Global Change – The IGBP Series

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Coastal Fluxes in the Anthropocene

The Land-Ocean Interactions in the Coastal Zone Project of the International Geosphere-Biosphere Programme

With 121 Figures

Springer

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Library of Congress Control Number: 2005926496

ISSN 1619-2435
ISBN-10 3-540-25450-1 **Springer Berlin Heidelberg New York**
ISBN-13 978-3-540-25450-8 **Springer Berlin Heidelberg New York**

Springer is a part of Springer Science+Business Media
springeronline.com

Printed in Germany

Cover design: Erich Kirchner, Heidelberg
Typesetting: Klaus Häringer, Büro Stasch · Bayreuth (stasch@stasch.com)
Production: Luisa Tonarelli
Printing: Stürtz AG, Würzburg
Binding: Stürtz AG, Würzburg

Printed on acid-free paper 32/2132/LT – 5 4 3 2 1 0

Preface

In an ever-changing world, the global coastal zone stands out as an area of extraordinary changes. These changes are shaped by natural processes and phenomena that influence the Earth systems – on land, in the ocean, in the atmosphere, at their interfaces and at planetary scales – and ensure a dynamic coastal environment that has continued to respond and adapt biologically, physically and chemically in unique ways. Now there is a greater catalyst for change in the coastal zone – human society – impacting directly on coastal processes and systems and indirectly through modification of the natural processes and events.

The world's coastal zone is a long narrow feature of mainland, islands and adjacent seas denoting a zone of transition between land and ocean. Humans have lived in the coastal zone for millennia utilising its many and rich resources for their survival and socio-economic benefit. The coastal zone is the area where 25% of global primary productivity occurs, and it supplies about 70% of global fish catch. Some 50% of the people in the world live in this relatively small but highly productive, highly valued and highly dynamic domain which occupies 12% of the surface of the Earth. The density of coastal populations varies dramatically among different coastal regions, and there is a general trend of people moving from inland regions to the coast. The richness and diversity of resources found in coastal areas has long been recognised by humans, and there has been a corresponding concentration of human activities and settlements along shorelines and estuaries throughout the world. It is clear that the coast will continue to sustain the livelihoods of a very large proportion of the human population, both those living there and those living inland. The coastal zone is therefore an important asset to people worldwide.

At the same time, the coastal zone is a domain of constant change and one of the most threatened areas on Earth. Changing wave and current regimes, climate, morphological processes and fluxes of materials between land, atmosphere and oceans are causes of high natural variability which is still imperfectly understood. In the last several decades, with their increasing technological capabilities, humans have accelerated the rate of change and increased their influence on already highly variable ecosystems (Steffen et al. 2004). Pollution, eutrophication, changing sediment load, urbanisation, land reclamation, overfishing, mining and tourism continuously threaten the future of coastal ecosystems. Impacts on the coastal zone originate locally, regionally and globally, and an understanding of these impacts is now obligatory within the context of global change, including climate change. Although most impacts are addressed at local and regional levels, the scale of development and population growth along all coasts of the world is increasing such that it has become a truly global issue. Despite the rapidly increasing knowledge about coastal ecosystems, crucial questions on the causes of natural variability and the effects of human impacts are still unanswered. Although the perception of environmental managers of our coasts is shifting from one of mainly short-term economic approaches towards long-term economic, ecological and sustainable perspective, the need for this shift in management practice is often ignored or difficult to communicate to policy-makers. In particular there is a widespread ignorance among coastal stakeholders of the multiplicity of temporal and spatial scales across which coasts are affected including the continuum from river catchment to the coastal ocean (Meybeck and Vogler 2004). The major challenge that we face today is managing the human use of coastal habitats so that future generations can also enjoy the many visual, cultural, edible products and sustainable resources that they provide.

Sustainable use and protection of the Earth's coastal areas are now items high on international agendas. The increasing international instruments, such as the United Nations Convention on the Law of the Seas (UNCLOS), Rio Agenda 21, and the Conventions on Wetlands, Biodiversity and Desertification provide important mechanisms for coastal management.

The need for increased knowledge about global change and its ramifications for the functioning of Earth systems motivated the establishment by the International Council for Science (ICSU) in the late 1980s of the global research initiative – International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) which aims "*to describe and understand*

- *the interactive physical, chemical and biological processes that regulate the total Earth system,*
- *the unique environment that it provides for life,*
- *the changes that are occurring in the system, and*
- *the manner in which they are influenced by human actions.*" (*http://www.igbp.kva.se*)

The Land-Ocean Interactions in the Coastal Zone (LOICZ) project was established in 1993 as one of eight core projects of IGBP, and was directed to provide scientific information to answer the IGBP core question: "*How will changes in land use, sea level and climate alter coastal ecosystems, and what are the wider consequences?*"

Fundamental to answering this question is the need to recognise that the coastal zone is not a geographic boundary of interaction between the land and the sea but a global compartment of special significance, not only for biogeochemical cycling and processes but increasingly for human habitation and economies. Also, the spatial and temporal heterogeneity of the world's coastal zone is considerable. Consequently, challenging methodological problems are associated with developing global perspectives of the role of the coastal zone compartment in the functioning of the Earth system. Clearly, a useful and practical knowledge of the globally heterogeneous coastal zone depends on harnessing an array of research from natural and social sciences and integrating with those both anthropocentric and geocentric forces of change. The LOICZ project is designed to encompass these elements in providing science information to the global community, which should then be of use to decision-makers and coastal zone managers globally.

The LOICZ Science Plan (Holligan and de Boois 1993) developed four overarching objectives to address the IGBP question:

1. To determine at global and regional scales: the fluxes of materials between land, sea and atmosphere through the coastal zone, the capacity of coastal systems to transform and store particulate and dissolved matter, and the effect of changes in external forcing conditions on the structure and functioning of coastal ecosystems.
2. To determine how changes in land use, climate, sea level and human activities alter the fluxes and retention of particulate matter in the coastal zone, and affect coastal morphodynamics.
3. To determine how changes in coastal systems, including responses to varying terrestrial and oceanic inputs of organic matter and nutrients, will affect the global carbon cycle and the trace gas composition of the atmosphere.

4. To assess how responses of coastal systems to global change will affect the habitation and usage by humans of coastal environments, and to develop further the scientific and socio-economic bases for the integrated management of coastal environments.

These objectives, however, do not imply that LOICZ is actively undertaking coastal zone management, but rather it is providing knowledge and tools that underpin options for alternatives in development and decision-making. A clear goal is to provide a sound scientific basis for future sustainable use and integrated management of the components of coastal environments, under conditions of global change.

Following consultation with scientists globally, the LOICZ Implementation Plan (Pernetta and Milliman 1995) identified the array of issues and science that needed to be addressed, recognising the large (and somewhat prohibitive) funding requirements for a global coastal research programme. Operationally, LOICZ focussed on gaining an understanding at global scales of the following questions:

- Is the coastal zone a sink or source of CO_2?
- What are mass balances of carbon, nitrogen and phosphorus in the coastal zone?
- How are humans altering these mass balances, and what are the consequences?
- What is the role of the coastal zone in trace gas (e.g., DMS, NO_X) emissions?
- How do changes in land use, climate and sea level alter the fluxes and retention of water and particulate matter in the coastal zone and affect coastal morphodynamics?
- How can knowledge of the processes and impacts of biogeochemical and socio-economic changes be applied to improve integrated management of the coastal environment?

For the last decade, LOICZ has addressed these questions by focussing on horizontal material fluxes and scaling of processes through the application of environmental and socio-economic sciences. These activities have used results from research programs and contributions of individual scientists, and LOICZ has built a large network of researchers across more than 80 countries to develop collaborative and interdisciplinary projects to meet the goals outlined in the LOICZ science plan and implementation strategy.

This book provides a synthesis of the LOICZ work during its first decade ending 2002. It represents a milestone rather than a destination for the journey of collaborative inquiry into material fluxes and human interactions in the coastal zone. While compilation of the individual chapters have been the responsibility of the identified authors (see Authors and Contributors), the overall work represents an enormous amount of effort and research by many thousands of scientists who have contributed to the LOICZ enterprise. Some of these many contributions are found in LOICZ publications from workshops that have addressed regional and thematic coastal science (see Appendix A.1) as well as in the wider scientific literature.

This book addresses key elements of material flux in the coastal zone and indications of change, then draws together the biogeochemical information with an assessment of the influence of human society, before looking at future needs for targeted research and management actions in the coastal zone.

Chapter 1 provides a description and operational definition of the coastal zone. By discussing its spatial and temporal heterogeneity and natural variability, the authors differentiate between variability and change, and consider the dynamics of human population as a forcing factor for change. Changes in the intensity and extent of human drivers and pressures for change are outlined, along with a consideration of economic valuation of coastal resources and services. The challenges in assessing change at global scales and the approaches taken by LOICZ are presented, especially the new tool of typology.

Chapter 2 addresses the dynamics of a changing coastal boundary. Projections in sea level fluctuation are reviewed along with the implications for changed coastal and shoreline vulnerability. Changes in sediment and water fluxes to the coastal sea are undergoing major changes. The magnitude of the changes and their ramifications on coastal and estuarine morphologies are highlighted, noting especially the role of dams and reservoirs, other water impoundments and coastal water extraction. Submarine groundwater discharge is discussed, including new methods for assessment, the biogeochemical implications of these fluxes and the need for improved understanding and appropriate management of this regionally important freshwater resource.

Chapter 3 examines the biogeochemical fluxes of nutrients, especially carbon, nitrogen and phosphorus transport and transformations, within the coastal zone. The question of whether the coastal zone is a source or sink for carbon is examined. The role of estuaries and coastal seas as "incubators" of inorganic nutrients is assessed, including a system's capabilities as a region for net nitrogen gas release or retention. New estimates of inorganic nutrient discharge from river catchments are derived that show significant changes in loads to the coastal seas within the last 30 years. The typology approach developed by LOICZ is used to aggregate the many estimates of metabolic performance by relatively small-scale estuarine and coastal sea ecosystems to achieve global measures of nutrient and net metabolic changes, especially those related to nutrient discharges from the land.

Chapter 4 develops a broad picture of river catchment drivers and pressures and their impacts on coastal change. Where available, information on related governance response is provided. By looking at the river catchment-coastal sea continuum as a single system, the authors address individual catchment assessments and extrapolate information to regional or continental scales. Coastal change issues and related drivers are ranked, based on mostly qualitative information, including the identification of critical loads and thresholds for system functioning or geomorphologic stability. The regional difference in the relative role played by specific drivers in imposing coastal change, such as damming, intense agricultural, land use and urbanisation, are highlighted and expected trends are identified.

Chapter 5 provides a synthesis of major scientific findings determined in the first four chapters. It addresses the "So What?" relevance question by considering the ramifications of the findings for policy- and decision-makers involved in governance and management of the coastal zone. In so doing, the authors provide a glimpse of the remaining challenges and future directions for the next decade of LOICZ activities and the wider coastal community.

Text boxes have been used throughout the book to give both details on methodologies and examples of case studies which are referred to in the text. The Appendix includes a list of key LOICZ publications and abbreviations to assist the reader.

The LOICZ project is continuing into a second phase within IGBP, building on the findings and gaps identified here and responding to a new priority of issues that have emerged from discussions engaging the global scientific community and institutions. The new project has shifted in focus towards highlighting the societal and environmental management dimensions of coastal material fluxes (LOICZ II Science Plan and Implementation Strategy; *http://www.loicz.org*). LOICZ is expected to become the major contributor of interdisciplinary coastal science to the second stage of the IGBP and the International Human Dimensions Programme (IHDP), and to the Earth System Science Partnership of IGBP, IHDP, WCRP and DIVERSITAS.

Han Lindeboom

Chair, LOICZ Scientific Steering Committee 1997–2003

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Acknowledgements

The government of the Netherlands (Ministry of Education, Culture and Science, OcW NWO; Ministry for Transport and Public Works, RIKZ) has generously provided funding support for the LOICZ International Project Office over the last 10 years; the Royal Netherlands Institute for Sea Research (KNIOZ) has provided offices, scientific and administrative support for the IPO. Without this funding the international Scientific Steering Committee and the vital network of collaborating scientists could not have functioned. Acknowledgment is made to the many international and national organisations and agencies that have funded and supported the LOICZ enterprise described in this book, in particular: UNESCO's Intergovernmental Oceanographic Commission (IOC), United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF), the European Union (EU), Netherlands Foundation for the Advancement of Tropical Research (WOTRO), Royal Dutch Academy of Science (KNAW), Scientific Committee for Oceanic Research (SCOR), United States National Science Foundation (NSF), Asia-Pacific Network for Global Change (APN), Global Change System for Analysis Research and Training (START), Inter-America Institute for Global Change (IAI), and International Ocean Institute (IOI).

The preparation of this book has involved many people beyond the authors and editors in keeping with the networked and collaborative approach engendered within the LOICZ project. In particular, the work has benefited from the skilled services of Hester Whyte (LOICZ IPO) and Nelleke Krijgsman (KNIOZ) in the management and completion of the manuscript and associated graphics.

Valuable suggestions were contributed to drafts of the chapters by a panel of reviewers, including: Elena Andreeva, Franciscus Colijn, William Dennison, Goetz Floeser, Anthony T. Forbes, Alison Gilbert, Isao Koike, Felino Lansigan, Michel Meybeck, Alice Newton, Jozef Pacyna, John Parslow, Nancy N. Rabelais, Juan D. Restrepo, Eva Roth.

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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.

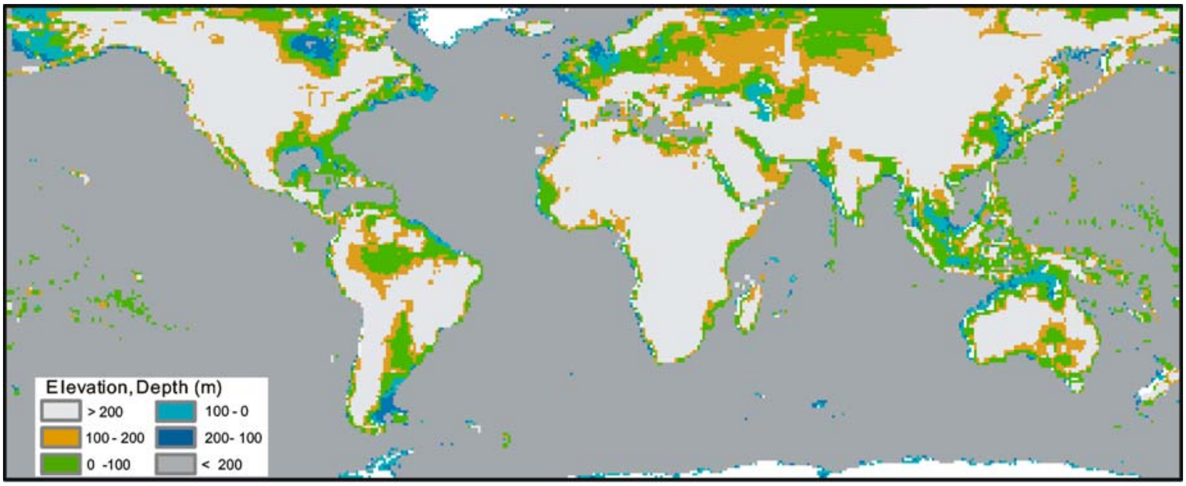

Fig. 1.1. The coastal zone. The LOICZ domain (terrestrial areas: *yellow* 100–200 m elevation, *green* < 100 m elevation; marine areas: *light blue* 100 m depth, *blue* 100–200 m depth)

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 km^2 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 km^2. 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

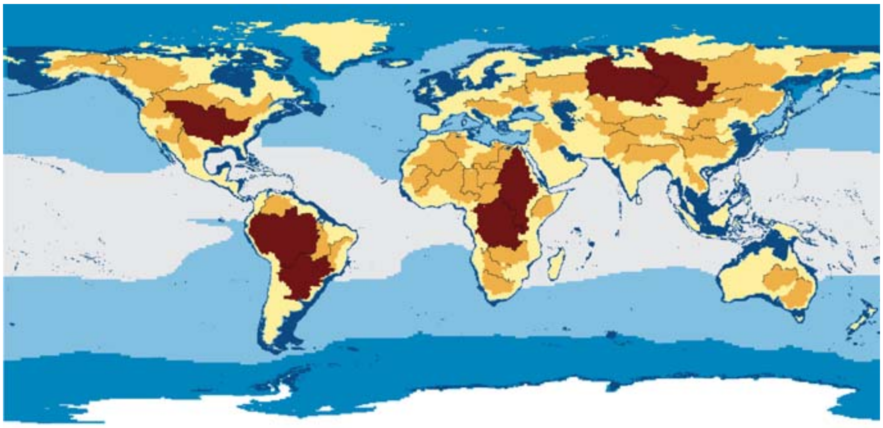

Fig. 1.2.
The coastal zone. Latitudinal relationships between the broad coastal domain (landward from the 200 m isobath, *dark blue*) and polar (< 4 °C, *light blue*), temperate (4–24 °C, *pale blue*) and tropical (> 24 °C, *grey*) regions defined by sea surface temperature. The *brown and orange areas*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

10^5

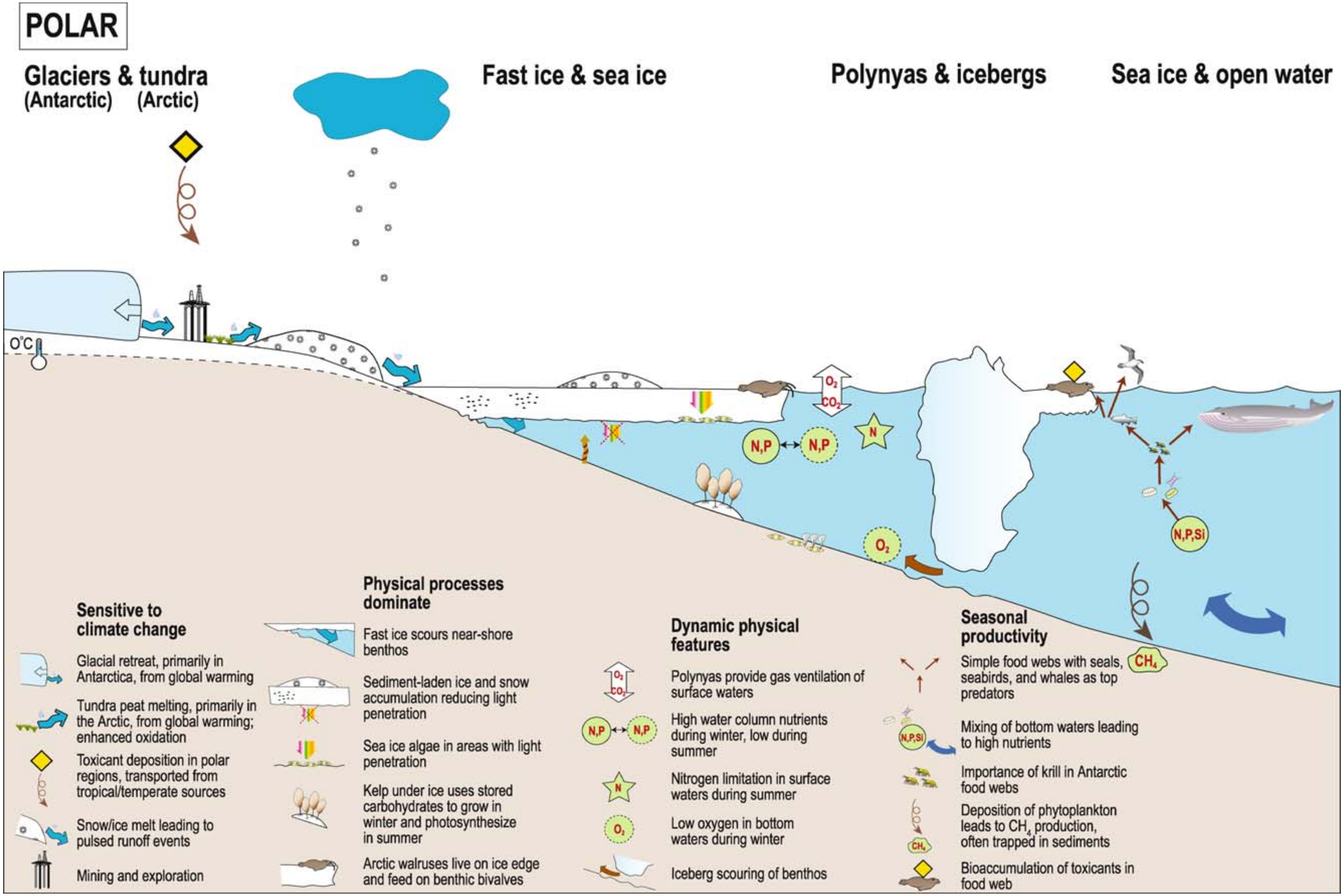

Fig. 1.3a. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in polar coastal zones

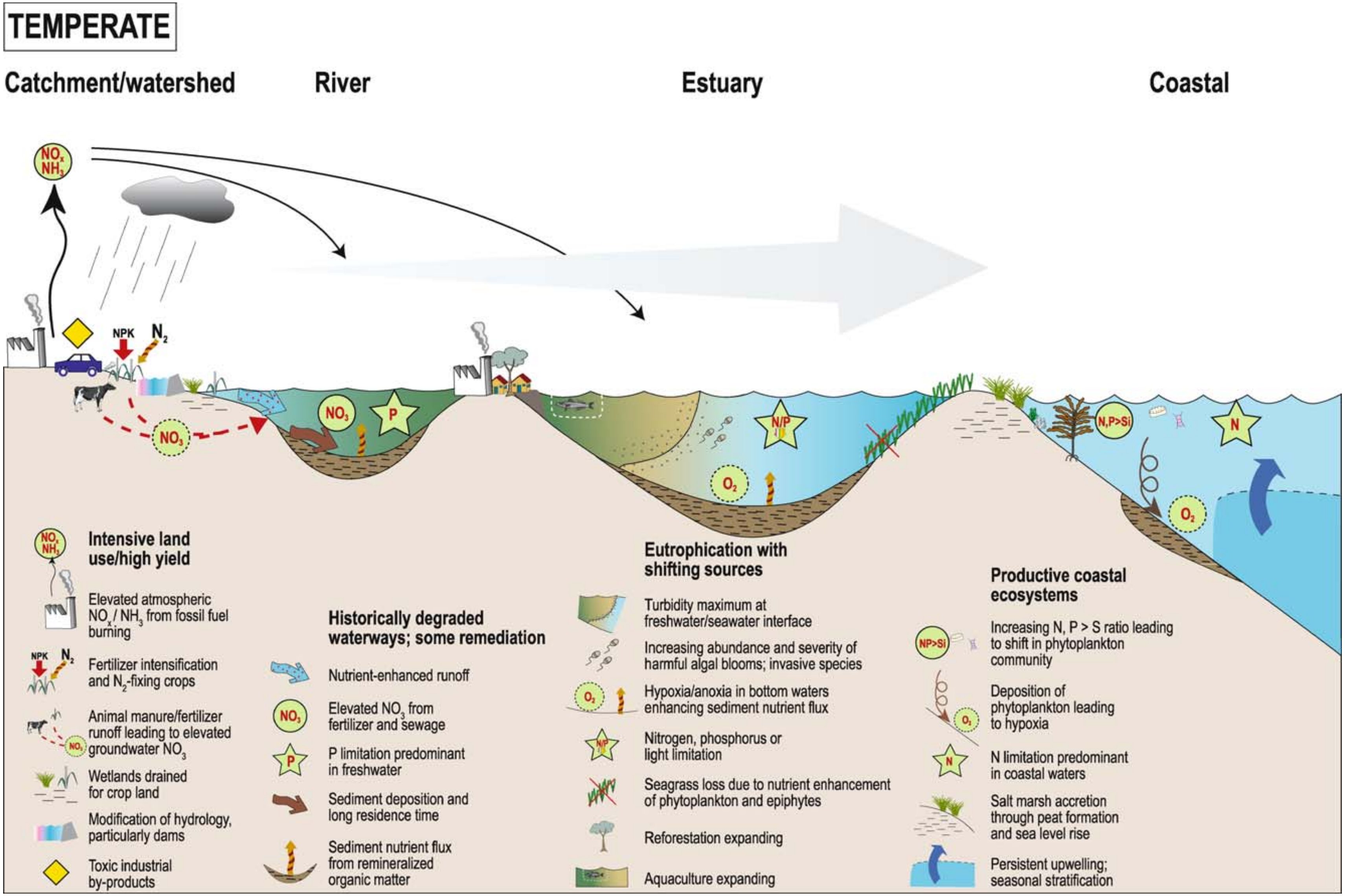

Fig. 1.3b. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in temperate coastal zones

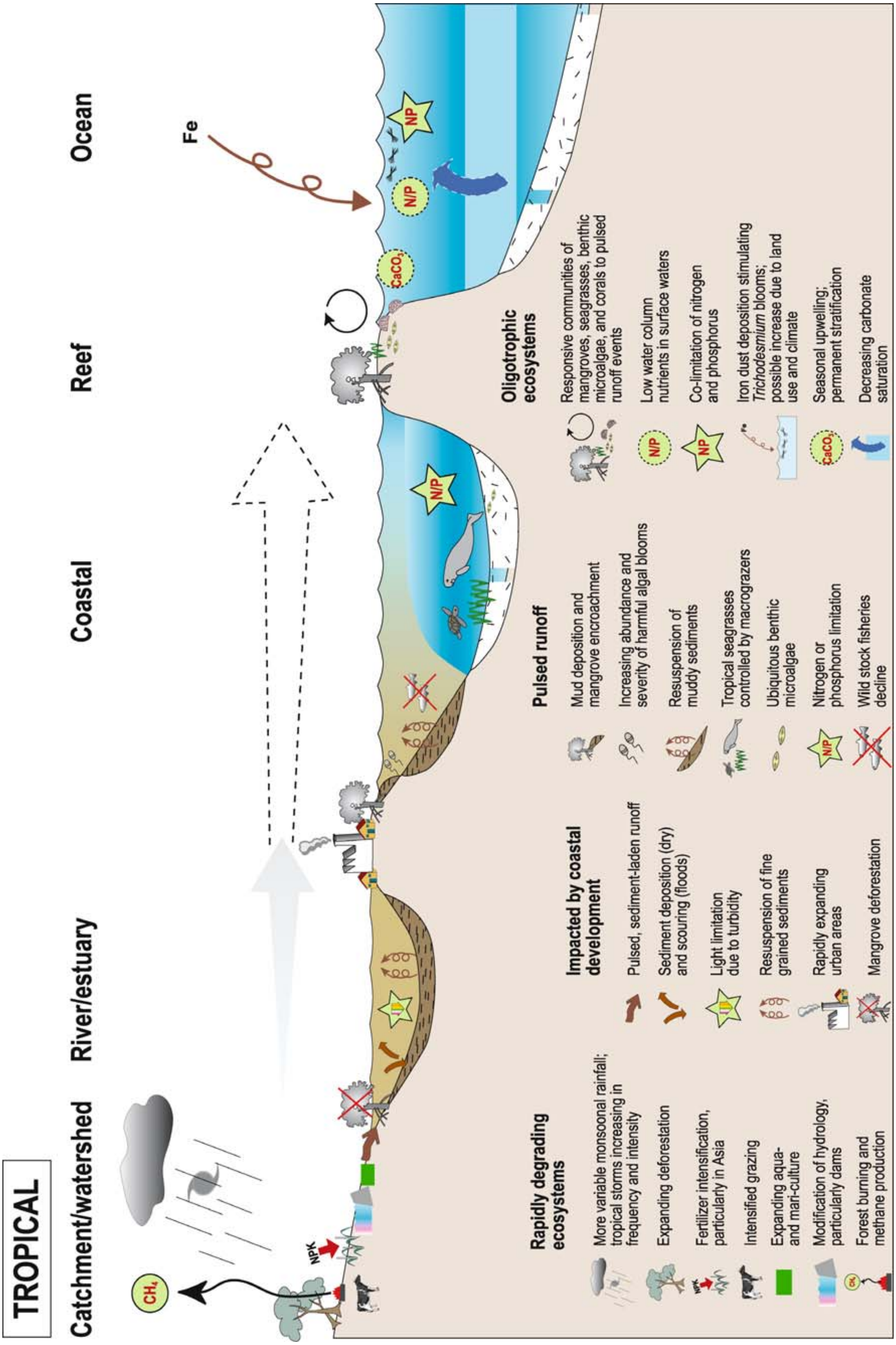

Fig. 1.3c. The coastal zone. Conceptual diagrams of processes and conditions affecting ecosystems and material fluxes in tropical coastal zones

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-