1 Shipping and the Environment

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Abstract

Humans have always had a close relationship with the aquatic environment, including the early use of the sea for food harvesting and communication. Today, the sea is an important component of the transportation system, with large amounts of cargo and passengers. This chapter provides a short introduction to ships and shipping, focussing primarily on commercial ships; nonetheless, many of the emissions, impacts and measures discussed throughout this book are common to other sectors, such as leisure, research and fishing. This chapter also introduces the environmental impacts related to ship operations. Ship transportation has increased tremendously since the industrial revolution, which has resulted in increased emissions due to shipping and increased stresses on the environment. However, this trend is not only related to shipping. Currently, there are several

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warning signs that we are not taking care of the Earth and its ecosystem in a sustainable manner, that the Earth's ecosystems are degrading and that natural capital is being exploited, e.g., by the burning of fossil fuels. The marine industry is a component of our society; similar to all industry sectors, it contributes to unsustainable patterns in our society. Although the marine industry is a contributor to these problems, it can also be part of the solution, yet several challenges must be addressed. Sustainability and related concepts, such as ecosystem services, planetary boundaries and resilience thinking, could be used as guidance in addressing these challenges.

Humans have always had a close relationship with the aquatic environment. Indeed, a scientific discussion debates whether the first humans evolved in a dry land environment, on the savannah, or in shallow water environments (as the "water man" or "aquatic ape") [1]. With respect to environmental awareness, the sea has come into focus relatively late compared with other natural areas. Independent of this observation, the sea has served as an important transportation route and a source of food and recreation throughout history. In a world where more than 70 % of the surface is covered by oceans, our interaction with and dependence on the sea in numerous aspects is obvious.

1.1 Man and the Sea

Early use of the sea consisted of food harvesting and communication. Increased trade and the population growth in Europe launched global explorations and led to "discovery" of the New World and new communication routes to Asia. A romantic view of nature in the 19th century evoked a new interest in the sea in art and in recreation. Much of this interest was related to the sea in terms of something to look at and enjoy. In the mid-20th century, science made discoveries below the surface of the sea possible, and public interest in diving and learning about the sea's ecosystem developed. These developments also led to additional observations of adverse effects on the environment and an increased awareness of the marine environment [2]. The increased use of oil for propulsion and increased global transportation of oil during the 20th century led to discharges of oil that were highly visible and produced demands for safer and less damaging shipping. The formation of what later became the International Maritime Organization (IMO) was a result of the need to enact international regulations for safety at sea and to prevent accidental oil discharges.

The fact that most of the water volume around us is not visible has rendered the events occurring below the sea's surface both frightening and unknown. There are many myths about strange beings, large sea monsters, mermaids, and "bottomless" lakes. An illustration from 1572 in the maritime atlas "Carta Marina" [3] by the Swedish cartographer Olaus Magnus that portrays creatures believed to be living in the sea gives an impression of the myths of the time (Fig. 1.1). In addition, the

Fig. 1.1 Map of the North Sea and the Baltic sea 1572. From: "Carta marina, opus Olai Magni Gotti Lincoensis, ex typis Antonii Lafreri Sequani", Rome 1572, National Library of Sweden, KoB, Kartor, 1ab

belief that the sea is greatly resilient and is a suitable place for discharging waste has survived for a long time. Organised dumping of waste at sea was a common practice around the world, including Europe, until the 1970s. An instructional clip from Swedish Television produced in the early 1960s and aimed at leisure boat owners provides the advice to attach a stone to on-board waste parcels before sinking them into the sea. The amount of waste ammunition and chemicals dumped into the sea after World War II is still a potential problem for fishing and installations at sea. Even today, large amounts of waste end up in the oceans on purpose or from uncontrolled sources. Recently, problems related to "micro-plastics" and "ghost fishing nets" have garnered more attention (see also Sect. 4.5).

In shipping and in other maritime activities, the sea remains close to working people, and the relationship between activities and environmental impacts is sometimes highly visible, see Fig. 1.2, although some shipping impacts occur far from the source of emissions or activity.

This book focuses on the interaction between shipping and the natural environment and discusses how the use of the oceans by humans is affecting the environment as well as and how these activities can be made more sustainable.

Fig. 1.2 Examples of observations of impacts on and emissions into the sea. *On the left*, algae belts have formed due to excess nutrients in the Baltic Sea; *on the right* an exhaust plume from a ship on the horizon. *Photo* Karin Andersson

1.2 Ships and Shipping

To discuss the relation among shipping, the environment, and sustainable development, it is useful to define certain terminology. The main focus of shipping is on commercial ships, although many of the emissions, impacts and measures are common to other sectors, such as leisure, research, and fishing. The different regulations also require definitions of a ship. Different definitions exist, although according to the glossary of the US Navy, a "boat" usually refers to small vessels that are often open, whereas "ships" are vessels of considerable size that are intended for deep-water navigation [4]. A ship can also be defined by its size: vessels longer than 12 m and wider than 4 m are referred to as ships, and smaller vessels are known as boats [5].

Common ship types can be identified according to their type of use:

- *Container ships*: These vessels carry most of the world's manufactured goods and products in standardised containers that also can be transported by rail and truck. These ships are usually scheduled liner services.
- *Bulk carriers*: These vessels transport unpacked cargo in large volumes. The cargo might be grain (e.g., wheat, oats, and maize), products such as concrete, or raw materials (e.g., iron ore, limestone and coal).
- *Tankers*: The vessels transport liquids, such as crude oil, chemicals and petroleum products.
- *Ferries*: Ferries usually perform short journeys that carry mixtures of passengers, cars and commercial vehicles. Most of these ships are RoRo (roll on–roll off) ferries, in which vehicles can drive straight on and off. Ferries that combine passengers and RoRo transport are often referred to as RoPax.
- *Cruise ships*: Cruise ships have different sizes, and several thousand passengers and crew are common on these vessels. These ships combine transport with the role of 'floating hotels'.

Many other types of ships operate regionally or locally. One size limit is up to 500 passenger vessels, which includes road ferries and public transport/shuttle ferries. Vessels might be intended for special purposes, such as pilot boats, fishing vessels, icebreakers and military vessels. Different ships are also adapted for transport on inland waterways in areas with rivers and canals. No universally applicable definitions of ship types exist, although IMO provides a list of ship types mentioned in various IMO instruments (see Chap. 3) [6].

1.2.1 The Infrastructure: Fairways, Canals and Ports

The infrastructure for ships covers a rather large proportion of the open sea, where there is no need for the specific construction of infrastructure and it is available for free. However, the need exists for connections to land. Close to land, fairways occur, which are commonly marked, as do ports for ships to enter. Inland infrastructure also exists in the form of canals and sluices.

In terms of environmental impacts, the fraction of shipping that occurs close to land accounts for an important contribution. Ports are often located in or close to large cites, and the sea traffic in and out of ports can affect the population in the area due to emissions to the air and water and from noise and waves.

In contrast to other shipping activities, the location and construction of ports and fairways are often regulated and assessed from an environmental perspective as a component of land-based activities in environmental impact assessments (EIAs, see Chap. 9) or in planning processes. The activities at sea are regulated in international, regional and national frameworks (see Chap. 3).

1.2.2 Marine Spatial Planning

Spatial planning is an essential process for managing land in several areas of the world. The use of spatial planning was triggered by the industrial revolution, when coal became an important raw material. People began to aggregate in areas close to a site of excavation, and villages soon became overcrowded with a subsequent lack of water or contaminated water supplies because no infrastructure was available to accommodate the rapidly increasing population. The need for and advantages of proper spatial planning soon became obvious. Today, terrestrial land-use planning and management is standard. This process of future spatial development and planning has not been implemented in marine areas (with a few exceptions). This lack of implementation does not mean that the ocean is fully unregulated or unmanaged; for example, shipping lanes, military zones, and marine protected sites exist, although only within individual economic zones. However, few frameworks have integrated the regulation and management of all activities occurring within an area. Marine spatial planning (MSP) is a tool that can be applied to avoid the problems that can arise when multiple activities occur simultaneously within a marine area [7]. The large development of wind power and fish, shellfish or biomaterial production at sea in coastal areas creates a challenge in terms of competition for space with shipping; a MSP document that covers these regions is important to avoid future conflicts. MSP is further discussed in Chap. 7. Within the European Union, legislation on a common framework for maritime spatial planning was adopted in 2014 [8].

1.2.3 What Types of Cargo Are Transported by Ships, and Where Is the Cargo Transported?

Shipping is a means of transport by different types of vessels, as mentioned previously, and the variety of cargo types and passengers is quite large. There are nearly 50,000 registered ships with over 1000 gross tons dead weight (GT DW), including offshore drilling and offshore production units [9] (military vessels and fishing vessels are not included in the statistics). If also smaller ships are included, over 70,000 ships with more than 400 GT DW are registered [10]. The majority of large ships transport goods of different types that are either packed in containers and tanks or handled as bulk goods in cargo holds. Common tank cargo includes petroleum products and chemicals. Bulk transport is used for various solids, such as grain, minerals or ores.

The use of container transport for various goods is a growing sector; more than 6000 large ships are used in international trade [11]. By value of transported goods, this segment is the largest, with over 50 % of the value of goods transported by sea [12]. In terms of fuel consumption, container and oil/gas transport are the largest categories, which indicates that oil and gas transport is a large sector in terms of volume, although it constitutes only approximately 20 % of the economic value.

The large cargo trade routes are located between continents, primarily North America to Europe and to South East Asia.

Possible future routes that could reduce transport distances while increasing environmental impacts are located in the Arctic region. Arctic shipping raises specific environmental issues, as discussed in Box 1.1.

In the passenger sector, the cruise ship industry is a growing sector, accounting for nearly 300 cruise ships and a total annual passenger capacity of 21 million in 2014 [13]. Together with RoPax ships (passenger/car ferries), this sector constitutes the largest sector involved in passenger transport in terms of fuel consumption.

However, sea transport includes local transport and a wide range of other applications; those mentioned above are important examples.

Box 1.1 The Arctic

The Arctic region has in recent years gained much attention due to its warmer climate and decreasing ice cover. The conditions for shipping routes in the Arctic area are changing, and as global energy reserves are declining, natural resources such as oil and gas in the Arctic are being explored.

There are today several definitions of the Arctic area: the area north of the Arctic Circle; the area north of the isotherm, with a mean temperature of 10 °C in July; or the area north of the tree-line. The Arctic coastal states with maritime jurisdictional claims are Canada, Denmark (Greenland), Iceland, Norway (Jan Mayen, Svalbard) the Russian Federation and the United States (Table 1.1, [14]) (see Chap. 3 for definitions). Together with Sweden and Finland, the Arctic coastal states and six representatives from the Arctic indigenous communities comprise the Arctic Council, a forum formed in 1996 that works towards the responsible development of the region.

The ice cover in the Arctic, which reaches its each year maximum in March and minimum in September, has in recent years decreased (recorded since 1970, [15]). There are different modes of transport in the Arctic. In the trans-Arctic transport, ships use either the Northern Sea Route/North East Passage or in some cases, the Northwest Passage for routes across the Arctic. In destinational transport, a ship goes to one Arctic destination; in intra-Arctic transport, ships are in route between destinations within the Arctic. One of the major driving forces for increased trans-Arctic transport is the shorter routes for shipping. As opposed to going through the Suez Canal, the distance can be shortened by 40 % by taking the Northern Sea route from Rotterdam in Holland to Yokohama in Japan, leading to savings in both time and fuel consumption.

Table 1.1 Arctic coastal state maritime jurisdictional zone claims. Data from the Arctic Council [14]

Arctic states	Territorial sea		200 NM zones		
	3 NM	12 NM	EEZ	Extended fisheries protection	Fisheries protection
Canada		x	x		
Denmark (Greenland)	x		x		
Iceland		x	x		
Norway		x	x		
-Jan Mayen		x		x	
-Svalbard		x			x
Russian Federation		x	x		
United States		x	x		

1.3 Sustainability and Shipping

The human population has increased by more than a factor of 10 since the industrial revolution, and it is expected to continue to increase to approximately 9 billion people by 2050. The standard of living for most people on Earth has improved during this period due to technical and social innovations, economic growth and international collaboration and trade. However, approximately one billion people still live in poverty. Several signs have also emerged that humans are not taking care of the Earth and its ecosystem in a sustainable manner. For example, we are consuming and producing an increasing number of products, leading to large energy and material requirements. We are degrading the Earth's ecosystems and exploiting the Earth's natural capital, e.g., by burning fossil fuel, which emits carbon dioxide to the atmosphere. Additional information on human impacts and environmental issues can be found in Sect. 2.7. The gaps between the richest and the poorest people on Earth are increasing. The marine industry is a component of our society. Similar to all industry sectors, it contributes to unsustainable patterns in our society. Although this industry is a contributor, it can also act as a component of the solution.

The following question is important: "What is sustainability?" Sustainability is a mainstream concept that is often used as an equivalent of all that is good and desirable in society. Concepts such as sustainable development, resilience thinking, socio-ecological principles and planetary boundaries can be helpful to place the Earth on a sustainable track. These concepts are introduced in the following sections and summarised in Box 1.2.

1.3.1 Sustainability and Sustainable Development

Sustainable development is a global goal that gained international attention due to the Report of the World Commission on Environment and Development in 1987, which is also known as the Brundtland Report [16]. This concept is related to a series of normative ideas that include protecting the environment, promoting human welfare (especially the urgent development needs of the poor), concern for the well-being of future generations, and public participation in environment and development decision-making [17]. However, sustainable development and sustainability are terms that lack consensus and suffer from a variety of different and vague definitions [18, 19]. Key questions for a relevant definition are provided below [19]:

- What is intended for sustainability?
  - Nature (earth, biodiversity and ecosystems)
  - Life support (ecosystem services, resources and environment)
  - Community (cultures, groups and places)
- What is intended for development?
  - People (child survival, life expectancy, education, equity, and equal opportunity)
  - Economy (wealth, productive sectors and consumption)

  - Society (institutions, social capital, states, and regions)
- For how long?
  - For example, 25 years or forever

The most common international definition of sustainable development is "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*", which was presented in the 1987 Brundtland Report [16]. Four primary characteristics of sustainable development also have been derived from the Brundtland Report: (1) safeguarding long-term ecological sustainability, (2) satisfying basic human needs, (3) promoting intra-generational equity, and (4) promoting inter-generational equity [20]. Several secondary characteristics are also important for sustainable development, e.g., preserving nature's intrinsic value, endorsing long-term effects, promoting public participation, and satisfying aspirations for an improved quality of life [21].

The importance of *safeguarding long-term ecological sustainability* is expressed in the Brundtland report, e.g., through such statements as, "At a minimum, sustainable development must not endanger the natural systems that support life on Earth: the atmosphere, the waters, the soils, and the living beings" [16] and "There is still time to save species and their ecosystems. It is an indispensable prerequisite for sustainable development" [16]. This characteristic has its origin in ecology and represents the conditions that must be present for the world's ecosystems to sustain themselves over long periods of time.

Satisfying basic human needs is at the core of the Brundtland definition of sustainable development. What are the basic human needs? The Brundtland Report mentions food, water, sanitation, clothing, shelter, energy and jobs as essential needs [16]. Other than these basic needs, aspirations for an improved quality of life can also be met as long as they do not endanger long-term ecological sustainability.

Promoting intra-generational equity and inter-generational equity is also at the core of the Brundtland definition, which emphasises the needs of the current and future generations. All previous and future generations share the Earth; therefore, each generation must pass on the Earth and its natural resources to the next generation in at least as good of a condition as they received them (inter-generational equity). It is argued in the Brundtland Report that social equity between generations "must logically be extended to equity within each generation" [16]. The allocation of resources among all members of a single generation should also be guided by fairness. The Brundtland Report also notes that "a world in which poverty and inequity are endemic will always be prone to ecological and other crises" [16].

Sustainable development is commonly represented as three pillars: *economic*, *social* and *environmental*. Another method used to visualise sustainable development uses the concept of carrying capacity, which represents how both economy and society are constrained by environmental limits (Fig. 1.3).

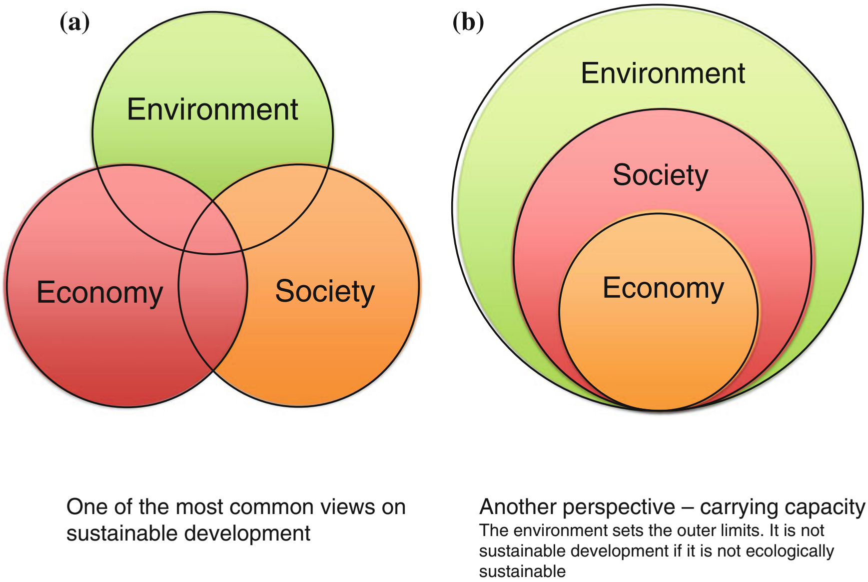

Fig. 1.3 Visualisations of sustainable development showing the three pillars of sustainable development as overlapping circles (**a**) and the environment, as the outer limit for society and the economy, representing the carrying capacity (**b**) of the Earth's systems

1.3.2 What Is an Environmental Concern?

The extent of human activities is increasing with the population, and changes in the natural environment and in the use of resources are also increasing. Humans are a natural component of the environment; thus, human activities should be a natural component of the environment. However, there is an increased concern over the negative effects of human activities in public debate and legislation.

In contrast to other species, humans have developed aspects that differ in nature, such as the large-scale use of tools, the creation of products ("artefacts"), and the development of a culture with an exchange of information and thoughts, including ethical and religious aspects. These developments have not only made the potential impact on the natural environment from human activities large but have also enabled the emergence of views on acceptability in terms of environmental impacts and resource use. The discussion of negative impacts on the environment is not new, although it has been increasing since World War II, with large public debates and legislations appearing in many places around the world. The early discussions on environmental issues were primarily related to the land environment, freshwater systems, such as lakes and rivers, and threats to human health. For a long time, the ocean was viewed as a place for dumping waste and an environment that was resilient to human impact. The only concern was over oil spills, which could impact sea birds and contaminate beaches. The potential impact “under the surface” was less known or observed.

Before discussing environmental impacts, it is necessary to define what is meant by environmental concerns and priorities. When the global population was lower, nature could easily recover from the effects of human activities, and the visible effects from use of non-renewable resources were small. An increased population means that the use of natural and renewable resources has become increasingly intense, and nature might face difficulties in recovering. Additionally, non-renewable resources have become depleted. Even in a situation with few inhabitants, the effects of the use of nature can be observed. What we consider as “nature” today is to a small extent untouched by humans, although it is in fact a product of culture. We typically do not regard farmed land or planted forests as environmental problems; instead, these regions are viewed as natural components of our environment. This viewpoint means that traces of human activities in nature are not viewed as an environmental problem. When will they become a problem?

Changes in the environment from the state untouched by humans are not sufficient to constitute a concern or problem; thus, concerns must stem from another source. That source is a general agreement in society that an effect or change is unwanted. At that point, it becomes an environmental problem. A sociologist would say that environmental problems are a “social construction”, meaning that nature does not have an opinion on this topic and that the values come from society. This

Fig. 1.4 Different views on nature may cause conflicts. *Photo* Karin Andersson

philosophy implies that the process for agreement on what constitutes an environmental concern is long and involves stakeholders with different perspectives and priorities. Certain priorities stem from necessities, such as prioritising the growth of food and preventing disease before protecting nature, whereas others might originate from the prioritisation of either economic or natural preservation interests. These differences can cause conflicts, as illustrated in Fig. 1.4.

Additionally, the process of observing a change in nature, identifying the change as a problem that should be handled, and enacting different measures (such as regulations) can be extensive and involve many areas of society, including international bodies. One common observation is that the public debate and opinion process might be much faster than the reaction from society in the form of regulations. This aspect can force changes in technology or behavioural changes before they are requested via regulations.

1.3.3 Ecosystem Services

Human society depends on the Earth and its ecosystems. In many ways, the services obtained directly or indirectly by humans from ecosystems are known as ecosystem services. Examples of ecosystem services include the maintenance of hydrological cycles, cleaning of air and water, biological diversity, seafood, and recreational services [22]. A diverse and healthy environment is important to human well-being, and protecting the ecosystems and the services they provide is necessary for life. Three different types of ecosystem services are generally acknowledged: (1) provisioning (which includes food and bio-energy), (2) regulating (which includes the regulation of waste and pollution or of the physical environment), and (3) cultural services (which can be symbolic or intellectual/experience-based) [23].

In addition to providing waterways for the shipping industry, the ocean provides other functions or ecosystem services. The ocean serves as a source of food and natural resources, participates in the ecological and geochemical cycling of elements, and also provides a place for recreation. It is estimated that approximately 10 % of human protein intake comes from the sea. Minerals, such as salt (NaCl), are harvested from the sea, and life in the oceans also provides a source of oxygen to the atmosphere. The surface layer of the oceans absorbs approximately half of the heat radiating from the Sun to the Earth and distributes it around the world, thus playing a major role in determining the climate on our continents. Recreation and tourism have developed into a multibillion Euro and fast-growing industry [24].

The concept of ecosystem services can be used as a tool to solve environmental issues because these services demonstrate the importance of the ocean to the general public and provide arguments in policymaking debates [25]. Comparing the values of coastal and open ocean areas is difficult due to the large range of various ecosystems in the two areas. However, the most biologically productive zones and most of the world's fisheries are located in coastal areas, where human impacts are greatest in general [26, 27]. In addition, many important shipping routes pass through coastal areas.

1.3.4 Planetary Boundaries

The Earth's environment has been relatively stable for the last 10,000 years, making it possible for humans to develop, thrive, settle, and invent agriculture and industrialisation. This stable state, which is known as the Holocene, might be threatened due to impacts from human actions. The Earth is severely affected by the activities of humans; some scientists have claimed that we have entered the Anthropocene, a human-dominated geological epoch [28]. To avoid a shift from this environmentally stable period in Earth's history, a research group has developed the concept of *planetary boundaries* [29, 30]. Planetary boundaries are boundaries that we cannot cross if we want to sustain the Earth in its current stable state. The boundaries are human-determined values of the control variables set at a "safe" distance from a dangerous level or threshold [29]. A threshold or a tipping point is a point in a system that will cause the system to react in an abrupt and non-linear manner if crossed and will most likely result in irreversible changes. The planetary boundaries and selected other environmental issues of special importance for ship operations are described in Sect. 2.7.

1.3.5 Resilience Thinking

Resilience thinking addresses the dynamics and development of complex systems, such as ecosystems and societies. Resilience can be simply described as the long-term capacity of a system, e.g., an ocean, port or economy, to address change and continue to develop [31]. A resilient system will maintain the same "identity" or essentially the same functions, structure and feedback during periods of change. The term resilience was originally used to understand the ability of ecosystems to persist during perturbation, although it is now used as a wider concept for all types of complex systems [32]. Ensuring resilient systems can contribute to a more sustainable Earth.

Box 1.2 Some concepts related to sustainability

Biosphere: The biosphere contains all of Earth's living things, including all microorganisms, plants, and animals, together with the dead organic matter produced by them (see also Chap. 2).

Carrying capacity: The number of people that can be supported by the earth; describes that economy and society are constrained by environmental limits (see Sect. 1.3.1).

Circular economy: An economy built on the concept of reuse, recycling and refurbishment of materials and products.

Decoupling: In environmental context, the ability of an economy to grow without corresponding increases in environmental pressure.

Ecosystem: A community of organisms interacting with each other and with their physical environment.

Ecosystem services: The benefits that people obtain from ecosystems, e.g., provisioning of clean water, decomposition of wastes and fisheries (see Sect. 1.3.3).

Planetary boundaries: Planetary boundaries are boundaries that we cannot cross if we want to sustain the Earth in its current stable state. The concept as developed by a group of researchers in 2009 (see Sect. 1.3.4 and Sect. 2.7).

Rebound effect: The effect of increased consumption when prices are decreasing due to energy efficiency measures. For example, a more energy-efficient car might be used more frequently because the cost of fuel per kilometre driven is lower. Therefore, the increased consumption might offset the energy savings that could otherwise be achieved. This concept is important to consider if using energy efficiency as a strategy to reduce environmental impact.

Resilience: Resilience can be simply described as the long-term capacity of a system, e.g., an ocean, port or economy, to address change and continue to develop (see Sect. 1.3.5).

Sustainable development: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" Defined in the "Brundtland report" [16] (see Sect. 1.3.1).

1.4 Ships and Their Environmental Impacts

Before discussing the various impacts that ships have on the environment, it is important to provide a short background on ships and how they interact with the maritime environment. The main environmental impacts associated with shipping are shown in Fig. 1.5.

The following chapters describe the different types of environmental impacts from ships. Chap. 4 focuses on *discharges to the sea* and their impacts on the marine environment, and Chap. 5 addresses *emissions to the air* and their impacts on the atmosphere. However, for a correct understanding, it is important to discuss introductory information on how ships are built and the reasons for the presence of components that generate pollution.

A ship is a vessel for use at sea that has a hull and can be steered, e.g., by a rudder. A ship's mission can vary substantially depending on the ship, such as the transportation of passengers or goods through international waters, servicing of other vessels, exploiting the sea in the form of fishing, or building underwater pipelines. The different systems on a ship must be able to perform the functions that are necessary to fulfil its mission.

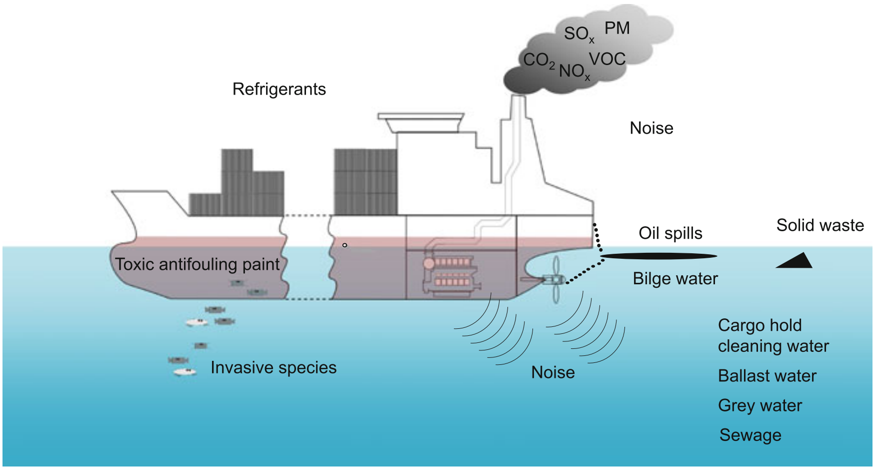

Fig. 1.5 Environmental impacts of marine transportation during the use of a vessel

Even if absolute generality can rarely be obtained, it is reasonable to state that every ship must be able to *provide mobility*. This basic function is provided by the propulsion system and by several additional systems related to the functions of steering, navigation, and anchoring. The propulsion system and its main components are described in Sect. 1.4.3.

Because a ship is assumed to perform a specific mission, this capacity will often require specific *operational functions* related to the specific mission. This functionality involves the need for given systems that are largely dependent on the mission, i.e., container cranes for small container ships, cargo pumps for tankers, equipment for handling fishing gear for trawlers, and kitchens and sanitary systems for cruise ships. Even if the large variety of possible operational functions does not allow us to specifically address each and every of them, these functions are often associated with a large consumption of heat or electric power and, sometimes, with the handling of hazardous material.

Every ship has several on-board operations that must be directly performed by humans. Therefore, the crew must be provided with *hotel facilities* that fulfil the basic needs of accommodation, food, and services. Additional details on this topic are provided in Sect. 1.4.4.

Finally, several *general support functions* must be performed, such as providing electric and hydraulic supplies, fuelling and lubrication, and heating and cooling. Selected details on the machinery involved in these functions are given in Sect. 1.4.5.

1.4.1 A Ship's Life Cycle

Similar to all products, ships pass through different stages in their life cycles, including the design, construction, operation (with maintenance and refurbishments), and scrap phases.

The design and construction phases allow for a large range of options for technical solutions and offer a large opportunity to influence environmental impacts and energy usage. It is also important in these stages to allow for refurbishment and technical improvements during the long operation time of a ship (often 30 years or more). Additionally, the possibility of scrapping a ship in an organised manner that allows for its components and materials to be recycled is largely determined in the design phase. Operation is the main phase of the life cycle and is the time during which most energy usage occurs.

1.4.2 The Hull and Ship Structure

The main function of a ship is to safely carry its cargo, crew and passengers. Therefore, a ship must be a safe and trustworthy vehicle that can handle various sea states and reduce damage in the case of accidents.

The main structure of a ship is the hull, which provides a carrying platform and protection against the environment. The hull must be resistant to loads of different types and intensity over its entire lifetime and to possible collisions. These requirements translate into different solutions and technologies depending on the ship type and its trade.

Ships sailing on international routes, particularly in the North Atlantic Ocean, tend to be specially loaded as a consequence of frequent heavy seas, and they must meet higher requirements in terms of hull structure resistance compared with ships sailing in inland waterways or in less harsh seas.

The possible consequences of accidents also influence the selection of hull structure, shape and materials. The extensive consequences of accidents with large oil tankers (e.g., the *Exxon Valdez*, the *Amoco Cadiz* and the *Prestige*) led to stricter regulations for these vessels, including requirements for double-hull construction to limit the consequences of such accidents (see Sect. 3.2). However, ferries and passenger ships have also experienced several accidents (e.g., the *Estonia* and the *Costa Concordia*) that have led to increased standards in safety requirements.

A stronger and thicker hull comes at a cost. Additional material is required for construction, which impacts both the investment cost and the life cycle demand of materials. In addition, a heavier hull requires a higher lightweight (i.e., the weight of the ship's structure alone), which results in reduced cargo carrying capacity (weight) for a given ship size and shape. This trade-off can pose a challenge for tankers and bulk carriers, for which weight is the limiting factor.

Modern ship hulls are almost always constructed from steel. Lighter materials, such as aluminium and composite materials, are currently being investigated and have been used in highly specific applications. The choice of materials used in ship manufacturing has an impact on the emissions associated with shipping (see Sect. 7.4).

1.4.3 The Propulsion System

Several methods are available to generate the thrust required for a ship to move through water. However, nearly all of the world's commercial fleet is currently based on the concept of converting the chemical energy contained in fuel to mechanical energy, which in turn is converted into ship thrust. Box 1.3 depicts the historical changes in marine propulsion.

1.4.3.1 Ship Resistance

Ship movement through water generates a resistance from the water. This resistance depends primarily on a ship's speed (a standard approximation correlates the propulsive power requirement with the third power of a ship's speed) and on a resistance coefficient, which in turn depends on the hull (e.g., the shape, state, and wetted surface). However, a ship operates in the natural environment, which can lead to the attachment and subsequent growth of various marine organisms on the surface of the hull. These organisms can significantly enhance the hull drag, increasing the power needed by the engine to propel the ship (see Sect. 4.3). It has been estimated that fuel consumption increases by 6 % for every 0.1 mm increase of hull roughness due to fouling [33]. To reduce this phenomenon, so-called "antifouling" treatments are often used to hinder marine growth. Antifouling paints are applied to hulls to prevent the growth of fouling organisms, such as barnacles, mussels, bryozoans and algae. Antifouling systems are required when unwanted biological growth occurs, and the need to protect ship hulls from fouling is as old as the use of ships [34]. However, the release of biocides from antifouling into the water can result in a harmful impact on the marine environment (see Sect. 4.3).

1.4.3.2 Propulsors

Several different types of propulsors are used on ships. The *screw propeller* is the most commonly used and generates thrust through its rotation in water, thus converting the mechanical power delivered from the engine into the thrust required to overcome the ship's resistance and maintain the required speed. Propellers are often highly loaded, and this loading can generate the typical phenomenon of cavitation. This event, in addition to damaging the propeller surface, also generates intense noise, which is a source of disturbance to marine life (see Chap. 6).

1.4.3.3 Transmission Components

Mechanical power produced by the prime mover is subsequently transferred to the propeller by the propeller shaft, and the thrust bearing. The thrust shaft transmits the thrust generated by the propeller to the hull.

Because the propeller is located outside of the hull, the need exists for a sealing system that prevents sea water from entering the ship and discharge of the bearing lubrication oil to the sea. Even if the stern tube fulfils this purpose, small discharges of lubricant to the sea are common. The presence of lubricating oils in different areas of a ship can lead to oil leakage, which is collected in the bilge. This bilge water must be treated before it is released into the ocean (see Sect. 4.1).

1.4.3.4 The Prime Mover

Although several different technologies (mostly diesel engines, gas turbines, and steam turbines) are used as prime movers for ships, all of these options are based on the conversion of the chemical energy contained in the fuel to thermal energy via a combustion process and to mechanical energy via a thermodynamic cycle.

Combustion is the process that generates the largest amount of emissions to the air from ships (see Chap. 5). The exhaust emissions from internal combustion engines depend on the combustion process, the fuel used and the engine. The main compounds that are emitted include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HCs),[1] sulphur dioxide (SO_2) and particulate matter (PM). The emissions of exhaust gases and particles from ocean-going ships contribute to the environmental and health impacts caused by shipping, especially in coastal communities because nearly 70 % of the exhaust emissions from ships occur within 400 km of land [36].

The reaction of carbon with oxygen (which generates the largest portion of energy during the combustion process using modern fuels) generates CO_2, which is one of the main anthropogenic contributors to the greenhouse effect from fossil fuels (see Sect. 5.1). The sulphur contained in the fuel reacts with oxygen to form sulphur oxides (Sect. 5.2), which are precursors to the formation of secondary pollutants (Sect. 5.4.2). Modern marine fuels have much higher sulphur contents than road fuels. Sulphur oxides contribute to the formation of acid rain and impact human health [37]. The high temperatures reached during the combustion process make it possible for nitrogen (which comprises nearly 80 % of combustion air) to react with oxygen, thus generating nitrogen oxides (Sect. 5.3). Incomplete combustion and ashes lead to the formation of particulate matter (Sect. 5.4). Secondary particles are formed in the atmosphere, e.g., from SO_2 and NO_x emissions, and create sulphate and nitrate aerosols via coagulation and condensation of vapours (see Sects. 5.3.2 and 5.4.2). The main concerns related to particle emissions are health effects [37],[2] although particles also contribute to climate change due to both direct effects on the radiative balance and indirect effects via increased cloud

[1]Hydrocarbons are compounds consisting of hydrogen and carbon; the term *volatile organic carbons* (VOCs) is also used. VOCs are formally defined as organic compounds with boiling points between 50 and 260 °C [35]. It is also common to separate VOCs into methane and non-methane volatile organic compounds (NMVOCs).

[2]The smallest particles are considered to be most harmful to humans [38].

formation [36, 39]. Emissions of HCs are a consequence of the incomplete combustion of fuel and consist of unburned and partially oxidised HCs. Unburned lubrication oil from cylinder lubrication is also a major contributor to HC emissions from two-stroke engines [40]. HCs act as precursors to photochemical ozone, and certain HCs are toxic, e.g., benzene and polycyclic aromatic hydrocarbons (PAHs) [37]. In addition, the HC methane is a strong greenhouse gas.

1.4.3.5 Oil Spills

Accidental oil spills from tanker vessels have decreased since the 1970s, although numerous small spills still occur in ecologically sensitive locations [41]. The release of oil to the environment from shipping originates from the transportation of fuels in tanker vessels and from fuel used for propulsion. The portion that originates from fuel used for propulsion is affected by the choice of fuel for marine transportation. Only approximately 7 % of oil spills originated from non-tank vessels during the period 1990–1999 [42]. Operational oil pollution also originates from various sources, such as bilge water and propeller shaft bearings (see also Sect. 4.1).

Box 1.3 Historical development of marine propulsion

Marine propulsion has changed over the course of history (Fig. 1.6). Human power (oars) and wind power were initially used, followed by steam engines and steam turbines fuelled with coal at the beginning of the nineteenth century. Early steam ships used masts and sails because the engines were generally treated as auxiliaries for assisting the sails [43], and the full transition from sail to steam power spanned more than 50 years [10]. The steam engine changed marine transport in the sense that marine transportation was no longer dependent on the wind.

Most steam engines were replaced with marine engines fuelled by diesel and residual oil. Between the shift from steam engines to internal combustion engines (ICEs), a fuel shift also occurred from coal to oil that made this transition possible. During World War I, warships were built with oil-fired boilers or were converted from coal to oil. This shift increased the steam boiler output and/or reduced the storage requirements, thereby increasing the power output of warships [43]. Furthermore, oil-powered steam engines required smaller crews and provided a greater operational range and the possibility of easier refuelling at sea [44]. The first diesel-powered ship went into service in 1912 and was followed by a transition to diesel engines from steam over the next 50 years except for the most powerful ships [10]. Steam turbines are still used in most LNG carriers, which use the boil-off gas as fuel.[3] However, over the past decade, other types of propulsion systems have been considered for LNG carriers, involving various configurations of diesel engines, electric drives and gas turbines [45]. Steam turbines are less efficient

[3]The boil-off gas is the vapour created due to the ambient heat input (while maintaining constant pressure in the storage of cryogenics).

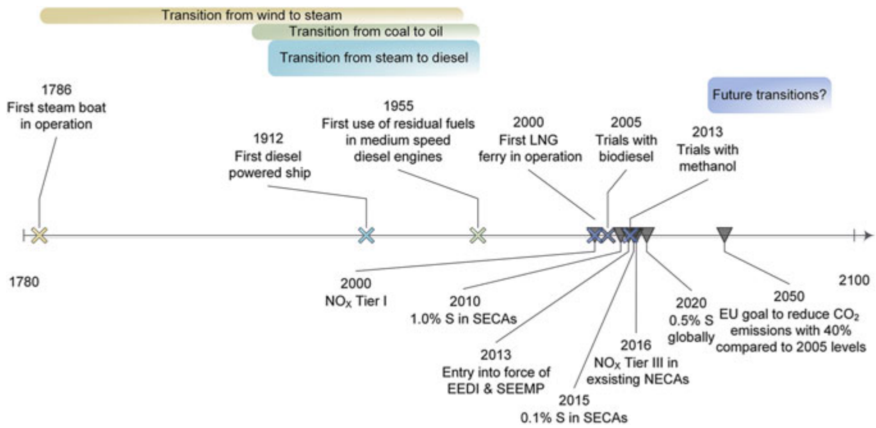

Fig. 1.6 Timeline for transition of marine fuels from 1780 to 2100; selected events in history and environmental regulations are depicted

than diesel engines, and the trend in new LNG carriers points towards propulsion by diesel or dual-fuel engines [46, 47].

Currently, residual fuel or heavy fuel oil, HFO[4] is used in most marine engines. In 2007, nearly 350 million tonnes of fuel were consumed by shipping, and approximately 250 million tonnes of these fuels were residual fuels [48]. The use of HFOs in marine engines followed John Lamb's experiments in the early 1950s, where it was first applied to slow-speed diesel engines and came into general use in medium-speed diesel engines in the 1960s [49].

Although HFO is now the dominant shipping fuel, several *alternative fuels*[5] have been proposed and tested, including liquefied natural gas (LNG), biodiesel, methanol and glycerol. LNG is used in Norway and is promoted as a future ship fuel. Biodiesel has been tested for marine propulsion by a large container shipping company [50] and by the US Navy [51]. This fuel also has been promoted as a suitable fuel for marine propulsion [52, 53]. The potential use of methanol as a marine fuel gained attention in a Swedish research and development project [54]. As a result of this work, a large ferry operator in northern Europe plans to convert several of their vessels to methanol propulsion [55]. A Japanese ocean shipping company signed a contract in December 2013 to build and charter three methanol carriers equipped with flex-fuel engines that can run on methanol, fuel oil or gas oil [56]. Glycerol is under evaluation in the GLEAMS project in the UK [57], and the use of

[4]The terms residual fuels and HFO are used interchangeably in this book.

[5]The term *alternative fuels* is used in this book to describe fuels that are alternatives to HFO in shipping. The term is occasionally used elsewhere as a synonym for renewable fuels.

synthetic fuels produced from carbon dioxide and hydrogen has also been suggested [58]. Thus, many alternatives exist for selection and evaluation. These fuels vary in terms of the energy carrier of the fuel, the primary energy sources used to produce the fuel, and the type of prime mover used to convert the energy carrier to work. A set of criteria for future marine fuels is used to compare the fuels and their various characteristics; the marine fuels are subsequently evaluated using these criteria

1.4.4 Hotel Facilities

A ship can sail for several days without reaching land; thus, it must be able to provide accommodation, food, and services for the people on-board. Cruise ships that can carry several thousand passengers and a crew of several hundred will specifically require a large capacity, and the waste and wastewater that is generated must be handled either on-board or in port (see Sect. 11.4).

A ship is generally designed for operation in many different environmental settings, i.e., from the hot and humid tropical seas to the cold conditions of the North Sea and Arctic areas.[6] For this reason, in addition to considerations related to space and comfort, accommodation of the crew on-board involves fulfilling substantial needs for heating or cooling depending on the period of the year and location. Therefore, heat, ventilation, and air conditioning (HVAC) systems are installed on-board. In particular, the systems related to cooling involve the use of cooling media that can have strong impacts on the environment (Sect. 5.6). Provisions required to feed the crew (between 10 and 40 people on cargo ships and up to one thousand crew members and up to several thousand passengers on cruise ships) for several days must be stored on-board in safe conditions, which requires extensive cooling for the provisions at low temperatures (−20 °C). In addition, accommodations for the crew require several systems to handle various waste products and sewage (Sects. 4.2, 11.4 and 11.5).

1.4.5 Auxiliary Systems

Many technical auxiliary systems are installed on-board to perform supporting functions, such as providing heating, cooling, and lubrication. Together with the propulsion train, these systems require the handling of fuel and lubricating oil, and spills result in the formation of bilge water, which is a mix of water, oil and several different chemicals. Bilge water must be treated on-board and is a source of oil released into the sea (Sects. 4.1.1 and 11.1.3).

[6] Arctic navigation is closely associated with a highly specific design because navigating through ice and extreme weather conditions requires specific measures and equipment.

Tanks are used to store fuel, engine oil, and fresh water. Ballast water is needed to ensure vessel stability during operation without cargo and to balance the weight when the cargo is not evenly distributed. In port, the ballast water might be pumped into specially designed tanks to compensate for changes in the weight distribution as cargo is removed and subsequently released when cargo is loaded. It is estimated that at any given time, approximately 10,000 different species are transported between geographic regions in the ballast tanks alone [59]. Although many alien species become integrated components of the background flora and fauna, others are invasive and will eventually take over and dominate the native flora and fauna. This may have associated economic impacts such as a decrease in economic production by fisheries, aquaculture, tourism and marine infrastructure. Human health can also be affected. For example, the Asian strain of the bacterium responsible for cholera was probably introduced into Latin America via the discharge of ballast water [60]. The environmental impacts related to ballast water are further discussed in Sect. 4.4.

1.5 Sustainability Challenges for the Maritime Industry

Many problems remain to be formulated and solved before the shipping industry can be deemed sustainable [61], e.g., the combustion of fuel in ship engines impacts global warming, acidification, eutrophication and human health (Chap. 5); invasive species spread via ship ballast water (Chap. 4); the scrapping of old ships on beaches causes heavy metal contamination (Chap. 7) [62]; and seafarer working conditions vary depending on the flag state [63]. Another question that arises is related to how shipping can contribute to sustainable development.

IMO has developed the concept of a Sustainable Maritime Transportation System for the “safe, secure, efficient and reliable transport of goods across the world, while minimising pollution, maximising energy efficiency and ensuring resource conservation” (p. 9) [64]. This concept is divided into the following areas with specific goals and actions for each area:

- Safety culture and environmental stewardship
- Education and training in maritime professions and support for seafarers
- Energy efficiency and ship-port interfaces
- Energy supply for ships
- Maritime traffic support and advisory systems
- Maritime security
- Technical cooperation
- New technology and innovation
- Finance, liability and insurance mechanisms
- Ocean governance [64].

In addition, independent organisations as well as different consortia in industry and academia have discussed strategies on sustainable shipping [65, 66].

The future challenges and opportunities for shipping to contribute to a sustainable future are further discussed in Chap. 12.

We hope that this book can contribute to a more sustainable shipping sector by providing knowledge, information, and selected methods and tools related to the environmental issues associated with shipping.

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