodology used to determine the spatial units and dimensions that encapsulate the coastal zone (Shi and Singh 2003).

Recent estimates of population in the coastal zone range from 23% (Nicholls and Small 2002) to about 50% (Watson et al. 1997). Burke et al. (2001) cited estimates based on CIESIN 2000 data derived from census of administrative units that yielded values of 2.075×10^9 people in 1990 and 2.213×10^9 people in 1995 (39% of global

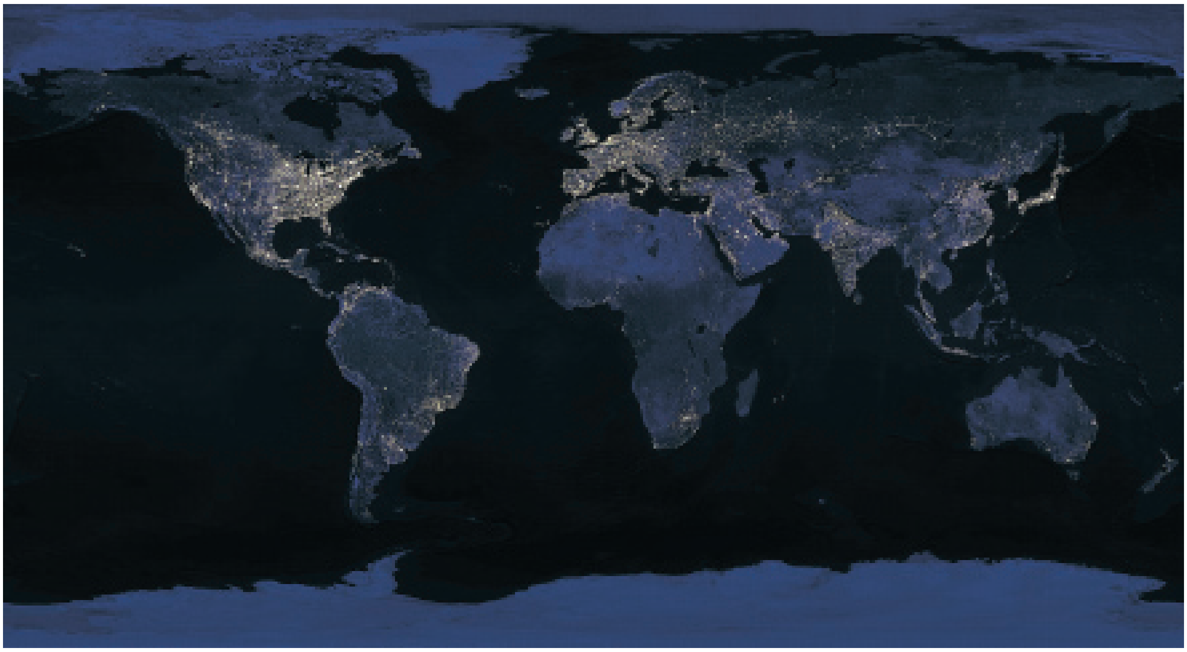


Fig. 1.5. Night light image of Earth (NASA, *http://www.gsfc.nasa.gov*)

population) living within 100 km of the coast. Using the relatively robust dataset for 1990 contained in the Gridded Population of the World Version 2 (CIESIN 2000 data; *http://sedac.ciesin.org/plue/gpw*), and an elevation model (*http://www.edcdaac.cr.usgs.gov/landdaac*), Nichols and Small (2002) estimated that 1.2×10^9 people (23% of global population) live in the "near coastal zone" (the coastal area within 100 m elevation and 100 km of the coast).

The LOICZ typology database (*http://www.kgs.ukans.edu/Hexacoral/Environdata/envirodata.html*), using gridded population data for the coastal domain derived from LandScan for 1998 (*http://www.ornl.gov/sci/gist/landscan*), yielded an estimated 2.69×10^9 people (44% of global population) within the coastal zone. For this technique, the coastal zone is contained within a grid of half-degree cells, representing a linear measurement at the equator of 100 km landward of the coastline (see Text Box 1.7). These estimates are still lower than the generalised value of $> 3 \times 10^9$ people often broadly ascribed to the coastal zone by various authors through the mid 1990s (e.g., Hinrichsen 1998). Improved data collection and application of consistent methodologies would provide robust estimates of the current coastal population for application to trend analyses, modelling and prediction of human pressures and changes in the coastal zone.

The coastal population is increasing disproportionately to the global population increase. In their analyses, Shi and Singh (2003) estimated an average population density for the coastal zone (within 100 km from the coastline) of 87 people km^{-2} in 2000 compared with 77 people km^{-2} in 1990 (UNEP/GRID database, *http://www.na.unep.net*). The average global population in 1990 was 44 people km^{-2}. Elevated population densities coincide with urban conurbations and "altered" landscapes (Burke et al. 2001). In 2000, 17 of the world's 24 megacities were coastal (Klein et al. 2003). There is a marked diminution of population density with distance from the coast, with 40% of the "near coastal" population occupying only 4% of the land area at densities > 1 000 people km^{-2}, with greatest densities in Europe and in South, Southeast and East Asia (Nicholls and Small 2002). Illustrated in Fig. 1.5, this highlights the additional observation by Nicholls and Small that "… *despite the concentration of people near coasts, at the global scale, the majority of land area within the 'near coastal zone' is relatively sparsely populated*". This coastal density imbalance is likely to increase with time

Table 1.3. The coastal zone. Estimated and projected average population density for the coastal zone and inland areas (derived from Shi and Singh 2003) and projected global population estimates (UN/DESA 2001–03)

Date	Average population density (people km^{-2})		Estimated global population (billion)
	Coastal Zone	Inland	
1990	77		5.2
2000	87	23	6.1
2010	99	38	6.9
2025	115	44	7.9
2050	134	52	9.3

Table 1.4.
The coastal zone. Natural and anthropogenic forcings and associated phenomena of interest in coastal marine ecosystems (adapted from UNESCO 2003)

	Forces
Natural	▪ Global warming and sea level change ▪ Storms and other extreme weather events ▪ Seismic events ▪ Ocean currents , waves, tides and storm surges ▪ River and ground water discharges
Anthropogenic	▪ Physical restructuring of the environment ▪ Alteration of the hydrological cycle ▪ Harvesting living and nonliving resources ▪ Alteration of nutrient cycles ▪ Sediment inputs ▪ Chemical contamination ▪ Inputs of human pathogens ▪ Introductions of non-native species
	Phenomena of interest
Marine services, Natural hazards and Public safety	▪ Increasing in sea level ▪ Changes in sea state ▪ Changes in surface currents ▪ Coastal flooding events ▪ Changes in shoreline and shallow water bathymetry
Public health	▪ Seafood contamination ▪ Increasing abundance of pathogens (in water, shellfish)

Ecosystem health	▪ Habitat modification and loss
	▪ Changes in biodiversity
	  ▪ Eutrophication
	  ▪ Water clarity
	  ▪ Harmful algal bloom events
	  ▪ Invasive (non-indigenous) species
	  ▪ Biological affects of chemical contaminants
	  ▪ Disease and mass mortalities of marine organisms
	  ▪ Chemical contamination of the environment

Living resources	▪ Abundance of exploitable living marine resources ▪ Harvest of capture fisheries ▪ Aquaculture harvest

(Table 1.3). The coastal zone now contains more than 45% of the global population, within < 10% of the global land area. The projected global increases in population will occur mostly in developing countries (Burke et al. 2001).

Some of the migration towards the coast is temporary, although it can be significant during certain periods (Cook 1996). Patterns of tourism and global trade exacerbate coastal population densities, locally and regionally. For example, the Mediterranean coastal zone population swells from 130 million to 265 million for most of each summer, increasing transportation and pollution problems, and the number of visitors is expected to rise to 353 million by 2025 (Salomons 2004).

Thus, population pressure in the coastal zone poses major challenges for coastal management and planning agencies. This is complicated because human pressures are highly variable in type and intensity at local levels and are often connected across wide geographical distances by global tourism, transportation and trade patterns. It is now considered that "*… human activities are influencing or even dominating many aspects of the Earth's environment and functioning …*" leading to the suggestion that we are now in "*… another geological epoch, the* ***Anthropocene*** *era*" (Steffen et al. 2002).

1.4 Changes to the Coastal Zone

Numerous natural and human-induced forces influence coastal ecosystems. These forces have direct and indirect effects on coastal ecosystems, modifying various aspects of societal interest, including marine services, natural hazards and public safety, public health, ecosystem health and living resources. Each of these is affected or impacted by one or more phenomena, as shown in Table 1.4. The distinction between natural and anthropogenic forcings is somewhat artificial. Although some forcings are clearly of human origin (e.g., harvesting of marine resources, chemical contamination), there are few if any natural phenomena that do not now have a human signature of some sort (e.g., climate change, river and groundwater discharges, nutrient enrichment) (UNESCO 2003).

Coastal ecosystems are diverse but inter-related through common functional processes and subject to the same natural and anthropogenic impacts. The response of different systems to one or more phenomena may not be the same, because some are more resilient than others. However, management of coastal ecosystems requires an integrated, holistic philosophy and practice as opposed to a piecemeal approach (Allanson and Baird 1999).

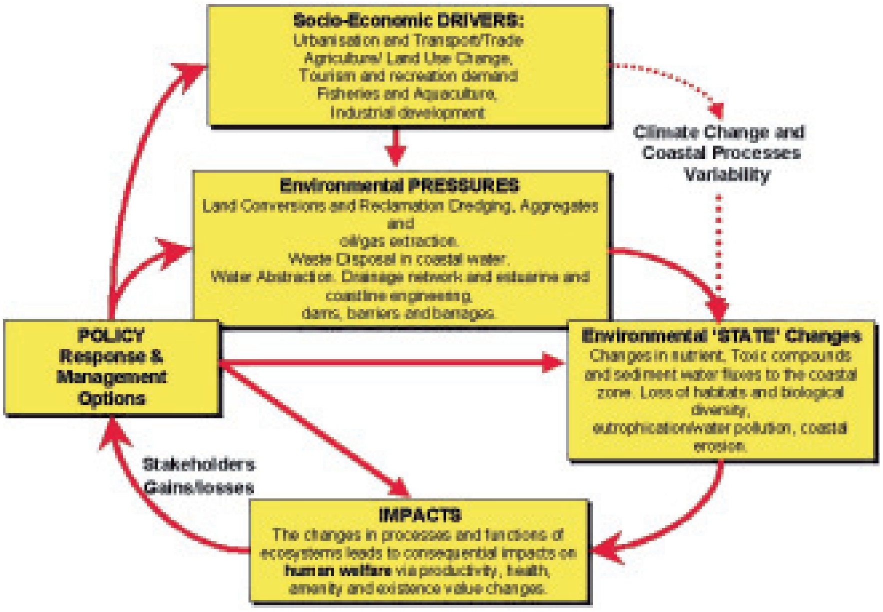


Fig. 1.6.
The coastal zone. Schema of DPSIR framework (adapted from Turner et al. 1998)

Research and environmental management approaches during the last decade have markedly improved our knowledge of how global environmental change and human activities influence the coastal zone – its ecology, function, products and benefits. We know there is continuing degradation of ecosystems, their benefits and resources. We know there are opportunities for wiser use of the coastal zone and that there is a need for greater preparedness to meet changes in the coastal zone. However, we are limited in our ability to scientifically and objectively measure, assess and predict the natural and human dimensions of these changes and the effects of different pressures on ecosystems.

Differentiating human-induced changes from naturally-forced changes remains a challenge. These problems derive from the complexity of endogenous natural functions and biogeochemical interactions, the inherent complexity and scales of the human dimension and the synergies, feedbacks and disconnects in the scale of linkages and relationships between natural ecosystems and socio-economic interactions in the heterogeneous landscape of the coastal zone. However, targeted research and new tools for measurement and conceptualisation are delivering exciting and often surprising outcomes (see, for example, Steffen et al. 2002, 2004). While the intellectual challenges in this work are high for people involved in the science, management and policy arenas, an equally important challenge is to find ways to effectively communicate and apply the knowledge across the wider global community as well as to specific users of the information (Ducrotoy and Elliot 1997, Crossland 2000, Olsen 2003).

LOICZ has adapted and used the Driver-Pressure-State-Impact-Response (DPSIR) framework (Fig. 1.6; Turner et al. 1998, Turner and Salomons 1999) to organise commentary and research approaches (see Sect. 1.5.3) on the dominant forcings (Pressures) and effects (Impacts) on the global coastal zone (Table 1.5). The Drivers and Pressures on coastal systems are predominantly the result of societal function and human behaviour and may be amenable to management and policy decisions (Response). It is increasingly apparent that forcings on coastal ecosystems by most natural Drivers and Pressures are greatly modified by human activities in both extent and intensity.

The natural dynamics of Earth's interlinked geophysical systems provide stressors that result in structural, ecological and biogeochemical changes to all regions of the globe. Human activities greatly exacerbate many of these changes. Recent assessments by the global research alliance IGBP-IHDP-WRCP-DIVERSITAS concluded: "*… we know that the Earth System has moved well outside the range of natural variability exhibited over the last half million years at least*" (Steffen et al. 2004).

The magnitudes and rates of changes now occurring in the global environment are unprecedented in human history, and probably in the history of the planet. Earth is now operating in a "*no-analogue state*" (Steffen et al. 2002). The system changes and changed forcings or stressors act as Pressures and Drivers on the state and function of natural systems and processes within the coastal zone. The global coastal zone has been highly dynamic through geological time in response to natural forcing. The actions of human society are drastically impacting on the structures, resources and processes of the coastal zone. Human pressures and forcings will increase, with probable unforeseen ramifications for global society.

Table 1.5. The coastal zone. Systems and their key pressures (from GESAMP 2001)

System	Key pressures
Coral reefs	Eutrophication, sediments, over-fishing, destructive fishing, reef mining, aquarium and curio trade, diseases
Wetlands	Reclamation and development
Seagrass beds	Siltation, coastal development, eutrophication, physical disturbance
Coastal lagoons	Reclamation, pollution
Mangroves	Excessive exploitation, reclamation, development, aquaculture
Shorelines	Development, habitat modification, erosion
Watersheds	Deforestation, soil erosion, pollution, habitat loss
Estuaries	Reduced water flow, siltation, pollution
Small islands	Sea level changes, waste management
Continental shelves	Pollution, fishing, dredging, navigation
Semi-enclosed seas	Pollution, coastal development, fishing

1.4.1 Pressures on the Coastal Zone from Natural Forcing

1.4.1.1 *Global Systems and Climate Patterns*

Large-scale phenomena influence climate, including the global "ocean conveyor belt" or thermohaline circulation pattern (Broeker 1994) and, regionally, ENSO (El Niño-Southern Oscillation) in the Pacific Ocean and the NAO (North Atlantic Oscillation) (Fig. 1.7; see Sect. 1.3.3.1). Evidence is accumulating of historical shifts in the patterns and intensities of these phenomena that can influence biotic distribution and diversity and affect coastal processes. The "ocean conveyor belt" influences heat fluxes and greenhouse gases in the atmosphere and its flow intensity may change on various time-scales with major effects on climate and thus parameters such as temperature and precipitation patterns, trade-wind intensity and wave climates (Steffen et al. 2004).

ENSO is driven by major climate patterns in the Pacific but the effects extend to at least Europe and North America where elevated sea level, increased erosion and changes in rainfall patterns have been observed. There are indications of much greater intensities and frequencies of ENSO events over geological time-scales, beyond those experienced in recent years (Bradley 2002). ENSO is known to affect global distribution and concentrations of CO_2.

The potential for change in these global-scale phenomena is well demonstrated. Thus, further and probably dramatic changes in the current level of forcing from these phenomena on many natural and human-related pressures in the coastal zone are likely. Recent major global bleaching events in shallow coral reefs are ascribed to high sea-surface temperatures (Wilkinson 2000), a forcing parameter linked to these large-scale phenomena.

1.4.1.2 *Sea Level*

Sea-level change is an issue of major concern in the coastal zone, particularly for ecosystems and residents in river deltas and low-lying areas, and in small island states. Relative sea level has fluctuated across hundreds of metres at millennial time-scales. The dominant Driver of sea-level change is sea and air temperature. With an estimated rise of 0.6 °C in average global sea surface temperature during the 20th century and a further predicted rise of between 1.5 °C and 4.5 °C over the next 100 years (Houghton et al. 2001), sea-level rise is a phenomenon of vital concern when considering the State of the coastal zone and the potential for changes in both natural systems and human society, now and well through the next century.

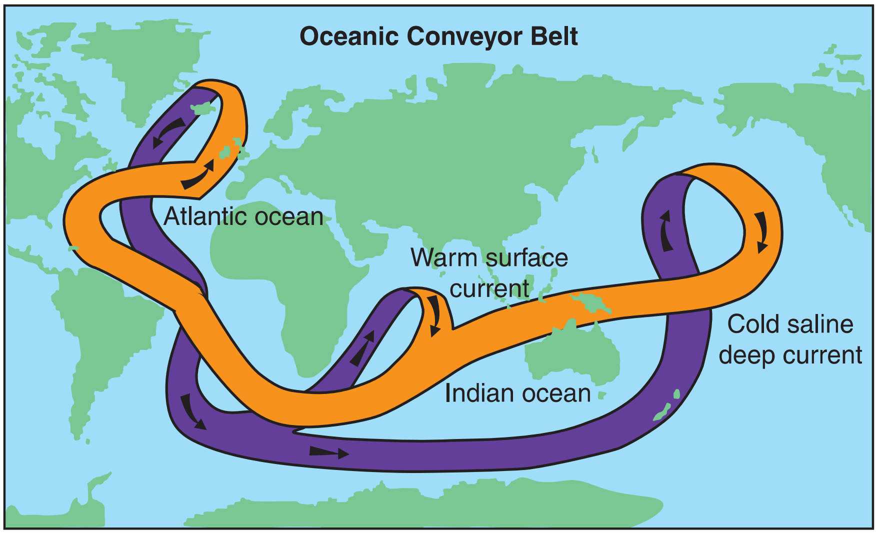
The IPCC has estimated sea level to have risen at rates of 1.0–2.5 mm yr^{-1} over the last century, and modelling scenarios project a further increase in the range of 9–88 cm over the next 100 years (see Sect. 2.2, Chap. 2). Other IPCC projections indicate with high confidence that:

- natural systems will respond dynamically,
- the responses will vary locally and with climate,
- wetlands may survive, where vertical accretion rates are sufficiently nourished by sediments, and
- engineering infrastructure in the coastal zone may be a barrier to the landward dynamics of ecosystems.

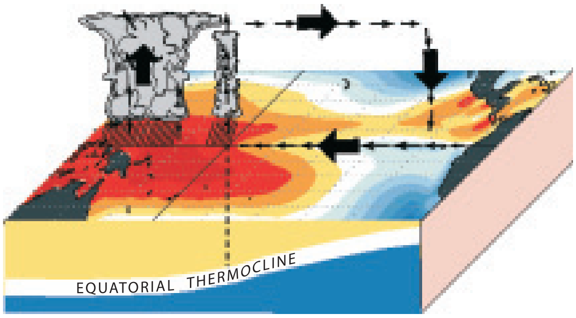
Potential impacts include shoreline erosion, severe storm surge and flooding, saline intrusions into estuaries and groundwater aquifers, and altered tidal ranges. The resilience of coastal ecosystems and human habitation to these projected increases in sea level is of vital concern (Arthurton 1998, Klein et al. 2003).

A global network of coastal scientists, engineers and managers has applied a common methodology for the as-

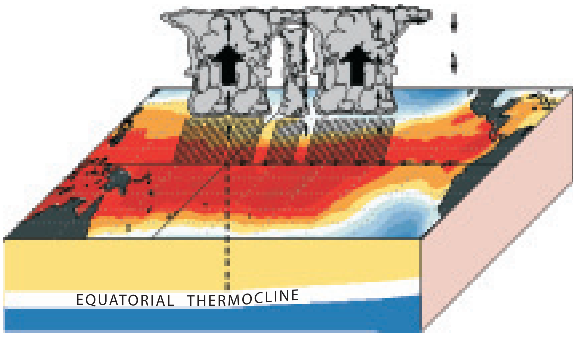
Fig. 1.7.
The coastal zone. Diagram of the global thermohalocline circulation process (*top*) and the El Niño-Southern Oscillation (ENSO) and La Niña processes in the southern Pacific Ocean (*bottom*) (from Steffen et al. 2004, as adapted from Broecker 1991; NOAA, *http://iri.colombia.edu/climate/ENSO/background/basic.html*)



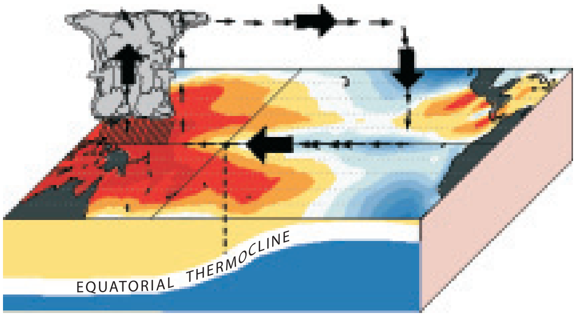
a December–February Normal Conditions



b December–February El Niño Conditions



c December–February La Niña Conditions



sessment of coastal vulnerability and adaptation to accelerated sea-level rises across regions of the world (Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies (SURVAS), *http://www.survas.mdx.ac.uk/*). An EU-funded project "Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-level Rise" (DINAS-COAST) is expanding the approach, building a CD-ROM-based tool to incorporate quantitative information on a range of coastal vulnerability indicators and to relate these to socio-economic scenarios and adaptation policies at national to global scales (*http://www.dinas-coast.net/*).

Already many coastal regions are experiencing significant increases in relative sea level because of subsidence resulting from isostatic and tectonic adjustments or human activities (see Sect. 2.1, Chap. 2). Taking advantage of new space platforms that measure sea surface levels, a new global program of research is looking to evaluate these and related changes to improve modelling and understanding (Goodwin et al. 2000).

1.4.1.3 *Carbon Dioxide and Greenhouse Gases*

Changes in CO_2 concentration and other greenhouse gases in the atmosphere have implications for the coastal zone directly and indirectly from effects on temperature elevation and climate (Text Box 1.3). Over the last 150 years atmospheric CO_2 has increased by 30% to around 370 ppm – to beyond the maximum levels experienced over the last 400 000 years, as inferred from ice-core records (Steffen et al. 2002; see Fig. 1.4 above). However, current projections suggest that this CO_2 concentration will double over the next 100 years, placing us well outside the range of previous experience; human activities continue to influence this increase (Houghton et al. 2001).

Text Box 1.3. Trace gases (other than CO_2) in the coastal zone

From Pacyna and Hov 2002

The coastal ocean is a source of selected trace gas emissions to the atmosphere. The most important trace gases emitted in appreciable amounts from the coastal ocean include methane, nitrous oxides, dimethyl sulphide (DMS), carbonyl sulphide (COS), and mercury. The production of these gases in coastal ecosystems, particularly estuaries, and the sea-to-air flux have been studied, mostly in Europe. Information on the production and sea-to-air flux of other trace gases in coastal ecosystems is very limited, and it is difficult to draw conclusions on the significance of these fluxes.

Processes of trace gas production and transport from the ocean surface to the atmosphere are complicated and require multidisciplinary studies, including various aspects of biology, meteorology, hydrology, chemistry and physics. The vast majority of efforts to explain production and water-to-air transport have been carried out with the use of models and measurements in the open ocean rather than in the coastal ocean.

Flux rates for transport of trace gases from surface waters to the air are higher for the coastal zone than the open sea, up to several orders of magnitude for some gases (Table TB1.3.1), using the data from the EU BIOGEST project (Frankignoulle 2000) and other literature data. This contribution can be 50% and more for nitrous oxide and COS. The contribution of emissions of these gases from European estuaries to total European emissions is relatively low, except for nitrous oxide.

Limited information on flux rates for methane, nitrous oxide, DMS, COS and mercury in other regions of the globe makes it difficult to assess the coastal contribution on a global scale. First approximation of trace-gas emissions on a global scale indicate that estuaries contribute up to 2%, except for nitrous oxide which is higher. At local and regional scales, emissions in coastal areas can contribute substantially to the total emissions of these gases. Further studies are needed to provide a more accurate understanding of the production and sea-air exchange processes for these gases globally.

Changes of sea-air fluxes of trace gases in the coastal zone are directly and indirectly dependent on the changes to socio-economic and natural drivers of environmental change in coastal ecosystems. Sea-to-air fluxes form one of the pressures on the coastal ecosystem. Direct relationship between socio-economic drivers changing the coastal ecosystem and the fluxes of trace gases from the coastal ocean to the air can be illustrated through the enhanced input of various trace gas precursors, including organic matter, nitrates, ammonium, sulphates and mercury deposited to the sea on particles from the air or transported by rivers to the coast. Indirect relationships between drivers and the fluxes of trace gases can be analysed, taking into account the natural drivers of environmental change in the coastal zone, such as climate change and its consequences including biodiversity reduction, habitat loss and modification.

Table TB1.3.1. Fluxes of biogases from estuaries and their global contribution

Compound	Estuary to open ocean flux rate ratio	Estuary emissions in Europe (kt yr^{-1})	Estuary contribution to total European emissions (%)	Coastal sea contribution to the total sea-to-air flux (%)	Coastal sea contribution to global emissions (%)
CH_4	~1000	580	2.5	up to 30	0.2–2.0
N_2O	~100	120	9.4	up to 60	2.0–15.0
DMS	1–3	60 (as S)	1.0[a]	up to 10	2.0[a]
COS	10–100			up to 50	
Hg	~10	12×10^{-3}	3.5	up to 20	~0.5

[a] Contribution to the total European or global emissions of sulphur.

Vital issues of research and debate include changing CO_2 concentrations, impacts on terrestrial crops and agriculture, biological processes of the ocean (the major sink for global atmospheric CO_2), climate, temperature regimes and marine coastal systems (Walther et al. 2002, Buddemeier et al. 2004, Steffen et al. 2004, *http://www.globalcarbonproject.org*). Changing patterns of productivity in marine waters are forecast (Fasham 2003), while a decrease in calcification rates by as much as 30% has been projected for coral reefs in response to a doubling in CO_2 concentration (Kleypas et al. 1999, Guinotte et al. 2003; see Text Box 3.2, Chap. 3).

1.4.2 Pressures on the Coastal Zone from Human Forcing

1.4.2.1 *Land-based Resource Uses*

1.4.2.1.1 *Agriculture*

While the conversion rate of forests and grasslands to managed agricultural systems is not as rapid as in the mid-20th century (Wood et al. 2000), the intensification of cropland and agricultural production is increasing through application of fertilisers, pesticides and herbicides and the use of irrigation or drainage. Alienation of wetlands (mangroves, salt-marshes, dune systems) continues as sugarcane, rice and fish mariculture are expanded regionally throughout the world. Freshwater used for irrigation accounts for significant changes in river flows affecting, *inter alia*, coastal sedimentation processes and river delta maintenance (see Chap. 2). For example, in the Nile River, flows reduced by more than 90% with concomitant coastal erosion and changes in the trophic systems of the coastal receiving waters (Nixon 2003).

Emissions and inputs from agriculture are a significant source of pollution to the coastal zone and to the atmosphere. Global production of nitrogen fertilisers by humans now exceeds the natural rate of biological nitrogen fixation in terrestrial ecosystems (Bouwman et al. 1995, van Drecht et al. 2001). Much of the increased nitrogen load finds its way into surface and artesian waters, thus elevating nutrient loads in the coastal zone (Vitousek et al. 1997, Kroeze et al. 2001). The development of the superphosphate industry in the late 19th century brought a concomitant rise in industrial production and global use of phosphatic fertilisers. Recent estimates suggest that P storage in freshwater and terrestrial systems has almost doubled, and fluvial drainage of P to coastal seas has risen nearly 3-fold, since pre-industrial times (Bennett et al. 2001). Use of fertilisers continues to increase from levels of about 150×10^6 tonnes per year in 1990 to projected use in excess of 200×10^6 tonnes per year within the next decade (Bumb and Baanante 1996, cited in WRI 2000). Recent assessments by UNEP (Munn et al. 2000, GESAMP 2001) considered the global nitrogen overload to be one of four major emerging environmental issues for effects on eutrophication, human health and general water quality of fresh and marine coastal waters and within allied ecosystems.

1.4.2.1.2 *Forestry/Deforestation*

Forests yield valuable timber and non-wood products (food, cash crops, industrial raw materials) for human society. Estimates for global trends in deforestation are uncertain (Matthews et al. 2000), but significant tracts of forest continue to be lost to deforestation in river basins in many parts of the world, reducing watershed protection and increasing erosion. River flow, water quality and coastal ecosystems are affected through increased sedimentation rates and elevated nutrient inputs (Scialabba 1998). Major re-forestation projects are being carried out in some regions, especially in developed countries, as a move to increase carbon sequestration from atmospheric CO_2 as well as for improved management of land and riparian zones.

1.4.2.1.3 *Damming and Irrigation*

Globally, more than 41 000 large dams (> 15 m high) are in operation impounding 14% of runoff. This represents a 7-fold increase in dams built over the last 50 years, and numbers are still increasing (WRI 2000). These provide hydroelectric power, industrial and other human needs including flood mitigation. Small reservoirs and dams in local catchments number in the millions. Globally these impoundments may account for sequestration of almost 2 gigatonnes C per year – equivalent to the "missing carbon" in current global models (Smith et al. 2001).

The effects of damming and irrigation on water flow are manifested in multiple examples of coastal erosion in response to reduced sediment flows throughout all regions of the world (Milliman 1997). Such effects impact coastal ecosystems by increasing saline intrusions, diminishing coastal groundwater discharge and reducing biodiversity. Freshwater inputs reduced by construction of impoundments in the catchment of rivers in South Africa altered the patterns of productivity, biodiversity and ecosystem properties of estuaries (Baird and Heymans 1996). More subtle pressures through changes in water quality include reduced silicate loads to coastal waters (Conley et al. 1993) with a resultant shift in phytoplankton communities from dominantly diatoms to flagellates (e.g., Black Sea, Humborg et al. 2000). Ramifications for coastal biogeochemical cycles include sequestration of carbon and acceleration of eutrophication processes, while trophic structures in estuaries and coastal seas that depend on land-derived nutrient inputs are also affected; for example, the Bay of Bengal and other areas receiving major river plumes, such as the receiving waters of the Mississippi, Amazon and Nile river flows (Turner et al. 1998, Ittekkot et al. 2000, Nixon 2003).

1.4.2.2 *Industrial and Urban Development*

1.4.2.2.1 *Industrialisation, Urbanisation and Wastes*

The location and intensity of development of the coastal zone to meet urban and industrial needs is mirrored by the global distribution of the population. Both the intensity and the areal extent of these developments are increasing concomitantly with population. The resultant pressures and effects on the natural resources and ecosystems can be measured through assessments allied with integrated coastal zone management initiatives (e.g., Jickells 1998, Ducrotoy and Pullen 1999).

Nutrient and contaminant wastes, atmospheric loads, sewage and other urban and industrial materials including oils and detergents have been identified as continuing global concerns (GESAMP 2001). The GESAMP report noted some recent advances in control of contaminant and point-source discharge and diminished pressures in response to environmental management and technological solutions.

Technological and legislative advances for controlling substance emissions are increasingly associated with industrialised locations in the developed world and in some localities in the less-developed world. The destruction of coastal habitats by the insidious spread of urban development remains a major issue. Megacities have specialist footprints of influence which may haverequire unique management approaches. For example, Paris has significant impacts measurable 75 km downstream in the River Seine basin and water quality remains affected 200 km downstream (Meybeck 1998); even upstream, the "Paris effect" is detectable, since the water demand and the flood protection needs of the city have resulted in extensive river management and reservoir constructions affecting flow patterns. The advance of "the global economy" is raising new coastal management concerns about local industrial performance and environmental impacts, especially by multinational companies that operate in a range of locations around the world, with differing environmental standards.

1.4.2.2.2 *Reclamation and Shoreline Development*

The extent of the conversion of natural ecosystems – wetlands, estuarine and coastal habitats – by land reclamation and engineering structures (sea walls, revetments, groynes, breakwaters) generally reflects population pressures and attempts to protect coastal infrastructure from storms and other high-energy events (Arthurton 1998, Burke et al. 2001). Construction of road causeways and shoreline ribbon developments for tourism facilities and industries adjacent to marine transport infrastructure often destroy habitats serving as natural fisheries and bird nurseries. Hard structural engineering options including flood mitigation barrages and dykes (e.g., the Ijsselmeer in the Netherlands) affect water quality, habitats and sediment processes.

Coastal structures can modify sediment transport along a coast, resulting in increased local and displaced erosion, which then requires mitigation by costly and continuous sand nourishment schemes. This may lead to intensified dredging from near-shore and riverine systems. The application of hard engineering structures as an option for coastline defence can preclude subsequent alternatives for coastal management of dynamic coastlines (e.g., Pethick 2001).

While shoreline protection measures through coastal armouring continue around the world, natural mitigation services are more frequently included in shoreline planning. In Cuba, recent tourist developments are constrained behind a coastline setback zone of several hundreds of metres. For the highly-engineered coastline of the Netherlands, new policy strategies encompass "building with nature" instead of "working against nature" (de Vries 2001); coastal flats and sand-dune systems are now being set aside from human development and maintained in order to act as natural dynamic buffer zones.

1.4.2.3 *Transportation*

Transportation by sea is the life-blood of global commerce, with 95% of world trade moved by shipping. Many port and infrastructure developments require dredging, with associated mobilisation and distribution of sequestrated nutrients and contaminants, while engineering structures modify estuaries and coastal shorelines. Port facilities engender further development of road and rail transportation systems and allied growth in population, which affect coastal land-use patterns, natural resources, environmental goods and services and other ecosystem amenities.

The translation of products and minerals from one global location to another has impacts and management ramifications for waste and landfill, pollutants and contaminants. One example is the use of the food-chain toxic tributyl tin in anti-fouling paints, which in recent years has been greatly restricted by conventions (within the International Maritime Organisation) and by national or local management regulations.

Ballast water is responsible for biological species transfer, particularly of pathogens, spores and cysts that can result in harmful algal blooms and human diseases. Introduction of non-indigenous biological species can have devastating effects on receiving systems, affect local fisheries and aquaculture economies and impact on public health. Measures are being taken to minimise ballast water transfers of living propagules (*http://www.imo.org*) and to reduce further negative impacts. Treatment of ballast water is a major issue for the International Maritime Organisation, the International Council for the Exploration of the Seas and port authorities.

Transient population shifts closely allied with tourism and commerce affecting coastal zones require transport. Infrastructure of airports, burned-fuel emissions and dumping of excess fuel over water (NRC 2002), ground transportation systems and associated settlements to service air transportation facilities affect both the natural environment and societal structures (see Text Box 2.10, Chap. 2).

1.4.2.4 *Mining and Shoreline Modification*

Mining for minerals and construction materials, oil and gas extraction and dredging of sediments have a multitude of environmental consequences including dispersal and resuspension of sediments, bathymetric changes, altered groundwater flows, loss of habitats and fisheries and altered natural sedimentation-erosional processes that affect shoreline stability.

Dredge materials account for 80 to 90% by volume of materials dumped into the ocean; several hundred million cubic metres of coastal sediments are dredged worldwide annually. The effect of sediment extraction remains an issue in many parts of the world (see Text Box 1.4).

The coastal zone is a major focus for oil and gas extraction with concomitant ecosystem impacts. In recent years, the application of new extraction techniques, spill management and contingency plans has seen a relative decline in oil spills (Burke et al. 2001, Summerhayes and Lochte 2002). However, there are mounting concerns about land subsidence, erosion, and allied impacts on coastal ecosystems resulting from subterranean removal of oil and gas (and also groundwater). For example, along the West African coast, the natural barrier-lagoon structure is undergoing subsidence and erosion (among other pressures) which are causing shoreline retreat at a rate of about 25–30 m per year, with potentially huge impacts on human habitation and ecosystems (Awosika 1999).

1.4.2.5 *Tourism*

Tourism is a benefit to the economies of most countries, generating US$ 4.9 trillion and about 200 million jobs worldwide, and has grown enormously over the last decade (WTTC 2003, *http://www.wttc.org*). In many countries, especially small island states, it is the major sector of the economy. As the coastal zone is a major focus for global tourism, economic and societal benefits are invariably offset by impacts on the environment, leading to doubts about the sustainability of tourism in some locales. Coastal development and localised population expansion, often seasonal, are legacies, while tourist activities frequently place direct and poorly-regulated pressures and impacts on the coastal system. These pressures depend on the type and style of tourism (Pearce 1997).

Pressures from tourism encompass and exacerbate the array of factors associated with urban developments and expand elevated population densities into new localities in the world. Concepts of sustainable tourism have been introduced into the industry by the World Tourism Organisation and related bodies to enhance industry management and awareness (Moscardo 1997). Demands for eco-tourism and a quality environment are apparently increasing and there are examples of well-managed tourism facilities and activities, such as in the Great Barrier Reef region where partnerships between industry and environmental management agencies ensure quality of visitor experience and sustained ecosystems (Crossland and Kenchington 2001). However, societal support and infrastructural developments to underpin tourist populations continue to exert negative pressures on many coastal systems globally.

Text Box 1.4. Sediment extraction in the North Sea

Russell K. Arthurton

The sedimentary nature of the North Sea (a relatively enclosed coastal sea) has provided a source of aggregate for building materials, especially from the extensive sand and gravel beds in the southern area and along the eastern coast of England. Direct impacts of coastal building and development on coastal integrity are most apparent in the shallow southern North Sea where construction and maintenance of dykes, artificially maintained dunes and underwater barriers have traditionally required skilled engineering. With an increase in the use of soft-engineering techniques such as beach nourishment for coastal protection, offshore sands such as those forming the Race Bank area off eastern England provide material for beach replenishment of coastal areas. The intense longshore drift along the coast of the Netherlands also requires constant beach nourishment.

The marine aggregate extraction industry (habitat excavation by dredging) in the North Sea is well-established and expanding in the shallower regions, having grown from 34×10^6 m^3 in 1992 to 40×10^6 m^3 in 1996. Extracted materials include shell and the calcareous red alga, *Lithothamnion* sp. The potential physical impacts of sand and gravel extraction are site-specific and depend on numerous factors including extraction method, sediment type and mobility, bottom topography, and bottom current strength. Suitable materials are unevenly distributed and should be considered as finite, except for additions from coastal erosion and, locally, river discharge. Long-term forecasts for supply are required and international co-operation needs to be envisaged for sustainable use of the resource.

1.4.2.6 *Fisheries*

Global fisheries have high socio-economic significance, providing more than 6% of the protein consumed by humans, and are especially important in developing country economies and food supplies (see WRI 2000). Fisheries yields have declined from almost 100 million tonnes to about 90 million tonnes annually over the last decade. While global wild-stock catches have been declining, pressures have not; even in the mid-1990's, fleet capacity was estimated as being 30–40% greater than need (Grainger and Garcia 1996).

An estimated 90% of the marine fish catch comes from the coastal zone (freshwater fisheries are important regionally) with about 30% currently derived from aquaculture. Aquaculture, with associated natural habitat destruction and pollution impacts, has grown substantially over the past three decades and, in many parts of the world, aquaculture in coastal and marine waters is the only growth sector within marine fisheries. While most of the finfish production stems from fish species low down the food chain, a growing proportion comes from higher trophic levels.

Over-fishing is a major problem for most regions of the world and the practice of "fishing down the trophic levels" (Pauly et al. 1998, Pauly and Maclean 2003) is a major concern for ecosystem function as well as for socio-economic performance of the fisheries system (see Text Box 1.5). The activity of fishing itself can impact on coastal ecosystems in several ways. The removal of piscivorous fish species, for example, not only can affect the age and size composition of the exploited species, but also can impact on energy flow pathways in the ecosystem. Life-history changes, increased growth rates and a lowered age at maturity have been reported in plaice (*Pleuronectes platessa*) and cod (*Gadus morrhua*) in the North Sea (Lindeboom et al., in press). It has been shown that through selective fishing, even the genotypic characteristics of exploited species have changed (Walker 1998, Ducrotoy et al. 2000).

In addition to over-fishing, fishery operations can have a destructive physical impact on the seabed and can affect population levels of non-target species through incidental catch; these problems are of particular significance for cetaceans, sea turtles and seabirds such as the albatross in different parts of the world. Direct effects of trawling and by-catch issues in coastal systems are well-documented and show major impacts on ecological structure and influences on biogeochemical cycles (e.g., Sainsbury et al. 1997, Kaiser and de Groot 2000). Poison and explosive fishing techniques used in many coral reef regions cause reef destruction and trophic alterations (Wilkinson 2000). Commercial and recreational fisheries in coral reefs and associated systems may be leading to symptoms of eutrophication by removal of herbivores (see Szmant 2001).

Changes in climate, such as the North Atlantic Oscillation, appear to be affecting fish distributions and their spawning patterns (ICES unpublished reports 1999). These changes are coupled with pollution effects on fish and bioaccumulation of pollutants (GESAMP 1996).

The expansion of aquaculture through the last decade, particularly in Southeast Asia and China, has major ramifications for coastal zone management from allied pressures imposed on an array of ecosystems, including supply of stock from the wild, restriction of water flows in estuaries, benthic system changes, physical and chemical changes in sediments, oxygen depletion and coastal eutrophication.

Overall, the long-term indirect effects of fisheries on coastal marine ecosystems concern the trophodynamics of the system, viz., the efficiency of energy transfers be-

Text Box 1.5. Fish population changes in the North Sea

Han Lindeboom

The rich North Sea grounds support one of the world's most active and intensive fisheries, with highest landings per unit area in the North East Atlantic. The North Sea fishery removes 30–40% of the annual biomass of exploited fish species (Gislason 1994). Landings were highest in 1996 when 3.5×10^6 t were fished. Stocks of herring, cod, mackerel and plaice were fished beyond sustainable biological limits in the second half of the 20th century and the extensive over-fishing has forced drastic managerial measures to reduce the damaging effects of the fishing practices on both biomass and structure of fish populations. For herring, this led to a notable recovery. In 2002 the EU imposed an 80% cut in quotas of cod, the socio-economic consequences of which will be extremely painful for the industry. In some cases (e.g., cod, plaice and starry ray), the gene pools have been selected in favour of smaller animals reproducing at an earlier age, hence inflicting an impact at ecosystem level.

On the other hand, there are higher numbers of the seabirds which survive on discards and offal. The total mass of discards in the German Bight in 1991 was estimated at 36×10^3 t fish, 58×10^3 t starfish and 800 t swimming crabs; the number of individuals included 420 million fish, 5 800 million starfish and 120 million swimming crabs. More than 8 kg of unwanted animals were discarded per kg of marketable fish. Beam trawling and other demersal methods have affected benthic communities and trophic interactions (Jennings and Kaiser 1998) and there is increasing concern about the loss of juvenile fishes and the shift in age distribution towards younger fish.

Fishing also causes mortality of non-target species of benthos, fish, seabirds and mammals. In Dutch waters, ray populations have been annihilated. Heavy towed gears disturb the uppermost layer of the seabed, while gillnets accidentally entangle seabirds and marine mammals (Kaiser and Spencer 1996). The high fishing pressure within the North Sea gives cause for concern regarding the loss of mature and breeding fish populations as well as other ecosystem changes (see, for example, Jennings and Kaiser 1998). The creation of Marine Protected Areas, effort reduction and more selective gear are seen as major managerial tools which may turn the tide.

tween trophic levels. Trophic changes in predator-prey relationships and energy flows as well as habitat alterations have clearly created new conditions in many coastal systems. Genetic changes and selection of individuals and species adapted to such new environmental conditions are potentially major imposts by humans on natural ecosystems; focussed research needs to gauge any harmful consequences, including loss of biodiversity (Ducrotoy 1999).

Coastal ecosystems are vulnerable and subject to many development activities by humans. The effects of such activities and their eventual impact on coastal systems will vary within and among systems. Challenges facing coastal scientists and managers include assessment of the magnitude of these impacts and development of appropriate remedial conservation policies. For example, it can be predicted that a reduction in freshwater input into an estuary will affect the diversity and productivity of the constituent plant and animal communities. The magnitude of the predicted changes, however, is difficult to quantify; even more so, the response of the system as a whole. These changes can be analysed in retrospect and the response of the system assessed. Baird and Heymans (1996), for example, found that despite large fluctuations and divergent trends in abundance, productivity and diversity of individual components of an ecosystem following severe freshwater reduction in an almost pristine estuary, only marginal changes were apparent at the whole-system scale.

The matrix in Fig. 1.8 summarises the impacts of development activities on coastal ecosystems and provides a subjective index of the potential severity of these in the coastal zone. The matrix illustrates that few systems are immune to development activity and that invariably any kind of development activity impacts on more than one system. What the matrix does not show is the unique characteristic of the Anthropocene Age: the rapidity of changes inflicted by humans on natural systems.

1.4.3 Economics and Coastal Zone Change

The resources, products and amenities of the coastal zone are crucial to the societal and economic needs of the global population. Equally, the natural functions of wetlands, forests, agricultural regions, estuarine and coastal marine ecosystems play a vital role in Earth's function – for example, wetlands act as system "kidneys" for nutrient transformations and exchange, and as variable time-scale sinks and reservoirs for materials storage (Ibanez and Ducrotoy 2002). These benefits from the coastal zone are obvious for both society and nature, and are frequently the focus of societal conflicts at local and sometimes regional scales; conflict resolution is usually addressed through integrated coastal zone management approaches (e.g., Burbridge 1999, von Bodungen and Turner 2001).

The importance of the coastal zone and its constituent ecosystems is recognised by society from ecological, economic, social and aesthetic points of view, but the more recent recognition of the consequences of human activities on coastal zone ecosystems has led to increased interest in environmental economics and estimations of the cost of ecosystem degradation and rehabilitation. For

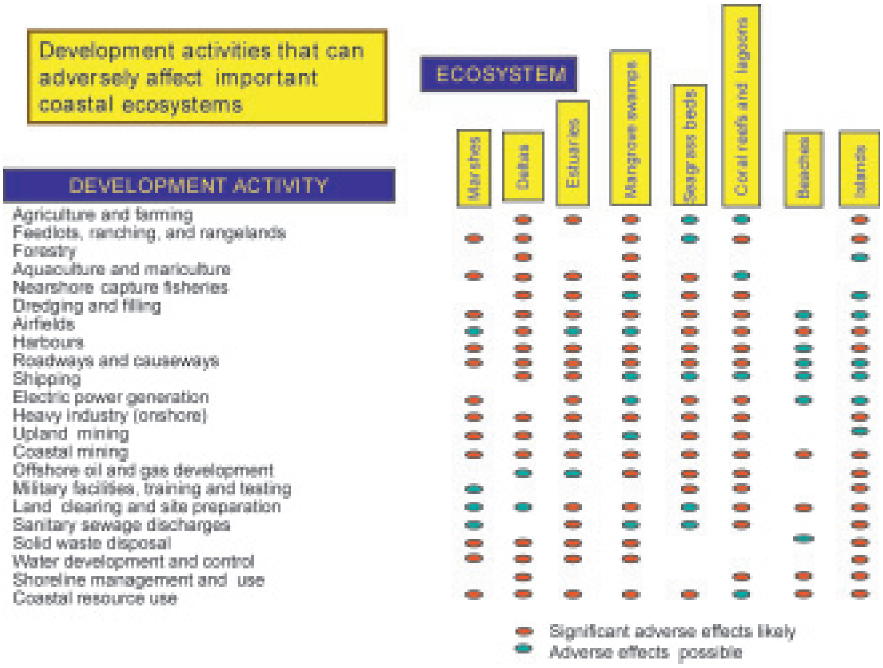


Fig. 1.8.
The coastal zone. Relationship between development activity and coastal systems

example, the 1997–98 ENSO event was associated with widespread coral-reef bleaching (Hoegh-Guldberg 1999, Wilkinson 2000). Although many coral reefs that had suffered mass mortality are showing signs of recovery, the socio-economic impacts have been severe. The loss of coral reef habitats has probably exacerbated over-fishing in regions where this was already a problem. Income from coastal tourism has probably declined, and coastal erosion has increased in areas where degrading coral reefs formed lesser barriers to wave action (e.g., Sri Lanka). Estimates of the economic losses in the Indian Ocean alone due to coral reef losses range from US$ 700 to US$ 8 200 per hectare over 20 years (Wilkinson et al. 1999).

Globally, the societal importance of the coastal zone can be related to two key elements, namely: (*1*) ecosystem goods (de Groot et al. 2002) and services (Daily 1997) concentrated in coastal marine and estuarine systems and (*2*) the growing coastal human population and its demands on ecosystem goods and services, including those of the adjacent river basins (Costanza et al. 1997, Hinrichsen 1998, Daily and Walker 2000).

Coastal ecosystems provide a wide range of goods and services which constitute the natural capital of the coastal zone. The coast provides two kinds of benefits: direct and indirect. Direct benefits include goods and services that are produced by coastal ecosystems such as fish for human consumption, kelp used for fertilisers, coastal tourism, mining (e.g., for diamonds, titanium) and timber-harvesting. Indirect benefits are ecological functions performed by coastal ecosystems: for example, wetlands detoxify wastewater, the land-sea interface creates a mild climate, the recycling of essential elements (e.g., C, N, P, Si), the upwelling process with its biological consequences, and erosion control. Environmental economists sometimes include other benefits (Ledoux and Turner 2002). For example, an option value that reflects the benefit of conserving resources for the future, an existence value that illustrates the benefit from coastal resources simply because they exist, and a bequest value that reflects the benefit of knowing that the preserved natural environment and its resources will be passed on to future generations.

The demands on ecosystems to generate and provide commercial goods, recreation and living space and to receive, process and dilute the effluents of human settlements will continue to grow. For example, land-based sources account for about 80% of the annual input of contaminants to the oceans (UNEP 1995). At the same time, coastal ecosystems are experiencing unprecedented changes that affect their capacity to provide these services and support valuable resources. The phenomena of interest include sea state, surface currents, sea-level rise, coastal erosion and flooding, habitat modification and loss (e.g., coral reefs, seagrass beds, tidal wetlands), loss of biodiversity, oxygen depletion, harmful algal bloom events, fish kills, declining fish stocks, beach and shellfish bed closures and increasing public health risks (Table 1.4). Apparent increases in the occurrence of these phenomena indicate profound changes in the capacity of coastal systems to support living resources.

Such changes make the coastal zone more vulnerable to natural hazards, and make more costly the management of its resources in a sustainable manner. The conflict between commerce, recreation, development and the management of ecosystems and their living resources will become increasingly contentious and politically sensitive in the absence of realistic coastal zone management policies and mechanisms to detect and predict the impact of environmental changes on the socio-economic fabric of the coastal zone. Informed decision-making is vital in this context (von Bodungen and Turner 2001).

Putting a value on human resource use and natural environmental services of the coastal zone has been a topic of increasing effort over the last decade. It has proven difficult and has frequently led to contentious outcomes, often because of differences between the models, metrics and methods (especially in dealing with time-scales) of the more traditional economic and social science disciplines and those of the evolving approach of ecological economics (Jickells et al. 2001). Monetary units are the more commonly used measures of both approaches but there is well-founded debate on both the rigour of each approach (and levels of uncertainty) and the ability of monetary terms to capture and measure human perceptions and ecosystem functions (Turner 2000, Faber et al. 2002).

Despite this uncertainty, it is clear that the global coastal zone has a high value. For example, Costanza et al. (1997) concluded that the global value of ecosystem services was in the order of US$ 33 trillion per annum, or about 1.8 times the global GNP. They further estimated that marine ecosystems provided about 63% of these goods and services, and that coastal ecosystems, which comprise about 8% of the world's surface, provided 43% (or US$ 12.6 trillion per annum) of the global total. Wilson et al. (2004) have recently updated these values, estimating that the coastal zone has a total economic value of about US$ 17 trillion per annum and provides 53% of the total annual ecosystem service value of the world. The greatest value for a single ecosystem service was ascribed to nutrient cycling. On a smaller scale, Glavovic (2000) calculated that the direct and indirect benefits derived from the coastal zone of South Africa were in the order of US$ 22 billion and US$ 18 billion per year, respectively; combined, these services comprised about 63% of the country's GDP. These and other analyses (e.g., Daily and Walker 2000) clearly illustrate the value of coastal ecosystems and their importance to society on global and local scales.

Irrespective of any debate on details and the rigour of the estimates, it is generally agreed that ecosystem coastal services are of high value. Recent attempts to gain a measure of the various economic sectors of the global economy show similarly high values for the coastal zone. Global tourism was estimated at US$ 4.9 trillion per year (WTTC 2003), most of which takes place in the coastal zone. Fisheries exports are > US$ 50 billion per year (FAO 1999). Around 1 billion people depend on fish as a source of protein (Laureti 1999 cited in WRI 2000), an estimate not normally captured in the fisheries export monetary values.

The research approaches for valuation and measurement of benefits from the coastal zone offer a field of challenge that is attracting much current effort (Turner et al. 1998, Voinov et al. 1999, Gren et al. 2000, Aguirre-Munoz et al. 2001). Modelling approaches and scaling mismatches between model elements in particular are being tackled (e.g., Talaue-McManus et al. 2001), in addition to resolution of more basic parameters such as temporal parameterisation and metrics for expression. It seems likely that future assessments will not only ascribe even greater gross value to the coastal zone, but new tools should contribute significantly to improving estimates of trade-offs and options for integrated coastal management decisions (Ledoux and Turner 2002).

1.5 Measuring Change and Status of the Coastal Zone at the Global Scale – LOICZ Approaches and Tools

The coastal zone is a domain of convergence for terrestrial, oceanic and atmospheric forcings and human influences. The heterogeneity in the intensity of these forcings and the diversity of human influences provide a fine spatial tapestry of biophysical processes interacting with human society. These are associated with a dynamic for change across a range of temporal scales extending well beyond human life spans. Consequently, we are severely constrained in our ability to realistically describe and model the extraordinary array of interactions in a detailed and strictly quantitative manner and to meet all expectations of scalar assessment within Earth's coastal systems. Most coastal zone assessments are at local and sub-regional national scales. They are often unique (or one-off) evaluations, frequently addressing single issues of forcing and are usually founded on the application of only one or two traditional scientific disciplines, for example, oceanography, biology, sociology, demography or economics. Rarely are multi-disciplinary approaches used to address holistic issues of status and change in the coastal zone.

Our approach for measurement of changes in the coastal zone has needed to encompass elements that are approximate, semi-empirical, iterative and evolutionary. The LOICZ approach takes two forms. First is the development of horizontal and, to a lesser extent, vertical material flux information and models across continental basins and through regional seas to continental shelf margins. This has been based on our understanding of biogeochemical processes for coastal ecosystems and habitats and their interactions with the human dimensions. Second is the development of ways to incorporate scaling of the material fluxes, spatially from local to global levels and across decadal temporal scales. While we have made good progress on the first element, the second remains a challenging activity for the research community.

We have recognised that there is a large amount of existing (secondary) data and work being carried out around the world on coastal habitats and ecosystem processes at a variety of scales, but that there are gaps in this work. Hence, LOICZ has sought to build networks of global researchers in order to capture and initiate the gathering of new scientific data. LOICZ has established a number of thematic approaches and tools to address material fluxes and human dimensions in the coastal zone. These have provided regional and global descriptions of:

- material fluxes and human interactions across various spatial (and limited temporal) scales,
- biogeochemical transformations in estuaries and coastal seas (generally from locally-scaled data),
- coastal fluxes at regional and global scales by consistent up-scaling methods (typology),
- socio-economic implications of changes in coastal ecosystem status,
- river basin fluxes of materials and interaction with pressures derived from natural phenomena and human activities, and
- key global change phenomena, such as sea-level and global warming, and submarine groundwater discharge (*http://www.loicz.org*).

New tools include concept developments and new research, adaptation and extension of existing methodologies and scientific assessment approaches (see LOICZ Reports & Studies publications, Appendix A.1). Supportive and additional information was obtained from new research commissioned, sometimes by LOICZ but usually by regional and national agencies in response to initiatives by the LOICZ community. The LOICZ network of scientists has collaborated in evaluating and synthesising the results from commissioned research and other emergent data into regionally- and globally-scaled information about the coastal zone. Some of the key tools developed by LOICZ described below form the basis of the approach for many of the thematic assessments described in detail in subsequent chapters.

1.5.1 Biogeochemical Fluxes of C, N and P

The questions of interest to LOICZ and IGBP are:

- Globally, is the net metabolism of the coastal zone a CO_2 source or sink?
- How is this net trophic status changing in response to local human intervention and global environmental change?
- Given the spatial heterogeneity of the coastal zone, what is the spatial distribution of net metabolism in the coastal zone?

LOICZ has implemented an approach for evaluating biogeochemical processes for C, N and P in the coastal zone (Gordon et al. 1996, Smith 2002) in tandem with the development and application of a scaling or typological tool and global datasets, (see Sect. 1.5.2 below).

The issue of carbon and its biogeochemical cycling is central to this dual LOICZ approach. A major target is to determine the relative poise of the coastal zone with regard to net carbon flux by answering the question:

- Is the coastal zone an autotrophic or a heterotrophic global compartment? (Holligan and Reiners 1991, Pernetta and Milliman 1995).

A body of literature argues that the coastal zone is heterotrophic but this conclusion remains controversial (see Chap. 3). Although the heterotrophy argument has been supported by some researchers, other workers have argued that coastal systems are presently autotrophic. There is evidence that some coastal ecosystems are autotrophic, which is to be expected in systems receiving higher discharges of inorganic nutrients relative to organic loads.

The LOICZ approach has been directed at existing (secondary) data from individual estuaries and coastal seas. It was felt that insufficient time and resources existed in the lifespan of LOICZ to collect an adequate amount of primary data to address this question at a global scale. Further, it was recognised that there are very few sites around the globe with direct estimates of net carbon metabolism for the entire estuarine or coastal sea system. Thus, net metabolism has been inferred indirectly, via relatively widely available data on nutrients in specific coastal ecosystems. Using secondary data for each estuarine site or coastal sea, a water budget and salt budget were constructed, N and P budgets were derived (mostly reliant on dissolved inorganic N and P data) and stoichiometric calculations yielded net metabolism values for the system.

The principle of this analysis is as follows. Net carbon metabolism can be represented simplistically by the following equation:

$$CO_2 + H_2O \xleftrightarrow{[p-r]} CH_2O + O_2 \qquad (1)$$

where $[p - r]$ represents the difference between primary production (the forward reaction, p) and respiration (the reverse reaction, r). This difference represents the Net Ecosystem Metabolism (NEM) of the system and describes the role of organic metabolism in that system as a source or sink of CO_2. The formation of organic matter via primary production also sequesters nutrients (notably nitrogen and phosphorus) along with carbon; oxidation of that organic matter (respiration) releases nutrients. For any nutrient, Y, taken up in the ratio α with respect to carbon, Eq. 1 can be modified as follows:

$$CO_2 + H_2O + \alpha Y \xleftrightarrow{[p-r]} CH_2O \cdot \alpha Y + O_2 \qquad (2)$$

The familiar Redfield C : N : P ratio of 106 : 16 : 1 would give α values of 6.6 and 106 for N and P in planktonic systems (Redfield et al. 1963).

Equation 1 greatly simplifies reality, for three major reasons. First, use of the equation to estimate NEM assumes that the forward and back reactions (that is, p and r) are based on the same value of α. Second, it is assumed that α is known. Third, it is assumed that reactions of Y not involving this simple stoichiometry are minor.

Lacking data to the contrary, the first two assumptions (constant and known value for α) usually are addressed by the use of the Redfield ratio. With more detail in any particular system, these assumptions can be fine-tuned. The third assumption (minor reaction rates in the system not conforming to the simple Y : C stoichiometry) is perhaps the most critical. In the case of P, inorganic sorption and precipitation reactions clearly occur. When NEM is near 0, these "non-stoichiometric reactions" probably do cause error; this is unlikely to be a serious problem when NEM is well removed from zero. In the case of N, inorganic reactions are probably usually minor. However, the processes of nitrogen fixation (i.e., conversion of N_2 gas to organic N) and especially denitrification (conversion of NO_3 to N_2 and N_2O gases) are likely to be of great importance in many benthic systems. Therefore, this simple stoichiometric approach clearly will not work for N in such systems.

This contrast between P and N stoichiometry leads more or less directly to the LOICZ approach. Budgets of the delivery of dissolved P and N to coastal aquatic ecosystems, minus the export of dissolved P and N from these systems, allow estimates of net dissolved N and P uptake or release by these systems. For the most part, these dissolved nutrient budgets are based on water and salt budgets to establish the advection and mixing of water in these systems. Thus, the dissolved N and P are said to "behave non-conservatively" with respect to water and salt flux. The non-conservative behaviour of dissolved P (scaled by the proportionality constant α) is used as a simple estimate of NEM. The difference between the expected non-conservative behaviour of dissolved N, according to this simple model and the observed non-conservative behaviour, is an estimate of the difference between nitrogen fixation and denitrification [nfix – denit].

Where possible, each of these rates (water exchange, [$p - r$], [nfix – denit]) was compared with independently obtained data; sometimes the rates were close to one another, sometimes they were not. Moreover, the estimate of NEM was compared, where possible, with primary production (p), and was typically less than 10% of primary production. Thus, like the ocean, the role of the coastal zone as a source or sink of CO_2 is represented by only a relatively small fraction of the gross production of the system.

The resultant biogeochemical budgets and inferred rates of net metabolism represent site-specific estimates of metabolism in the coastal zone. More than 200 site-specific budgets now form a global nutrient and carbon inventory (*http://data.ecology.su.se/MNODE*). The budgeting approach has evolved from its initial description (Gordon et al. 1996) during implementation by LOICZ (Talaue-McManus et al. 2003), with the inclusion of a number of sub-models allowing assessment of, for example, freshwater and nutrient inputs (San Diego-McGlone et al. 2000). Scientists from around the world have contributed site budgets to a central database (*http://data.ecology.su.se/mnode/*) with review for quality control imposed before public listing on the web site. A series of regional workshops (see Appendix A.1), convened by LOICZ and supported by a UNEP GEF project, provided opportunities both to build a network and train scientists in the budgeting approach and to develop a global spread of budgeted sites. Details of application and synthesis of the budget approach are described in Chap. 3.

A major challenge has been to extrapolate from the individual budget sites to the global coastal zone and this has been approached via the development of a "typology," or classification, of the global coastal zone (see Sect. 1.5.2). The budgeted sites were mapped in association with their catchment(s) at 1-km scale to provide complementary data on the terrestrial parameters that influence coastal systems, e.g., climate, population, catchment area.

1.5.2 Typology Approach to Scaling and Globalisation

A primary LOICZ objective was to describe the role of the coastal zone in critical biogeochemical fluxes (C, N, P). These fluxes must be understood at global spatial scales, and at temporal scales up to and including those of climate variability and change. Currently, there are relatively few measurements of coastal zone fluxes, and their spatial and temporal coverage is limited. As a practical approach to developing and improving quantitative estimates of coastal zone fluxes at all scales, LOICZ addressed the upscaling of flux measurements by coastal zone typologies (Talaue-McManus et al. 2003, see Chap. 3).

Here, upscaling is primarily used to mean the development and application of techniques to predict, quantitatively or semi-quantitatively, the behaviour of large spatial regions based on observations made at much smaller scales. Typology is the development of environmental classifications or categories of data that can be related to local and regional observations in ways that permit inferences about areas in which local observations are lacking.

The typology approach consistently characterises functional data (essentially, the biogeochemical flux and budget information described in Chap. 3, Sect. 3.5.1) and information on the environmental context of the individual budget sites so that classification and upscaling of the functional information could be achieved. In this way, the information from the array of small, site-specific biogeochemical sites collected globally can be aggregated and, through developed typologies, used as proxies to ascribe coastal metabolic performance in low- or no-data coastal areas. Biogeochemical performance of coastal systems at regional and global scales can be inferred.

The objective of the typology approach was the identification of functionally-related coastal categories on the basis of relevant typology variables through the use of geospatial clustering with a software package (LOICZView) developed by the LOICZ Typology Group (*http://www.kgs.ukans.edu/Hexacoral/Envirodata/envirodata.html*). Consequently, the development of the typology approach has involved two primary elements: (*a*) a set of analytical and data management tools, mainly the geospatial clustering tools, and (*b*) a set of geo-referenced global environmental and biogeochemical databases. Internet access was provided to each element.

The geospatial clustering tool (LOICZView; *http://www.palantir.swarthmore.edu/loicz*) was developed to manipulate the typology datasets, with statistical and mapping capability to visualise results (see Text Box 1.6). This tool has been recently extended into a new platform, DISCO (*http://narya.engin.swarthmore.edu/disco*), which includes a fuzzy clustering routine and a time-series clustering capability.

Three typology datasets were developed for use in analysis and upscaling of the coastal zone biogeochemical flux assessments:

A global half-degree gridded environmental database (also referred to as the typology database), with the cells classified according to their relationship to the coastal zone. Some 259 200 half-degree cells describe Earth's surface and 47 057 of these cells have been identified as typology cells that describe the global coastal zone. Fig-

Text Box 1.6. Spatial clustering

Bruce Maxwell

When faced with a large amount of data, it can be difficult to extract meaningful information or discover structure within the data by simple observation. One quantitative procedure for extracting structure from data is spatial clustering, which groups similar data points and describes those groups using aggregate statistics such as means and standard deviations. The resulting set of extracted groups, or clusters, represents an abstraction of the original data that is simpler to manipulate and understand, while still retaining the relevant characteristics of the initial data.

One of the most widely applied algorithms for spatial clustering is the *K*-means algorithm (MacQueen 1967). The *K*-means algorithm falls into the category of unsupervised clustering algorithms, which means it begins with no prior knowledge of the characteristics of individual clusters in the data. In other words, the basic *K*-means algorithm requires only the number of clusters to be found, without any initial specification as to where the clusters might be.

The *K*-means algorithm is an iterative algorithm that starts by guessing where the clusters might be and then iteratively improves the guess until it converges to a stable answer (Fig. TB1.6.1). Given that we want to find *N* clusters in a dataset, the steps are as follows:

- Randomly select *N* data points as the initial cluster representatives $R_{1..N}$
- For each data point Xi, calculate the distance to each Rj using a distance measure *d*(Rj, Xi).
- Label each data point Xi as belonging to its closest cluster representative Rj.
- For each cluster representative Rj, calculate a new value for Rj by averaging the values of all data points belonging to that representative.
- Repeat the algorithm from step 2 until the cluster representatives $R_{1..N}$ do not change.

There are three primary issues when working with the *K*-means algorithm:

- How many clusters should there be?
- What distance measure is appropriate?
- Will the algorithm always converge to the same solution?

Of the three issues, the first is actually the most difficult to answer because it requires knowing the inherent structure of the data, which is what the method is trying to discern. Beyond simply making educated guesses, the general approach to answering this problem is to define a method of measuring the "goodness-of-fit" or "fitness measure" of a particular clustering of any given data. This measure should reflect the desire to have clusters that are compact within themselves and yet distant from other clusters. In a very practical sense, these measures often try to indicate how closely a clustering generated by a computer would match a clustering of the same data executed by a person. The optimal number of clusters should be the number that results in a clustering that maximises the measure of fitness.

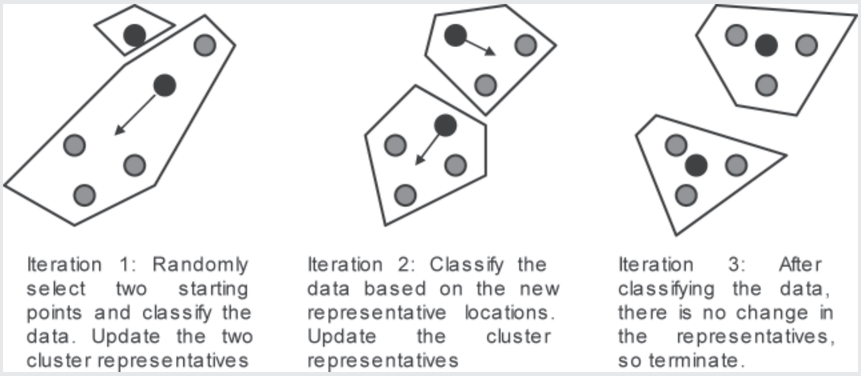
Within the LOICZ typology group we have used Rissanen's minimum description length as a measure of fitness that balances the desire for compact clusters – which is generally achieved by having more clusters – with the desire for as few clusters as possible to maximise the benefits of clustering (Rissanen 1989). To discover a range of reasonable values for the number of clusters we test a range of clusterings and then graph the resulting fitness measure. This usually results in a small range of values that produce reasonable clusterings.

The second issue, distance measures, is dealt with in a separate part of the clustering software package. In short, the distance measure should reflect the user's understanding of similarity and should be appropriate to the data.

Finally, the answer to the third question is that the *K*-means algorithm will not always converge to the same answer. The algorithm is a "gradient descent" type algorithm, and it can get caught in local minima where the resulting cluster is stable but not optimal. To overcome this problem the user generally runs the algorithm multiple times from different starting points. The clustering that produces the least error in terms of the sum over all points of the distance to the nearest representative point is the result selected as the best answer. It is not uncommon for some datasets to be inherently unstable with respect to a small number of data points that do not really belong to any particular cluster. It is often the case, however, that these data points, upon further examination, are actually interesting and represent unique situations that are not well captured by a particular typology or classification.

Overall, the *K*-means clustering algorithm provides a useful tool for identifying structure in both small and large datasets. The key to producing useful results is to intelligently select the number of clusters and distance measure. The resulting clusters represent an abstraction of the data that may be more amenable to understanding and knowledge generation than the original compiled data.

Fig. TB1.6.1.
A simple example of the *K*-means clustering algorithm



ure 1.9 illustrates the grid system; the coastal zone is represented primarily by the coastal cells (containing actual shoreline), the Ocean I cells (~ one degree seaward of the coastline) and the terrestrial cells (~ one degree landward of the coastline). The remainder is classified as Ocean II (enclosed seas or basins), Ocean III, or In-

land. This database contains a wide variety of public domain, global or near-global datasets, presented in a common grid format at 30' (half-degree) resolution (see Text Box 1.7). The variables represented are those that have relevance to either general coastal zone classification or to the factors believed likely to control or influence the fluxes of interest, including terrestrial, marine, coastal, atmospheric, human dimension, geomorphic and river-basin variables. The data for each variable has been georeferenced and scaled to the 30' cell array; a number of the variables have much finer resolution and all are accompanied by metadata descriptions. The native resolution of the data sets ranges from 1 km to several degrees. Where higher resolution data are aggregated into the half-degree cells, statistics on the sub-grid scale distributions are included in the database.

1. The biogeochemical budget database (also referred to as the budget database). The budget variables from the site and biogeochemical budget characteristics assembled by the LOICZ biogeochemical budgets activity (see Chap. 3, Sect. 3.2, Buddemeier et al. 2002, *http://data.ecology.su.se/mnode/*) include standardised nutrient load and flux data and calculations of nutrient sources and sinks (i.e., non-conservative fluxes) for more than 200 sites worldwide.
2. Km-scale basins: A database was derived from the HYDRO1k dataset (HYDRO1k Elevation Derivative Database, *http://edcdaac.usgs.gov/gtopo30/hydro*) using GIS to identify the drainage basins associated with the biogeochemical budget sites. The associated basin entries were populated with terrestrial, climatic, geomorphic and human variables by "clipping" GIS coverages of the parent datasets with the HYDRO1k basin coverage. This provided a more accurate and precise representations of those variables associated with the biogeochemical budget sites than can be obtained from the half-degree database. However, it did not address the issue of marine variables for which comparable data are not available.

The typology upscaling, for practical reasons, has evolved into two related processes. The km-scale river basin (catchment) data are used to identify relationships between terrestrial, hydrologic and human forcing functions and aspects of the biogeochemical fluxes that are or should be sensitive to those functions. This effort examined and compared relationships across a wide range of spatial scales, but did not in itself "upscale" by using measurements derived at one scale to characterise performance at another scale. The km-scale basin data were also used to compare the site-specific basin characteristics with characteristics inferred from the half-degree database alone. This comparison allowed determination of which budget characteristics, sites and environments

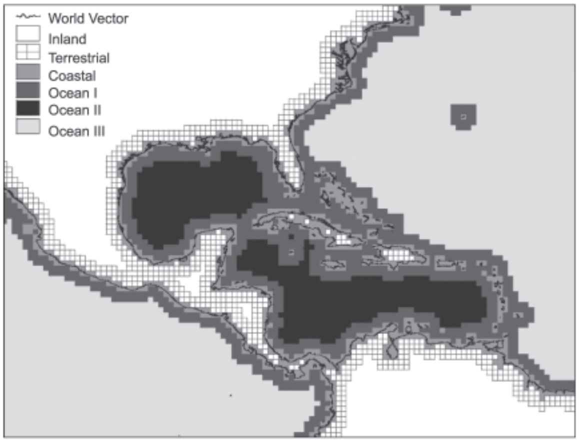


Fig. 1.9. Typology. Illustration of the scale and categories of the LOICZ half-degree grid cell definitions

Text Box 1.7. Area of grid cells vs latitude

Dennis P. Swaney and Robert W. Buddemeier

It is useful to remember that the cell area of any grid system based on latitude-longitude-coordinates on the globe has a strong latitudinal dependence (Figs. TB1.7.1, TB1.7.2).

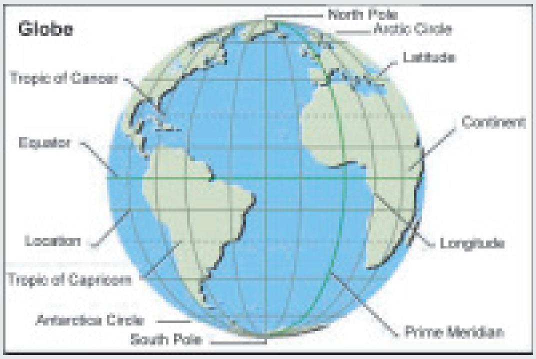


Fig. TB1.7.1. Latitude-longitude grid of the Earth. As latitude increases, the grid area decreases significantly because of narrowing of the longitudinal bands

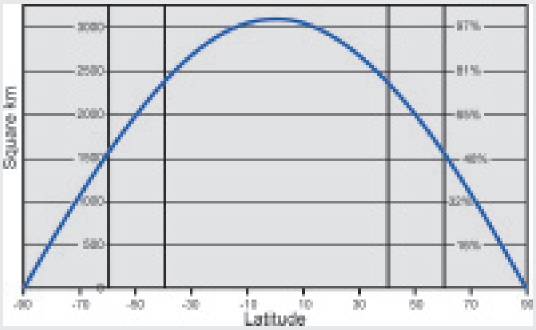


Fig. TB1.7.2. Relationship between latitude and the absolute area (km^2) of a half-degree (30' × 30') grid cell, and the area as a percentage of the grid cell area at the equator were most amenable to upscaling with the existing datasets, and where (or whether) the additional effort involved in systematically developing coastal datasets based on km-scale budgets could be justified. The comparison also permitted assessment of the biases and uncertainties involved in upscaling.

The application of the typology approach to the global assessment of coastal metabolism is described in Chap. 3. In addition the work has yielded a number of related scientific products including a global pattern of nutrient loading (Smith et al. 2003). Importantly, the typology approach and tools have applications in a number of other assessment initiatives including the NOAA National Estuarine Eutrophication Assesssment Program in the United States and in coastal management assessments by National Institute of Water and Atmospheric Research (NIWA) in New Zealand. The NSF-sponsored project "Biogeography of the Hexacorallia" (a project of the US Ocean Biogeographic Information System, OBIS; *http://www.iobis.org*) has been a major collaborator, along with strong institutional support from Swarthmore University and the Kansas Geological Survey, as part of its major initiative in biogeoinformatics.

1.5.3 Socio-economic Evaluations

The importance of human activities in modifying the structure and function of the coastal zone was clearly recognised and incorporated into the strategic direction of LOICZ (Holligan and de Boois 1993). However, available socio-economic approaches and tools for assessment were few, especially for evaluating biogeochemical changes and for furthering "the scientific and socio-economic bases for the integrated management of the coastal environment" (a key LOICZ objective). Observational studies and modelling approaches were needed to provide an understanding of the external forcing effects of socio-economic changes (e.g., population growth, urbanisation) on material fluxes and to assess the human welfare impacts of flux changes.

LOICZ adopted and further developed several approaches to assess the drivers and consequences of societal pressures on coastal systems and the valuation of allied changes. The socio-economic initiatives were deliberately integrated into the biogeochemical activities rather than being developed as stand-alone initiatives.

The DPSIR framework (Turner et al. 1998, Turner and Salomons 1999; Fig. 1.6) provided a framework for identifying the key issues, questions and the spatial distribution of socio-economic activities and land uses, particularly for the assessment of drainage basin and linked coastal seas. The assessments derived from expert workshops provided the foundation for development and implementation of the LOICZBasins approach (see Sect. 1.5.4 below). River-basin studies in a number of the continental regions yielded observational and model-based socio-economic assessments involving both monetary valuations and multi-criteria assessments methods and techniques to identify practicable management options (see Chap. 4). In addition, products of socio-economic workshops and discussions in LOICZ, along with the direct involvement of sectoral expertise in other science projects, has led to a wider evaluation of human influences in studies directed at understanding biogeochemical fluxes, including the building of typology databases.

Effort was made to translate directly the largely observational information derived from the DPSIR framework into socio-economic input/output models that could be juxtaposed and linked to biogeochemical nutrient flux models. A major study across four sites in Southeast Asia, the SARCS-WOTRO-LOICZ project, yielded useful outcomes and, importantly, critically evaluated the methodology, identified limitations and uncertainties, and indicated useful modifications (Talaue-McManus et al. 2001). An improved understanding of the different scales (especially temporal) and richness of site data needed for model resolution was a vital result of the study.

The global valuation approach to ecosystem goods and services developed by Costanza et al. (1997) was explored. The evolution of ideas and methodologies being applied to this area of environmental economics was captured in a revised global valuation of ecological goods and services (Wilson et al. 2003).

1.5.4 River Basins – Material Fluxes and Human Pressures

The LOICZBasins approach involves regional assessment and synthesis of river catchment–coast interactions and human dimensions (Kremer et al. 2002). It addresses the impact of human society on material transport and catchment system changes, assessing their coastal impact, and aims to identify feasible management options, recognising the success and failure of past regulatory measures. Since the changes in fluxes are mostly land or river-catchment derived, each catchment–coastal sea system was treated as one unit – a water continuum.

Through standardised workshops, LOICZBasins provided a common framework for analysis, assessment and synthesis of coastal zone and management issues in most global regions. It comprised methodologies, common assessment protocols (qualitative and quantitative depending on data availability) and project designs for future work. LOICZBasins applied the DPSIR descriptive framework to determine the critical loads of selected substances discharging into the coastal seas, within diverse biophysical and socio-economic settings, under different development scenarios. The LOICZ Basins approach provided an expert typology of the current state and expected trends of coastal change in systems responding to land-based human forcing and natural influences.

Core actions for each regional workshop were:

a to identify and list key coastal change issues and related drivers in the catchment;
b to characterise and rank the various issues of change based on either qualitative information (i.e., expert judgement) or hard data from investigations or archived material, including identification of critical load and threshold information for system functioning; and
c to identify current or potential areas of impact ("hot spots") representing different types of pressures or changes in catchment-coast systems and to develop a relevant research proposal.

The following parameters were evaluated in each regional assessment:

- material flow of water, sediments, nutrients and priority substances (past, current and future trends);
- socio-economic drivers that have changed or will change the material flows;
- indicators for impacts on coastal zone functioning; and, where possible,
- a "critical load" for the coastal zone and "critical thresholds" for system functioning.

Assessment and ranking followed a sequence of scales allowing a full regional picture to be generated with the spatial scales increasing from local catchments, via subregional or provincial scales, up to regional scales, including country by country (in the case of large countries such as Brazil) or subcontinent.

For relatively data-rich Europe, the critical load and threshold concept developed within the United Nations Economic Commission for Europe's convention on Long-Range Transboundary Air was extended to the marine environment, and used for a cost-benefit analysis of management options. Critical loads provide key information for the development and application of indicators for monitoring. The indicators and targets were used to derive critical concentrations and, allowing for material transformations and dispersion in the coastal environment, a critical load to the coastal zone was calculated. This critical load, the critical outflow of the catchment, combined the inputs from socio-economic activities and transformations within the catchment. Scenarios for cost-benefit analysis and trade-offs were developed based on knowledge of the process links and the transformations of the material loads. Scenario-building was an integral part of this analysis.

A full assessment of all global regions has yet to be achieved. To date successful workshops have been held in Europe, Latin America, East Asia, Africa and Russia; the outcomes are presented in Chap. 4. In February 2001, the more detailed EuroCat research project (*http://www.iia-cnr.unical.it/EUROCAT/project.htm*) began with support from the EU; the findings discussed in Chap. 4 provide a case example which can be applied to other regions during LOICZ II (2003–12). Regional "Cat" projects are now underway in Africa, Latin America and East Asia.

1.5.5 Key Thematic Issues

In assessing global changes to the coastal zone, LOICZ has taken steps to assess and synthesise information about key thematic issues that influence and contribute to material fluxes being examined by core projects of the LOICZ program of activities. Specific thematic issues were addressed by specialist workshops, establishing collaborative international working groups and enlisting contributing projects from national and regional governments and agencies. The Contintental Margins Task Team, a working group jointly sponsored by LOICZ and the IGBP oceans project (Joint Global Oceans Flux Studies, JGOFS), evaluated the status and changes in materials and fluxes in the continental shelf margins (Lui et al. in press).

Collaboration with other scientific organisations on issues of common interest led to the establishment of co-sponsored working groups with the Scientific Committee on Oceanic Research (SCOR; *http://www.jhu.edu/scor*) to address: Coral reef responses to climate change: the role of adaptation; Working Group 104 (Buddemeier and Lasker 1999); and submarine groundwater discharge, Working Group 112 (Burnett et al. 2003). A LOICZ-sponsored working group addressed global changes in river delta systems (*http://www.deltasnetwork.nl*). The evolution of scientific understanding about trace gas emissions in the coastal zone and the measurement of sea-level changes were subjects of specialist review papers (Pacyna and Hov 2002, Goodwin et al. 2000). Expert international workshops to address thematic topics underpinned a number of LOICZ assessments e.g., sediment fluxes in catchments.

Contributed projects initiated by LOICZ-associated scientists have formed the basis of discussions at global LOICZ scientific conferences. The UK-based SURVAS (Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies; *http://www.survas.mdx.ac.uk*) and its offspring project DINAS-COAST (Dynamic and Interactive Vulnerability Assessment; *http://www.dinas-coast.net*) have contributed greatly to the establishment of common measurements and methodologies for assessing the vulnerability of coastal areas to the consequences of sea-level rise.

Integrated national studies were initiated by a number of countries to contribute to the LOICZ goals e.g., China, Japan, Portugal, the Netherlands, Russia, have added to the depth of regional assessments of coastal change. These were co-ordinated by national IGBP or LOICZ committees supported by national funding. Regional programs (e.g., EU ELOISE) have provided a strong basis for thematic and regional evaluations. International collaboration in coastal zone science and capacity-building in integrated coastal zone management (e.g., UNESCO's Intergovernmental Oceanographic Commission) has led to synergies in assessments and training in targeted regions (e.g., Africa) and in addressing thematic interests (e.g., the coastal module of the Global Ocean Observing System – GOOS).

1.6 Responses to Change

There are many responses by environmental management and policy-makers to the changing pressures and status of the coastal zone, with varying levels of success (GESAMP 1996, Cicin-Sain and Knecht 1998, von Bodungen and Turner 2001, Olsen 2003). In some cases, initiatives were already developed or in place prior to the first Earth Summit (United Nations Conference on Environmental Development, UNCED) held in Rio de Janeiro in 1992; in others, efforts have been developed in response to the Rio Conference and the World Summit on Sustainable Development in Johannesburg, 2002. However, the wheels grind slowly in governments and in major international agencies, particularly to fit consultative and funding cycles, and thus the advent of a number of programs to address key issues is only now becoming apparent. The increase in local and sometimes wider participatory management approaches based on local communities is a noteworthy advance during the last decade, as environmental awareness and knowledge in many coastal communities and national populaces have improved.

There are major efforts in the global scientific assessment of the coastal zone to determine the pressures, state and impacts on the systems in order to provide a basis for building management approaches and policy actions. The IGBP program has completed its first 10-year assessment of global change (Steffen et al. 2002, 2004). The Intergovernmental Oceanographic Commission of UNESCO in 1995–6 moved to embrace the "brown waters" of the coastal seas and has initiated a number of actions including the Global Ocean Observing System (GOOS, *http://ioc.unesco.org/goos*). The Global Coral Reef Monitoring Network has been established (*http://www.gcrmn.org*). The UNEP Regional Seas program, FAO programmes and GESAMP continue with vital initiatives. Through the GEF (Global Environment Facility) and within the framework of UNEP (United Nation Environmental Programme), large-scale programmes have been launched to monitor Large Marine Ecosystems (LME) and to strengthen the development of governance in the management process in these LMEs (*http://www.edc.uri.edu/lme*). A global water programme, GIWA (Global International Waters Assessment; *http://www.giwa.org*), is being led by UNEP with financial participation of various international organisations to assess the environmental conditions and problems of water. The Millennium Ecosystem Assessment, begun in 2001, aims to provide a global environmental assessment to underpin various international Conventions (Biological Diversity, Combat of Desertification, Wetlands) and to provide information for policy and decision-making. Regional policy directives relate to and underpin coastal zone management and assessment. These include the European Union's Water Framework Directive announced by the European Union in November 2000, the European Commission's communication to the European Parliament on a proposal for a coherent strategy for coastal zone management, and HELCOM and OSPAR for the Baltic and North Atlantic Seas.

Global assessments in programmes run by intergovernmental organisations and non-governmental organisations (WRI 2000, Millennium Ecosystem Assessment, *http://www.millenniumassessment.org*) involving structured regional scientific networks are helping make inroads into the problems of mapping and determining the extent and status of key coastal habitats. For example, the UNEP-World Conservation Monitoring Centre (*http://www.unep-wcmc.org*) continues mapping assessments for coral reef, mangrove and seagrasses atlases; the Intergovernmental Oceanographic Commission of UNESCO (IOC) coordinates a global network actively monitoring coral reef changes (Wilkinson 2000).

Ecological considerations show that the coastal zone comprises evolving ecosystems and that the variability of natural conditions is due to factors ranging from the local to the global, including human and non-human effects. Current and developing research programmes, despite clear signs of being more focused on socio-economic issues, still remain remote from the wider public. Education is clearly the main instrument to promote dialogue and help bring research results into practical application. Such an approach should not be based on just an analysis of direct causes for concern but should result from the consideration of the convergence and interrelationships between science and a multifaceted society (Ducrotoy 2002). The global perspective offered in this book should help in linking elements that form the coastal system in a holistic context, providing a large-scale interpretation of biogeochemical processes that can contribute to management, policy and community education.

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