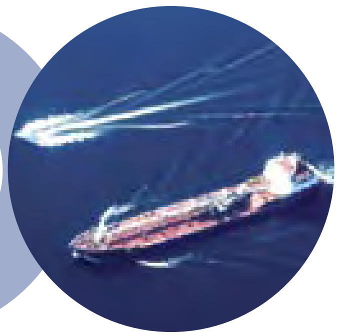

Air Pollution and Greenhouse Gas Emissions from Ocean-going Ships:

Impacts, Mitigation Options and Opportunities for Managing Growth

icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

The goal of the International Council on Clean Transportation (ICCT) is to dramatically reduce conventional pollutant and greenhouse gas emissions from personal, public, and goods transportation in order to improve air quality and human health, and mitigate climate change. The Council is made up of leading regulators and experts from around the world that participate as individuals based on their experience with air quality and transportation issues. The ICCT promotes best practices and comprehensive solutions to improve vehicle emissions and efficiency, increase fuel quality and sustainability of alternative fuels, reduce pollution from the in-use fleet, and curtail emissions from international goods movement.

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In a world of global supply chains and rapidly expanding trade, ocean shipping—currently the dominant mode of transport for international cargo—is becoming an increasingly important source of air pollution and greenhouse gas emissions.

Today, ocean-going vessels transport 90 percent of all trade by volume to and from the 25 members of the European Community (EC), and nearly 80 percent by weight of all goods shipped in and out of the United States (EC 2006, US DOT 2003). Over the last three decades, activity in the marine shipping sector, as measured in metric ton-kilometers, has grown on average by 5 percent every year, as shown in Figure ES-1. Since emissions from ocean-going vessels have only been moderately controlled, this growth has been accompanied by a commensurate increase in the sector's contribution to local and global air pollution.

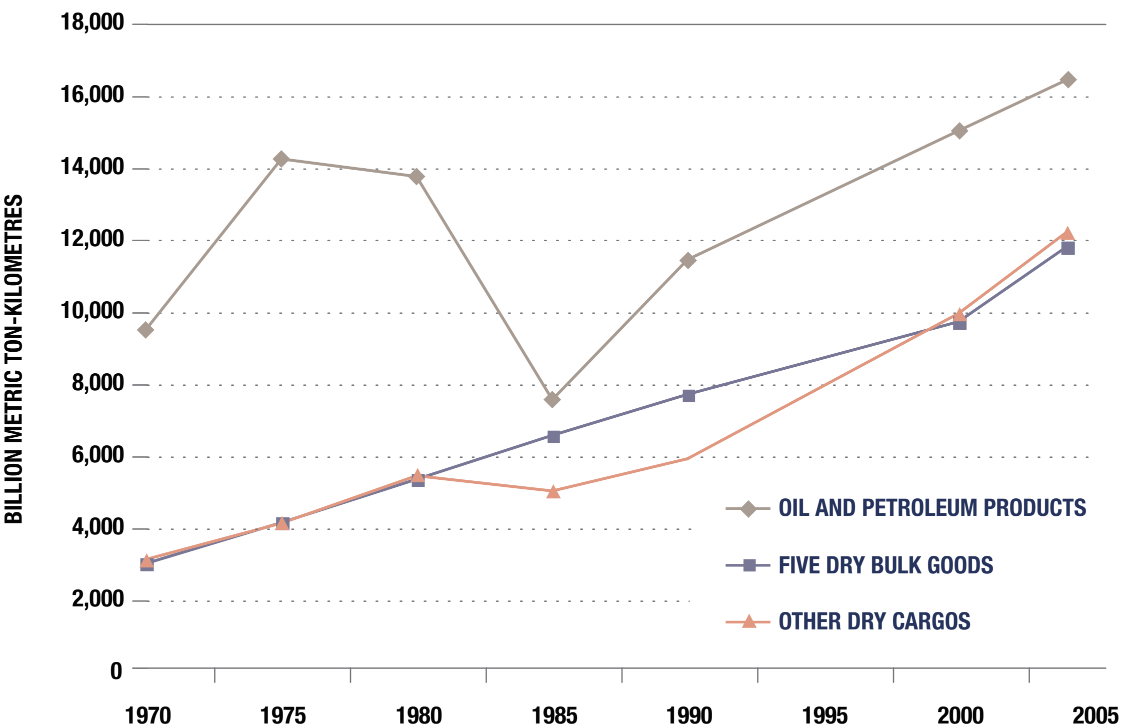

FIGURE ES-1. World Seaborne Freight Transport in Metric Ton-Kilometers by Type of Freight (UNCTAD 2005)

Ocean-going vessels contribute significantly to global emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM). Indeed it is estimated that by 2020, ship emissions contributions to the European Union (EU) NO_x and SO_x inventories will surpass total emissions generated by all land-based mobile, stationary and other sources in the twenty-five nations (EC 2005). Figure ES-2 and Figure ES-3 show projected NO_x and SO_x emissions from marine and land-based sources in Europe. Air quality impacts from ocean-going vessels are especially significant in port cities and nations with extensive coastlines adjacent to shipping corridors. Studies making use of geographic marine activity data have estimated that about 70–80 percent of all ship emissions occur within 400 km (248 miles) of land (IMO 2000, Corbett et al. 1999). Pollutants such as NO_x, SO_x, and PM have been linked to a variety of adverse public health outcomes, including increased risk of premature death from heart and pulmonary diseases and worsened respiratory disease. Marine emission sources are therefore responsible for a growing share of the public health impacts of exposure to air pollution in many regions. Although ocean-going vessels are among the most efficient modes of freight transport, they also generate substantial quantities of greenhouse gas emissions. Currently, carbon dioxide (CO_2) emissions from the international shipping sector as a whole exceed annual total greenhouse gas emissions from most of the nations listed in the Kyoto protocol as Annex I countries (Kyoto Protocol 1997).

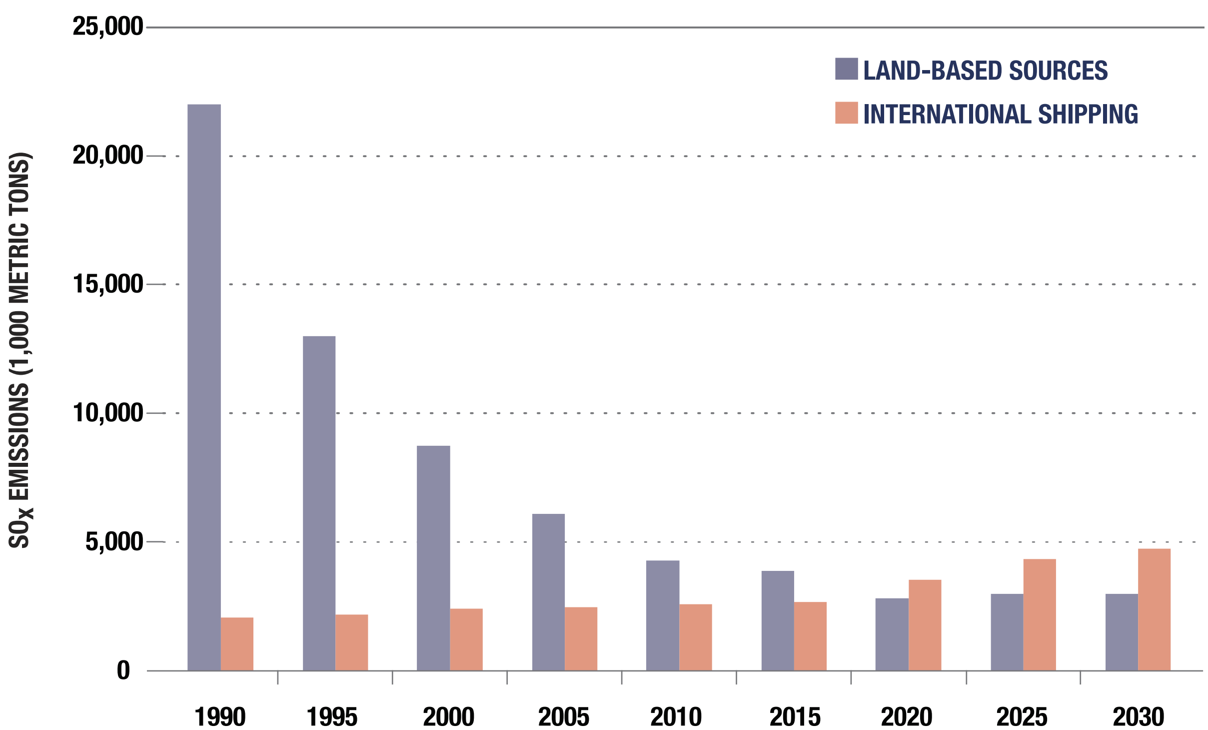

FIGURE ES-2. Inventories and Projections of SO_x Emissions in Europe from Land-based and International Shipping Sources (EC 2005)

Relative to other sectors, the regulation of commercial marine vessels represents a significant political and legal challenge as ships operate largely outside of national boundaries. Ocean-going vessels are mainly subject to oversight by the International Maritime Organization (IMO), under the purview of the United Nations. Unfortunately, IMO efforts to mitigate environmental impacts of emissions from global shipping have not kept pace with the industry's growth and the evolution of control technologies for controlling emissions. The international process for establishing new regulatory requirements is further complicated by the complex relationships that exist between those nations to which most ships are registered under so-called "flags of convenience" and the large shipping interests (typically headquartered in other nations) that own most of the ships. As a result, the IMO adopted standards in 1997 that represented only a modest improvement in emissions from unregulated engines. When these standards entered into force they reflected levels already achieved by the average in-use engine. The IMO's current fuel sulfur limit of 4.5 percent is almost twice the average sulfur content of fuels in use in ships today and several thousand times the sulfur level of fuels used on-road in Europe and North America. These standards at best codify the industry's existing practices.

Under these circumstances, accelerated adoption of cleaner marine fuels and wider deployment of existing pollution control technologies and emission reduction strategies could dramatically improve the environmental performance of

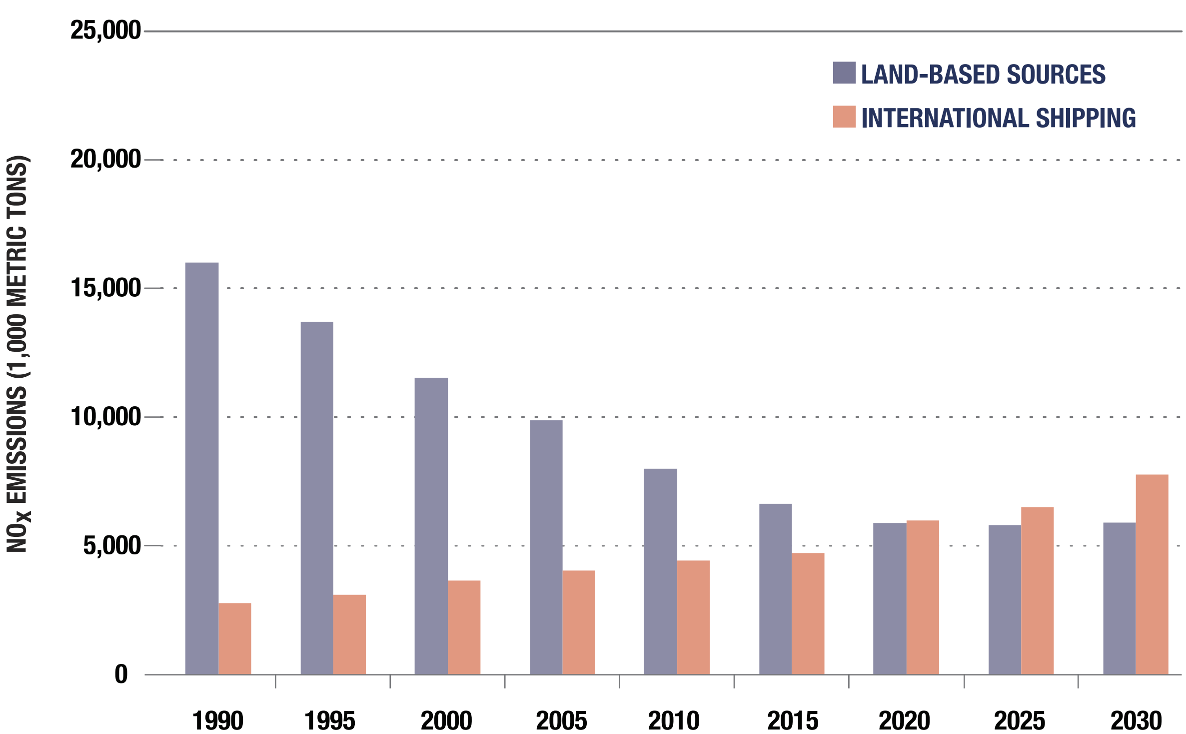

FIGURE ES-3. Inventories of NO_x Emissions in Europe from Land-based and International Shipping Sources (EC 2005)

the shipping sector. To explore these opportunities, the ICCT undertook a review of the status of pollution control measures and programs implemented to date throughout the world. This report describes the results of the ICCT review, focusing on the emission-reduction potential, feasibility, costs, and cost- effectiveness of available environmental mitigation measures for the shipping sector. It also analyzes the legal context within which local, regional, and international programs can be developed. The report concludes with a series of policy recommendations aimed at achieving steady, incremental progress towards reducing emissions from marine vessels that will result in significant environment and public health benefits.

Lower sulfur fuels, optimized engines, and exhaust after-treatment, such as selective catalytic reduction (SCR), have been shown to significantly improve the environmental performance of marine vessels. Other measures such as shoreside electricity and improved auxiliary engines can reduce so-called "hotelling" emissions—that is emissions generated while ships are docked at port. The feasibility and cost-effectiveness of these measures has been demonstrated at several ports. As shown in Figure ES- 4, available options for reducing marine NO_x emissions are very cost-effective compared to remaining pollution control options for other mobile and stationary sources, especially in countries that have adopted a range of regulations to limit land-based emissions.

Nations in Europe and North America—along with port cities throughout the world—have deployed a suite of strategies to address air pollution from ships. These strategies have included regulations, voluntary programs, and

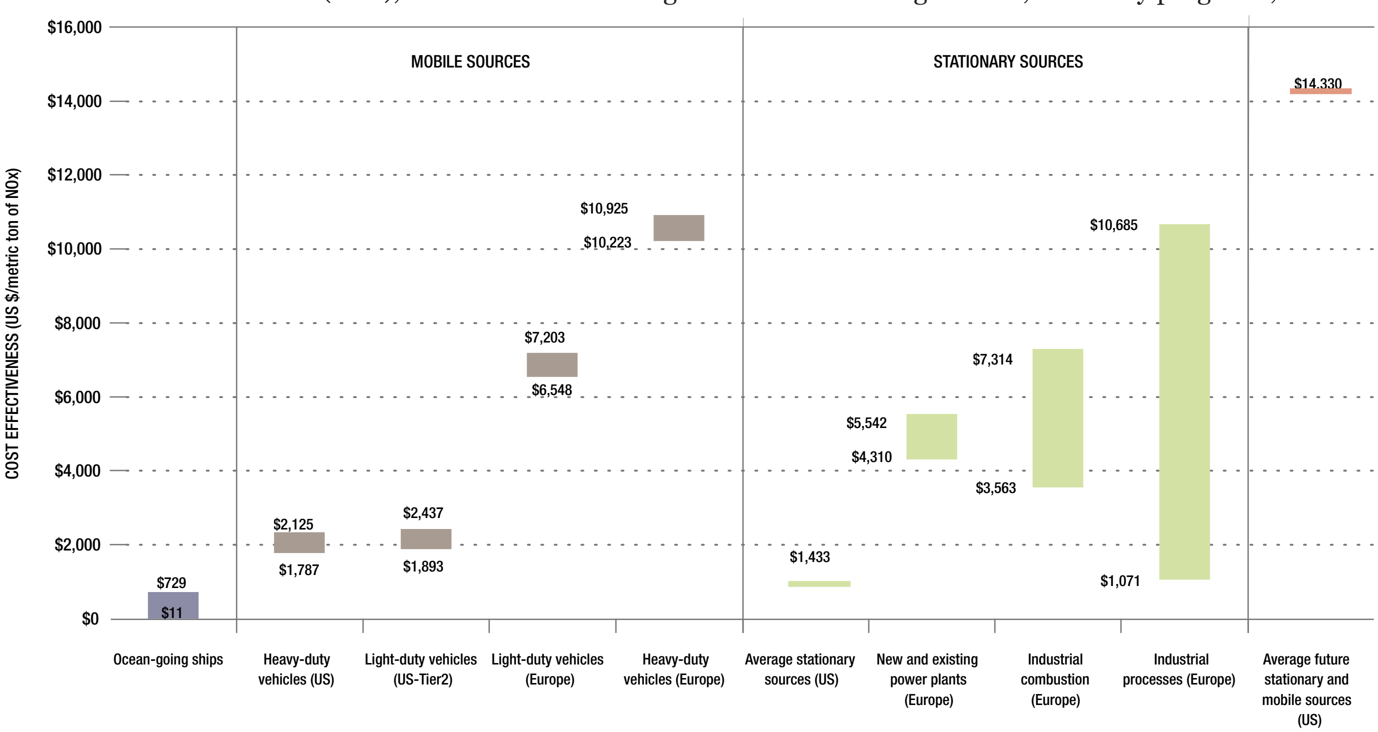

FIGURE ES-4. Comparing the Cost-Effectiveness of NO_x Control Options for Various Source Categories (Entec 2005b, US EPA 1999, 2000, 2005) market-based programs. Examples of regulatory approaches have included national engine standards for the domestic vessel fleet and fuel sulfur standards for vessels operating in coastal waters and harbors. The voluntary harbor speed limits implemented in the San Pedro Bay by the ports of Los Angeles and Long Beach provide an example of a voluntary approach. Meanwhile, Sweden has experimented with a market-based approach by imposing a system of environmentally differentiated fairway and port dues that vary with ship emissions. This successful program has led to increased use of lower-sulfur fuels and to the installation of SCR systems on a number of ships calling on Swedish ports.

The recommendations advanced in this report identify implementation milestones in each of several distinct categories: (1) marine fuels, (2) new engines, (3) new vessels, (4) existing engines and vessels, (5) greenhouse gas emissions, (6) and in-port emissions. In the near-term, these recommendations generally call for widespread adoption of proven best available technologies in the 2010 timeframe. The ICCT's medium-term recommendations propose intermediary steps to be taken between 2012 and 2017. Finally, technology-forcing, long-term recommendations are proposed for the post-2020 period. Implementing these recommendations will require the active engagement of numerous stakeholders, including ship owners and operators, ports, and regulators. Leadership from the businesses that demand shipping services is also crucial. Shipping customers are uniquely positioned to create incentives for improved performance in the shipping sector because they can require that their goods be transported with the least possible impact on the environment.

MARINE FUELS

Reducing fuel sulfur content is an essential component of any strategy aimed at reducing SO_x and PM emissions from marine vessels. Lower sulfur fuel also enables the use of advanced after-treatment for NO_x reductions. Existing plans to implement SO_x Emission Control Areas (SECAs), starting in 2006 in the Baltic Sea and expected in 2007 for the North Sea and English Channel, mean that a portion of the world's ships are now or will soon be using 1.5 percent sulfur fuels or equivalent after-treatment. In the short term, the ICCT recommends including other major shipping areas, such as the Mediterranean and parts of the North Atlantic and Pacific Rim, in the SECA program. Moreover, decisions concerning future SECAs should take into account sulfur- and particle-related public health impacts as well as impacts on land and sea ecosystems. Finally, ICCT recommends that the fuel sulfur limit in SECAs be lowered from 1.5 percent to 0.5 percent to achieve further emissions reduction in the 2010 timeframe and to facilitate the shift to lower sulfur fuels on a global scale.

As a next step, the ICCT recommends that a uniform global fuel sulfur standard of 0.5 percent be introduced in the medium term. Relative to the 2.7 percent average sulfur content of current marine fuel, this step alone will reduce SO_x emissions by approximately 80 percent and PM emissions by a minimum of 20 percent. At this level of fuel quality, selective catalytic reduction (SCR) will be fully enabled. Although SCR can function at higher fuel-sulfur levels, durability is significantly improved at lower levels.

Some uncertainty remains regarding the widespread availability of lower sulfur fuels in the recommended timeframe. However, there has been significant momentum among various stakeholders to reduce the global fuel sulfur limit. For example, some industry groups have recently expressed support for a global fuel standard requiring the use of 1 percent sulfur distillate fuel in the near term (INTERTANKO 2006). In addition, current regulations in California and Europe require low-sulfur fuels in coastal waters, inland waterways, and at ports ahead of the ICCT-recommended dates. For example, the California auxiliary engine program requires the use of 0.5 percent sulfur fuel in the state's coastal waters and at port by 2007. The allowed sulfur level is lowered to 0.1 percent by 2010. Fuel with 0.1 percent sulfur content will also be required in ports and inland waterways in Europe by 2010

Adoption of a lower global fuel sulfur limit would provide the refining industry the clear signal it needs to invest in upgrading production facilities and ensure increased fuel availability. The ICCT also encourages further efforts to implement lower sulfur fuel ahead of the recommended schedule in coastal waters, inland waterways, and at ports. These programs can facilitate a transition to fleet-wide use of lower sulfur fuels while ensuring emissions reductions in proximity to the potentially impacted populations. In the long-term, fuel standards for marine fuels should be harmonized with standards for on-road fuels (500 ppm to 10-15 ppm).

NEW ENGINES

The IMO's recent decision to review NO_x standards for ocean-going vessels represents an opportunity to make significant progress in improving the performance of marine engines. The ICCT recommends requiring new engines to achieve NO_x limits that are 40 percent lower than the current standard in the near term. This level can be reached primarily through engine upgrades. New engine standards should also be set to ensure significant reductions in PM emissions. A medium-term standard set at a level 95 percent below current standards for NO_x would require the use of additional emission control technologies, including after-treatment controls. Further PM reduction should also be required. These near- and medium-term standards should be adopted at the same time to give manufacturers sufficient lead time to prepare for compliance and to direct their research and development activities accordingly. In addition to more stringent standards, the ICCT recommends that manufacturers be (1) required to certify engines using fuels that reflect actual in-use fuel quality; (2) be liable for in-use compliance and subject to in-use testing; and (3) be required to demonstrate the durability of emission control systems used to achieve compliance.

The production and use of engines that are significantly cleaner than the proposed standards should be encouraged both in the short and medium term through incentives to engine and technology manufacturers as well as vessel operators. Support for early technology demonstrations is necessary to ensure viable technology options are available to meet increasingly stringent standards. In the long term, the ICCT recommends deploying incentives and other strategies to further promote the use of advanced technologies, especially technologies that achieve near-zero emissions, in promising applications.

NEW VESSELS

Many opportunities exist during a vessel's design and construction phases to make changes that would facilitate the use of low-emission control technologies. In the near term, the ICCT recommends that engine rooms be designed with enough space to allow for retrofit technologies including SCR as well as tank capacity for fuel switching in SECA and coastal areas. New vessels, especially ferries and cruise ships with regular routes and ports of call, should be built with the needed on-board equipment to utilize shore power when port-side facilities exist. Standardization of international shore power requirements is also needed to ensure compatibility between shore-side facilities and ships. The ICCT supports the ongoing efforts within IMO to develop guidelines for shore-side electricity. In the long term, the ICCT encourages the use of advanced vessel design concepts that optimize energy efficiency as well as emissions performance and that incorporate propulsion from renewable energy sources including solar and wind power, where feasible.

EXISTING VESSELS AND ENGINES

Control measures targeted at existing vessels and engines are necessary to significantly impact fleet-wide emissions. A low fleet turnover rate means that the largely uncontrolled vessels that make up the majority of the international marine shipping fleet today will continue to pollute for several decades before they are retired. Most existing control technology options have been developed and demonstrated on in-use vessels, suggesting that a large-scale retrofit program should be technically feasible. In the near term, the ICCT recommends that in-use standards reflecting best available control technologies be developed within the IMO. These standards would allow, for example, future market-based programs (including the range of possible differentiated fee programs) to harmonize their emission requirements. The ICCT further recommends that any in-use standards used in market-based programs be designed to become more stringent over time so as to provide ongoing incentives for adopting the newest control technologies as they become available, proven, and cost-effective. The program should provide additional incentives to demonstrations of advanced technologies that provide emission reductions beyond the adopted in-use standards. Also in the short term, the ICCT recommends exploring the feasibility of early ship retirement as an extension of the ship recycling programs being developed by the IMO. If determined feasible, this type of program could be implemented in the medium to long term.

GREENHOUSE GASES

The shipping sector's contribution to gases and particles that impact the Earth's climate is only beginning to be fully understood. Here, the ICCT recommends that near-term efforts focus on developing a baseline for the climate impacts of the world's vessel fleet. Once a baseline is established, market-based measures to reduce greenhouse gas emissions can be introduced, also in the near term. If cap and trade programs are developed for GHGs, they should only cover shipping sources and not include land-based sources. If the shipping sector becomes a source of credits for greenhouse gas emissions reductions, steps must be taken—as with any source of credits—to ensure that reductions are recognized only to the extent that they are quantifiable, enforceable, surplus to otherwise mandated reductions, and permanent. The ICCT also recommends that the IMO develop fuel economy standards for ships applicable to new vessels in the near term and existing vessels in the medium term.

AT PORT

The ICCT recommends that emission mitigation measures should be adopted at all major port facilities and be fully integrated with local and/or regional air quality plans. Each port type has access to a range of implementation mechanisms to reduce emissions from ships at berth. For example, landlord ports can include emission reduction requirements in their lease agreements with tenant operators. Operating ports can directly implement some infrastructure measures.

Providing shore power is often the most effective emission-reduction option for vessels while at port. In some locations, however, pollution impacts from electricity generation may make this option less attractive. The ICCT recommends that port authorities and regulators select the strategy or combination of strategies that cost-effectively provides the most environmental benefits. If shore power does not meet these criteria, other options should be implemented including requiring hotelling ships to use the lowest sulfur on-road fuels available and/or engine emission controls. The implementation of shore power and alternative mitigation technologies should prioritize new terminals as well as those that are near residential areas.

In the medium-term, the ICCT recommends that incentives be provided for utilizing low-carbon sources for shore-side power (including renewable solar and wind generators). In the long-term, the development of cost-effective energy storage technologies and advanced low- or non-carbon generating options should make it possible to achieve near-zero hotelling emissions.

Table ES-1 summarizes the ICCT recommendations towards mitigating the impact of ocean-going vessels on air quality and climate change.

In conclusion, supplemental international action within the IMO is necessary to produce reasonable progress in addressing ship impacts on local air quality and global climate change. National and regional policy-makers are increasingly seeking to accelerate the introduction of emission control technologies and cleaner fuels into the international marine sector. Within the IMO process, several countries including Sweden, Norway, and Germany have emerged as proponents of further measures to reduce emissions from ships. The few environmental organizations that have obtained consultative status with the IMO have also been leading efforts to accelerate progress on these issues. Other environmental NGOs with related activities and expertise should consider applying for consultative status to bolster these efforts. Finally, these efforts within the IMO must be brought to the attention of the larger public. Greater public awareness of the environmental impacts of routine ship activity will undoubtedly result in added pressure to reduce emissions in much the same way that highly publicized oil spills led to an increased focus on accident prevention, impact mitigation, and accelerated phase-out of single-hull tanker ships by the IMO. Best practices and local or national successes should be shared with a global audience to demonstrate that dramatic reductions in emissions from marine vessels, both at sea and in port, are not only feasible but also cost-effective. In the end, collaboration between the public and private sectors and across a wide set of stakeholders will be essential to forge support for sustainable long-term measures to mitigate the public health and environmental impacts of shipping around the world.

TABLE ES-1. ICCT Recommendations for Ocean-Going Vessels

ICCT RECOMMENDATIONS		IMPLEMENTATION MECHANISM
Fuels	— Short term: ○ Lower fuel sulfur level in SO_x Emission Control Areas (SECAs) from 1.5% to 0.5%. ○ Include SO_x/PM related health effects in addition to impacts on air, sea, and land as justification for SECA. ○ Expand SECA program to high ship-traffic areas in Mediterranean, Pacific Rim and North Atlantic. ○ Regional limits in coastal areas, inland waterways, and at ports — Medium term: 0.5% sulfur fuel globally — Long term: Harmonization with on-road diesel fuels (500 ppm to 10-15 ppm over time)	— International standards (IMO)
New engines	— Short term: ○ NO_x standards 40% percent below current IMO standards (2000 level). ○ PM standards ○ Encourage new technology demonstration — Medium term: ○ NO_x standards 95% percent below current IMO standards (2000 level) ○ PM standards further reduced ○ Encourage new technology demonstration — Long term: Encourage the use of advanced technologies, especially near-zero emission technologies in promising applications	— International standards (IMO)
New vessels	— Short term: ○ Adopt international requirements for shore power standardization. ○ All new ships built with shore-side electricity capability, especially cruise ship and ferries — Long term: Promote the use of advanced vessel design concepts in promising applications	— Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges — International regulation (IMO)

Table continues on next page

TABLE ES-1., continued

ICCT RECOMMENDATIONS		IMPLEMENTATION MECHANISM
Existing vessels and engines	— Short term: ○ Adopt emissions performance standards by vessel class and engine characteristics based on demonstrated retrofit potential. ○ Study feasibility and potential impact of programs to promote early ship retirement and environmentally sound disposal	— International standards (IMO) — Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges
GHG	— Short term: ○ Develop GHG emission inventory and fleet baseline ○ Market-based measures for vessels ○ Implement fuel economy standards by vessel class and engine characteristics for new vessels — Medium term: Implement fuel economy standards by vessel class and engine for existing vessels	— Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges — Cap and trade program for shipping sector only — International standards (IMO)
At port	— Short term: Select strategy that provides maximum emissions reduction benefits depending on local fuel availability and environmental performance of electricity generation ○ Shore-side electricity ○ Lowest sulfur on-road fuel and NO_x and PM after-treatment — Medium term: Market-based measures to promote low- or non-carbon energy sources to supply shore-side electricity for docked ships	— Port authority requirement — Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges

I. INTRODUCTION

Every day, thousands of ships travel between the world's large ports, transporting the manufactured goods, agricultural commodities, and petroleum products that supply the world's stores, markets, and gas stations. Ocean-borne commerce has been steadily increasing through the last two decades and is expected to continue to play a significant role in the globalized world economy. A growing fleet of ships, trains, airplanes, and trucks, along with the ports, train yards, airports, and roads that support them, are the backbone of global commerce.

In the age of "just in time" logistics and global supply chains, the fast and efficient movement of goods is an economic imperative. Significant investments are currently being deployed to modernize and expand ports and intermodal facilities and to accommodate growing cargo volumes. Expected growth in ship traffic will add significantly to local air quality problems and global climate-change risks unless ship emissions are further controlled. To date, improvements in ship environmental performance have not proceeded at the same pace as the increase in shipping activity and ship emissions remain largely unregulated.

Local and regional air quality problems associated with ship emissions, especially in coastal areas, are a concern because of their public health impacts. Exposure to air pollution is associated with a host of health risks including premature death, cancer, heart and respiratory diseases. Communities located in the vicinity of ports are additionally burdened by their proximity to these facilities. Because their air pollutant emissions remain comparatively unregulated, ships are now among the world's most polluting combustion sources per ton of fuel consumed (Corbett et al. 1999). Depending on the methodology used, ocean-going ships currently account for roughly 10–20 percent of world oil consumption and produce 14–31 percent of the global emissions of oxides of nitrogen (NO_x) and 4–9 percent of global emissions of oxides of sulfur (SO_x) (IMO 2000, Endresen et al. 2003, Eyring et al. 2005a, Corbett and Koehler 2003). In Europe, NO_x and SO_x emissions from seagoing vessels will exceed emissions from all land-based transportation, stationary, and area-wide sources combined starting in 2020 (EC 2005).

Existing technologies could dramatically improve the environmental performance of ships. Ocean-going vessels are powered by massive diesel engines that run on very high sulfur fuels composed mainly of residuals from the refining process. Because emissions are heavily influenced by the quality of the fuel burned in the engine, major improvements in ocean-going ship engine technology are likely to require simultaneous improvements in the quality of marine fuels. Borrowing from the emission control technologies in commercial use in the on- and off-highway diesel sector would lead to considerable reductions in emissions of all major pollutions. Opportunities for significant, cost-effective emission reductions through technology and fuel improvement have been comprehensively demonstrated. In addition, operational changes at ports can mitigate the important local air quality impacts of shipping.

The challenge of the last twenty years has been to incorporate these environmentally beneficial technologies and operational practices into the industry's mainstream operations. Relative to other sources, controlling emissions from commercial marine vessels represents a significant political and legal challenge. Indeed, ships operate largely outside of national boundaries and are subject to oversight by the International Maritime Organization (IMO), under the purview of the United Nations. The IMO has not demonstrated a willingness to establish requirements based on the best available technologies and fuels. Instead, its actions have served to codify technologies already largely adopted by the industry as a result of market forces.

Addressing emissions from both new and existing vessels is crucial. Marine vessels have a long service life relative to most mobile sources: as of January 2004, 38 percent of the world merchant shipping fleet was at least 15 years old (UNCTAD 2005). As a result, new equipment will penetrate the service fleet and bring about intended emission reductions only slowly. It is, therefore, critical that regulatory decisions with regard to future environmental performance occur efficiently and with significant foresight. In addition, retrofit technologies or other measures that can reduce emission from the existing fleet must be included in the solutions considered.

This report discusses regulatory, market-based, and voluntary approaches to reduce the air quality and global warming impacts of marine-vessel emissions. Chapter II summarizes the sector's contribution to local and global air pollution inventories. Chapter III reviews international law related to the control of air pollution from ocean-going vessels. Chapter IV focuses on the most promising emission control technologies, operational measures, market-based and regulatory measures, and voluntary efforts and describes ongoing efforts in individual countries, the European Union (EU), and the IMO to address air quality issues from marine sources. The report concludes in Chapter V with recommendations for policymakers and other stakeholders based on the report findings.

II. INTERNATIONAL SHIPPING, PORTS, AND AIR POLLUTION

This chapter focuses on the air quality and global warming impacts of emissions from international ships with 100 metric tons and greater gross registered tonnage (GRT). GRT is an industry term that refers to a ship's carrying capacity. Ships of 100 metric tons GRT or greater include bulk cargo, tanker, and container ships spanning an enormous range of cargo capacity. Tanker specifications vary, but the largest are over 400 meters long with a cargo capacity of over a half million metric tons, or up to 4.1 million barrels of crude oil. The size of container ships has quadrupled over the last half century—the largest of these vessels is now over 250 meters long. Other ocean-going vessels not dedicated to cargo transportation, such as fishing ships, are also included in the inventories discussed in this chapter.

The vast majority of these ocean-going ships are powered by diesel engines. These engines range in size from a typical heavy-duty truck engine to very large 980mm/2660mm (bore/stroke) designs. A single cylinder of the latter is about 3 meters high and over 1 meter in diameter. As many as 15 of these cylinders can be combined to produce over 100,000 horsepower (over 73,000 kW). Because these engines are so large, they are often custom designed for a particular vessel and become part of its structure.

The next section provides a broad overview of the industry's activity levels as background to a discussion of its air quality impacts.

A. INTERNATIONAL SHIPPING INDUSTRY OVERVIEW

Measured by weight or value, most international freight is transported by ship. Seagoing vessels transport 90 percent of all trade by volume to and from the 25 members of the European Community, and nearly 80 percent by weight of all goods shipped in and out of the United States (EC 2006, US DOT 2003). Trade flows are increasing all over the world, with the highest increases between the United States and China (i.e., a 44 percent growth between 1999 and 2003) (US DOT 2003). Except for a temporary decline between 1980 and 1985, the industry has been expanding steadily for the last 35 years (UNCTAD 2005). Maritime metric ton-kilometers and the carrying capacity of the world's merchant fleet have nearly tripled since 1970 (UNCTAD 2005).

Today's international marine fleet of roughly 90,000 vessels is typically divided into two groups of vessels: cargo and non-cargo. According to Lloyd's Maritime Information System, in 2001 the world's cargo fleet consisted of approximately 11,000 tankers, 3,000 container ships, 6,000 bulk carriers, and 24,000 general cargo ships. For the same year, the non-cargo ships included 1,000 fish factories, 22,000 fishing vessels, 12,000 tugs, and 10,000 other ships (ferries, passenger ships, cruise ships, research vessels, etc.) (Eyring et al. 2005a).

Globalization and growth in international trade are placing more demands on the world's seaports. One of the most important trends in maritime trade worldwide in recent decades has been the growth in containerization and a resulting rise in longer distance shipments. Today, about three-quarters of all general cargo is containerized. Container traffic at some of the largest ports is growing at a remarkable rate: traffic increased by 14.4 percent between 2003 and 2004 alone at the 71 world ports that have a volume greater than 1 million twenty-foot equivalent unites (TEUs)[1] annually (ISL 2005). Approximately two-thirds of the container traffic in 2004 was related to Asian ports, with the eight largest Chinese ports accounting for over a quarter of world container traffic (ISL 2005). In Europe, major container ports such as the Port of Rotterdam and the Port of Hamburg have also seen a significant increase in traffic (ISL 2005). Waterborne import tonnage at U.S. ports grew by 67 percent between 1990 and 2003, while container traffic through the Port of Los Angeles, a major trading partner with Asian ports, has nearly doubled in just the last five years (US DOT 2003).

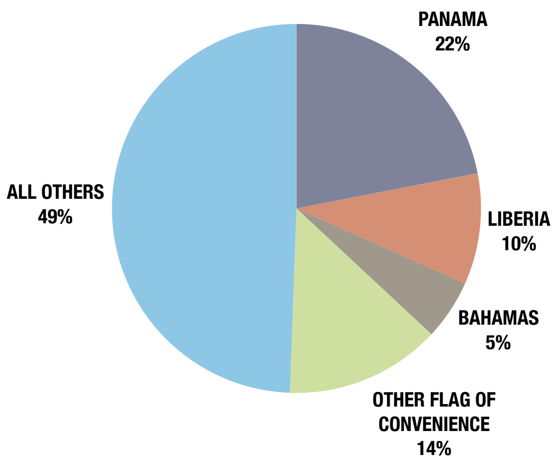

FIGURE 1. Distribution of the World Shipping Fleet above 1,000 GT by Flag in 2004 (MARAD 2006a)

The vessel building and marine diesel-engine manufacturing industries are relatively concentrated. The overwhelming majority of new vessels are built in South Korea, China, and Japan, mainly due to shipyard subsidy programs in these countries. Countries that do not offer similar types of subsidies have seen a significant decline in shipbuilding activity in the last two decades. For example, in the United States most, if not all, domestic production involves vessels that are required by law to be built in the United States.[2] Engine production is dominated by a small number of major manufacturers. In 1998, just four manufacturers (MAN B&W Diesel, Wärtsilä/New Sulzer, Catepillar/MaK, and Mitsubishi) accounted for 75 percent of the 1,300 new marine diesel engines with a displacement of 30 liters per cylinder or above produced (MER 2001).

Many marine vessels are not registered in the country where their corporate headquarters are located. Often the domicile of the parent company that holds a controlling interest in the vessel is located in one country, and the vessel is registered in another country, this is called a "flag of convenience" (Molenaar 1998).[3] Flag-of-convenience countries typically offer lower fees and taxes as well as fewer regulatory requirements. Figure 1 illustrates the distribution of ship registrations. The main flag-of-convenience countries, in numbers of ships registered, are Panama, Liberia, Malta, and the Bahamas.

Based on the nationality of the parent companies that own these ships, top ship-owning countries include Greece, Japan, Germany, and China. Table 1 presents the top ten countries by owned cargo vessel capacity in deadweight metric tons above 1,000 metric tons (a subset of the vessels above 100 GRT).

TABLE 1. Cargo Vessels above 1,000 Gross Metric Tons by Owner's Country in 2004 (MARAD 2006b)

COUNTRY	NUMBER OF VESSELS	DEADWEIGHT TONNAGE (1,000 METRIC TONS)
Greece	2,900	160,000
Japan	2,700	111,000
Germany	2,300	51,000
China	2,200	49,000
Norway	1,100	42,000
United States	900	40,000
Hong Kong	500	37,000
Korea South	800	26,000
United Kingdom	600	24,000
Singapore	700	24,000
Taiwan	500	24,000
Grand Total	29,000	849,000

Most ship owners are large multinational corporations with diversified activities including freight logistics and terminal management. For example, the A.P. Moller-Maersk Group, one of the world's largest carriers, not only operates a large fleet of container and tanker ships, but also provides terminal management, inland container transportation, and shipyard services (APMM 2006). Other shipping companies have significant investments in container manufacturing, real estate, tourism, and aviation. Table 2 provides a list of some of the world's major shipping companies.

Another measure of international shipping activity, besides carrying capacity, is obtained by multiplying the amount of freight (in metric tons) by the distance it is transported (in kilometers). The result is in a unit commonly referred to as "ton-kilometers." According to the U.S. Bureau of Transportation Statistics, ton-kilometers are the primary physical measure of freight transport output, and provide the best single measure of the physical volume of freight transport services. The United Nations Conference on Trade and Development (UNCTAD) provides statistics on ton-miles generated by types of cargo: oil, five dry bulk goods, and other dry goods. The five dry bulk goods are iron ore, coal, grain, aluminum, and phosphate. These statistics are presented, converted to metric ton-kilometers, in Figure 2. Transport volumes for each type of cargo have grown strongly and steadily—at average annual growth rates of 4–6 percent—over the last three decades. As is evident from the figure, the only exception to this trend was a sharp, but short-lived, decline in the volume of oil transported between 1980 and 1985. Overall, however, ton-kilometers have increased by about 70 percent for oil and petroleum products, and almost tripled for all cargo types combined, since 1970. An increase in distance traveled accounts for more of this growth than an increase in tonnage hauled (UNCTAD 2005), reflecting the rise in global demand for finished products and the shift of manufacturing activities to Asia.

Unsurprisingly, most commercial marine activity is concentrated in Asian, European, and U.S. ports and in the shipping channels of the Pacific

TABLE 2. World Major Ocean Shipping Companies (alphabetically)

COMPANY NAME	HEADQUARTERS	SHIP TYPES
APL (NOL Group)	Singapore	Container
A.P. Moller-Maersk Group	Copenhagen, Denmark	Container, tanker
China Shipping Line	Shanghai, China	Container
CMA CGM	Marseille, France	Container
COSCO Group	Beijing, China	Bulk, container, tanker
Evergreen	Taipei, Taiwan	Container
Hanjin Group	Seoul, Korea	Bulk, container, tanker
Hapag-Lloyd (TUI Group)	Hamburg, Germany	Container, cruise
Hyundai Merchant Marine (Hyundai Group)	Seoul, Korea	Bulk, container
K-line	Tokyo, Japan	Bulk, container, car carrier, tanker
Mediterranean Shipping Company	Geneva, Switzerland	Container
NYK Line	Tokyo, Japan	Container, car carrier
OOCL	Hong Kong	Container
Teekay Shipping	Vancouver, Canada	Tankers

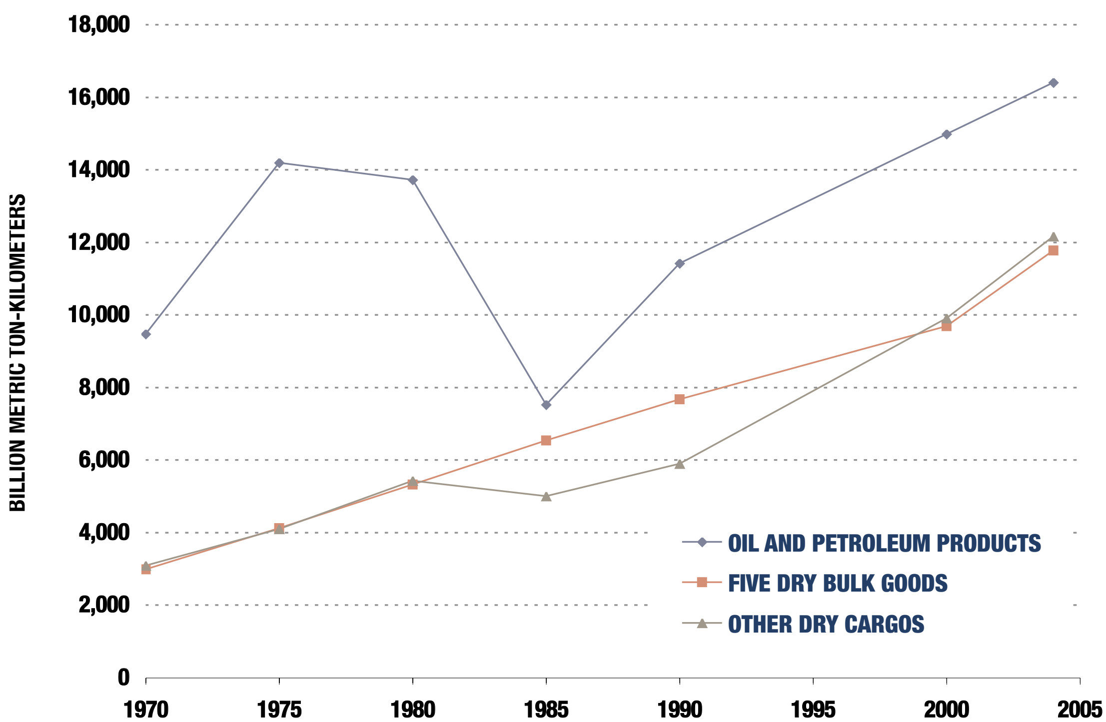

FIGURE 2. World Seaborne Freight Transport in Metric Ton-Kilometers by Type of Freight (UNCTAD 2005)

Rim and North Atlantic. Table 3 presents the latest statistics on container volume (in TEUs) for the world's top ten ports, as reported by the U.S. Department of Transportation Maritime Administration (MARAD).

TABLE 3. Top Ten Ports by Container Volume in 2004 (MARAD 2005)

RANK	PORT	COUNTRY	VOLUME (1,000 TEUS)
1	Hong Kong	China	42,600
2	Singapore	Singapore	31,000
3	Busan	South Korea	17,700
4	Kaohsiung	Taiwan	16,500
5	Rotterdam	Netherlands	13,100
6	Los Angeles/Long Beach	United States	11,800
7	Shanghai	China	9,900
8	Port Klang	Malaysia	9,900
9	Yantian	China	9,700
10	Hamburg	Germany	9,300

The top five container ports are also the top five ports in terms of vessel traffic (MARAD 2005). Singapore and Hong Kong are distinguished by more than two times higher levels of ship and container traffic than are other major ports in these categories. As a consequence, these two locations probably also experience disproportionate air quality impacts from ship-related pollution emissions.

The ports of Hong Kong, Singapore and Rotterdam are also among the top five ports in terms of non-containerized goods handling (AAPA 2004). Non-containerized goods consist of bulk cargo such as petroleum, chemicals, and agricultural products. Other important bulk cargo ports include the ports of Shanghai and South Louisiana.

Since the world merchant fleet regularly uses specific routes, emissions tend to be concentrated along certain channels—the equivalent of highways in the ocean. At any given time, approximately 80 percent of the worldwide fleet is either harbored (55 percent of the time) or near a coast (25 percent of the time). This means most ships spend only about 20 percent of the time at sea and far from land (Corbett et al. 1999). It also means that most ship emissions occur near enough to land to influence not only local air quality in coastal and harbor areas but also soils, rivers, and lakes in those areas. Studies making use of geographic marine activity data have estimated that about 70–80 percent of all ship emissions occur within 400 km (248 miles) of land[4] (IMO 2000, Corbett et al. 1999). The vast majority (85 percent) of ship emissions occur in the northern hemisphere. The most affected coasts, as indicated by more darkly shaded areas in Figure 3, are in the Northern Hemisphere: the North Atlantic (Europe, North and West Africa, Eastern North America, and the Caribbean) and the Pacific Rim (Asia and Western North America).

The following sections review results from studies that have attempted to estimate global emissions from the international operation of commercial ships over the last decade, along with their contribution to local inventories of pollutant emissions.

B. GLOBAL SHIPPING EMISSIONS INVENTORIES

A review of the technical literature reveals that evolving inventory methodologies have produced sharply higher estimates of emissions from international marine vessels over the last decade. The first globally resolved emissions inventory for

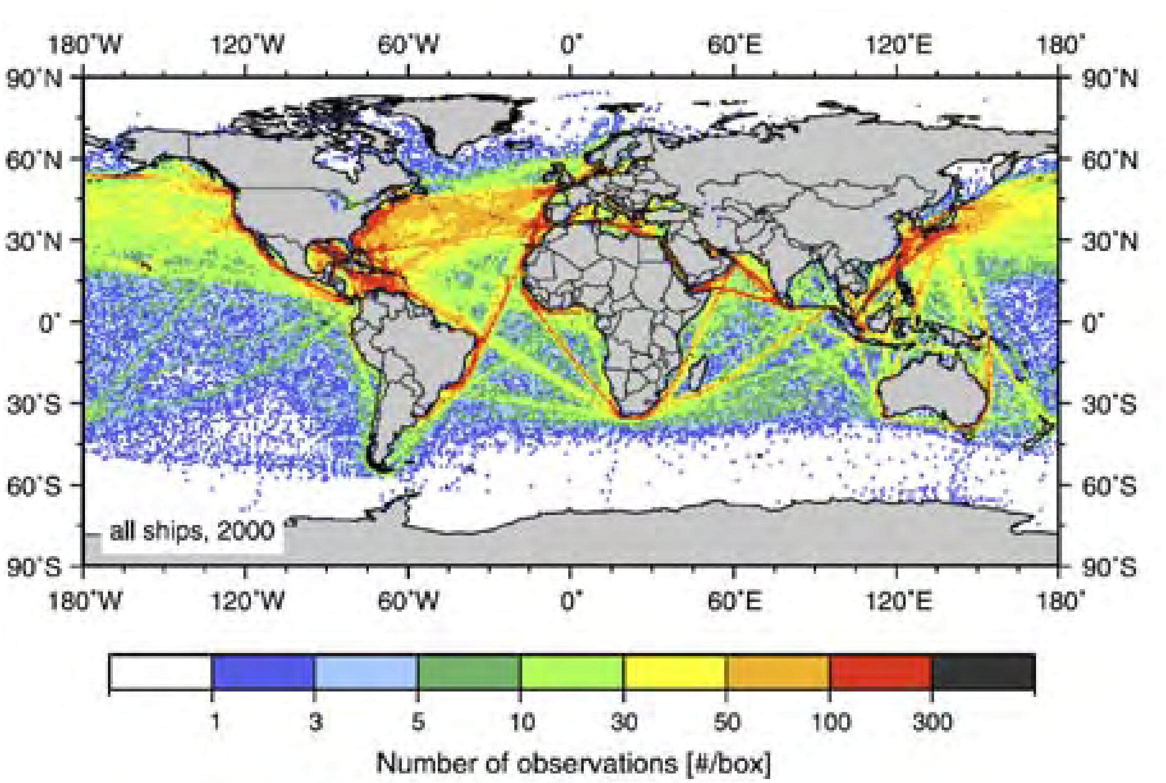

FIGURE 3. Vessel Traffic Density in 2000 (Eyring et al 2005b)

ocean-going ships was developed by Corbett and Fishbeck in 1997. This assessment found that ocean-going ships are major contributors to global emissions of nitrogen and sulfur, and, to a lesser extent, to global emissions of carbon dioxide (CO_2), fine particulate matter (PM), hydrocarbons (HCs), and carbon monoxide (CO). Because such a high proportion of ship emissions occur relatively close to coastal areas and port cities, the ship contribution to emission inventories in many heavily populated land areas ranged from 5 percent to 30 percent (Corbett et al. 1999).

Three factors are typically necessary to characterize ship emissions: (1) data on activity levels (e.g., hours of operation, engine load), (2) engine emission factors, and (3) information about where ships operate so that air quality impacts can be modeled.

- *Activity levels*. Early studies estimate ship activity levels using a top-down approach based on estimates of marine bunker fuel consumption provided by the International Energy Agency (IEA) (Corbett et al. 1999, IMO 2000). More recent studies, such as Endresen et al. (2003), Corbett and Koehler (2003), and Eyring et al. (2005a), estimate energy consumption and emissions using a bottom-up approach that takes into account the number of registered ships in service as well as the number of engines on each ship, and applies engine load factors, average fuel consumption rates, and emission factors for each engine.

- *Emission factors*. Emission factors by engine type, fuel type and engine power levels (cruising at sea, in port, and maneuvering) were developed by Lloyd's Marine Exhaust Emission Program in 1995. More recently, these emission factors have been updated with manufacturer data and compiled by the European Commission (Corbett and Koehler 2003, Eyring et al. 2005a).

- *Geographic location*. Information on vessel traffic density is available through several government and private sector sources. Four sources are commonly discussed in the reviewed literature: (1) the U.S. government's system for collecting data on meteorological conditions and geographic locations from ships,[5] (2) a UK-based private company that has developed a security and asset management service that plots ship position by communicating with each ship's navigational system (called purplefinder), (3) a voluntary global ship reporting system sponsored by the U.S. Coast Guard to facilitate worldwide search and rescue at sea, and (4) Lloyd's Register data. Since 2004, all ships on international voyages are required to transmit data on their position using an Automatic Identification System (AIS). This data as well as other data sets from regional monitoring systems such as the vessel monitoring system in Europe are expected to improve the availability of vessel traffic data.

Table 4 presents different estimates of global fuel consumption and NO_x, SO_x, PM_{10},[6] and CO_2 emissions from various studies of the international shipping industry's emissions contribution. Also included is the estimated percentage contribution to global emissions. To calculate this contribution, results from the various studies were compared with an average global emissions estimate for all sources based on inventories compiled by the Intergovernmental Panel on Climate Change (IPCC 2000).[7] The summary table reveals a general trend over time towards larger estimates of fuel consumption and emissions.

The earliest study included in Table 4 was prepared for the IMO by three consultants from Norway, the Norwegian Marine Technology Research Institute (Marintek), Econ Analyse, and Det Norske Veritas (DNV), and a fourth group of researchers from Carnegie Mellon University in the United States. The report's emission estimates for CO_2, NO_x, and SO_x were based on an estimate of marine bunker fuel consumption and a statistical model. The authors found that ocean-going vessels accounted for about 1.8 percent of global CO_2 emissions in 1996. The study employed the US-NOAA data on ship locations to support a finding that approximately 80 percent of ship emissions occur near the world's coastlines, which is consistent with Corbett et al.'s findings in 1999.

The Endresen et al. (2003) study was performed by researchers from DNV and the University of Oslo. Instead of relying on fuel purchase statistics, the researchers developed a statistical model of fuel consumption. They obtained results comparable to the study prepared for IMO in 2000. This is not surprising because the assumptions used were designed to reconcile the model's results with fuel use statistics. In addition to estimating NO_x, N_2O, SO_x, PM, CO, and CO_2 emissions, the study provides an assessment of the impact of ship emissions on ozone formation, sulfate deposition, and atmospheric methane concentrations.

Studies by Corbett and Koehler (2003) and Eyring et al. (2005a) have produced substantially higher estimates of emissions from international maritime vessels. Using a bottom-up methodology, Corbett and Koehler estimated marine bunker fuel consumption at 289 million metric tons (MMTs), almost two times greater than the estimate used in the IMO (2000) and Endresen et al. (2003) studies. As a result, their analysis finds

TABLE 4. Fuel Consumption, Emissions, and Percent Contribution to Estimated Global Inventories (in parenthesis) from International Ships Greater than 100 tons GRT (as listed and Appendix A)

SOURCE	YEAR OF PUBLICATION	FUEL CONSUMPTION (10^6 METRIC TONS)	NO_X (10^6 METRIC TONS)	SO_X (10^6 METRIC TONS)	PM_{10} (10^6 METRIC TONS)	CO_2 (10^6 METRIC TONS)	INVENTORY YEARS
Eyring et al.	2005a	280	21.4 (29%)	12 (9%)	1.7	813 (3%)	2001
Corbett and Koehler	2003	289	22.6 (31%)	13 (9%)	1.6	912 (3%)	2001
Endresen et al.	2003	158	12 (17%)	6.8 (5%)	0.9	501 (2%)	1996 and 2000 (shown)
IMO	2000	~ 120 – 147	10 (14%)	5 (4%)		419 (1.5%)	1996

that international marine vessels account for about 30 percent of global NO_x emissions from all sources and 9 percent of global SO_x emissions. The results developed by Eyring et al. (2005a) using a similar bottom-up methodology are comparable to those of Corbett and Koehler (2003).

Unlike the IMO (2000) and the Endresen et al. (2003) studies, the methodologies used in Corbett and Koehler (2003) and Eyring et al. (2005a) are independent of reported fuel sales. Furthermore, the Eyring et al. (2005a) paper provides new evidence that data on reported sales of marine bunker fuel are likely to be inaccurate. Indeed, comparing energy statistics with ship numbers and cargo movement over time suggests that international sales data for marine bunker fuel substantially underestimate actual fuel consumption by this sector. Eyring et al. (2005a) provides a useful graphic, reproduced here as Figure 4, which suggests that marine bunker fuel consumption does not reflect growth in the number of international ships over time. From 1970 to 2001, the world-merchant fleet grew by 70 percent, with the most rapid expansion occurring in the 1980s. Yet based on sales data, consumption of marine bunker fuel was stagnant or declining during those same years, as shown in Figure 4. The result suggests that sales of marine fuel are poorly accounted for in current reporting systems.

Emissions from marine source emissions compare well to emissions from the on-road transportation sector.[8] Figure 5 and Figure 6 are useful to put the range of results shown in the larger context of global air pollutant and greenhouse gas inventories. Figure 5 and Figure 6

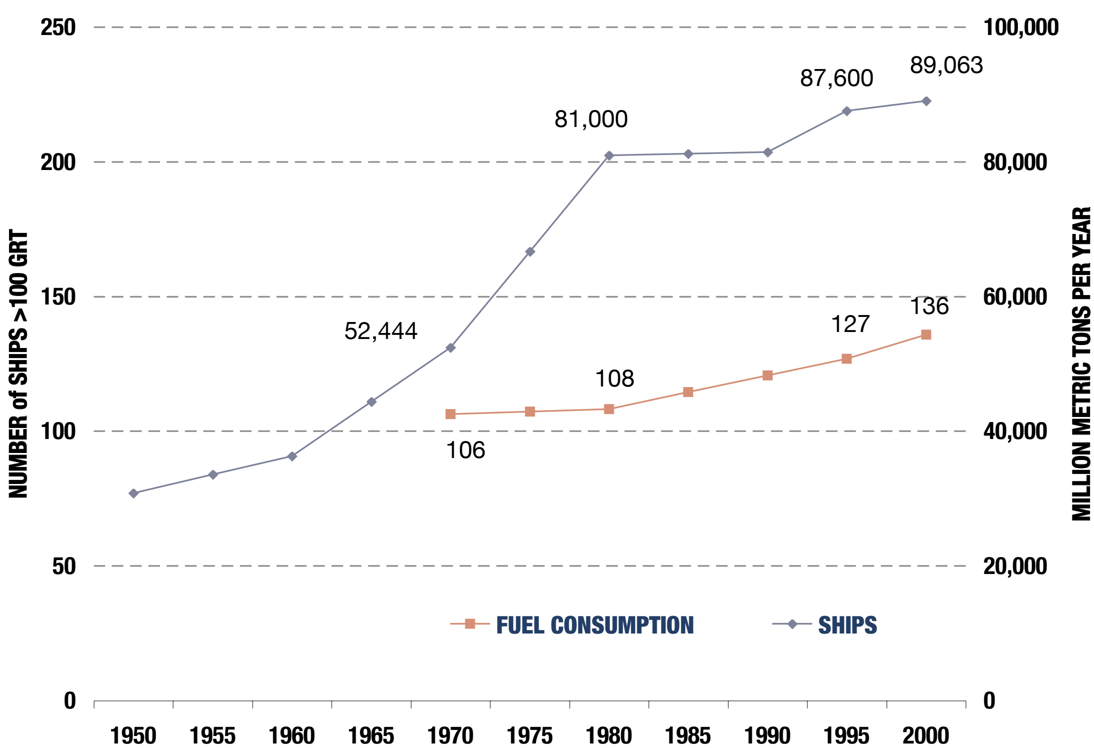

FIGURE 4. Number of International Marine Ships and Estimates of Marine Bunker Fuel Consumption (Eyring et al. 2005a)

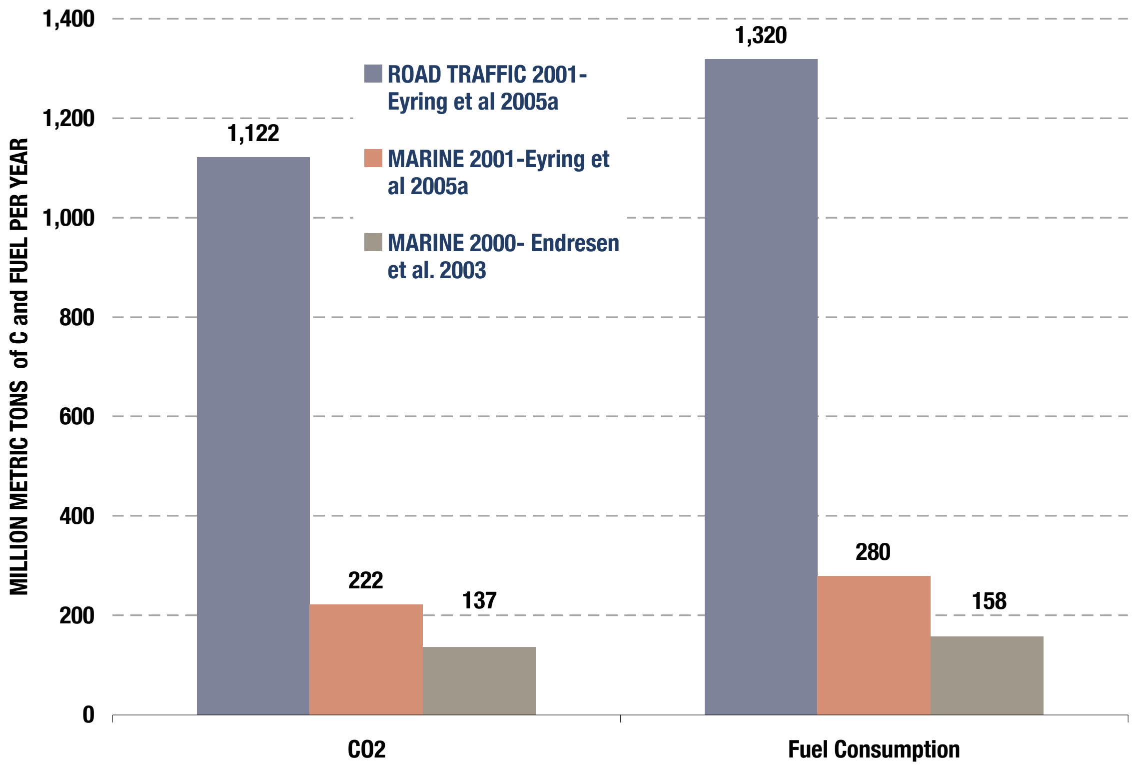

FIGURE 5. Estimated Global CO_2 Emissions and Fuel Consumption for Marine Vessels and On-Road Vehicles in 2001 (Eyring et al. 2005a, Endresen et al. 2003)

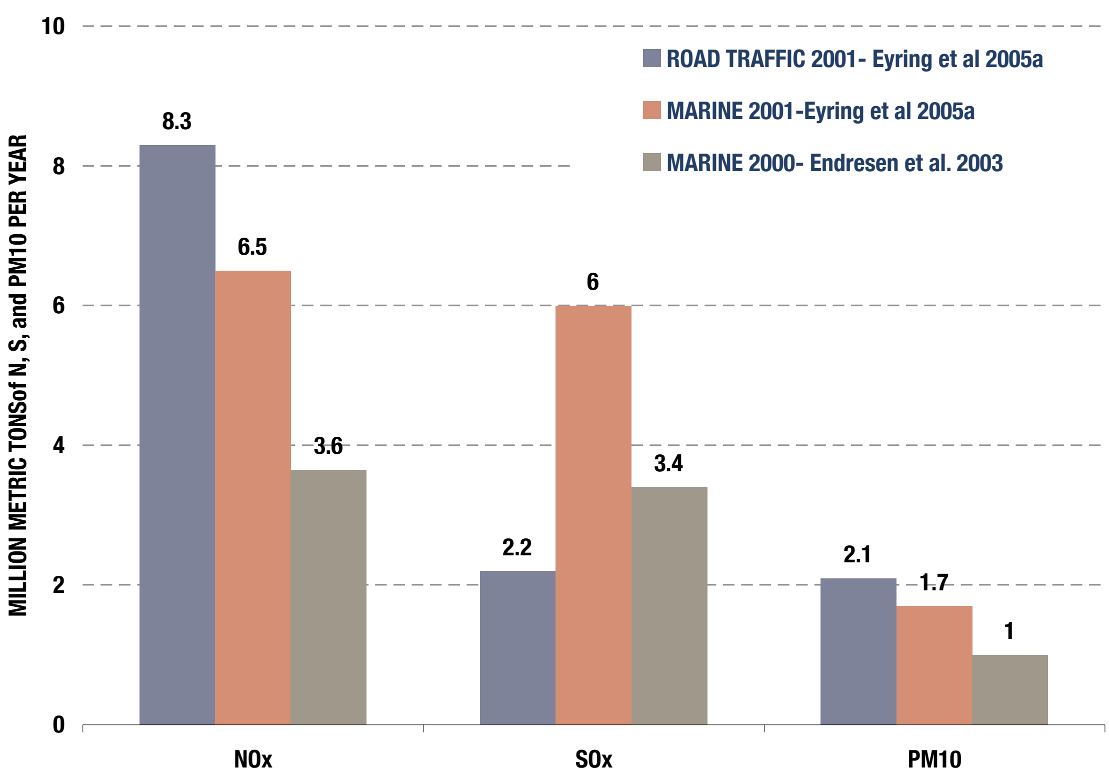

FIGURE 6. Estimated Global NO_x, SO_x, and PM_{10} Emissions for Marine Vessels and On-Road Vehicles in 2001 (Eyring et al. 2005a, Endresen et al. 2003)

compare emission inventories and fuel consumption for all on-road and marine sources using different sets of estimates for the marine contribution. Figure 5 suggests that global fuel consumption and CO_2 emissions from marine sources are about 12– 21 percent the contribution from on-road transportation sources. However according to Figure 6, criteria pollutant levels are on par with, or even greater than, emissions from all on-road vehicles. Emissions of SO_x from international ships exceeded SO_x emissions from on-road sources by a factor of 1.6 to 2.7. NO_x and particle emissions from ships are lower than the estimated emissions from all on-road vehicles (44 to 78% for NO_x and 48 to 81% for PM_{10}). Although the emission estimates from Endresen et al. (2003) are approximately a factor of two lower than those from Eyring et al. (2005a), both sets of results support the finding that ship emissions are significant compared to emissions from on-road sources.

C. CONTRIBUTION OF SHIP EMISSIONS TO LOCAL AIR POLLUTION INVENTORIES

In the 1990s, ship SO_x emissions were estimated to account for 5–30 percent of ambient sulfur concentrations near many populated land regions (Capaldo et al. 1999). Recent studies in Europe and the United States have confirmed these earlier findings and have reached similar conclusions concerning the ship contribution to NO_x and PM concentrations (EC 2005, Corbett and Koehler 2003). Table 5 presents the estimated contribution of ship NO_x and SO_x emissions to national air pollution inventories in several European countries (EMEP 2000). The contribution from ship emissions tends to be especially significant in small nations with large coastlines and thriving ports. The figures presented in Table 5 tend to support the finding (noted in the previous section) that ship emissions make a larger contribution to NO_x inventories than to SO_x inventories.

Because their air emissions remain comparatively unregulated, ships are now among the world's most polluting combustion sources per ton of fuel consumed (Corbett et al. 1999). Due to government policies implemented over the last several decades, land-based pollutant emissions in many countries have declined rapidly, even as energy use

TABLE 5. Ship Contribution to National Emission Inventories for Selected European Countries (EMEP 2000)

COUNTRY	NO_x EMISSION CONTRIBUTION	COUNTRY	SO_x EMISSION CONTRIBUTION
Malta	38%	Malta	16%
Cyprus	24%	Denmark	15%
Denmark	20%	Sweden	13%
Sweden	16%	Netherlands	13%
Greece	15%	Cyprus	10%
Portugal	14%	Norway	9%
Netherlands	13%	Portugal	9%
Finland	13%	Belgium	9%

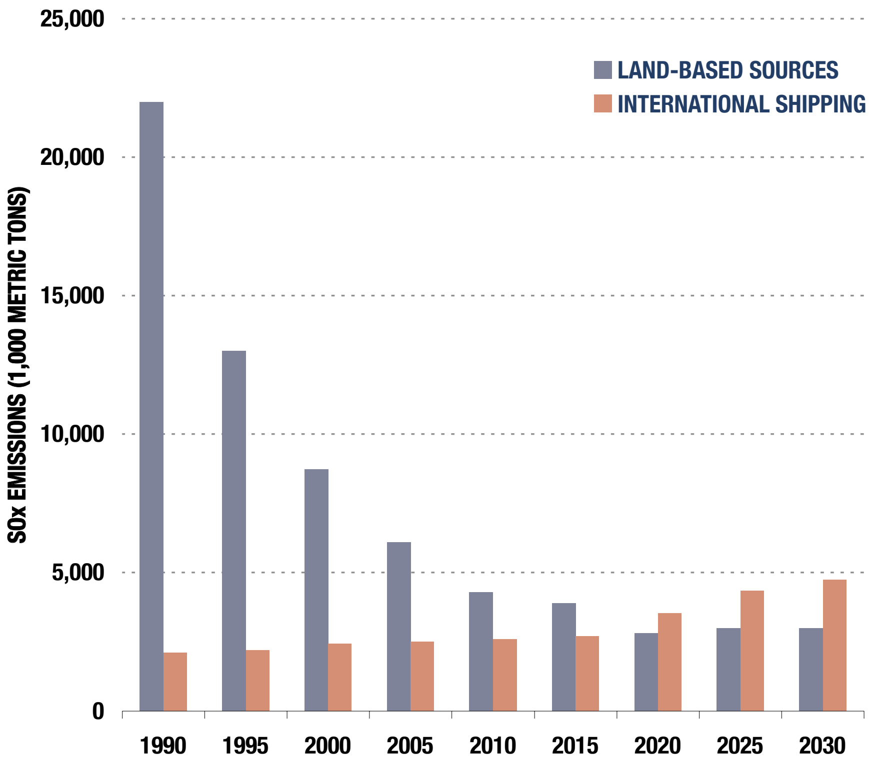

FIGURE 7. Projected SO_x Emissions in Europe from Land-based and International Shipping Sources (EC 2005)

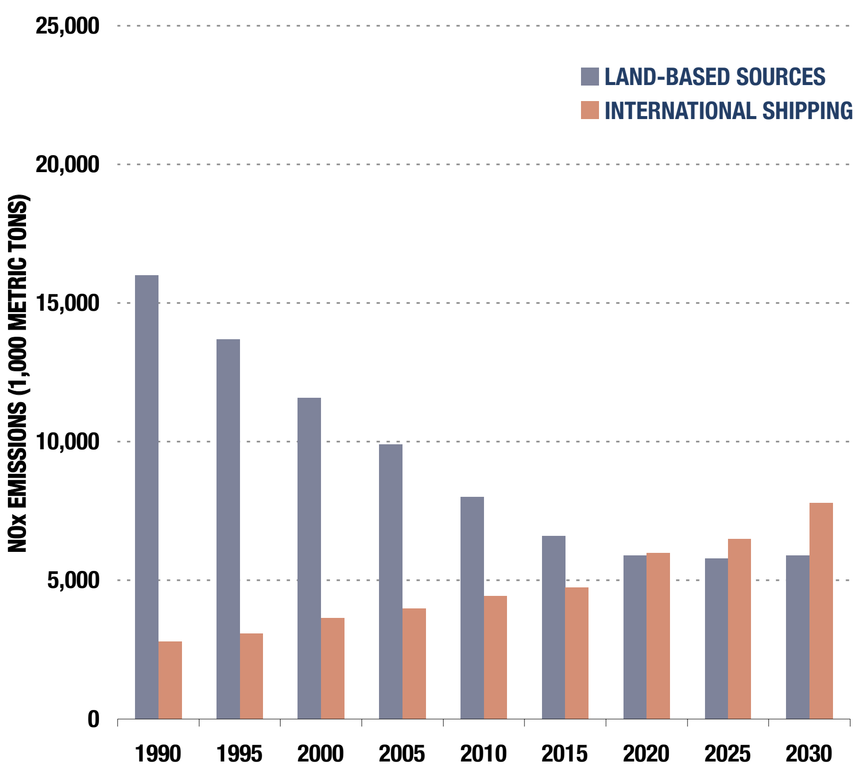

FIGURE 8. Projected NO_x Emissions in Europe from Land-based and International Shipping Sources (EC 2005)

and transportation demand have grown. Land-based SO_x emissions in Europe have declined by 56 percent over the last two decades, and are projected to continue to decline as new standards are phased in (EMEP 2000). Land-based emissions of other air pollutants such as NO_x and volatile organic compounds (VOCs) have also declined in many countries, but to a lesser extent. Figure 7 and Figure 8 from the European Commission's thematic strategy on air pollution show a continued decline in projected land-based emissions of these pollutants. By contrast, emissions from international shipping are projected to continue growing. Current projections indicate that the ship contribution to NO_x and SO_x inventories for the 25-nation EU region will surpass total emissions from all land-based sources by 2020.

In Hong Kong, home to the world's busiest container port, marine sources are the only emission sources that have exhibited continued growth over the last decade (Civic Exchange 2006). Figure 9 and Figure 10 show the relative contribution to the Hong Kong NO_x and SO_2 inventories of three mobile source categories: vehicles, aviation, and marine. Ships are currently the main mobile sources SO_2 emitters and, if current trends are sustained, could surpass vehicles as a major emitter of mobile source NO_x.

The data presented in Table 6 compares the emissions in 2004 in the bay of Tokyo from anchored ships to other air pollution sources operating on the coast. Again, ships are shown to be one of the major sources of SO_x and a significant contributor to NO_x inventories in the port city.

By 2030, the U.S. Environmental Protection Agency (EPA) estimates that international shipping will account for 12 percent of the United States' overall NO_x inventory and 45 percent of total diesel fine particle emissions. Not surprisingly, air quality impacts from ships and port activities are concentrated in U.S. cities with large harbors. Table 7 presents data on ship emissions as a percent of local emissions inventories for several major U.S. port cities. In Santa Barbara, California ship emissions are projected to exceed emissions from all land-based sources by 2015 (US EPA 2003).

Emissions from port activities have been linked to significant health impacts in neighboring communities. A recent study by the California Air Resources Board (CARB) estimates that diesel PM emissions from the Port of Los Angeles and Long Beach increase the cancer risk for 60 percent of the neighboring population by at least 100 in a million (CARB 2006). The study also estimated other, non-cancer health impacts and concluded that 14–43 additional premature deaths and 180–1,300 additional asthma attacks could be attributed to emissions from these ports each year (CARB 2006).

TABLE 6. Tokyo Bay Inventory of Coastal Pollution Sources in 2004 (Metric Tons/Year) (Tokyo Metropolitan Government 2006)

POLLUTANTS	VESSELS (ANCHORING)	OTHER COASTAL SOURCES	
		VEHICLES	STATIONARY SOURCES
NO_x	2,086	8,280	4,730
SO_x	1,898	240	1,400
Soot and Dust	145	690	210

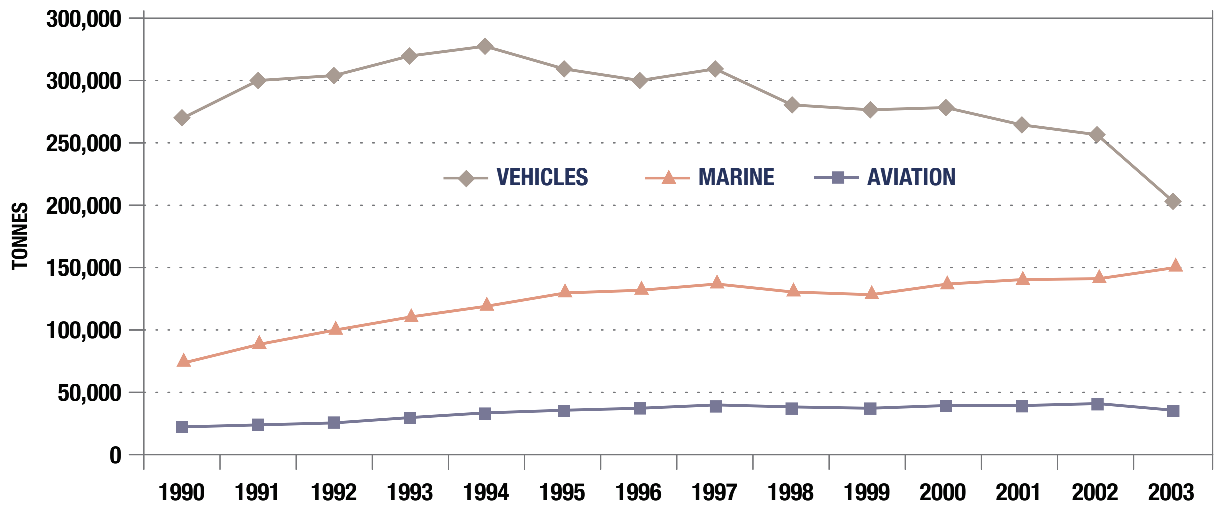

FIGURE 9. Mobile Source NO_x Emissions in Hong Kong (Gall and Van Rafelghem 2006)

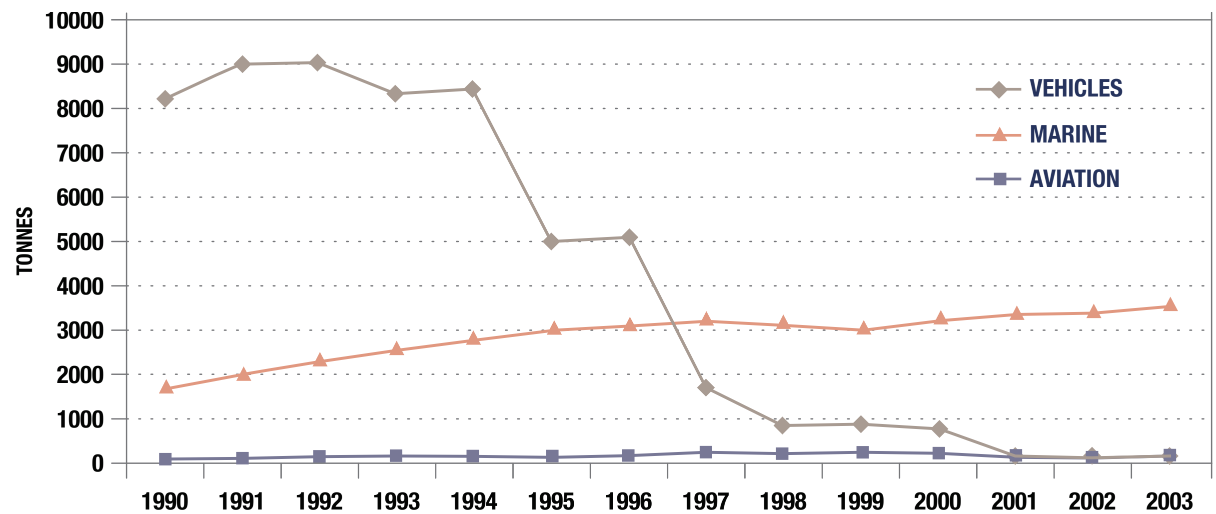

FIGURE 10. Mobile Source SO_2 Emissions in Hong Kong (Gall and Van Rafelghem 2006)

TABLE 7. NO_x and PM Contributions from International Ships to Air Pollution Inventories in Major U.S. Port Cities in 2020 (US EPA 2003, France 2005)

CITY	NO_x EMISSION CONTRIBUTION	CITY	PM EMISSION CONTRIBUTION
Miami, FL	28%	Miami, FL	29%
Wilmington, NC	27%	Seattle, WA	25%
Seattle, WA	26%	Baton Rouge and New Orleans, LA	23%
Baton Rouge and New Orleans, LA	16%	Wilmington, NC	22%
Corpus Christi, TX	12%	Los Angeles, CA	11%
Baltimore / Washington DC	11%	Baltimore / Washington DC	10%
Los Angeles, CA	9%	Corpus Christi, TX	10%

TABLE 8. Contribution to Total Emissions from the Movement of Goods in California (CARB 2006)

SOURCE	DIESEL PM		NO_x		SO_x	
	2001	2020	2001	2020	2001	2020
Ships	43%	75%	23%	55%	92%	100%
Harbor craft	24%	14%	21%	20%	1%	-
Cargo handling equipment	5%	1%	5%	2%	-	-
Trucks	15%	6%	31%	12%	2%	-
Transport refrigeration units	3%	-	1%	-	1%	-
Trains	10%	1%	19%	11%	4%	-

In sum, ships already play a significant role in local emission inventories, especially in port areas. Their contribution as a percent of total freight transport emissions is even larger and is projected to grow larger in the future, as emissions from other land-based transportation sources decline. The state of California is currently developing a plan that will link infrastructure improvements with efforts to reduce air quality and other environmental impacts from freight transport. Recent emission estimates summarized in Table 8 show that ships will account for the largest share of emissions associated with the movement of goods in California by 2020. While all other sources will have lower emissions in 2020 than in 2001, ship emissions within 24 nautical miles (44.5 kilometers) of the California coast will more than double: from 8 tons per day (tpd) in 2001 to 21 tpd by 2020 for diesel PM; from 94 tpd to 220 tpd for NO_x, and from 49 tpd to 160 tpd for SO_x.

D. GREENHOUSE GAS EMISSIONS FROM INTERNATIONAL SHIPPING

Ships are considered to be one of the most energy efficient cargo transportation modes. Mode switching to ship transport is often proposed as an option to reduce CO_2 emissions from cargo transportation. However to fully understand the impact of shipping on greenhouse gas emissions, it is important to consider in addition to CO_2 the different types of emissions that affect the Earth's climate, including NO_x, SO_2, methane, aerosols, and chlorinated hydrocarbons. While the impacts of these emissions in terms of their radiative forcing potential (that is, their net warming or cooling effect on the atmosphere) are relatively well understood only a few studies have looked specifically at the ship contribution to global climate-change risks. Typically, these studies consider the following types of ship emissions:

- *Carbon dioxide:* CO_2 emissions from ships contribute directly to global warming, regardless of where they occur. Emissions from ocean-going vessels are estimated to account for 1.5–3 percent of overall CO_2- related radiative forcing (Corbett and Koehler 2003, Endresen et al. 2003, Eyring et al. 2005a, IMO 2000).

- *Nitrogen oxides:* In combination with hydrocarbons, which are widely available in the marine environment, NO_x emissions contribute to the formation of ozone. Although the global warming effect of ground-level ozone is low, both NO_x and ozone can be transported higher in the atmosphere where ozone has a significantly greater radiative forcing impact. NO_x emissions also play a role in the reduction of methane, which has a smaller cooling effect. Overall, however, ship NO_x emissions are believed to have a net warming effect—one that is potentially equivalent to the warming effect from ship CO_2 emissions (IMO 2000).

- *Primary and secondary particulate matter:* Sulfates are estimated to have an overall cooling effect. The ship tracks, clouds that form in the wake of a ship's passage seeded by its PM emissions, are expected to have a slight cooling impact. Black carbon emissions are anticipated to have a warming impact. Black carbon from all sources, may be responsible for as much as 25 percent of observed global warming, and may have a climate-forcing efficacy twice that of CO_2 (Hansen and Nazarenko 2004). The net impacts of primary and secondary particulate matter from ships on climate change risks are currently uncertain, as it is difficult to model all effects (including impacts on the albedo—or reflectiveness—of snow and ice surfaces, as well as impacts on cloud formation).

- *Refrigerant gases:* Fluorinated and chlorinated hydrocarbons (such as R-22) are still used as cooling agents in refrigerated ships and fishing vessels (UBA 2004). These hydrocarbons are highly potent greenhouse gases (UBA 2004). It has been estimated that 50 percent of the hydrofluorocarbons (HFCs) or perfluorocarbons (PFCs) used on a ship are released to the air during operation and that an additional 15 percent are emitted during maintenance (Drewry 1996).

Taken together, CO_2 emissions from international shipping exceed total greenhouse gas emissions from most nations listed in the Kyoto protocol as Annex I countries (Kyoto Protocol 1997). The magnitude of the ship contribution (in terms of the total atmospheric forcing associated with all ship emissions combined) remains uncertain (IMO 2000). Future research efforts should focus on improving inventory methodologies as well as understanding the net radiative forcing associated with different types of ship emissions.

E. FUTURE EMISSIONS FROM INTERNATIONAL SHIPPING

Commercial shipping is at the heart of an ongoing expansion of global trade. Ship traffic has increased steadily over the last two decades and is predicted to continue growing for the foreseeable future. This growth has important implications for the magnitude of the ship contribution to future air pollution and greenhouse gas inventories. Figure 11 through Figure 13 summarize emissions projections for marine operations through 2050. The projections were developed

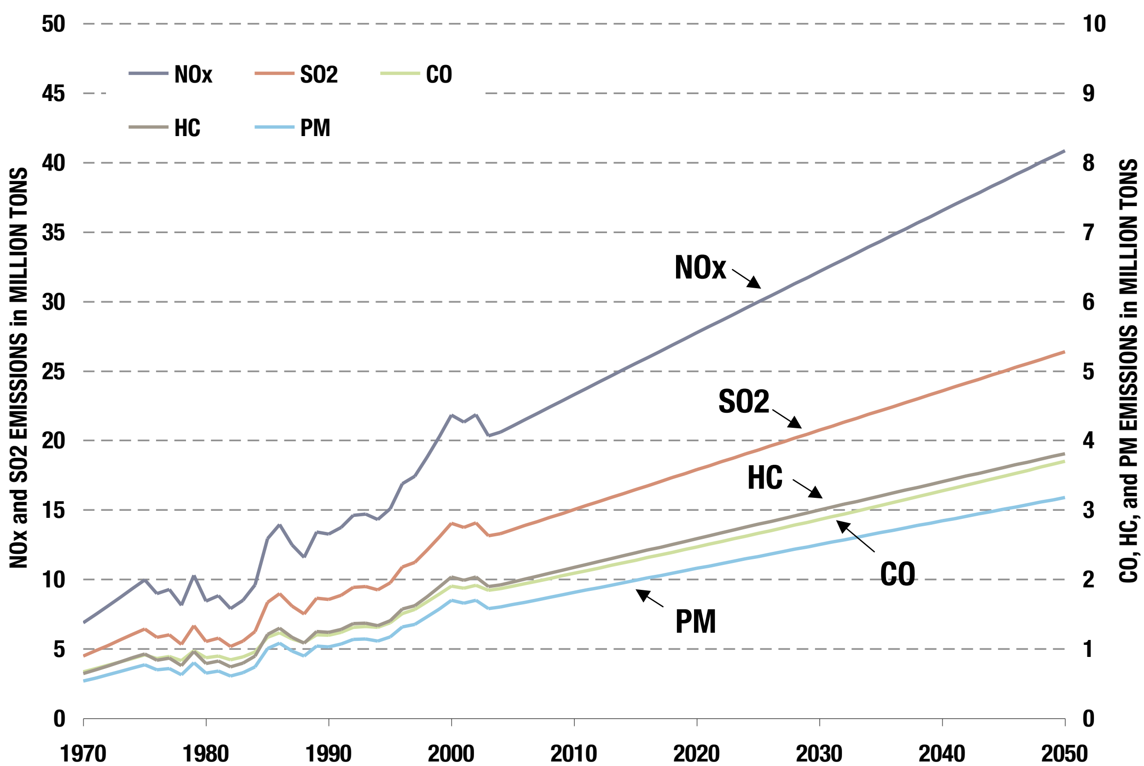

FIGURE 11. NO_x SO_2, CO, HC, and PM Emissions from International Shipping: 1970–2050

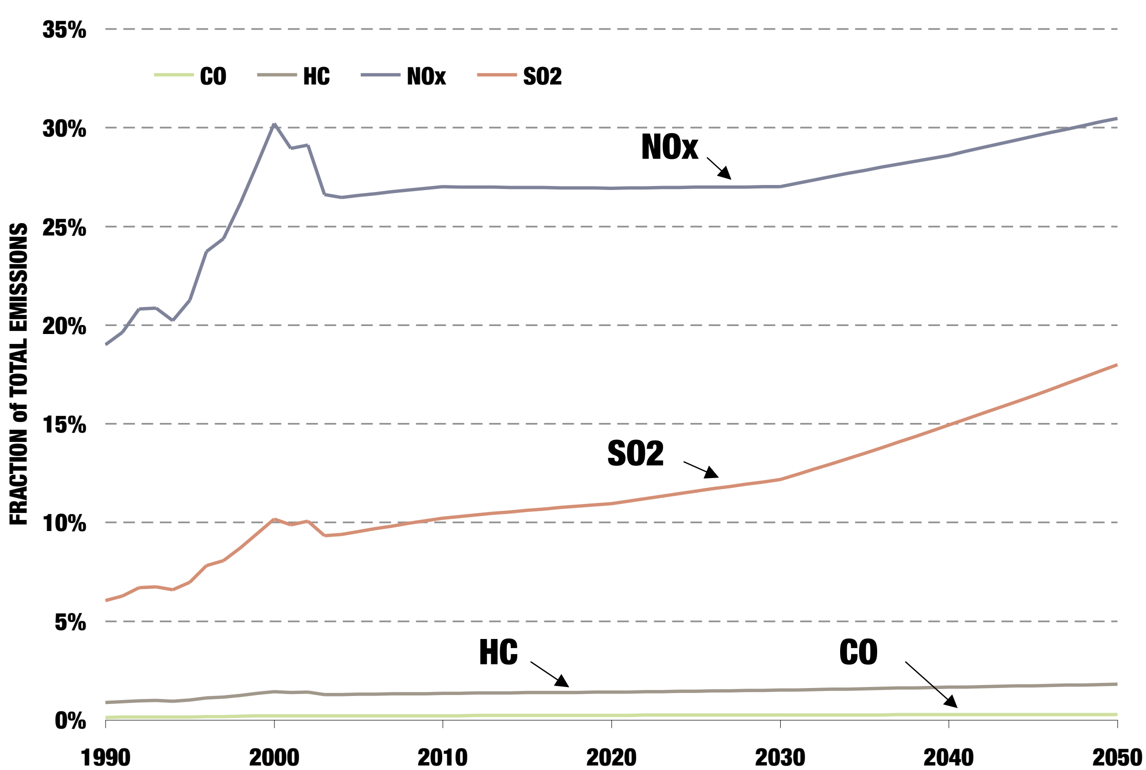

FIGURE 12. Shipping Emissions as a Fraction of Estimated Global NO_x, SO_2, CO, and HC Emissions: 1990–2050

for this report by Meszler Engineering Services (Appendix A). Figure 12 and Figure 13 present the shipping sector's contribution relative to projections of emissions from the Intergovernmental Panel on Climate Change (IPCC). PM is not included because an estimate of global emissions for this pollutant is not currently available.

The Meszler Engineering Services emission inventory is based on a simplified bottom-up approach in which global marine cargo shipments were used to derive historic and future activity levels for the international shipping fleet. As with the Corbett and Koehler (2003) and the Eyring et al. (2005a) analyses, the Meszler Engineering Services analysis did not rely on marine bunker fuel statistics. Energy consumption for the international shipping fleet was calculated by multiplying global marine cargo movements in ton-kilometers by global marine operating efficiency. The Meszler Engineering Services analysis is more limited than the studies summarized in previous sections in that it does not attempt to place emissions spatially. It also makes some judicious simplifying assumptions that tend to underestimate rather than overestimate fuel consumption and emission levels.

In 2005, international shipping accounted for 27 percent of global NO_x emissions, 10 percent of global SO_x emissions, and 3 percent of global CO_2 emissions. If current trends continue, the ship contribution as a percent of global emissions in 2050 is expected to rise to more than 30 percent for NO_x, 18 percent for SO_x, and 3 percent for CO_2. Total ship emissions of fine particles are also estimated to more than double in that period.

The sector's share of SO_x emissions, in particular, is expected to grow significantly over the analysis

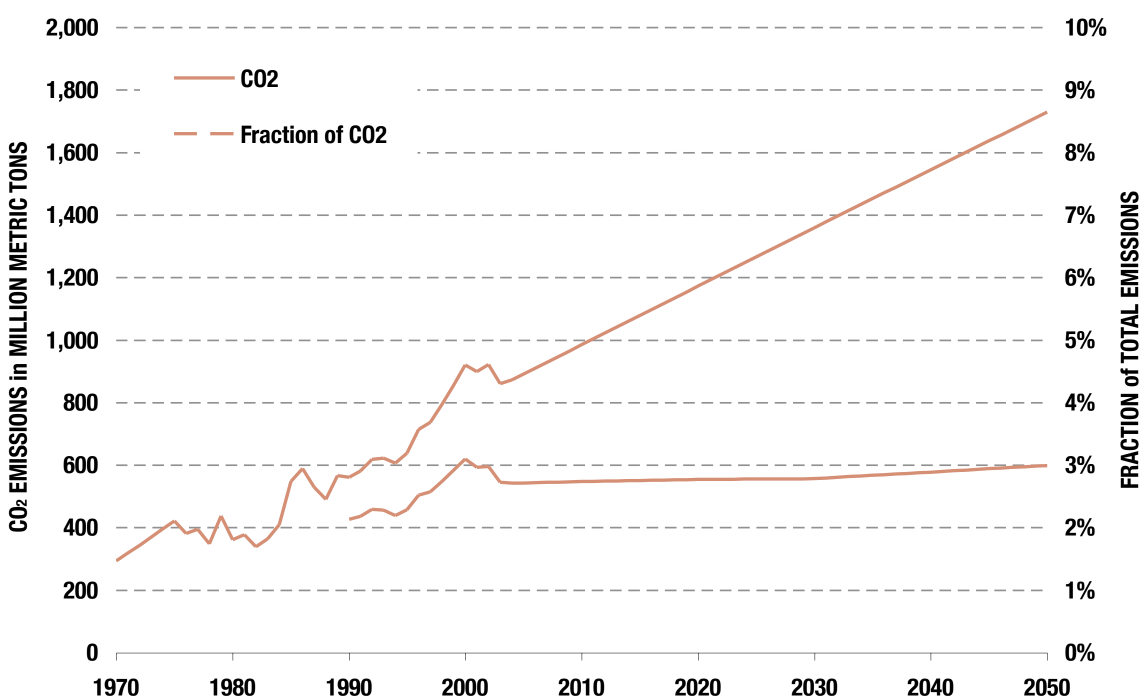

FIGURE 13. Global CO_2 Emissions from International Shipping and Fraction of Total Emissions: 1970–2050

period, primarily due to continued progress in reducing land-based sulfur emissions from coal-fired power plants and on-road vehicles. Similarly, progress in regulating land-based NO_x emissions means that the shipping contribution as a share of global emissions of this pollutant is also projected to grow, albeit less dramatically than in the case of SO_x. The trend is different for CO_2 simply because carbon emissions from all other sources are not yet being significantly regulated on a global basis. As a result, projected growth in ship emissions is mostly matched by projected growth in overall carbon emissions and the percent contribution from marine operations increases only slightly. The air quality impacts of projected growth in ship emissions of NO_x, SO_x, and PM are likely to be especially significant in the Pacific Rim and North Atlantic regions due to the concentration of shipping activities in those regions.

The environmental impacts of marine shipping are not limited to air quality and global climate change. In recent decades, the most visible environmental impacts have involved oil spills that have affected large coastal areas worldwide. Other significant environmental impacts include disturbances to ecosystems from organism exchange through ballast water, grey and black water discharges, the presence of toxic substances in the antifouling paint used to prevent algae and other organisms from attaching to ship hulls, the use of ozone-depleting cooling liquids, and the disposal of solid waste materials. Impacts from these ship-related sources of pollution have been documented at every level of marine ecosystems. They occur not only during ship operation on the high seas, but also near land—especially in ports and harbors. For example, ship building and dismantling produces toxic chemicals and generates serious health risks for exposed workers. Waste disposal, dredging, dust, and noise associated with ship activity have been identified as primary environmental concerns for European ports (ECOPORTS 2005). These concerns extend to residential communities located near ports throughout the world.

The global nature of the international shipping sector and its impacts in developed and rapidly industrializing nations alike provide a unique opportunity to develop innovative and collaborative strategies to address both local air quality concerns and global warming. The challenge lies in navigating the opportunities and constraints created by the legal framework that currently governs international shipping. That legal framework—particularly as it pertains to the regulation of air emissions—is discussed in the next chapter.

III. INTERNATIONAL MARITIME LAW

This chapter focuses on the authority of coastal and port nation-states to establish and enforce environmental policies affecting foreign-flagged ships. The point of departure for this discussion is the 1982 United Nations Convention on the Law of the Sea (UNCLOS). This convention was negotiated over a nine-year period by close to 150 nations and many of its provisions leave states with considerable latitude in interpretation and application. A full understanding of jurisdictional boundaries between flag, port, and coastal states requires a careful review of other relevant topics such as state practice[9] and treaties and other actions taken by the International Maritime Organization (IMO). A central theme throughout the discussion that follows is the recognition that maritime law continues to evolve over time to accommodate the changing demands and interests of all nations, including environmental interests (Molenaar 1998).

A. BACKGROUND

The control of air pollution from ocean-going vessels constitutes a relatively new area of maritime law. For centuries, the prevailing view was captured in the "freedom of the seas" doctrine—a 17th century principle that limited national rights and jurisdiction over the oceans to the narrow belt of sea surrounding a nation's coastline (UN 2006). By the middle of the 20th century, there was a general recognition that this doctrine needed to be updated to effectively address technological, political, and environmental challenges concerning the world's oceans (UN Agenda Item 92 1967). When it was adopted UNCLOS was heralded as "a constitution for the oceans" (Koh 1982); it formally entered into force in 1994. The Convention's 25 subject areas cover nearly every aspect of the uses and resources of the sea, including navigational rights, territorial sea limits, legal status of resources on the seabed, passage of ships through narrow straights, conservation and management of marine resources, protection of the marine environment, a marine research regime, and a binding procedure for settling disputes between states (UN 1982). A major feature of the Convention was its definition of different maritime zones: the territorial sea, the contiguous zone, the exclusive economic zone, the continental shelf, the high sea, the international sea-bed area, and archipelagic waters. As of 2006, 147 nations or territories were parties to UNCLOS.

The IMO was established in 1948, prior to the process leading to UNCLOS, by an international conference of nation's in Geneva. The purposes of the organization, as summarized by Article 1(a) of its founding convention, are "to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships". In 1973, the IMO adopted the International Convention for the Prevention of Pollution from Ships. That convention, which is also known as the MARPOL 73/78 treaty, was amended in 1978. It covers accidental and operational oil pollution; pollution by chemicals, goods in packaged form, sewage, and garbage; and air pollution. MARPOL applies to all ships of the flag states that have ratified it. It also applies to ships of non-signatory states while operating in waters under the jurisdiction of Parties to MARPOL. Table 9 lists the major treaties related to air pollution from ocean-going ships.

UNCLOS grants the IMO a pivotal role in establishing international rules and regulations for ocean-going ships. While UNCLOS gives some jurisdiction to port and coastal states in the control of marine air emissions, the Convention professes a clear preference for international regulations wherever possible. Though IMO is explicitly mentioned only once in UNCLOS (Article 2 of Annex VIII), UNCLOS frequently refers to the "competent international organisation" in connection with the adoption of international shipping safety and pollution standards. In most cases, the phrase "the competent international organisation" has been interpreted to refer to the IMO.

The primary mechanism for regulating pollution from ocean-going vessels under UNCLOS is through international rules and standards set by the IMO, or in some cases, through other international treaties. In fact, there is nothing to prevent key port and coastal states from negotiating bilateral or multilateral treaties concerning air pollution with major flag states, although the large number of flag states makes this approach difficult to implement in practice (BMT 2000). The key pollution provisions within UNCLOS instruct states to establish international rules and standards to control pollution "acting through a competent international organization or general diplomatic conference (Art. 211(1))" or "taking into account" internationally agreed rules, standards and recommended practices (Art. 212(1))." IMO standards are ratified and go into force once they are approved by at least 55 states that represent more than 55 percent of shipping tonnage by registered vessels.

Implementation and enforcement of IMO standards falls primarily to the flag states that hold primary jurisdiction over those ships registered in their country. By definition, a flag state is the state in which a vessel is registered. As discussed in the industry overview provided in Chapter II, the majority of ships above 1,000 GT are registered under flags of convenience. The flag state is required to "ensure compliance with international rules and standards" for vessels registered to it and to provide for "effective enforcement" no matter where violations occur (Art. 217). UNCLOS requires a "genuine link" between the flag state and the registered shipping company; as such, inter-

TABLE 9. Major Treaties Related to Air Pollution from Ocean-going Ships

DATES	NAME OF TREATY AND KEY EVENTS
	International Maritime Organization
1948	• Convention establishes IMO
1958	• Ratified: Enters into force
	International Convention on Prevention of Pollution from Ships (MARPOL 73/78)
1973	• Codified
1978	• Amended and Codified
	United Nations Convention on the Law of the Sea (UNCLOS)
1973	• First meeting of United Nations Convention
1982	• Codified
1994	• Ratified: Enters into force
	MARPOL Annex VI (Regulations for the Prevention of Air Pollution from Ships)
1997	• Codified
2005	• Ratified: Enters into force

national legal scholars debate whether states with "open registries," such as Panama and Liberia, are permitted under UNCLOS.

UNCLOS also grants some supplemental regulatory and enforcement authority to port and coastal states. This authority has grown over time as flag states have not shown themselves to be the most vigilant stewards of IMO rules and standards and as growth in international shipping has exacerbated environmental and other impacts from ocean-going vessels on port and coastal states. UNCLOS provisions that allow coastal and port states to establish regional agreements to enforce IMO rules and regulations have been frequently used over the last several decades.

In addition to regional agreements to better enforce existing IMO rules and standards, states also have authority—within certain key constraints—to regulate foreign flagged ships that enter their territory (inland waterways, ports, and territorial waters). This jurisdictional-based authority includes the ability to establish rules and standards that exceed IMO regulations. Articles 211 and 212 permit states to adopt laws and regulations that "shall at least have the same effect as generally accepted internationally rules and standards established through a competent international organization" (Art. 211(2)) and may "take other measures as may be necessary" (Art 212(2)). The text and structure of UNCLOS clearly envision additional unilateral national-level regulatory actions by individual states or by groups of states (Molenaar 1998). Moreover, states, or groups of states, that establish rules going beyond IMO regulations as a condition for the entry of foreign vessels into their ports are required to publicize those additional requirements to the maritime community and to communicate them to the IMO (Art. 211(3)).

MARPOL 73/78 does not prevent a country from setting standards for its ships. Annex VI specifically allows a country to set alternative standards that would apply to engines on ships that operate solely in waters under its jurisdiction. The United States and several European nations have begun to address shipping emissions in their waters based on this authority.

B. DEFINITION OF POLLUTION IN UNCLOS

The definition of pollution in UNCLOS is limited to the marine environment—that is, the world's seas, oceans, estuaries, etc. UNCLOS identifies and seeks to prevent or limit pollution from reaching the marine environment through six distinct avenues: (1) from land based sources, (2) from seabed sources subject to national jurisdiction, (3) from activities in the Area, (4) by dumping, (5) from vessels, (6) from and through the atmosphere (Art. 4). Where air pollution is explicitly mentioned in Article 212, it is only in relation to the deposition of pollution "from" or "through" the air into the marine environment: "States shall adopt laws […] to control pollution of the marine environment from or through the atmosphere." While the IMO has focused primarily on those pollutants that pose a risk to the marine environment (i.e., NO_x and SO_x), it has also departed from the narrow definition in UNCLOS by examining the feasibility of addressing greenhouse gas emissions. State environmental agencies typically apply a broader definition that seeks to address adverse public health and environmental consequences from direct exposure to air pollution. That definition often includes not only NO_x and SO_x, which contribute to the eutrophication or acidification of inland bodies of water as well as marine environments, but also pollutants such as PM and greenhouse gases.

C. JURISDICTION OF FLAG, PORT, AND COASTAL STATES IN UNCLOS

UNCLOS sought to balance the international shipping community's interest in the free passage of sea-going vessels with the local and national interests of coastal and port states. It did so by adopting a zonal approach, where the legal status of an ocean-going vessel depends on its physical location in three zones: (1) on the high seas, (2) along a coast, and (3) at port.

HIGH SEAS JURISDICTION On the high seas, flag states hold sole jurisdiction over ocean-going vessels. In other words, ocean-going vessels on the high seas are required only to comply with globally agreed upon standards subject to enforcement by the flag state (Art. 217). With only limited exceptions—such as when a foreign-flagged ship enters the territorial waters (e.g., harbor) of another nation—flag state jurisdiction is the general rule under UNCLOS (BMT 2000). Over time, the exclusive enforcement jurisdiction of flag states has been pared back by the IMO in order to promote more effective implementation of maritime safety and pollution standards (DOALOS 2003). Groups of port states surrounding major seas (e.g., Caribbean, Mediterranean, Black Sea, North Atlantic basin) have entered into regional agreements (e.g., Paris MOU) to collaborate on inspections and enforcement. Once a regional MOU for the Gulf of Mexico enters into force, there will be a complete network of regional MOUs covering most of the world's major shipping areas (DOALAS 2003).

COASTAL STATE JURISDICTION Coastal states exercise sovereignty over their territorial sea, which is defined as a band of water 12 nautical miles (22.2 kilometers) beyond the low water mark. Foreign vessels are allowed "innocent passage" through those waters. Activities inconsistent with innocent passage include fishing, spying, launching military devices, or "any willful and serious pollution contrary to this Convention (Art. 19)." Coastal states have the right to claim additional jurisdiction beyond territorial waters: an additional 12 nautical miles (22.2 kilometers) in the contiguous zone, and up to 200 nautical miles (370 kilometers) in the exclusive economic zone (EEZ). Coastal states are entitled to enforce pollution control requirements that exceed MARPOL 73/78 standards only in their territorial seas and may not establish regulations that apply to the design, construction, manning, or equipment of foreign ships (Art. 21). California has adopted sulfur fuel standards for auxiliary and diesel electric engines on ocean-going vessels operating within 24 nautical miles (44.5 kilometers) of the state's coastline that will go into effect in 2007. The regulation states that only marine gas oil or marine diesel oil with a sulfur content limited to 0.5 percent or less can be used in auxiliary engines operated within 24 nautical miles (44.5 kilometers) of the state's coastline. By 2010, only marine gas oil with sulfur content limited to 0.1 percent or less will be allowed.

In general, charges may not be levied on foreign ships traveling through territorial waters. Charges may, however, be levied as payment for "specific services rendered to the ship (Art. 26)" as long as the charges are not discriminatory.

PORT STATE JURISDICTION As a general rule, foreign ships enjoy no automatic right of access to ports of other nations, except in times of distress when lives are at stake or when another treaty is applicable. States have the right to exclude foreign vessels from their ports and inland waterways, and may apply national laws and regulations to foreign ships when at port (BMT 2000). As a result, the port state has concurrent jurisdiction with the flag state when a ship is at port. Port state efforts to regulate foreign-flagged ships are subject to certain limits. Any regulation must not be an abuse of rights, it must not seek to exercise jurisdiction over matters considered the "internal economy" of the ship, it cannot hamper "innocent passage," and it must not have the practical effect of impacting the "construction, design, equipment or manning (CDEM)" of ships (Art 21(2)). If any port state requirements run afoul of these constraints, they are said to "travel with the ship" onto the high seas, and are likely to be "hotly disputed" (BMT 2000). According to one legal treatise on this topic, a standard that can only be met using selective catalytic reduction (SCR)—an exhaust after-treatment system—is a good example of a requirement that would impact ship CDEM: once the technology is paid for and fitted, there is little point in leaving it off when the engines are running except to avoid the added cost of the urea needed to operate the SCR system (BMT 2000). Nevertheless, the Swedish Environmental Supreme Court ruled in 2006 that "a local environmental board in a harbor city has the right to set requirements for ships that regularly call at the harbor in order to protect people's health" (Environmental Board 2006). The decision forces two ferry companies operating in Helsingborg to install NO_x control systems on their new and existing vessels.

Thus the two major limitations affecting port state jurisdictional authority relate to the right of innocent passage and the prohibition on requiring changes in the construction, design, manning or equipment of foreign vessels. UNCLOS Part 2, Section 3 guarantees innocent right of passage for foreign-flag vessels in the territorial sea without being subject to any charges, except for services received. This restriction is clearly relevant to the control of emissions from shipping, since under a strict reading of this requirement, payments or charges designed to limit emissions from foreign-flag vessels would have to be couched in a framework of providing services to those vessels. In addition, one aspect of the right of innocent passage, stated in Article 21 of UNCLOS, precludes coastal states from enforcing any regulations that apply to the design, construction, manning or equipment of foreign vessels. As already mentioned, this could be interpreted as restricting the ability of coastal states to require pollution abatement equipment or engine modifications on foreign vessels. One reason for considering market-based approaches to emissions regulations is that they offer a flexible means of complying with environmental regulations, thereby potentially making it easier to promote the use of low-emissions technologies in certain sea areas without impinging upon ships' right of innocent passage.

D. CONCLUSION

In general, the primary mechanism for regulating pollution from ocean-going vessels under UNCLOS is through international rules and standards set by the IMO, or in some cases, through other international treaties. States have the authority to subject foreign-flagged vessels to air pollution standards that go above and beyond international minimum requirements as long as certain conditions are met. Those conditions include allowing innocent passage to foreign vessels in territorial waters and refraining from imposing any rules that would have the practical effect of creating additional hardware or staffing obligations that "travel with the ship" into the high seas. In many cases, the legality of state action is inextricably tied to the practical effect of a regulatory policy. As port and coastal states throughout the world seek to limit the adverse effects of air pollution from ocean-going vessels by enacting various new policy instruments, a new body of international rules and practice will evolve on a case-by-case basis. And it is likely that the existing balance between flag, coastal, and port state authority will be reshaped over time to better serve the interests of all parties.

IV. EMISSIONS MITIGATION OPTIONS FOR INTERNATIONAL MARINE VESSELS

Emissions control options for marine vessels can generally be classified in three broad categories. *Technology improvements* can reduce both local and global emissions by replacing or upgrading older, less-efficient or higher-polluting engines with more efficient and lower-emitting propulsion systems. *Operational changes* reduce local emissions by modifying how vessels operate while entering and docking in the harbor. Although the fraction of global ship emissions that occurs during in-port operations is modest compared to at sea emissions (with the exception of CO emissions), in-port emissions—because they generally occur near populated areas—are likely to have a disproportionate impact on local emission inventories and public health risks. *Market-based programs,* such as variable port fees and emissions trading programs, can spur both operational and technology changes if they are well designed and implemented.

The discussion below focuses on marine vessels, the largest source of emissions related to ocean-borne commerce as discussed in Chapter II. However, it is important to note that both local and global air quality would benefit from an integrated approach to addressing all sources of emissions associated with the worldwide movement of goods. Indeed, many cost-effective measures exist to reduce emissions from trucks, trains, and cargo handling equipment. This section starts with a review of current international and national emission standards for ships before discussing specific marine source control technologies and measures.

A. INTERNATIONAL AND NATIONAL FUEL AND EMISSION STANDARDS

The IMO's Marine Environmental Protection

Committee (MEPC) is responsible for regulating emissions from seagoing ships. Starting in the 1950s and 1960s, the IMO initially focused on marine safety (i.e. the SOLAS agreement), oil tanker accidents (e.g. Torre Canyon), storage tank cleaning, and dirty ballast water. In the 1990s, the MEPC widened its scope to start addressing concerns about air pollution. As discussed previously, the underlying international agreement for this work is MARPOL 73/78 Annex VI. It was adopted in 1997, ratified by 15 states representing at least 50 percent of world shipping tonnage in May of 2004 and went into effect 12 months later (in May 2005) (IMO 2004).

The Annex VI standards set limits for NO_x emissions that vary with engine speed. Table 10 provides the formula used to calculate maximum NO_x emissions based on engine crankcase revolutions per minute. The IMO characterized the NO_x standards as a 30 percent reduction from current levels, but the U.S. EPA more recently determined that the standards would reduce NO_x levels by 20 percent (US EPA 2003). No standards have been set for particles, hydrocarbon, or carbon monoxide emissions.

TABLE 10. MARPOL 73/78 Annex VI NO_x standards

ENGINE SPEED (N IN RPM)	NO_x (G/KWH)
n <130 rpm	17
130 ≤ n < 2,000 rpm	45 * n -0.2
n ≥ 2,000 rpm	9.8

Annex VI sets a global cap on fuel sulfur at 4.5 percent. The average sulfur content of fuels currently used in ships is 2.7 percent, a little more than half of the IMO's global cap. Consequently the benefits of the IMO fuel program are expected to be limited. Annex VI also establishes the first SO_x Emission Control Area (SECA) in the Baltic Sea. Ships operating in this area must use lower (1.5 percent) sulfur fuels beginning in May 2006. The next SECA is planned for the North Sea per an amendment to Annex VI adopted in 2005. The North SECA enters into force in November 2006 and will be fully implemented and enforced in November 2007 after a 12-month grace period.

Existing international standards for NO_x emissions and fuel sulfur content merely codify existing industry practices. It is expected that a significant portion if not all of these reductions would have been obtained without regulation. Thus the costs and benefits associated with current IMO regulations have been characterized as "negligible" by the U.S. EPA compared to a business-as-usual baseline (US EPA 2003).

In 2003, the United States adopted standards equivalent to the Annex VI NO_x limits for international marine diesel engines built in 2004 and later. Voluntary standards—called Blue Sky standards—were also established during this rulemaking consistent with EPA's assessment of emission levels achievable with the application of existing technologies. At the same time, the agency indicated that it would consider a subsequent round of standards (or "tier," in U.S. regulatory parlance) that would reflect further reductions achievable through additional engine-based controls. These future standards would apply to engines on US-flag vessels, and may also apply to engines on foreign flag vessels operating in United States waters.

While its standards are currently identical to the IMO Annex VI standards, the U.S program differs from the IMO program in important details of compliance and certification. Engine manufacturers have been allowed additional time to comply with these new aspects of the U.S. system, which are summarized below.

- *Liability for In-Use Compliance.* Engine manufacturers are responsible for ensuring compliance with emission standards for the full useful life of the engine under the U.S. EPA program. Placing in-use compliance obligations on engine manufacturers creates an ongoing incentive to produce durable emission control systems. In contrast, Annex VI makes ship operators responsible for ensuring in-use compliance.

  U.S. EPA requires operators to perform a field measurement test. The Annex VI program requires only periodic surveys of the engine, which can take the form of a simplified onboard test or, more frequently, a parameter check.

- *Durability Demonstration.* Manufacturers must demonstrate in-use compliance for the full useful life of the engine prior to production, where useful life is assumed to be three years before the engine's first rebuild. The Annex VI program only requires manufacturers to demonstrate compliance when an engine is installed in a vessel. There is no Annex VI durability demonstration. Given the long life of marine diesel engines, this is a significant omission.

- *Certification Test Fuel.* It is well established that fuel quality directly influences engine emissions—thus the quality of the fuel used to certify the engine should reflect the quality of fuels likely to be used in actual operation. The U.S. program requires the use of marine bunker fuel, the fuel used in most marine applications, for certification testing while Annex VI specifies that a distillate fuel be used for engine testing. Because the distillate fuel specified is much cleaner than bunker fuels, its use for engine testing does not reflect real world operating conditions and results in artificially low emissions for purposes of demonstrating compliance.

Figure 14 illustrates the difference between the IMO and US EPA Blue Sky standards discussed above. The figure also includes data on the levels achieved by controlled and uncontrolled marine engines. The IMO NO_x standards are the least stringent limits on engine NO_x emissions over the range of engine speeds shown. Emission results for uncontrolled engines and those modified to meet the IMO standards (NO_x optimized engines) are also included in the figure. The U.S. EPA Blue Sky Voluntary standards are several times lower than the IMO standards and are easily met with the use of a well-established SCR after-treatment technology. Since January 2005, the Swedish Maritime Administration's environmentally differentiated fairway dues program has offered dues reductions to vessels that achieve NO_x emission limits within 11 categories between 10 and 0 g/kW-hr (SMA 2005). The lowest emission performance category (0.5–0 g/kWh) is specifically intended for auxiliary engines. The next section describes SCR and other technology options for controlling ship emissions.

The European Union issued its strategy to emissions from ships in 2002 (EC 2007). The strategy's primary focus is on reducing SO_2 and PM emissions to reduce the impacts of these pollutants on acidification and local air quality respectively. Consequently, recent EU regulations and recommendations have focused on marine fuel sulfur content and emissions at port.

The EU adopted Directive 2005/33/EC in August 2005 to address the sulfur content of fuel oils used in European waterways (Europa 2005). The amendment requires progressive implementation of lower sulfur fuels by geographic region and /or by vessel type between 2006 and 2010. Table 11 summarizes the directives fuel requirements. Starting in 2006, all fuel used in the Baltic Sea and in passenger vessels regardless of operation location must meet a 1.5 percent sulfur limit. This requirement is extended to the English Channel and the North Sea in 2007. These requirements are in line with to the IMO SECA requirements. A review is scheduled for 2008 when the feasibility of further reducing the sulfur limit to 0.5 percent will be examined. Marine fuel used by ships traveling along inland waterways will have to meet a 0.1 percent sulfur content limit starting in 2010. Ocean-going and inland waterway ships will also be required to use 0.1 percent sulfur fuel while at berth. Ships that use shore-side electricity are exempt from this requirement.

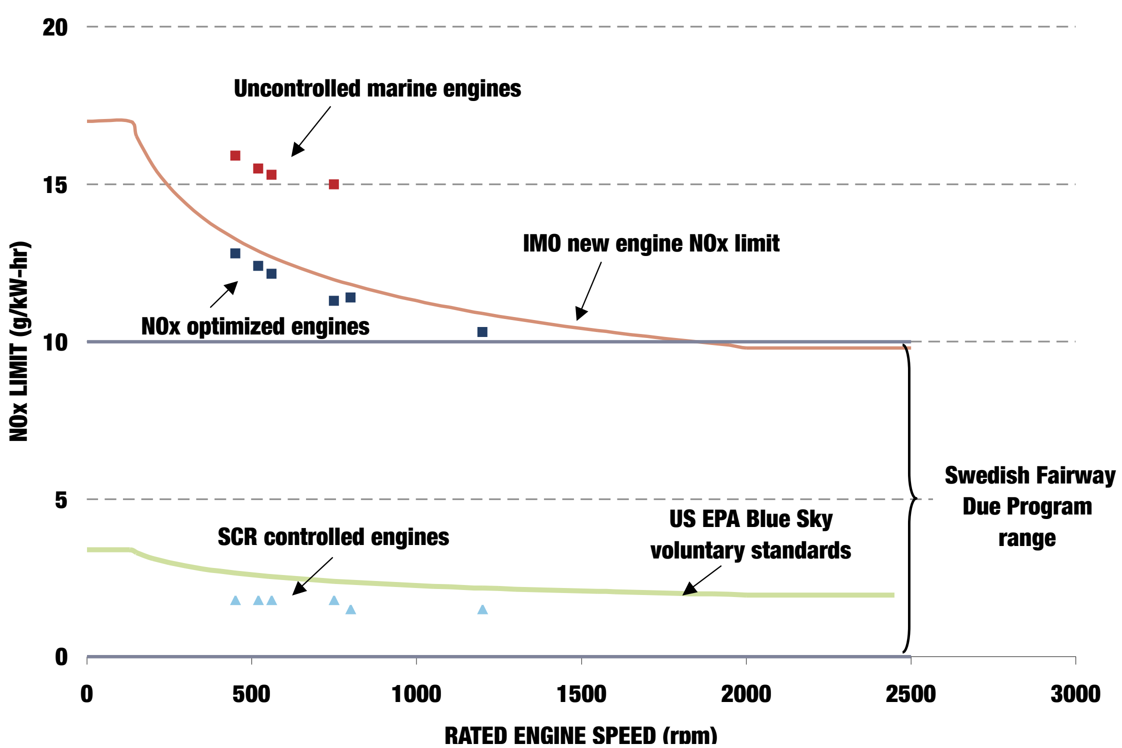

FIGURE 14. Marine Engine NO_x Standards in the United States, EU, and Sweden (Eyring 2005a, SMA 2005)

In May 2006, the European Commission issued a non-binding recommendation that encourages member states to pursue policies including economic incentives to encourage the development of shore-side electricity to mitigate ship emissions at berth (EC 2007).

B. EMISSION CONTROL TECHNOLOGIES AND POTENTIAL REDUCTIONS

Because the international marine sector is one of the least regulated sources of anthropogenic emissions, the potential for emission reductions through technology improvements in this sector is significant (Eyring et al. 2005b). The basic diesel internal combustion engine (ICE) employed on large commercial marine vessels is quite similar in design and function to ICEs used in stationary source applications. In both applications, engine load and speed tend to be constant over most of the duty cycle. There are two categories of diesel marine engine: two-stroke slow-speed engines and four-stroke medium- or high-speed engines. Slow speed engines are typically used in container, cargo, tanker, and dry bulk vessels. Ferries and cruise ships are usually powered by four-stroke engines. Four-stroke engines are also used as auxiliary power units in vessels of all types.

Gas turbines are increasingly replacing diesel engines in a number of applications, particularly in high-speed ferry and military applications that take advantage of their lower weight per unit of power delivered (Genesis Engineering 2003). On newer cruise ships, gas turbines are often used to supply power during peak demand periods, supplementing the diesel engines that provide the ships' baseline power (Genesis Engineering 2003). Tanker ships transporting liquefied natural gas are also often powered by gas turbines.

The operation of large diesel marine engines is typically characterized by extended operation under cruising conditions. This high usage rate, combined with the very high power of international marine engines, makes fuel costs a significant factor for these vessels. As a result, these engines have the lowest brake-specific fuel consumption rates (BSFC) of any internal-combustion engine (as low as 176 g/kW-hr). Manufacturers achieve these results with very high brake mean-effective pressures (up to 2,200 kPa) and low mean piston speeds (7 to 9 m/s). These engine parameters maximize mechanical and propeller efficiencies. Compared with smaller marine engines, these designs for optimum efficiency result in lower power den-

TABLE 11. European Union Marine Fuel Sulfur Content Requirements (Europa 2005)

START DATE	GEOGRAPHIC AREA/ LOCATION	VESSEL TYPE	SULFUR LEVEL (PERCENT)
May 2006	Baltic sea	All	1.5
	European Waters	Passenger vessels	1.5
Fall 2007	North Sea	All	1.5
	Channel	All	1.5
January 2010	Inland Waterways	All	0.1
	At Berth	All	0.1

sity, the power output for a given engine weight or cylinder displacement.

Marine engines generally produce emissions of SO_x, NO_x, HC, CO, and PM at a far higher rate than their stationary source and mobile source counterparts. This is in part due to the lack of stringent pollution control requirements on these engines and in part due to the poor quality of the fuel they burn. Marine fuel used in ocean-going vessels is often referred to as bunker fuel or by its industrial name, Intermediate Fuel Oil (IFO). IFO is mainly composed of residual oil—the lowest grade of fuel oil available—mixed with varying levels of distillate oil. Residual oil is the heavy oil product remaining after distillation in a refinery (EIA, 2006). It is very viscous; that is, it is partially solid at low ambient temperatures and requires heating to turn it into a liquid state before it is delivered to the engine. Hazardous products such as polycyclic aromatic hydrocarbons (PAHs) and metals are concentrated in residual fuel, which is classified as a carcinogenic substance in Europe (OEHHA 2004, Ahlbom and Duus 2004). Concerns have been raised about residual fuel streams contamination by used oil and other hazardous chemicals including solvents, PCBs, metals, and acidic materials (OEHHA 2004, Ahlbom and Duus 2004). Bunker fuel was not introduced to the shipping sector until the end of the 1970s when technological developments allowed for its use. Bunker fuel now accounts for about 80 percent of the energy used in the marine shipping sector (Beicip-Franlab 2002).

Table 12 provides details on the four fuel types most commonly used in marine applications: two grades of IFO (380 and 180), marine diesel oil (MDO) and marine gas oil (MGO). Marine diesel oil often contains traces of residual oil and is used to blend residual oil to produce IFOs. Marine gas oil is pure distillate mainly used in harbor crafts and fishing vessels (OEHHA 2004). The sulfur content of all these fuels is very high— two to three orders of magnitude higher than the sulfur content of land-based transportation fuels used in Europe, Hong Kong, Japan, Thailand, and the United States.

The combination of low fuel quality and limited pollution control requirements for engines and vessels has led to the marine sector's poor environmental performance with respect to air emissions. Nevertheless, many of the technologies developed to reduce emissions from stationary

TABLE 12. Most Common Marine Fuels (Vis 2003, BP 2004, Exxon Mobil Marine 2006, CARB 2005)

INDUSTRIAL NAME	ISO NAME	COMPOSITION	ISO SPECIFICATION SULFUR WEIGHT %	WORLD AVERAGE
Intermediate Fuel Oil 380 (IFO 380)	MRG35	98% residual oil 2% distillate oil	5%*	2.67%
Intermediate Fuel Oil 180 (IFO 180)	RME 25	88% residual oil 12% distillate oil	5%*	2.67%
Marine Diesel Oil	DMB	Distillate oil with trace of residual oil	2%	0.65%
Marine Gas Oil	DMA	100% distillate oil	1.5%	0.38 %

* IMO regulation capping sulfur at 4.5% supercedes ISO specification

sources are suitable for application, with some modifications, to marine sources. A variety of strategies for reducing ship emissions—from the use of lower sulfur fuel to engine improvements and exhaust after-treatment—have been demonstrated in a full range of ocean-going vessel types. These strategies generally focus on NO_x or SO_x emissions because they are currently the only internationally regulated ship air pollutants.

NO_x emission reductions can be obtained by engine upgrades aimed at reducing combustion temperatures, for example by adding water at different stages of the combustion process or re-circulating exhaust gas. NO_x reductions can also be obtained by using exhaust after-treatment such as selective catalytic reduction. SO_x emission reduction strategies primarily consist of switching to lower sulfur marine fuels. These strategies can also provide substantial PM emission reductions.

NO_x, SO_x, and PM emissions while at port are an important focus of local air quality strategies. The main options being pursued include the use of lower sulfur alternative fuels in auxiliary engines, electrification with use of a shore-based power supply, and shore-based emission treatment.

Efforts to reduce greenhouse gas emissions have focused on efficiency gains achievable through improved hull design and advanced propulsion systems, and on renewable energy sources. The increased use of alternative fuels such as natural gas and, in the future, advanced technologies such as fuel cells can reduce emissions of all pollutants at sea and in port.

Specific technology options for reducing NO_x, SO_x, PM and greenhouse gas emissions from ocean-going vessels are described in the following sections.

STRATEGIES FOR REDUCING SHIP NO_X EMISSIONS DURING CRUISING

Basic engine modifications are the short-term strategy adopted by most manufacturers to reduce engine NO_x emissions and meet the IMO standards. For example, all new 2-stroke slow speed engines are outfitted with slide valves that optimize spray distribution in the combustion chamber and thus reduce in-cylinder temperature and NO_x formation (Entec 2005b). One manufacturer, MAN B&W, also offers slide valve retrofits for one of its engine families (Entec 2005b). Manufacturers have developed additional engine modifications; these include but are not limited to optimizing injection and valve timing, turbocharger improvements, and implementing common rail (Entec 2005b). These engine technology upgrades are expected to allow production marine engines to attain emission levels 20–30 percent below the current IMO NO_x standards within the next five to ten years (Eyring et al. 2005b).

Although engine modifications have been sufficient to meet international emission standards, local voluntary programs such as the environmentally differentiated fairway dues in place at Swedish ports offer economic incentives to achieve further emission reductions. These incentives, and the expectation that similar programs will be implemented in other regions, have led to the development of strategies that provide additional pollution control benefits compared to engine modifications alone.

A number of strategies that target NO_x emissions involve adding water to the combustion process to reduce combustion temperature and thereby limit NO_x formation, which increases at higher combustion temperatures. Fuel water emulsions (FWE) are stable mixtures of fuel and water. The NO_x reductions achieved by using FWEs are directly proportional to the water content of the fuel. Combining injection timing retard with the use of FWEs can yield moderate NO_x reductions. With direct water injection (DWI), fresh water is injected in the combustion chamber just before the fuel is injected. On cruise ships, grey water can be used as a source of fresh water, thus eliminating the need to either produce or store fresh water on board. Wärtsilä has commercialized DWI for its new 4-stoke engines and provides a retrofit for existing engines. The use of fuel with a maximum sulfur content of 1.5 percent is recommended (Lövblad and Fridell 2006). A version of DWI is under development for two-stroke engines. Both FWE and DWI are expected to increase fuel consumption—and hence CO_2 emissions—by up to 2 percent (Entec 2005b). In addition, DWI use may result in increased PM mass emissions (Entec 2005b).

The humid air motor (HAM) system reduces in-cylinder combustion temperatures by cooling the inlet air with evaporated seawater after it exits the turbocharger. The HAM concept is being developed by Munters and is currently being demonstrated on a ferry outfitted with a MAN B &W engines (Munters 2006). Fuel with 1.5 percent sulfur content or lower is recommended for HAM-equipped engines (Lövblad and Fridell 2006). Wärtsilä is developing a variation of the HAM system known as a combustion air saturation system in which pressurized water is injected into the intake air where it evaporates prior to entering the cylinder (Wärtsilä 2006).

Two additional NO_x technologies, SCR and exhaust gas recirculation (EGR), are directly derived from stationary source pollution reduction strategies. These technologies have provided cost-effective emission reductions in stationary engines and have been adapted for heavy-duty highway engines. SCR has been used on hundreds of marine engines since the early 1990s (US EPA 2003, Holmström 2006). It involves spraying a reducing agent over a catalyst, promoting the reduction of NO_x to N_2 as the exhaust gas flows by. The reducing agent, ammonia, is typically stored in a stable and non-toxic urea solution. SCR requires a 20 to 30 minute warm-up period at start-up (Entec 2005b). Catalyst poisoning by sulfur can affect the durability and cost of SCR systems; the use of fuels with sulfur content above 1 percent will require more frequent catalyst cleaning and replacement. Lower sulfur levels, on the other hand, can significantly prolong catalyst life. In Sweden, the Aurora of Helsingborg, which has been operating with the same SCR catalyst since 1992, uses marine diesel oil with sulfur content of 0.1 percent or less (SMA 2006). Used with 1.5 percent sulfur fuel, by contrast, catalyst replacement could be required as frequently as every five years (Lövblad & Fridell 2006). Additional emission controls, such as an oxidation catalyst placed after the

SCR catalyst, are also necessary to avoid emitting unreacted ammonia, a phenomenon referred to as "ammonia slip."

EGR systems redirect a portion of the exhaust gas into the charge air after it has been filtered of PM and other contaminants and cooled (US EPA 2003). No full-scale demonstration of EGR in marine-engine applications has been reported in the reviewed literature. One issue that would need to be addressed with EGR is the potential for engine deterioration due to PM that remains in the recirculated exhaust after filtration (Entec 2005b).

Table 13 summarizes the main NO_x emission reduction technologies reviewed above.

STRATEGIES FOR REDUCING SHIP SO_X EMISSIONS DURING CRUISING

The primary strategy for reducing ship SO_x emissions is using fuels with lower sulfur content. As mentioned in the previous section, international regulations require the use of 1.5 percent sulfur fuel oil in designated SO_x Emission Control Areas (SECAs) starting in 2006. Widespread use of fuel oil with 1.5 percent sulfur content would reduce global SO_x emissions from ships by over 40 percent. Several environmental organizations

TABLE 13. Summary of NO_x Emission Reduction Technologies (Entec 2005b, Eyring et al. 2005, Genesis Engineering 2003, Wärtsilä 2006)

TECHNOLOGY	NO_X REDUCTION	ENGINE APPLICATION	VESSEL APPLICATION	TECHNOLOGY STATUS	MANUFACTURERS
Engine Modification	20%–30%	2 and 4 stroke	All ship types	Some modifications are standard in some new engines, others expected in 5–10 years	Caterpillar/MaK, FMC, MAN B&W, Wärtsilä,
Selective Catalytic Reduction	85%– 95%	4 stroke medium and high speed, some 2 stroke especially if new due to space requirements	All ship types	Commercially available	Argillon Gmbh, Munters, Wärtsilä
Fuel Water Emulsion	0–30%	2 and 4 stroke	All ship types	Demonstration/ Custom order	MAN B&W, MTU, Orimulsion, PuriNOx,
Direct Water Injection	50%	4 stroke medium speed	With engines manufactured by Wärtsilä	Commercially available	Wärtsilä
Humid Air Motors	70%	4-stroke	Demonstration on a ferry	Limited demonstration	Munters, MAN B &W
Combustion Air Saturation Systems	30%–50%	4-stroke	Demonstration on an auxiliary engine	Research and Development	Wärtsilä
Exhaust Gas Recirculation	35%	4-stroke	n/a	Research and Development	MAN B&W

are advocating a move towards 0.5 percent sulfur fuel, which would reduce global ship SO_x emissions by approximately 80 percent. The use of lower sulfur fuels would also provide significant reductions in ship PM emissions (Entec 2005c). Fuel availability and incremental costs are addressed in Section F.

Seawater scrubbing is often presented as an alternative to the use of lower sulfur fuels. This after-treatment technology takes advantage of seawater's ability to absorb SO_2. As the exhaust passes through cascading seawater in a scrubbing tower, it is scrubbed of a large fraction of SO_2 and a smaller fraction of PM (MES 2006). Oil residue, particles, and other contaminants are removed from the scrubbing water before it is returned to the ocean. The remaining residue is supposed to be disposed of when the vessel is at port; heavy fuel-oil residue is disposed of in a similar manner. Concerns exist, however, about the potential environmental damage if removed waste is not disposed of appropriately. A preliminary analysis concluded that risks from the potential formation of sulfuric acid mist from scrubber air emissions are limited (Entec 2005c). Two seawater scrubber products, the EcoSilencer and the Krystallon, have been demonstrated on ferry applications and are available on a custom order basis. Table 14 summarizes the SO_x control options described above.

AT PORT EMISSION REDUCTION STRATEGIES

While docked at port, vessels use their auxiliary engines and sometimes their main engines to provide heating, cooling, and electricity, as well as for other ship functions such as loading and unloading. As discussed in Chapter II, emissions generated at dock (referred to as hotelling emissions) often contribute significantly to local emission inventories and to potential health risks from human exposure to harmful pollutants. To date, three main strategies have been implemented or proposed to reduce local emissions from marine activity: lower sulfur fuels, shore-side power, and shore-side emission treatment.

As discussed above, the use of lower sulfur marine diesel oil or pure distillate marine gas oil can provide significant SO_x and PM reductions compared to using heavy fuel oil. Availability and incremental cost are discussed in Section F.

Shore-side power (also known as cold ironing) is delivered by plugging the ship in to a land-

TABLE 14. Summary of SO_x Emission Reduction Technologies (Entec 2005c, Eyring et al. 2005b)

TECHNOLOGY	SO_x REDUCTION	ENGINE APPLICATION	VESSEL APPLICATION	TECHNOLOGY STATUS	MANUFACTURERS
1.5% S Heavy Fuel Oil	44%	2 and 4 stroke	All ship types	Commercially available	Oil refineries
0.5% S Heavy Fuel Oil	81%	2 and 4 stroke	All ship types	Commercially available	Oil refineries
Sea Water Scrubber	75%	2 and 4 stroke	All ship types	Demonstration/ custom order	Marine Exhaust Solutions BP-Kittiwake

based electric supply. Cold ironing eliminates all hotelling emissions from the ship at port. Emissions are displaced to the power generating facility, unless electricity is generated from zero emission sources such as solar or wind power. Cold ironing has been a common practice in military applications for several decades; it was first applied to commercial vessels in the late 1980s and early 1990s (CARB 2005, Entec 2005a). Implementing shore-side power not only requires building the landside power delivery infrastructure but also retrofitting ships so they can be connected. Such retrofits are often more complicated than building new ships designed for cold ironing. The size and proximity of power supplies to the port is a key factor in determining the required shore-side power delivery infrastructure (CARB 2005). The necessary infrastructure configuration also depends on vessel type. Ships that do not always dock in the same position or that must be loaded and unloaded by crane (such as container ships) require a more flexible cold ironing infrastructure than do ferries or tankers (Entec 2005a).

A shore-side emission treatment system is slated for demonstration as an alternative to shore-side power at the Port of Long Beach, California. The system is connected to the ship exhaust stack and the exhaust is funneled to a combined SCR and scrubber system installed on a barge or on the dock (POLB 2006). The system, developed by Advanced Cleanup Technologies, Inc. will be installed in partnership with Metropolitan Stevedoring Co. and is expected to reduce NO_x emissions by 95 percent and SO_x and PM emissions by 99 percent (POLB 2006). This pilot project will verify actual emission reductions as well as overall feasibility. Shore-side emissions treatment may be a promising control option for ships that cannot be cost-effectively modified to use shore-side power or that do not call frequently on ports with shore-side power infrastructure.

TABLE 15. Summary of Hotelling Emission Reduction Technologies (Entec 2005b, Eyring et al. 2005b, CARB 2005)

TECHNOLOGY	EMISSION REDUCTION	ENGINE APPLICATION	VESSEL APPLICATION	TECHNOLOGY STATUS	MANUFACTURERS
0.5% S Marine Diesel Oil	SO_x: 80% PM: 75%	2 and 4 stroke	All ship types	Commercially available	Oil refineries
0.1% S Marine Diesel Oil	SO_x: >90% PM: > 80 %	2 and 4 stroke	All ship types		Oil refineries
Marine Gas Oil	SO_x: >90% PM: > 80 %	2 and 4 stroke	All ship types	Commercially available	Oil refineries
Shore-side power	NO_x, SO_x, PM: >90%	2 and 4 stroke	All ship types. Currently implemented on ferries, cruise ships, tankers, and RORO	Commercially available (Existing installations: Sweden, Los Angeles, Juneau, Seattle)	Cavotech
Shore-side emission treatment	NO_x, SO_x:>90%	2 and 4 stroke	All ship types.	Pilot demonstration planned for Port of Long Beach	ACTI

Hotelling emission reduction strategies are summarized in Table 15.

OTHER NO_x, SO_x AND PM EMISSION REDUCTION STRATEGIES

In addition to the technologies described in the previous section, several other strategies have been proposed to reduce ship emissions of criteria pollutant. These include expanding the use of gas turbines to replace diesel engines and using land-based on-road and non-road diesel fuels instead of marine fuels. Research and development programs in Europe, the United States, and Japan are currently investigating fuel cell applications for marine vessels, principally for hotelling power applications.

GREENHOUSE GAS EMISSION REDUCTION STRATEGIES

Research and development efforts have explored the potential for reducing ship fuel consumption and greenhouse gas emissions at several phases of the vessel life cycle. During the design process, optimizing the shape of the hull to minimize resistance can lead to reduced fuel consumption (Hayman et al. 2002). Optimized hull from can be expected to improve fuel efficiency 5–20 percent (IMO 2000). Choosing the right propeller type can provide additional efficiency gains of 5–10 percent (IMO 2000). Diesel-electric propulsion such as pod propulsion is an emerging advanced propulsion concept. Pod propulsion is currently available from several manufacturers and has been demonstrated in cruise and ferry applications to reduce power requirements by approximately 10–15 percent (ABB 2006, Rolls Royce 2006).

In Germany, the Federal Ministry for the Environment (BMU) has funded the development of a feeder ship for operation in coastal and inland waters based on the Futura Carrier design concept. The project aims at demonstrating 30 percent reduction in fuel consumption per ton carried compared to conventional ships. A number of ship design and technical strategies were implemented to meet the ambitious target including a modified hull shape and air lubrication. The ship, which was christened in January 2007, is also equipped with NO_x and particulate matter control technologies (BMU 2007). Fuel consumption data are currently being collected (UBA 2007).

Innovative vessel designs now combine wind, a traditional ship energy source, and other renewable energy technologies such as solar panels with conventional diesel engines or even diesel-electric systems. A limited number of these hybrid vessels are currently being deployed (Solar Sailor 2006, SkySails 2006, Wallenius Marine 2006). A significant amount of research and development is also ongoing on the use of fuel cells in ocean-going vessel applications.

In addition to hull design, propulsion, and ship power improvements, proper ship maintenance can ensure that the vessel operates efficiently throughout its long useful life. Fouling of the ship's hull by marine organisms can impact fuel economy by increasing hull roughness. Several alternative coatings and active removal systems are available to replace the traditional toxic tin organic anti-fouling paints that are currently being phased out (Ahlbom and Duus 2006).

Finally operational changes can yield some efficiency gains. These changes include optimizing speed choices and operational parameters for fuel savings, adjusting ship routes to avoid weather patterns that would affect ship performance, and reducing the length of port visits (IMO 2000)

As with other mobile sources, different emission reduction technologies and strategies can and should be combined to optimize emission reductions in all the major criteria pollutant and greenhouse gas categories. Lower sulfur fuels are not only a key SO_x reduction strategy, they ensure better performance and durability from advanced NO_x control systems such as DWI and SCR. Although many regulatory programs have focused on NO_x and SO_x, there is growing interest in achieving PM and greenhouse gas reductions as part of a comprehensive effort to mitigate the environmental impacts of ship emissions and avoid tradeoffs between air pollutant emission reduction and fuel efficiency.

C. POTENTIAL EMISSION REDUCTIONS FROM OPERATIONAL CHANGES

The potential for operational modifications is generally limited to measures taken while ships are at the port. The technology improvements described above provide emission reductions under cruising and/or hotelling conditions, while operational changes only offer reductions in a pre-determined geographic area of operation. Most operational changes focus on harbor and at-dock or hotelling emissions. The potential emission reductions from operational changes are very important as they can significantly contribute to improving local air quality and reducing the exposure of nearby populations to harmful pollutants.

It is also possible, within certain legal constraints discussed in Chapter III, for port operators to require specific control technologies such as cold ironing or the use of lower sulfur fuels and other emission-control technologies when operating under port jurisdiction. While such requirements could produce significant local emission reductions, local programs may not be as cost-effective as a large-scale (preferably regional or international) programs, since the investment required to install control equipment is generally fixed regardless of how many ports require the control equipment to be used. It should be noted that there is often intense competition between ports to capture as much of the shipping market as their capacity permits. As a result, local ports are frequently reluctant to implement local environmental requirements out of concern that this will put them at a competitive disadvantage relative to other nearby ports.

Despite competitiveness concerns and the absence of national or international consensus on controlling ship emissions, several ports have gone forward with local pollution control requirements including operational changes. For example, a voluntary speed–reduction program in effect in the San Pedro harbor (ports of Los Angeles and Long Beach, California) is estimated to be reducing NO_x emissions by as much as 4–8 percent (CARB 2002). Speed reductions while approaching shore and navigating within ports reduces ship-engine NO_x emissions by reducing the load on the vessel's main engines.

As noted previously, California has adopted fuel-quality standards for auxiliary engines. Starting in 2007, marine gas oil or marine diesel oil with a sulfur content limited to 0.5 percent or less must be used in auxiliary engines operated within 24 nautical miles (44.5 kilometers) of the state's coastline. In 2008 regulators will evaluate the feasibility of requiring ships to operate on marine gas oil that meets a 0.1 percent sulfur standard beginning in 2010. Approved alternative compliance technologies include shore power, engine upgrades, exhaust after-treatment, or the use of alternative fuels.

D. POTENTIAL REDUCTIONS FROM MARKET-BASED MEASURES

In addition to regulatory measures, market-based strategies should be considered when reviewing policy options to address environmental impacts from the shipping sector. Emission reduction programs that are either based on market incentives or structured to allow variable industry responses generally allow regulated parties to tailor compliance actions to their specific circumstances. Such approaches can produce the optimum balance between technology and operational controls. Market-based programs can be implemented locally—for example, by imposing variable fees designed to reward low-emissions and/or high-efficiency vessels (and conversely penalize high-emissions and/or low-efficiency vessels)—or internationally, through an emissions cap-and-trade system.

MEASURES TO ADDRESS GREENHOUSE GAS EMISSIONS

The IMO was assigned the responsibility to regulate greenhouse gas emissions from the international shipping sector under the United Nations Framework Convention on Climate Change (Kyoto Protocol 1997). Market-based mechanisms for addressing greenhouse gas emissions have gained currency within the IMO over the last decade. They have emerged as the preferred approach for eventually dealing with ship-related climate-change emissions, whereas emission standards remain the preferred approach for addressing air quality issues. In 1997, the IMO adopted a resolution concerning CO_2 emissions from ships (Resolution 8 of the 1997 International Conference of Parties to MARPOL 73/78). In 2003, the IMO adopted a resolution that directs the Marine Environmental Protection Committee (MEPC) to develop a greenhouse gas emission index (Resolution A-963, 2003). The index scheme is intended to allow shipping CO_2 emissions to be included on a voluntary basis in international environmental management systems such as the International Organization for Standardization (ISO) 14001 *Environmental Management Systems*.

The scheme is based on the correlation between ship fuel consumption and CO_2 emissions, indexed to the amount of cargo transported and distance traveled. The basic formula is:

$$Index = \frac{m_{co_2}}{m_{cargo} * D}$$

where m_{CO2} is the amount of CO_2 emitted, m_{cargo} is the weight of cargo carried or the number of passengers/cars transported, and D is the distance traveled.

The index for a ship can then be defined to take into account different trips and loading as follows:

$$Index = Conversion\ Factor * \frac{\sum F_{ci}}{\sum (m_{cargo,i} * D_i)}$$

where F_{ci} is the fuel consumption of the main and the auxiliary engines for trip i, m_{cargo} is the mass of cargo carried or the number of passengers/cars transported during trip i, D_i the distance traveled between two points where a loading operation takes place for trip i.

Under the current approach, MEPC's indexing scheme will address only CO_2; no other shipping-related air emissions that contribute to global warming will be considered. Given current scientific understanding, this approach is inadequate because the radiative forcing of non-CO_2 greenhouse gases emitted by ocean vessel emissions is significant. Moreover, an investigation and comparison of indexes for different ship types showed a significant scatter in the index results that is not yet fully understood (IMO 2003). Technical issues aside, it must be emphasized that the IMO's voluntary indexing scheme merely offers a tool for assessing the relative climate impacts of different vessels. By itself, it will not produce emission reductions without further regulatory action or incentives.

Another market-based mechanism for addressing greenhouse gas emissions is a cap and trade system. Under such a program, specific global emissions caps would be set for the shipping industry either by the IMO or by states. These caps could decline over time as ecological considerations dictate and as new technology options become available for reducing emissions. Many issues would need to be resolved prior to the implementation of a cap and trade system, including the geographic scope (i.e., regional, national, or international) and coverage of the program (i.e., which pollutants and how much of the shipping fleet would be included); whether emission reduction credits from off-sector sources would be allowed; what baseline would be used to measure reductions; and how allowances would be allocated. The net effect of the policy should be to induce vessel operators to implement the most cost-effective fleet-wide emission reductions. Cap and trade approaches have become popular in a variety of regulatory contexts over the last decade because they provide industry with flexibility and allow the market to determine where and how emission reductions can be achieved most cost-effectively. Vessel operators that can curtail emissions less expensively can sell excess emission credits or allowances to vessel operators that would otherwise face higher costs to implement reductions.[10]

An important benefit of any mandatory program to regulate greenhouse gas emissions is that it would create market incentives for technological innovation. In general, market-based programs provide regulated entities with additional compliance flexibility to achieve emissions reductions. A cap-and-trade approach in the shipping context may have some disadvantages. The administrative difficulty of implementing such a program on a global basis may be substantial. And cap and trade programs are more suited to pollutants such as CO_2 (which have equivalent environmental impacts no matter where they are emitted) than to non-CO_2 GHG emissions, such as diesel PM, that are also associated with localized public health or environmental impacts and for which "hot spots" of concentrated emissions are a concern (Harrington et al. 2004). In general, global cap and trade systems and other market-based instruments should be designed to meet broad emission reduction goals while ensuring that local air quality objectives are also met. In other words, the implementation of a broad-based program need not and should not preclude local regulations or programs to protect port-neighboring or coastal communities.

At this time, mandatory policy measures to address greenhouse gas emissions from the shipping sector—such as a mandatory trading system for ship emissions under a declining emissions cap—are not being discussed or considered by the IMO. Rather, the IMO is considering only voluntary measures such as indexing. Recent efforts to initiate climate change policy discussions have met with strong opposition. During the MEPC meeting in March 2006, the United States, China, and Saudi Arabia blocked all measures to address greenhouse gases. As a result, the current expectation is that no action to address climate change pollutants will be put forward by the IMO in the near term.

MEASURES TO ADDRESS NO_X, SO_X, PM AND OTHER AIR POLLUTANT EMISSIONS

Within the EU, market-based measures are under discussion as a means of limiting not only greenhouse gases, but also SO_x and NO_x emissions. The European Commission Environment Directorate-General has indicated its intent to develop a system of market-based measures, outside the existing regulatory framework, for reducing air pollution from ships. Two recent studies for the European Commission describe a broad range of possible economic instruments for regulating these pollutants (NERA 2004, 2005). Considering the current legal and political situation, the study authors concluded that the following approaches deserve further consideration:

1. *Voluntary differentiation in port dues*. An example of this approach is already being implemented in Sweden where less polluting ships are entitled to a reduction in fairway as well as port dues in participating ports. Additional information on the Swedish program is presented in a text box. One potential barrier to a further geographic expansion of this type of program is that the competitive nature of the port business leads ports to treat fees as confidential business information precluding the fees transparency required for a differentiation program. Important customers can sometimes receive discounts of up to 50 percent below official levels.

2. *Consortium benchmarking approach.* Benchmarking programs apply an average emission rate to a set of covered sources. Sources subject to the program can trade credits among themselves to meet the target level. The Shipping Emissions Abatement and Trading group (SEAaT), a consortium of petroleum companies and ship owners, have proposed a benchmarking approach as an alternative means of complying with the 1.5 percent sulfur limit in certain areas. Instead of using 1.5 percent sulfur marine fuel, a group of shipping companies would have the option of installing scrubbers or other technologies to reduce SO_2 emissions. If these control technologies reduce sulfur emissions below the rate that would have been achieved using 1.5 percent sulfur fuel, then credits would be generated and could be traded to other members of the industry group. In order for trading to occur, SECA requirements would have to be modified to allow some ships to operate with higher sulfur fuel (Kågeson 2006).

3. *Rigorous credit-based approach.* Based on a defined baseline, participants would try to reduce their emissions on a voluntary basis in order to sell credits to land-based sources. At present, such a land-based emissions trading system for non-CO_2 pollutants does not exist in Europe and there are no plans to develop one. Regional and national trading programs for NO_x and SO_x emissions, respectively, do exist in the United States, but they were outside the scope of the NERA report. To lessen the risk that participants would generate credits for emission reductions that would have occurred even absent the policy (the problem of so-called "anyway tons"), such a program would need to be carefully designed and rigorously implemented, with a robust baseline certification program, continuous emissions monitors on board each vessel, and credits for criteria pollutant emissions that would vary by ship location. Another issue to consider is how to incorporate into the credit scheme the relative air quality and human health impact of emissions at sea compared to emissions at port and on land.

4. *Environmental subsidy approach.* Current subsidies to EU shipbuilders could be increased if new vessels incorporate air pollution control technologies or vessels are built to meet an emission performance target.

SWEDEN'S ENVIRONMENTALLY DIFFERENTIATED FAIRWAY DUES PROGRAM

The Environmentally Differentiated Fairway Dues Program in place in Sweden since 1998 represents the largest effort to date to implement a market-based policy for reducing harmful emissions from ocean-going vessels. This voluntary program was the result of an agreement between the Swedish Shipowner's Association, the Swedish Port and Stevedore Association, and the Swedish Maritime Administration (SMA), which is tasked with administering the program. The program's original goal was to reduce NO_x and SO_x emissions from ships traveling in Swedish waters by 75 percent over ten years.

PROGRAM FEATURES. Under the program, baseline dues are levied proportional to each vessel's gross tonnage (Swedish Kronor/GRT). Individual vessels can then qualify for reductions from the baseline dues based on their emissions performance. Since the program was designed to be revenue neutral, baseline fairway dues were first increased so as to create room for fee reductions without an overall loss of revenues. Fee reductions for NO_x performance are assessed based on vessel emissions in grams per kilowatt-hour (g/kWh) as measured by an independent body. Fee reductions for SO_x performance are assessed based on the sulfur content of the fuel used. NO_x and SO_x performance is certified for 3 years and periodically verified. The maximum NO_x emission and fuel sulfur categories were lowered in 2005 to reflect improvements in NO_x control technology and the availability of lower sulfur fuel. Currently, the maximum dues reduction is offered to ships that emit 0.5 g/kWh of NO_x or less and that use fuel with sulfur content less than or equal to 0.2 percent.

In addition to the SMA program for fairway dues, 30 of the 52 ports in Sweden impose environmentally differentiated port dues. These programs vary widely amongst individual ports and, because of the competition among ports, typically offer fee reductions that are smaller than the fairway dues program.

RESULTS. By 1999, about 1,350 ships calling to Swedish ports were using fuels with sulfur content lower than 1 percent. In 2005, 1,127 ships, accounting for 80 percent of the ferry tonnage and 50 percent of the cargo tonnage calling on Swedish ports, were participating in sulfur portion of the program (Kågeson 2006). Early estimates in 2006 showed a further drop to about 900 vessels mainly due to recent increases in oil prices. Over the program's eight years of implementation, a total of 44 vessels were outfitted with NO_x control technologies. Table A summarizes the types of ships qualifying for dues reductions on the basis of their NO_x emissions.

SWEDEN'S ENVIRONMENTALLY DIFFERENTIATED FAIRWAY DUES PROGRAM, continued

TABLE A. Summary of Ship Types in NO_x Program (SMA 2006)

SHIP TYPE	NUMBER OF SHIPS
Roll on-roll off	13
Roll on –roll off passenger ferry	12
Cruise	5
Icebreaker	4
High Speed Ferry	3
General Cargo	2
Tanker	2
Dry Cargo	1
Nuclear Waste	1
Work Vessel	1

The majority of vessels in the program have opted for installing SCR on their main engines to achieve NO_x reductions; as a result, average NO_x reductions totaled 87 percent. Table B summarizes average emission reductions per type of NO_x control technology implemented.

LESSONS LEARNED. Among the lessons learned early in the implementation of the Swedish program was the need for additional incentives to encourage the installation of NO_x control technologies. Unlike switching to lower sulfur fuel, reducing NO_x emissions requires additional capital investments. To overcome this hurdle, the program offered to cover up to 40 percent of the capital cost of low-NO_x retrofit technology for equipment installed before January 2000 and 30 percent for projects completed before January 2003. About a quarter of the vessels in the NO_x program took advantage of this incentive.

The program structure was revised in 2005 to ensure that it continues to provide appropriate economic incentives. An evolving program structure is necessary to ensure continued adoption of cleaner fuels and technologies. It is important that the program reflect advances in technology as well as changes in international regulations.

TABLE B. Summary of Projects under the NO_x Program (SMA 2006)

TECHNOLOGY	NUMBER OF PROJECTS	AVERAGE NO_x REDUCTION
Gas turbine	4	46%
Internal engine modifications	2	41%
Humid Air Motor (HAM)	1	71%
Selective Catalytic Reduction (SCR)	34	87%
Magnetizer	1	N/A
Water injection + SCR	2	60%
Program total	44	81%

Local market-based measures such as the Swedish program can have a significant impact on local emissions but their impact on global emissions is generally small since only the vessels calling at a few specific ports are affected. Nevertheless, they serve to demonstrate the viability of larger scale programs implemented regionally, nationally, or even internationally. If a system of fees was adopted such that operators would be subject to similar incentives or penalties throughout a region or in all their ports of call, they will have little alternative but to "price" the impact of such fees into their overall technology investment cost. The larger the geographic scope of a control program, the greater the incentive to consider investments in emission reduction strategies.

The concept of environmentally differentiated en-route charges has recently been proposed as a pilot program in the Baltic Sea (Kågeson 2006). The charges, to be collected by participating ports in the region, are calculated based on the amount of pollutants emitted in during a ship's voyage in the Baltic Sea. The distance traveled in the region can be easily assessed through data collected by the Automatic Identification System (AIS). The ship's emission performance would be determined through a certification system. NO_x and SO_x charges would be set, respectively, based on the costs of retrofitting vessels with SCR systems and using lower sulfur fuel.

General program design guidelines apply to all market-based initiatives including differentiated port dues or en route charges. The programs should be designed to foster broad port and ship owner/operator participation. Incentives, fees, or caps should be set to encourage cost effective emission reduction and should be periodically revised as technology availability and performance improves. Strict criteria must be developed to ensure the emissions reduced by the programs are permanent and surplus to those reduced through the implementation of adopted regulation. Finally, thorough enforcement of requirements, including periodic ship emission performance audits, is essential to any program's long-term success.

The two most important shipping regions, the Pacific Rim and the North Atlantic, could benefit from market-based measure such as differentiated fees. The major ports in the Pacific Rim, based on trade volume, are in China, Singapore, South Korea, Taiwan, Malaysia, Japan, and the West coast of the United States. In the North Atlantic, major ports are located in countries such as the Netherlands, Germany, Belgium, and on the East and Gulf Coast of the United States. A regional collaboration of major ports in either of these regions to establish a coordinated system of environmentally differentiated port dues or route charges would provide a significant impetus for large shipping companies to invest in emission control technologies for new and existing vessels. Lessons learned from previous port collaboration such as the New Hansa of Sustainable Ports and Cities project for Baltic Sea ports and the ECOPORTS for European ports could serve as a starting point for future port collaborations (New Hansa 2006, ECOPORTS 2006). The speed and magnitude of the ship owner response would depend on the level of economic incentive applied. A starting point for estimating the likely response to different fee levels might be gained by examining the successful experience in Sweden. In contrast to many other potential regulatory options for individual nations, a differential fee system can be designed and implemented so as to be consistent with international maritime law. It would also circumvent the issues related to a cap and trade program such as determining an accurate baseline, establishing the relative value of ship emission reductions with respect to other sources, and accounting for the location-specific impacts of pollutants other than CO_2.

E. OTHER VOLUNTARY ENVIRONMENTAL INITIATIVES

Industry- and government-led voluntary initiatives can provide an important complement to the types of technology- and market-based programs described in the previous sections. This section discusses three categories of voluntary initiatives: one aimed at benchmarking environmental performance, a second aimed at identifying and promoting specific policies, and a third that focuses on demonstrating and implementing technologies. To further illustrate each initiative type's features, specific programs are described. These programs are provided as examples and do not constitute an exhaustive list of all the voluntary initiatives in the marine sector.

Benchmarking initiatives involve the development and use of metrics for comparing environmental performance. Most of these initiatives are constructed on the framework of established environmental quality and management certification programs such as the ISO 9000 and 14000 series. Typically, performance metrics reflect current and proposed international environmental regulations. Current emissions regulations for marine vessels, however, seldom require implementing the best available control technologies and strategies.

- The Green Award Foundation was one of the first voluntary programs to recognize ship environmental performance. The foundation was started in 1994 by the Port of Rotterdam and the Dutch Ministry of Transportation and has been independent since the year 2000 (Green Award Foundation 2006). The Green Award is granted to oil tankers and bulk cargo vessels that meet various safety and environmental performance criteria. Currently 202 vessels from 38 different owners are certified, representing about 7 percent of the targeted vessel fleet. Green Award vessels benefit from reduced port dues in about 50 ports worldwide.

- The Blue Angel program is an environmental labeling program created by the German federal environmental agency, Umweltbundesamt. Each product criteria is established by a jury of industry and independent experts along with other relevant stakeholders. The criteria for ocean-going vessel was finalized in 2002 and since then four vessels have received the Blue Angel certification.

- The Det Norske Veritas environmental classification system also focuses on ship performance (DNV 2006). It offers two certification levels aimed at limiting and/or preventing operational and accidental discharges of pollution to air and water. The CLEAN certification for deep-sea ships codifies compliance with existing regulations with some limited additional requirements. The CLEAN DESIGN certification focuses on coastal vessels and short-sea shipping and includes accident mitigation requirements that need to be taken into account during ship design. In 2003, three years after the program's inception, an estimated 110 CLEAN ships and 10 CLEAN DESIGN ships were in operation or on order (DNV 2003).

- The Clean Cargo Working Group has designed tools for shipping customers interested in comparing the environmental performance of various carriers. The Clean Cargo Working Group is organized by Business for Social Responsibility, a membership organization active since 1992 that focuses on helping its corporate members to be more socially responsible (BSR 2006). The Clean Cargo Working Group is composed of major carriers that move about a third of the world's containerized cargo, as well as 20 percent of the top 50 importers of containerized goods in the United States (BSR 2003). The Environmental Performance Survey is a questionnaire for shippers that covers a range of environmental and safety issues. It requires carriers to calculate their SO_x, NO_x, CO_2 and other GHG emissions by vessel and trip.

- The ECOPORTS project, funded by the European Commission, was created to foster information exchange between European port administrators on best environmental practices and to develop and disseminate a suite of environmental management tools (ECOPORTS 2006). Between 2002 and 2005 the project developed five tools that designed to function as stepping stones towards ISO 14001 certification. ECOPORTS regularly holds national and European conferences to provide a venue for continued discussions on environmental issues at European ports.

A second type of voluntary initiative focuses on advancing specific policies. For example, the Shipping Emission Abatement and Trading (SEAaT) group was formed by shipowners to promote emissions trading as the main mechanism for obtaining emission reductions (SEAaT 2006). From April to December of 2005, the group conducted a Sulphur Emissions Offsetting Pilot Project to model emissions trading in a Sulfur Emission Control Area.

A third type of voluntary initiative focuses on promoting, demonstrating, and/or implementing specific emission control technologies. Such initiatives, whether they are initiated by government or industry, require strong cooperation between public and private interests. The examples highlighted below include the West Coast Diesel Collaborative Marine Vessels and Ports Workgroup and initiatives by Maersk Line in Southern California and Stora Enso in Sweden.

The US EPA-initiated West Coast Diesel Collaborative is a program to reduce emissions from all major diesel pollution sources operating in the western United States and includes a focus on marine sources. Within the broader Collaborative, a Marine Vessels and Ports Workgroup is working, as a partnership between private and public stakeholders, to share information and secure funding for projects related to shipping emissions (WCDC 2006). The Workgroup also acts as an information clearinghouse to support an application for a West Coast SECA. To date it has provided $360,000 in funding for six projects, including technology demonstrations for natural gas port equipment and incentives for lower sulfur fuels and shore power.

In May 2006, Maersk Line announced it would be using 0.2 percent sulfur fuel when its ships are operating within 24 nautical miles (44.5 kilometers) of the California coast and while they are docked at California ports (Veiga 2006). This initiative occurred about eight months ahead of the implementation of a California rule requiring that 0.5 percent (or lower) sulfur fuel be used within 24 miles (44.5 kilometers) of the state and while at port.

Stora Enso, an international paper and forest products company based in Finland, has partnered with its contracted carriers to reduce environmental impacts associated with the transport of its products in the North Sea. Several of the ships that operate between the ports of Göteborg in Sweden and Zeebrugge in Belgium have, at Stora Enso's request, installed SCR (Ahlbom and Duus 2006). In addition, Stora Enso and the Port of Göteborg partnered in 2000 to install a shore power facility supplied by a wind farm. Annual emissions reductions as a result of this facility are estimated to total 80 metric tons of NO_x, 60 metric tons of SO_x, and 2 metric tons of PM (Clean Marine Award 2004).

Most of the voluntary initiatives reviewed in this section have reached only a limited portion of the fleet or ports they intend to target. Taken together, however, these programs provide a useful foundation for future efforts to address environmental impacts from the shipping sector on a broader basis. Their emphasis on information sharing among public and private stakeholders and on learning by doing have yielded valuable insights concerning the importance of collaborative models for mitigating harmful emissions from ocean-going vessels.

F. INCREMENTAL COST AND COST-EFFECTIVENESS OF EMISSIONS CONTROL OPTIONS

Whether motivated by regulatory or market-based programs, reducing ship emissions during cruising and hotelling usually requires a capital investment in new or retrofit technology and often additional expenditures to cover incremental operating costs. This section summarizes the results of previous studies that have assessed the capital and operational costs of control technology options described in this report. As with estimates of emissions reduction potential, there remains some uncertainty about the cost estimates presented here. Most of the technologies under discussion are either in limited production by one or two manufacturers or are in still being demonstrated. As demand for these technologies grows and as a wider, more competitive market for control technologies emerges, costs would be expected to stabilize and adjust accordingly—probably leading to substantial cost reductions.

Lower sulfur marine fuels are key technology enablers and their use also generates significant SO_x emission reductions on its own. As such, low-sulfur fuels are an essential component of any marine emission reduction strategy. MDO and MGO sales currently represent about 20 percent of the marine fuels consumed world-wide (Beicip-Franlab 2002). The California Air Resources Board (CARB) has concluded that the availability of lower sulfur distillates (0.2 percent MDO or 0.1 percent MGO) before 2010 is uncertain (CARB 2005). However, the agency expects that fuel sulfur limits in Europe and California after 2010 should ensure their availability by 2010 and beyond.

Most lower sulfur residual fuel production is currently destined for use by stationary sources (Beicip-Franlab 2003). Prior to the designation of the Baltic Sea SECA, limited quantities of lower sulfur fuel were in use by ships in the North Sea and Baltic Sea regions where their use was encouraged by the Swedish market-based dues program discussed in previous sections. Recent studies that have assessed the future availability of 1.5 percent and 0.5 percent sulfur fuel in Europe have identified three paths to increasing the supply and use of these fuels (Beicip-Franlab 2002, 2003). They include re-blending high sulfur fuel with lower sulfur products, increasing the use of low sulfur crude oil, and upgrading refineries to produce lower sulfur residuals and distillates. It is expected that more than 80 percent of future 1.5 percent sulfur fuel and practically all of the 0.5 percent sulfur fuel will have to be produced by upgraded refineries (Beicip-Franlab 2002, 2003).

Table 16 provides a snapshot of fuel prices in mid-May 2006. As with all other fuels, marine fuel prices are volatile and respond to changes in the crude oil market. Better quality fuels such as MDO and MGO are typically more expensive than IFO 380 and IFO 180. The magnitude of the price increment varies over time and by fuel market.

Over the last several years, the price of IFO 180 has tracked the sharp rise in world oil prices. In major markets such as Rotterdam and New York, prices of IFO180 have more than doubled. The price of IFO180 per metric ton traded in Rotterdam ranged from a high of $318.50 in March 2006 to a low of $138.50 in December

TABLE 16. Bunker Fuel Prices on May 15 2006 ($/metric ton) (Bunkerworld 2006)

INDUSTRIAL NAME	SINGAPORE	HOUSTON	ROTTERDAM	FUJAIRAH
Intermediate Fuel Oil 380 (IFO 380)	$345.50	$334.00	$322.00	$344.00
Intermediate Fuel Oil 180 (IFO 180)	$355.00	$351.00	$342.00	$360.00
Marine Diesel Oil (MDO)	$633.50	$590.50	$583.00	$650.00
Marine Gas Oil (MGO)	$643.50		$625.50	$650.50

2003 (Bloomberg News 2006). In New York, the price of IFO180 ranged from a high of $387.50 per metric ton in December 2005 to a low of $146.00 in October 2002, reflecting a similar price spread with higher overall values (Bloomberg News 2006). In other words, IFO180 prices increased by 130 percent in Rotterdam and 165 percent in New York over this (roughly) three-year time period (see Figure 15).

Estimates of the incremental cost of lower sulfur marine fuels compared to conventional bunker fuels are summarized in Table 17. The difference in the incremental cost for improving the quality of residual fuels and the incremental cost for improving the quality of marine gas oil is a reflection of the baseline price difference highlighted in the previous table. It is not expected that removing sulfur from MGO would be more expensive than removing it from other fuels. Accordingly, the California Air Resources Board estimates that 0.1 percent sulfur MGO will have an incremental cost of about $21 per ton compared to conventional MGO, a cost difference of approximately 3 percent (CARB 2005). Estimates of incremental cost for lower-sulfur fuels, as the table indicates, are lower than the price increases witnessed over the last four years for conventional bunker fuel prices (as illustrated in Figure 15). An assessment of the cost of using 1.5 percent sulfur fuel on ferry applications in the North Sea found that the incremental fuel costs represented only about 4 percent of overall trip costs (Hader 2005).

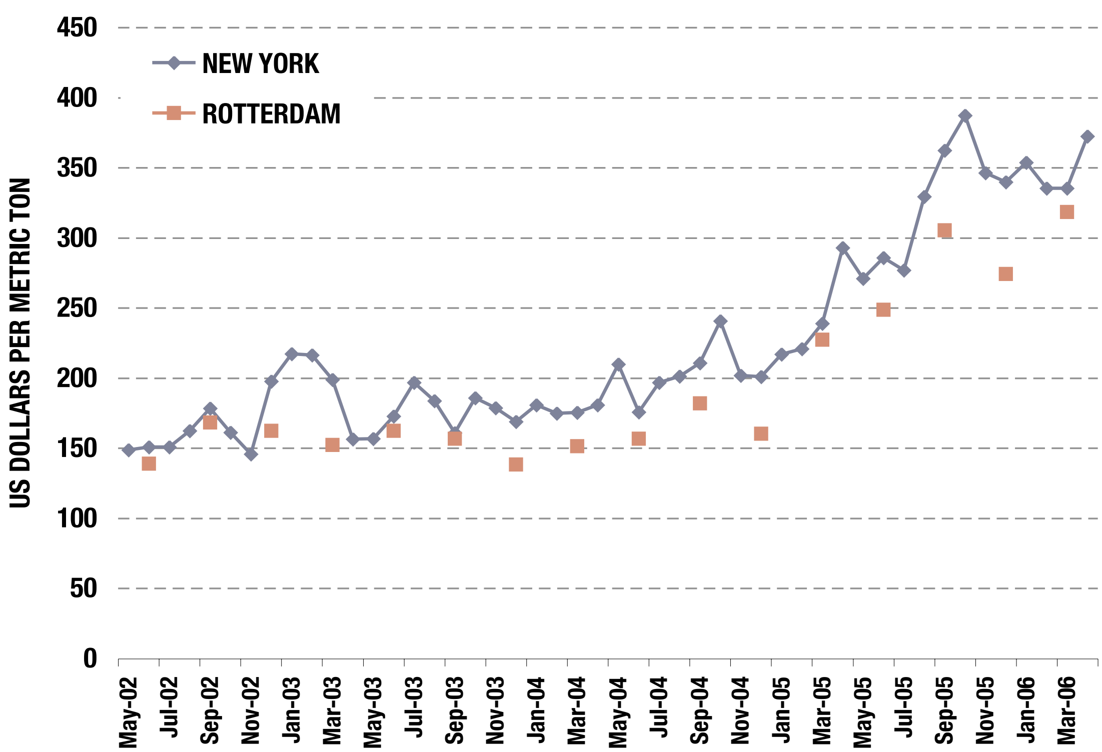

FIGURE 15. Marine Bunker Fuel Prices (IFO180) in New York and Rotterdam (2002–2006) (Bloomberg News 2006)[11]

TABLE 17. Estimates of Incremental Fuel Costs for Lower Sulfur Fuels Relative to Current Bunker Fuels ($/metric ton) (Beicip-Franlab 2003, Entec 2005c, CARB 2005)

FUEL TYPE	BEICIP-FRANLAB (2003) for EU (2002 $/Metric Ton)	ENTEC (2005c) for EU (2000 $/Metric Ton)	CARB (2005) for CALIFORNIA ($/Metric Ton)
1.5% S Intermediate Fuel Oil	35–78	46	–
0.5% S Intermediate Fuel Oil	41–88	59	–
0.2% S Marine Diesel Oil	–	102	–
0.1% S Marine Diesel Oil	–	120	–
Marine Gas Oil	–	–	257
0.1% Marine Gas Oil	–	–	278

A number of studies have estimated the incremental cost of available technologies for reducing ship emissions. The methodologies used in these studies to characterize capital and operation costs vary, as do baseline choices and other key assumptions. This makes it challenging to compare their results. For example, the characteristics of the typical baseline vessel such as application, engine type and size, age, and duty cycle depend largely on the study's geographic focus and affect the range of applicable technologies. Assumptions on usage rate, load factors, and equipment replacement schedules also affect estimates of operational costs. Other assumptions such as compounding rates, equipment life, and, importantly, average time spent in territorial water or at dock have a marked influence on cost-effectiveness results. Tables 18 and 19 present those estimates of incremental capital and operational costs that are most directly comparable, based on recent studies. Reported uncertainties associated with these estimates range from 30 percent to 50 percent. This high level of uncertainty is due to the relatively recent commercialization of most of these technologies and to the fact that only limited installations and field experience exist at this time.

Capital costs include all the upfront investment in purchasing cleaner engines or vessels or purchasing and installing retrofits. The results in Table 18 are expressed in $/kW for vessels with a power rating above 15,000 kW. Most of the cost estimates for each technology are of the same order of magnitude. One notable exception is shore-side power where capital investments are highly variable depending on the infrastructure upgrades needed, both to make electric power available dockside and to connect ships to a power supply. Engine modifications require the least capital investment. The highest capital costs are for technologies that are currently proprietary to one manufacturer such as humid air motors.

Table 19 presents estimates of operating cost for the main technology options in $/MWh. Here again, the results for most technologies are of the same order of magnitude, with the exception of shore-side power, fuel switching, and SCR with MDO. The variation across different operating cost estimates is mainly due to differences in assumed electricity and incremental fuel prices, as well as differences in baseline assumptions. For example, the Entec (2005a) study compares shore-power to using auxiliary engines with 0.1 percent marine distillate instead of the heavy-fuel oil assumed as the baseline in the Genesis Engineering (2003) study. Shore-side power projects have the highest incremental operating costs; this is because electricity is generally more expensive than marine fuel.

Figure 16 compares incremental capital and operating costs estimated by Entec for a range of emission reduction technologies (Entec 2005a, 2005b, 2005c).

As shown in Tables18 and 19 and illustrated in Figure 16, available technology options for reducing ship emissions range from capital-intensive projects with minimal operating costs to strategies that increase operating expenditures without requiring a significant upfront capital investment. There is a fair amount of agreement

TABLE 18. Capital Cost Estimates for Ship Emission Control Technologies (Entec 2005 a, 2005b, 2005c, US EPA 2003, Genesis Engineering 2003)

TECHNOLOGY	ENTEC (2005a, b, c) (Euros/kW)	ENTEC (2005a, b, c) ($/kW)	US EPA (2003) ($/kW) Medium Speed	US EPA (2003) ($/kW) Slow Speed	GENESIS ENGINEERING (2003) ($/kW)
CRUISING NO_x EMISSION REDUCTION STRATEGIES					
Basic Engine Modification-Slide Valves-Newer engines	0.29	0.4			
Basic Engine Modification-Slide Valves-Older Engines	0.42	0.5			
Advanced Engine Modifications	6	7	8	3	
Direct Water Injection	19	24	20	13	12
Humid Air Motor	113	141			
Selective Catalytic Reduction	63	78	54	50	49
CRUISING SO_x EMISSION REDUCTION STRATEGIES					
Scrubber	168	209			
HOTELLING EMISSION REDUCTION STRATEGIES					
Shore-side Power-New Build[12]	55	68			
Shore-side Power-Retrofit[13]	78	97			34

between the cost estimates developed using different assumptions in the reports reviewed here: most of the results for capital and operating costs are within the same order of magnitude. Several of the strategies reviewed produce only a relatively small increase in trip costs, implying that they are more likely to be implemented under regulatory, voluntary, or market-based policies to promote emission reductions. As demand for emissions reductions grows and as more vessels are equipped with various control technologies, their cost implications and operational characteristics will be better understood.

Comparing cost-effectiveness per unit of pollution reduced is often more useful than simply comparing absolute costs. Entec (2005a, 2005b, 2005c) found that all control strategies to reduce NO_x and SO_x cruising emissions on a large vessel, except for fuel switching, cost less than $700 per ton of SO_x or NO_x. Engine modifications are an order of magnitude more cost-effective than

TABLE 19. Operating Cost Estimates for Ship Emission Control Technologies (Entec 2005 a, 2005b, 2005c, US EPA 2003, Genesis Engineering 2003)

OPERATIONAL COST	ENTEC (2005a, b, c) (Euros/MWh)	ENTEC (2005a, b, c) ($/MWh)	US EPA (2003) ($/MWh) Medium Speed	US EPA (2003) ($/MWh) Slow Speed	GENESIS ENGINEERING (2003) ($/MWh)
CRUISING NO_x EMISSION REDUCTION STRATEGIES					
Slide Valves-Newer engines	0	0			
Slide Valves-Older Engines	0	0			
Advanced Engine Modifications	0	0	0	0	
Direct Water Injection	2	3	1	1	3
Humid Air Motor	0.15	0.19			
Selective Catalytic Reduction-2.7 % S Fuel	6.2	8			
Selective Catalytic Reduction-1.5 % S Fuel	4.5	6	9.5	9.4	
Selective Catalytic Reduction- MDO	3.4	4			19
CRUISING SO_x EMISSION REDUCTION STRATEGIES					
Scrubber	0.3	0.4			
Fuel switching-2.7% to 1.5% S Fuel	10	12			4
Fuel switching-2.7% to 0.5% S Fuel	13	16			12
HOTELLING EMISSION REDUCTION STRATEGIES					
Shore-side Power*	16.3	20			57.1

* Cost to ship, Entec study provides incremental cost compared to using auxiliary engines with 0.1% S MDO and Genesis Engineering provides a comparison to engines using heavy-fuel oil

other technology options for reducing NO_x emissions, with estimated costs in the tens of dollars per ton reduced. Switching to lower sulfur fuels, on the other hand, is estimated to cost in the thousands of dollars per ton of SO_x reduced, according to the Entec study. Genesis Engineering's assessment, on the other hand, yields opposite results with costs for fuel switching in the hundreds of dollars per ton of SO_x reduced and costs for SCR and DWI in the thousands of dollars per ton of NO_x reduced. These two studies differ in their fuel price estimates and baseline assumptions as mentioned previously. Also the Genesis Engineering study assumed far less time spent, on average, in the territorial waters of the study area (87 hours) than did the Entec study, which focused on European-flagged ships which spend about 6000 hours in the study area. Indeed the Genesis Engineering study focuses only on the Georgia Basin and Puget Sound area, whereas the Entec study applies to all European flagged ships operating in European waters. Lower cruising time reduces the cost-effectiveness of technologies with significant capital costs, such as SCR and DWI.

The cost of shore-side power is estimated to range from thousands of dollars to tens of thousand of dollars per ton of pollutant reduced, making it one of the less cost-effective control options (Entec 2005a, CARB 2005, Environ 2004). MGO and lower sulfur MDO in auxiliary engines was estimated by CARB to cost about \$6,000 per ton of SO_x reduced (CARB 2005).

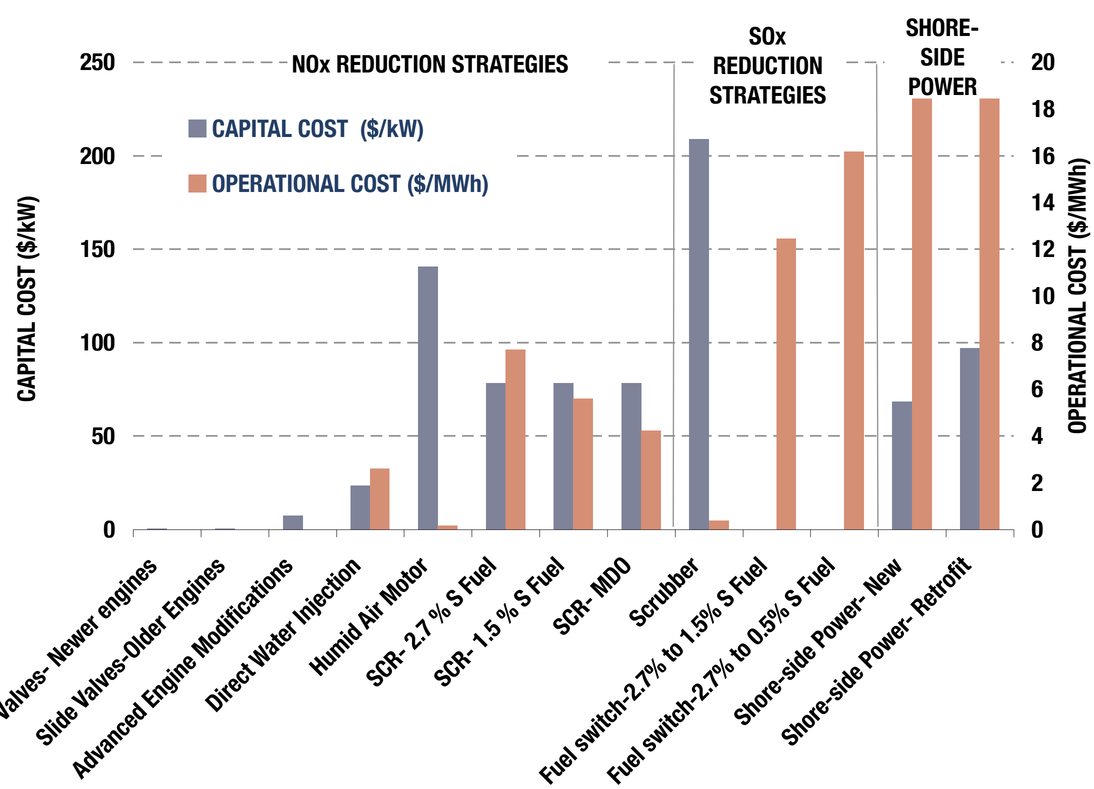

FIGURE 16. Incremental Capital and Operating Costs for Different Control Technologies (Entec 2005a, 2005b, 2005c)

Compared to other air pollution reduction measures for mobile and other sources in nations that have a mature air pollution program, marine source options are all very cost effective. Emissions mitigation options for ocean-going vessels combine relatively low costs compared to overall trip costs with favorable cost-effectiveness compared to other air quality measures. These results suggest that well-crafted regulatory or market-based programs to reduce ship emissions are likely to be successful and highly cost-effective. Figure 17 compares estimated costs per ton for additional emission controls on international marine vessels to the cost of other mobile and stationary source emission control programs in Europe and the United States. The results of the Entec study were chosen to represent international marine vessel strategies because it is one of the most recent studies and includes the widest range of control technologies. The figure reveals that reducing NO_x emissions from marine vessels is one of the most cost-effective means of improving air quality, especially in areas heavily affected by ship emissions.

As illustrated in Figure 17, the cost of available NO_x controls for ocean-going vessels ranges from \$11 to \$729 per metric ton of NO_x reduced, while estimates of the cost of past and future controls on other mobile and stationary sources in Europe and the United States range from \$1,071 to \$14,330 per metric ton. All European cost-effectiveness estimates are for future NO_x abatement measures from all sectors. These estimates were calculated in by Clean Air for Europe modeling program. All but one of the U.S. cost-effectiveness estimates are from past rulemakings and were calculated based on combined NO_x and non-methane hydrocarbon (NMHC) reductions. The only U.S. estimate of future cost-effectiveness was generated in the context of determining compliance costs for revised U.S. air quality standards in the late 1990s. This estimate is labeled "average future NO_x stationary and mobile sources (US)" in Figure 17. In general, future controls are likely to be more expensive than controls that have already been implemented. Thus it is not surprising that the costs of future NO_x abatement strategies for the shipping sector, which has not yet been extensively regulated, compare favorably with the costs of achieving further reductions in other source categories that have already implemented some controls.

Figure 18 compares cost effectiveness information for SO_x control measures. The cost effectiveness of reducing SO_x from ocean-going ships ranges from \$408 to \$2,609 per metric ton abated. All the European cost-effectiveness estimates are for future SO_x reduction while the Unites States estimates are for adopted regulations. Although SO_x control measures for ships are not as cost effective as NO_x measures, they still compare favorably with the cost of achieving further reductions from stationary and some other mobile sources.

G. LEGAL CONTEXT

Whether a particular regulatory instrument runs counter to the language of UNCLOS or other relevant provisions of international maritime law often depends on the nature of the policy and its practical effect on ocean-going vessels. This section reviews three different policies in light

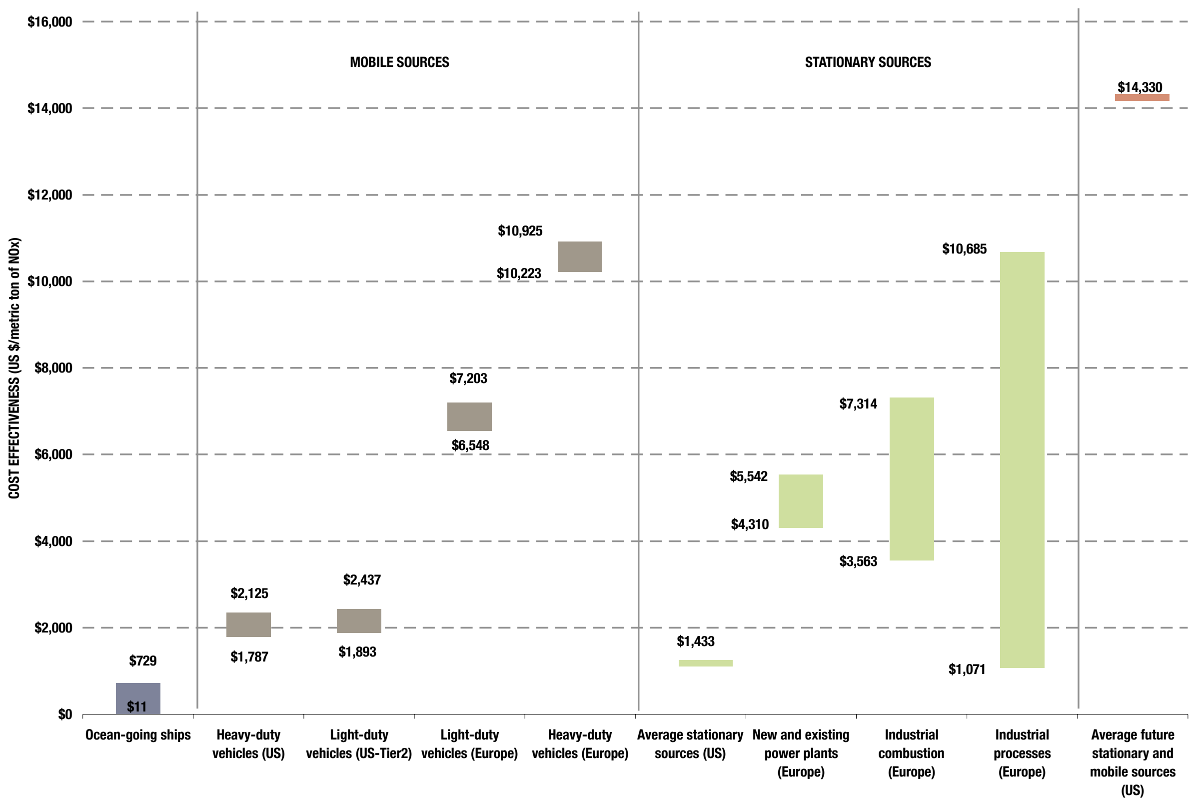

FIGURE 17. Comparing the Cost-Effectiveness of NO_x Control Options for Various Source Categories (Entec 2005b, US EPA 1999, 2000, 2005)

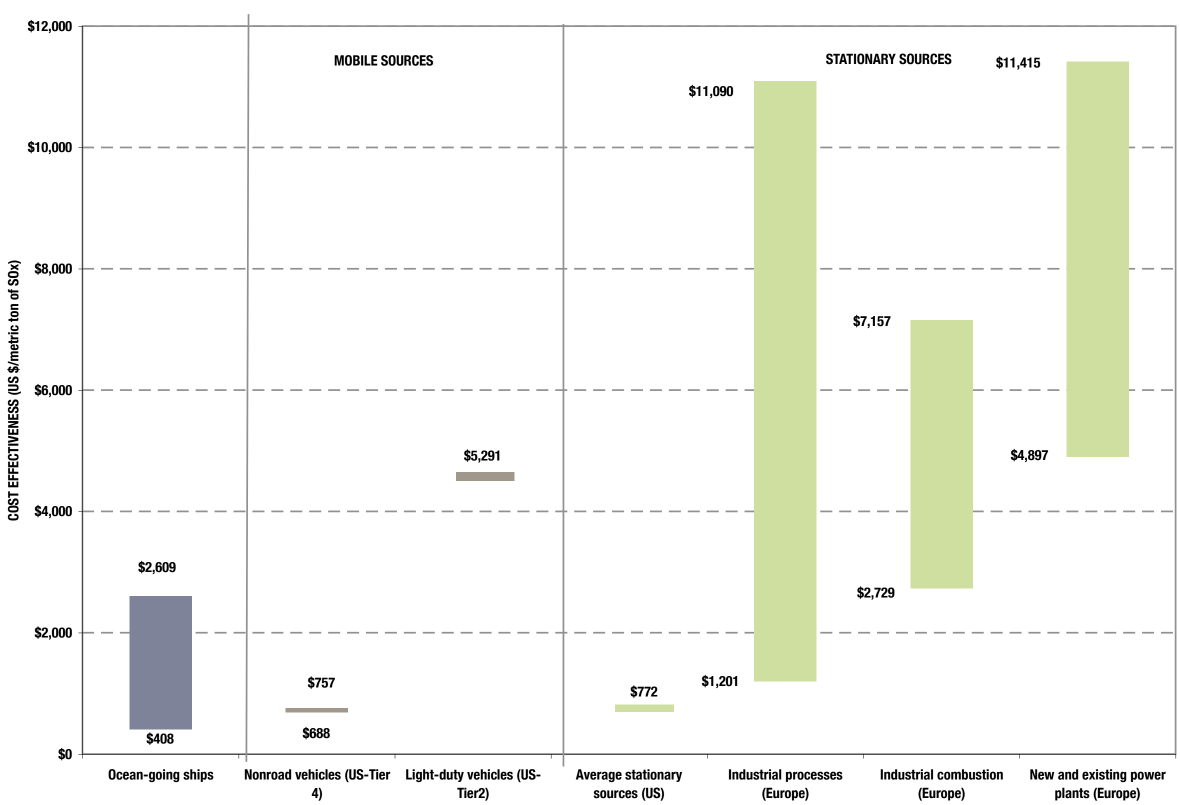

FIGURE 18. Comparing the Cost Effectiveness of SO_x Control Options for Various Source Categories (Entec 2005c, US EPA 1999, 2004, 2005)

of the legal constraints discussed in Chapter III: cold ironing, differential fees, and lower sulfur marine fuel. Relevant considerations are whether the practical effects of any port or coastal-state regulation follow the ship beyond the limits of the port or territorial waters (i.e., external effects), or hamper innocent passage. The specific technological or operational means available for complying with a particular policy or regulation matter a great deal in most of these cases, because it is often the practical effect of any policy or regulation that dictates its legal character.

SHORE-SIDE ELECTRICITY. Cold ironing only applies to vessels when at port, and does not have the practical effect of "running with" the vessel. In most cases, ports are likely to require cold ironing only for those vessels that use the port frequently and/or for extended periods of time. For existing vessels, the legal question is whether the retrofit hardware required for cold ironing impacts the "construction, design, equipment or manning (CDEM)" of the ship, and whether any of these additional equipment requirements run with the ship beyond the jurisdiction of the port State. For new ocean-going vessels that are built to accommodate shore power, cold ironing requirements would presumably be within the jurisdiction of port states.

DIFFERENTIAL FEES. This type of financial incentive system raises issues concerning the relative roles and powers of the ship's flag state and the port/coastal state seeking to impose differential dues. Provided ship operators have the option of either paying a higher fee or reducing emissions and thus avoiding the fee, many legal experts believe that this approach should withstand legal challenge. Indeed, experience with a program of this type in Sweden suggests that the international shipping community has accepted this policy, at least on a relatively small scale.

LOWER SULFUR MARINE FUEL. While economic instruments, such as differentiated port dues, raise only issues of "in port" jurisdiction between the flag state of the ship and the port state, requiring the use of lower sulfur fuel may raise questions about the jurisdiction and role of states beyond their ports (BMT 2000). This is a key legal distinction. Requiring ships to use low sulfur fuel when at port (or perhaps even within territorial waters) would appear potentially consistent with the temporary nature of the ships' presence. Should, however, the practical effect of the requirement be to necessitate an additional fuel tank and fuel lines, or should the absence of an additional fuel tank mean a ship has to use lower sulfur fuel throughout its voyage, including on the high seas, the requirement could be construed as affecting the "construction, design, equipment or manning" of the ship. An alternative is for a nation or group of nations to petition to be part of a SO_x Emission Control Area (SECA). Information concerning the SECA petition process under the relevant MARPOL Annex IV provisions is found in Chapter III of this report.

H. SUMMARY OF EMISSIONS MITIGATION OPTIONS FOR MARINE VESSELS

Several measures implemented to date to address emissions from shipping sources are summarized in Table 20. This is not an exhaustive list, rather it is meant to show the variety of voluntary and mandatory approaches that have been explored to date for going beyond IMO regulations. Most of these measures have been implemented on a local basis, such as the vessel speed reduction program in the Los Angeles and Long Beach harbors; one, the Swedish Environmental Differentiated Fairway Dues program, is national. Table 20 shows how some mitigation measures, such as shore power, are spreading to new ports based on lessons learned when they were first implemented.

Recently, the ports of Los Angeles and Long Beach together released a plan, known as the San Pedro Bay Ports Clean Air Action Plan, outlining measures the ports intend to undertake to reduce emissions from all port-related mobile sources, including ocean-going vessels. Shore-side electricity is one of the main technologies identified for reducing emissions from hotelling vessels under the plan, which will be implemented primarily through lease requirements for terminal operators (CAAP 2006). Additional funding for infrastructure improvements is being sought through the imposition of a regulatory fee

TABLE 20. Implemented Mitigation Options for Mariner Vessels

MEASURE TYPE	MEASURE	DESCRIPTION	EXAMPLES
Emission Control Technologies	Lower Sulfur Fuel	– Marine residual or bunker with sulfur content at 1.5% or below (44% SO_x reduction, 18% PM reduction) – Marine distillate and gas oil with sulfur content at 0.1% or below (>90% SO_x reduction, >80% PM reduction)	– EU (and IMO) Sulfur Emission Control Area: Baltic Sea (2006), English Channel and North Sea (2007) – San Pedro Harbor Maersk voluntary agreement (2006) – California auxiliary engine rule (2007)
	Selective Catalytic Reduction (SCR)	– Exhaust after-treatment technology providing over 90% reduction in NO_x. PM, CO, and HC reduction can be obtained when SCR is combined with a PM filter and an oxidation catalyst	– Units in service starting in early 1990's in applications ranging from ferry, cruise ship, to roll-on/roll-off vessels
Operational Changes	Vessel speed reduction	– Speed within harbor is reduced to reduce engine load and NO_x production (4%–8% reduction)	– Voluntary program in the Los Angeles/Long Beach harbor since 2001
	Shore power or cold ironing	– Land based power for docked ships (100% reduction in at-port emissions)	– Facilities operating in the Baltic and North Seas, Juneau (Alaska), Port of Los Angeles
Market-based measures	Environmentally differentiated fees	– Fee reductions based on vessel environmental performance. Emissions benefits depend on level of participation and implemented technologies.	– Voluntary Environmentally Differentiated Fairway Dues program in Sweden since 1998

on each TEU processed by the San Pedro Harbor Ports (Lowenthal 2006). Although recently passed bill instituting at fee was vetoed, legislators are expected to introduce a new statewide legislation in 2007.

The highlighted examples included in Table 20 point to nearly a decade of experience with various strategies and technologies for reducing air emissions from ocean-going vessels around the world. As ocean traffic grows with rapidly expanding international commerce, it is critical that best practices to limit this sector's environmental impact are also exported to ports and shipping lines around the world.

V. FINDINGS AND RECOMMENDATIONS

Pollution emissions from international marine vessels and port activities already have a significant impact on air quality and public health, especially in coastal communities. Moreover, emissions from this sector are expected to continue to grow strongly as the global economy expands and as international trade plays an ever larger role. Ocean-going vessels now transport 90 percent of all trade by volume to and from the 25 members of the European Community, and nearly 80 percent by weight of all goods shipped in and out of the United States. As progress is made in reducing emissions from land-based sources, the ship contribution as a percent of NO_x, SO_x, and PM inventories is likely to grow even faster than absolute emissions. Indeed, current trends suggest that NO_x and SO_x emissions from international ships off the coast of Europe will surpass total emissions generated by all land-based sources in the EU by 2020. Port cities and nations with extensive coastlines adjacent to shipping corridors are especially affected by emissions from seagoing vessels, which include pollutants or pollutant precursors that have been linked to a number of significant health risks (including the risk of premature death from heart and pulmonary diseases and an increased incidence of respiratory diseases). Ocean-going vessels are also important sources of greenhouse gas emissions. Currently, the annual contribution of CO_2 from the world's shipping fleet is larger than that from all sources in most of individual countries listed in Annex I of the Kyoto protocol.

Improved fuel quality, optimized engines, and exhaust after-treatment have been shown to significantly improve the environmental performance of marine vessels. Other measures such as shore-power, improved auxiliary engines, and speed reduction can reduce ship emissions while in harbor. The feasibility and cost effectiveness of these measures has been demonstrated by local and regional initiatives in several ports. Indeed, nations in Europe and North America—as well as port cities throughout the world—have deployed a variety of strategies to address air pollution from shipping. These strategies have included regulations, voluntary programs, and market-based programs. Regulatory approaches have generally consisted of setting engine and fuel-quality standards. Harbor speed limits have been implemented on a voluntary basis. Market-based programs, such as Sweden's environmentally differentiated fairway dues, have produced cost-effective results. Available emission control options for ocean-going vessels are generally at least an order of magnitude more cost-effective than the majority of remaining land-based pollution reduction options in nations with mature air quality programs.

Unfortunately, recent local and national efforts to promote improved environmental performance in the shipping sector have not been matched by equivalently ambitious international regulations. The IMO process, in particular, has not kept pace with the industry's rapid growth and with technological advances in emissions control. International mechanisms for addressing ship emissions have also been affected by the complex relationships between nations that register large numbers of ships under "flags of convenience" and large shipping interests. As a result, the process of changing international regulations is often protracted and has consistently resulted in the IMO setting emission standards at levels that are already achieved by the average in-use engine. The current international sulfur limit for marine bunker fuel, at 4.5 percent, is almost twice the average sulfur content of fuels in use today. These standards at best codify existing industry practices.

Dramatic reductions in ship emissions at sea and at berth are possible today with the use of readily available technologies. Longer-term, the development of advanced vessel designs and propulsion technologies that leverage renewable energy could provide additional benefits in some applications. The following ICCT recommendations are aimed at achieving steady, incremental progress toward mitigating emissions from marine

THE ICCT'S EIGHT OVERARCHING PRINCIPLES (from The Bellagio Principles)

1. Design programs and policies that reduce conventional, toxic, and noise pollution and greenhouse gas emissions in parallel, and ensure that future technologies provide major improvements in each of these areas.

2. Base policies solely on performance compared to societal objectives, and not give special consideration to specific fuels, technologies, or vehicle types.

3. In both industrialized and developing countries, expect and require the best technologies and fuels available worldwide; it is not necessary or cost-effective for developing nations to follow, step by step, the same path of incremental improvements that was taken by the industrialized nations.

4. Use combinations of economic instruments and regulatory requirements; make-related policies complementary.

5. Treat vehicles and fuels as a system, and move toward standards based on lifecycle emissions (including vehicle and fuel production, distribution, and disposal) in policies.

6. Prevent high in-use emissions with more realistic and representative test procedures, greater manufacturer accountability, improved inspection and maintenance programs, on-board monitoring and diagnostics, and retrofit and scrappage programs.

7. Consider the relative cost-effectiveness of near-term measures and the market potential of future technologies.

8. Work across jurisdictions, both nationally and internationally, to strengthen programs and give cohesive signals to affected industries.

vessels. They reflect careful consideration of the technological feasibility, legal viability, and cost-effectiveness of various approaches to promoting cleaner fuels and vessels and take into account results achieved to date by a variety of regulatory and voluntary programs worldwide. The ICCT's Bellagio principles are the basis of all the Council's proposals and, as such, provide a foundation for the recommendations presented here.

The ICCT recommendations identify three implementation milestones in each of the following categories: (1) marine fuels, (2) new engines and vessels, (3) existing engines, (4) existing vessels, (5) greenhouse gas emissions and (6) vessels at port. Near-term recommendations call for the implementation of proven best available technologies around 2010. Technology-forcing long-term recommendations are proposed for after 2020. Medium term recommendations are intermediary steps proposed for implementation in the 2012–2017 timeframe.

Implementing these recommendations will require active participation from the shipping sector's numerous stakeholders, including ship owners and operators, ports, and regulators. In addition to traditional regulatory and voluntary implementation mechanisms, the ICCT recommends expanded reliance on market-based measures to promote the adoption of cleaner fuels and low-emission technologies ahead of regulatory schedules. In developing such programs, regulators should consider what geographic scope, type of program administration, and incentive levels will best ensure policy success. Lessons learned from the Swedish program should guide efforts to develop environmentally differentiated fees or charges in other regions. Major shipping regions, such as the Baltic Sea, the Mediterranean Sea, the North Atlantic and the Pacific Rim, are potential candidates for the implementation of larger scale market-based measures.

Leadership from the businesses that demand shipping services is also crucial. Major producers and suppliers of goods are uniquely positioned to require that their wares be transported with the least possible impact on the environment. By requiring shipping companies and ports to compete not only on cost but also on environmental performance, businesses can significantly reduce the life-cycle environmental impacts of their products. In most cases, the extra cost of "green contracting" for shipping services would not be significant per item transported. For such approaches to succeed it will be necessary to develop environmental standards and rating systems so that interested companies can distinguish the environmental performance of competing suppliers. Regulators should work with shipping customers to refine existing multi-media impact criteria used to assess carrier performance.

Specific ICCT recommendations in each of the categories noted previously follow.

MARINE FUELS. Reducing fuel sulfur content is an essential component of any strategy aimed at reducing SO_x and PM emissions from marine vessels. Lower sulfur fuel also enables the use of advanced after-treatment for NO_x reductions. Existing plans to implement SO_x Emission Control Areas (SECAs), starting in 2006 in the

Baltic Sea and expected in 2007 for the North Sea and English Channel, mean that a portion of the world's ships are now or will soon be using 1.5 percent sulfur fuels or equivalent after-treatment. In the short term, the ICCT recommends including other major shipping areas, such as the Mediterranean and parts of the North Atlantic and Pacific Rim, in the SECA program. Moreover, decisions concerning future SECAs should take into account sulfur- and particle-related public health impacts as well as impacts on land and sea ecosystems. Finally, ICCT recommends that the fuel sulfur limit in SECAs be lowered from 1.5 percent to 0.5 percent to achieve further emissions reduction in the 2010 timeframe and to facilitate the shift to lower sulfur fuels on a global scale.

As a next step, the ICCT recommends that a uniform global fuel sulfur standard of 0.5 percent be introduced in the medium term. Relative to the 2.7 percent average sulfur content of current marine fuel, this step alone will reduce SO_x emissions by approximately 80 percent and PM emissions by a minimum of 20 percent. At this level of fuel quality, selective catalytic reduction (SCR), will be fully enabled. Although SCR can function at higher fuel-sulfur levels, durability is significantly improved at lower levels.

Some uncertainty remains regarding the widespread availability of lower sulfur fuels in the recommended timeframe. However, there has been significant momentum among various stakeholders to reduce the global fuel sulfur limit. For example, industry groups have recently expressed support for global fuel sulfur limit reduction (INTERTANKO 2006). In addition, current regulations in California and Europe require low-sulfur fuels in coastal waters, inland waterways, and at ports ahead of the ICCT-recommended dates. For example, the California auxiliary engine program requires the use of 0.5 percent sulfur fuel in the state's coastal waters and at port by 2007. The allowed sulfur level is lowered to 0.1 percent by 2010. Fuel with 0.1 percent sulfur content will also be required in ports and inland waterways in Europe by 2010

Adoption of a lower global fuel sulfur limit would provide the refining industry the clear signal it needs to invest in upgrading production facilities and ensure increased fuel availability. The ICCT also encourages further efforts to implement lower sulfur fuel ahead of the recommended schedule in coastal waters, inland waterways, and at ports. These programs can facilitate a transition to fleet-wide use of lower sulfur fuels while ensuring emissions reductions in proximity to the potentially impacted populations. In the long-term, fuel standards for marine fuels should be harmonized with standards for on-road fuels (500 ppm to 10-15 ppm).

NEW ENGINES. The IMO's recent decision to review NO_x standards for ocean-going vessels represents an opportunity to make significant progress in improving the performance of marine engines. The ICCT recommends requiring new engines to achieve NO_x limits that are 40 percent lower than the current standard in the near term. This level can be reached primarily through engine upgrades. New engine standards should also be set to ensure significant reductions in PM emissions. A medium-term standard set at a level 95 percent below current standards for NO_x would require the use of additional emission control technologies, including after-treatment controls. Further PM reduction should also be required. These near- and medium-term standards should be adopted at the same time to give manufacturers sufficient lead time to prepare for compliance and to direct their research and development activities accordingly. In addition to more stringent standards, the ICCT recommends that manufacturers be (1) required to certify engines using fuels that reflect actual in-use fuels quality; (2) be liable for in-use compliance and subject to in-use testing; and (3) be required to demonstrate the durability of emission control systems used to achieve compliance.

The production and use of engines that are significantly cleaner than the proposed standards should be encouraged both in the short and medium term through incentives to engine and technology manufacturers as well as vessel operators. Support for early technology demonstrations is necessary to ensure viable technology options are available to meet increasingly stringent standards. In the long term the ICCT recommends deploying incentives and other strategies to further promote the use of advanced technologies, especially technologies that achieve near-zero emissions, in promising applications.

NEW VESSELS. Many opportunities exist during a vessel's design and construction phases to make changes that would facilitate the use of low-emission control technologies. In the near term, the ICCT recommends that engine rooms be designed with enough space to allow for retrofit technologies including SCR as well as tank capacity for fuel switching in SECA and coastal areas. New vessels, especially ferries and cruise ships with regular routes and ports of call, should be built with the needed on-board equipment to utilize shore power when port-side facilities exist. Standardization of international shore power requirements is also needed to ensure compatibility between shore-side facilities and ships. The ICCT supports the ongoing efforts within IMO to develop guidelines for shore-side electricity. In the long term, the ICCT encourages the use of advanced vessel design concepts that optimize energy efficiency as well as emissions performance and that incorporate propulsion from renewable energy sources including solar and wind power, where feasible.

EXISTING VESSELS AND ENGINES. Control measures targeted at existing vessels and engines are necessary to significantly impact fleet-wide emissions. A low fleet turnover rate means that the largely uncontrolled vessels that make up the majority of the international marine shipping fleet today will continue to pollute for several decades before they are retired. Most existing control technology options have been developed and demonstrated on in-use vessels, suggesting that a large-scale retrofit program should be technically feasible. In the near term, the ICCT recommends that in-use standards reflecting best available control technologies be developed within the IMO. These standards would allow, for example, future market-based programs (including the range of possible differentiated fee programs) to harmonize their emission requirements. The ICCT further recommends that any in-use standards used in market-based programs be designed to become more stringent over time so as to provide ongoing incentives for adopting the newest control technologies as they become available, proven, and cost-effective. The program should provide additional incentives to demonstrations of advanced technologies that provide emission reductions beyond the adopted in-use standards. Also in the short term, the ICCT recommends exploring the feasibility of early ship retirement as an extension of the ship recycling programs being developed by the IMO. If determined feasible, this type of program could be implemented in the medium to long term.

GREENHOUSE GASES. The shipping sector's contribution to gases and particles that impact the Earth's climate is only beginning to be fully understood. Here, the ICCT recommends that near-term efforts focus on developing a baseline for the climate impacts of the world's vessel fleet. Once a baseline is established, market-based measures to reduce greenhouse gas emissions can be introduced, also in the near term. If cap and trade programs are developed for GHGs, they should only cover shipping sources and not include land-based sources. If the shipping sector becomes a source of credits for greenhouse gas emissions reductions, steps must be taken—as with any source of credits—to ensure that reductions are recognized only to the extent that they are quantifiable, enforceable, surplus to otherwise mandated reductions, and permanent. The ICCT also recommends that the IMO develop fuel economy standards for ships applicable to new vessels in the near term and existing vessels in the medium term.

AT PORT. The ICCT recommends that emission mitigation measures should be adopted at all major port facilities and be fully integrated with local and/or regional air quality plans. Each port type has access to a range of implementation mechanisms to reduce emissions from ships at berth. For example, landlord ports can include emission reduction requirements in their lease agreements with tenant operators. Operating ports can directly implement some infrastructure measures.

Providing shore power is often the most effective emission-reduction option for vessels while at port. In some locations, however, pollution impacts from electricity generation may make this option less attractive. The ICCT recommends that port authorities and regulators select the strategy or combination of strategies that cost-effectively provides the most environmental benefits. If shore power does not meet these criteria, other options should be implemented including requiring hotelling ships to use the lowest sulfur on-road fuels available and/or engine emission controls. The implementation of shore power and alternative mitigation technologies should prioritize new terminals as well as those that are near residential areas.

In the medium-term, the ICCT recommends that incentives be provided for utilizing low-carbon sources for shore-side power (including renewable solar and wind generators). In the long-term, the development of cost-effective energy storage technologies and advanced low- or non-carbon generating options should make it possible to achieve near-zero hotelling emissions.

In conclusion, supplemental international action within the IMO is necessary to produce reasonable progress in addressing ship impacts on local air quality and global climate change. National and regional policy-makers are increasingly seeking to accelerate the introduction of emission control technologies and cleaner fuels into the international marine sector. Within the IMO process, several countries including Sweden, Norway, and Germany have emerged as proponents of further measures to reduce emissions from ships. The few environmental organizations that have obtained consultative status with the IMO have also been leading efforts to accelerate progress on these issues. Other environmental NGOs with related activities and expertise should consider applying for consultative status to bolster these efforts. Finally, these efforts within the IMO must be brought to the attention of the larger public. Greater public awareness of the environmental impacts of routine ship activity will undoubtedly result in added pressure to reduce emissions in much the same way that highly publicized oil spills led to an increased focus on accident prevention, impact mitigation, and accelerated phase-out of single-hull tanker ship by the IMO. Best practices and local or national successes should be shared with a global audience to demonstrate that dramatic reductions in emissions from marine vessels, both at sea and in port, are not only feasible but also cost-effective. In the end, collaboration between the public and private sectors and across a wide set of stakeholders will be essential to forge support for sustainable long-term measures to mitigate the public health and environmental impacts of shipping around the world.

TABLE 21. ICCT Recommendations for Ocean-Going Vessels

ICCT RECOMMENDATIONS		IMPLEMENTATION MECHANISM
Fuels	— Short term: ○ Lower fuel sulfur level in SO_x Emission Control Areas (SECAs) from 1.5% to 0.5%. ○ Include SO_x/PM related health effects in addition to impacts on air, sea, and land as justification for SECA. ○ Expand SECA program to high ship-traffic areas in Mediterranean, Pacific Rim and North Atlantic. ○ Regional limits in coastal areas, inland waterways, and at ports — Medium term: 0.5% sulfur fuel globally — Long term: Harmonization with on-road diesel fuels (500 ppm to 10-15 ppm over time)	— International standards (IMO)
New engines	— Short term: ○ NO_x standards 40% percent below current IMO standards (2000 level). ○ PM standards ○ Encourage new technology demonstration — Medium term: ○ NO_x standards 95% percent below current IMO standards (2000 level) ○ PM standards further reduced ○ Encourage new technology demonstration — Long term: Encourage the use of advanced technologies, especially near-zero emission technologies in promising applications	— International standards (IMO)
New vessels	— Short term: ○ Adopt international requirements for shore power standardization. ○ All new ships built with shore-side electricity capability, especially cruise ship and ferries — Long term: Promote the use of advanced vessel design concepts in promising applications	— Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges — International regulation (IMO)

Table continues on next page

TABLE 21., continued

ICCT RECOMMENDATIONS		IMPLEMENTATION MECHANISM
Existing vessels and engines	— Short term: ○ Adopt emissions performance standards by vessel class and engine characteristics based on demonstrated retrofit potential. ○ Study feasibility and potential impact of programs to promote early ship retirement and environmentally sound disposal	— International standards (IMO) — Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges
GHG	— Short term: ○ Develop GHG emission inventory and fleet baseline ○ Market-based measures for vessels ○ Implement fuel economy standards by vessel class and engine characteristics for new vessels — Medium term: Implement fuel economy standards by vessel class and engine for existing vessels	— Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges — Cap and trade program for shipping sector only — International standards (IMO)
At port	— Short term: Select strategy that provides maximum emissions reduction benefits depending on local fuel availability and environmental performance of electricity generation ○ Shore-side electricity ○ Lowest sulfur on-road fuel and NO_x and PM after-treatment — Medium term: Market-based measures to promote low- or non-carbon energy sources to supply shore-side electricity for docked ships	— Port authority requirement — Preferential contracting of cleanest carriers — Environmentally differentiated fees and charges

ENDNOTES

[1] TEU: container volume in twenty-foot equivalent units, 1 TEU=39 m^3

[2] The Jones Act requires that domestic waterborne commerce between two points in the U.S. must be transported in vessels built in the U.S., registered under the American flag, and crewed and owned by U.S. citizens (Section 27 of the Merchant Marine Act of 1920 (46 U.S.C. 883; 19 CFR 4.80 and 4.80b).

[3] American ship owners registered ships in Panama to bypass drinking and gambling restrictions during the Prohibition era in the United States. After World War II, flags of convenience were used to evade fiscal, labor, safety, and environmental regulations.

[4] It is useful to note here for reference that the maximum scope of coastal state jurisdiction is defined by the 200-nautical mile exclusive economic zone (approximately 370 kilometers or 230 miles).

[5] This system is operated by the U.S. National Oceanic & Atmospheric Administration (NOAA).

[6] PM_{10} refers to a category of fine particulate matter: specifically, particles with an aerodynamic diameter of 10 microns or less.

[7] The IPCC publication presents emission inventories based on a number of differing estimation models and a number of possible future emissions scenarios, each designed to consider the implications of uncertainties in one or more emissions influences. As a result, the reference publication presents a series of 40 potential emissions inventories. For this study, these potential inventories were collapsed into a single "average"inventory.

[8] On-road sources include all the vehicles that move passengers and goods on the world's roads.

[9] International maritime law is in part reflected in the customs and practices of flag, port and coastal states. UNCLOS is a snapshot of customary maritime law and international practices in the early 1980s. As States interpret and apply the various provisions of UNCLOS, the body of international law will continue to develop and grow.

[10] For a general discussion of the features of a cap-and-trade approach see: US EPA. 2003. Tools of the Trade: A Guide to Designing and Operating a Cap and Trade Program for Pollution Control.

[11] Price information from New York represents a monthly average; Rotterdam data were only available on a quarterly basis

[12] Cost to ship owner

[13] Cost to ship owner

[14] If the fleet size estimates were inconsistent with the global cargo estimates, one might expect to see significant variation in predicted future cargo efficiency (tons per fleet deadweight ton) as compared to historic statistics. Since such variation is not observed, the two estimates appear to be consistent. Moreover, the estimates predict a modest (approximately 10 percent) increase in cargo efficiency over time, which seems reasonable for the extended timeframe evaluated.

[15] Additional support for the consistency of the global cargo and fleet size estimates is demonstrated in Figure A2-2, where increases in future cargo movement efficiency (ton-miles per fleet deadweight ton) are predicted, consistent with historic trends -- but at a declining rate of increase as would be expected over time (since further efficiency increases become more difficult as each "easier" increase is implemented). Moreover, a smooth transition between historic and predicted future statistics is observed.

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APPENDIX A: METHODOLOGY TO ESTIMATE GLOBAL MARINE EMISSIONS

MESZLER ENGINEERING SERVICES NOVEMBER 2006

1. Estimates of global marine mass cargo movement were obtained for 1970, 1980, 1990, 1995, and 1999-2003 from UNCTAD-2004 (Table 3, page 5 and Table 24, page 46). Corresponding estimates for 1971-1979, 1981-1989, 1991-1994, and 1996-1998 were obtained through interpolation.

2. Global marine mass cargo movement for 2004-2050 was estimated by applying a 1.5 percent annual growth rate to the 2003 data from UNCTAD-2004. A 1.5 percent annual growth rate is equal to the growth rate for marine bunker fuel estimated by WEC-1998, and on the low end of the 1.5-3 percent growth rate estimated in IMO-2000. To the extent that actual growth exceeds 1.5 percent annually, future marine emission estimates and impacts as determined in this analysis will be under predicted.

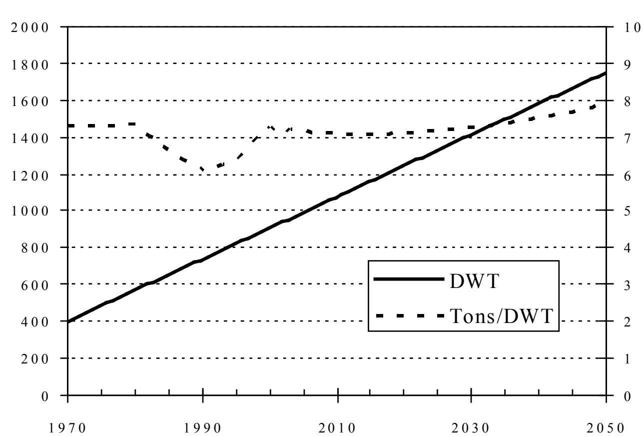

FIGURE A-1. Marine Fleet Size and Cargo Movement

3. Estimates of global marine fleet size (in deadweight tons) were obtained for 1990, 1995, 2000, and 2002-2003 from UNCTAD-2004 (Table 24, page 46). These data were regressed to determine the straight-line relationship between fleet size and calendar year. The resulting regression showed nearly perfect correlation (with an r^2 of 0.999) and a highly significant coefficient (t-statistic of 77.9), so that it was used to estimate the global marine fleet size for 1970-1989, 1991-1994, 1996-1999, 2001, and 2004-2050. The fleet size estimates are believed to be quite consistent with the global cargo movement estimates described in items 1 and 2 above since, as shown in Figure A-1, the mass of cargo moved per deadweight ton varies across only a small range throughout the entire 80 year forecast period.[14]

4. Estimates of global marine cargo movement in ton-miles were obtained for 1990, 1995, 2000, and 2002-2003 from UNCTAD-2004 (Table 24, page 46). These data were regressed to determine the straight-line relationship between cargo ton-miles and calendar year. The resulting regression showed excellent correlation (with an r^2 of 0.981) and a highly significant coefficient (t-statistic of 14.3), so that it was used to estimate global marine cargo ton-miles for 1970-1989, 1991-1994, 1996-1999, 2001, and 2004-2050. As shown in Figure A-2, cargo ton-miles per deadweight ton are estimated to increase modestly over the forecast period (by about 11 percent between 2000 and 2050).[15]

5. Estimates of U.S. commercial marine operating efficiency in Btu per ton-mile for 1970 and 1975-2002 were obtained from ORNL-2004 (Table 9.5, page 9-6). Corresponding estimates for 1971-1974 were obtained through interpolation. Since, as shown in Figure A-3, there is considerable year-to-year variability in these data, operating efficiency for 2003-2050 was assumed to equal the arithmetic average operating efficiency observed between 1970 and 2002. In the absence of alternative data, these estimates were also assumed to reflect average global marine operating efficiency.

6. Total global marine energy use in 1970-2050 was estimated by multiplying global marine cargo movement in ton-miles (from item 4 above) by global marine operating efficiency (from item 5 above).

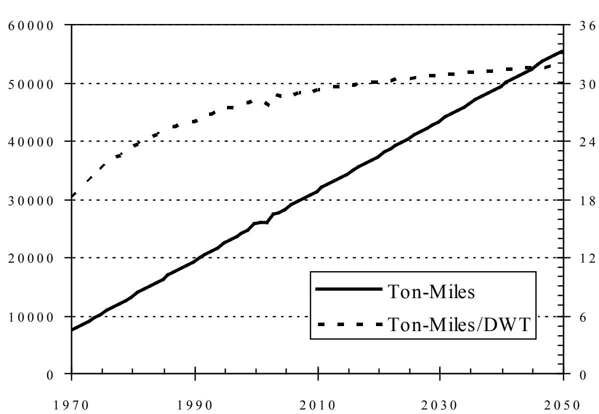

FIGURE A 2. Marine Ton Mile Estimates

FIGURE A-3. Marine Operating Efficiency

7. Estimates of U.S. sales volumes of distillate and residual fuel for marine bunkering for 1970-2002 were obtained from ORNL-2004 (Table A.9, page A-11). These data were converted to energy equivalents by assuming 138,700 Btu per gallon of distillate and 149,700 Btu per gallon of residual fuel, as per ORNL-2004 (Table B.4, page B-3). The share of total U.S. marine energy provided by residual fuel was then estimated as the ratio of residual fuel energy to the sum of residual plus distillate fuel energy. nce, as indicated in Figure A-4, the fraction total marine energy provided by residual fuel s generally been declining since 1970, re- lual fuel energy fractions for 2003-2050 were timated through straight-line regression of e 1970-2002 data. The resulting regression owed a highly significant coefficient (t-statistic -5.1), and indicates that the total fraction of arine energy obtained through residual fuel mbustion should decline from about 72 percent in 2003 to about 55 percent in 2050 if the historic trend continues (which was assumed in

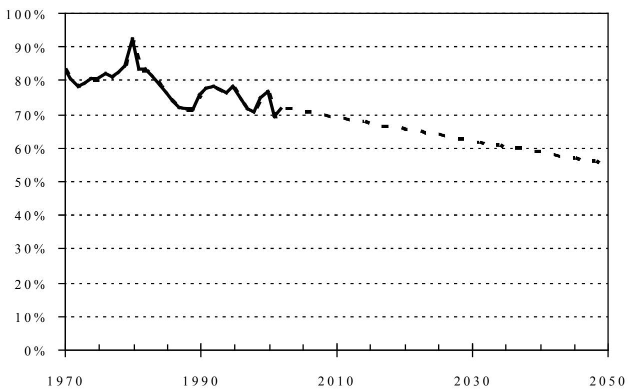

FIGURE A-4. Residual Fuel Fraction of Marine Energy

this analysis). In the absence of alternative data, these estimates were also assumed to reflect average global marine residual fuel energy fractions.

8. Global marine residual fuel energy use for 1970-2050 was estimated by multiplying total global marine energy use (from item 6 above) by the fraction of global energy provided by residual fuel (from item 7 above). Global marine distillate fuel energy use for 1970-2050 was estimated by subtracting global marine residual fuel energy use from total global marine energy use (from item 6 above). These energy use estimates were converted to mass estimates by assuming volumetric energy contents of 138,700 Btu per gallon of distillate and 149,700 Btu per gallon of residual fuel, as per ORNL-2004 (Table B.4, page B-3), and fuel mass densities of 7.0 pounds per gallon of distillate and 8.2 pounds per gallon of residual fuel. Total global marine fuel mass was estimated as the sum of distillate and residual fuel mass.

9. Specific fuel consumption rates (mass of fuel consumed per unit work performed) were developed using two methods. First, aggregate consumption rates were obtained from Eyring-2005 (Table 1, page 3 of 12). Second, in order to validate the Eyring-2005 estimates, specific fuel consumption rates by engine load condition for marine engines were independently estimated using measured fuel consumption data from LR-1990 and LR-1991. These data indicate specific fuel consumption rates for a range of ships and measured operating conditions. A total of 228 observations, as shown in Figure A-5 and representing measurements taken for 39 ships over engine loads ranging from 1 to 115 percent (generally each ship was tested at 5-7 specific loads), were subjected to regression analysis. The analysis indicates that specific fuel consumption is inversely related to engine load as follows:

$$\text{Grams Fuel per kW-hr} = \left[\frac{20.61}{\text{Fractional Engine Load}}\right] + 187.47 \quad [1]$$

with an r^2 of 0.8 and a coefficient significant at 99.9 percent confidence (t-statistic of 30.4).

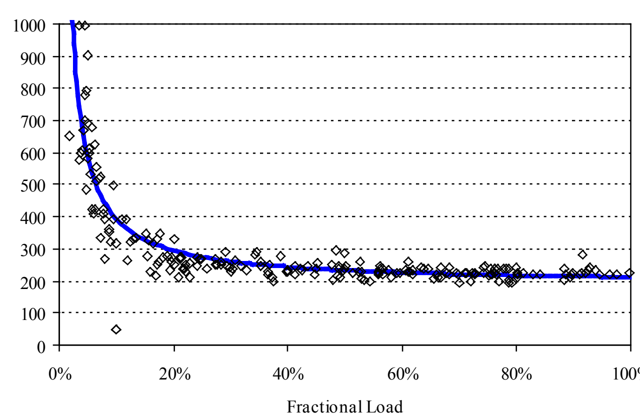

FIGURE A-5. Specific Fuel Consumption for Marine

10. Eyring-2005 indicates an average marine engine fuel consumption rate of 212 g/kW-hr. If a fractional engine load of 80 percent is assumed for global cruise operations (based on EEA-1999 (Table 4-2, page 4-7)), specific fuel consumption is estimated to be 213.2 g/kW-hr using the relationship presented in equation 1 (from item 9 above). Based on the similarity of these independent estimates, the Eyring-2005 value of 212 g/kW-hr was used as the average marine engine fuel consumption rate.

11. The total global marine work performed in 1970-2050 was estimated by dividing the total global marine fuel mass for 1970-2050 (from item 8 above) by the specific fuel consumption rate for global cruise operations (from item 10 above).

12. The total number of port calls associated with global marine operations in 1970-2050 was estimated by dividing global marine cargo tonnage (from items 1 and 2 above) by an estimated 10,174.5 cargo tons per port call. This latter estimate was developed using marine cargo data from WSC-2005, in conjunction with supplemental cargo data from PMA-1999. WSC-2005 indicates that in 2002, 19.7 million TEUs (twenty-foot equivalent container units) of cargo were imported or exported into the U.S. through about 17,000 port calls. This equates to 1,158.824 TEUs per port call. PMA-1999 indicates that each U.S. import TEU weighed about 8.27 tons in 1998, while each U.S. export TEU weighed about 9.29 tons. A simple arithmetic average of these data indicates a "typical" TEU weight of about 8.78 tons. Combining this estimate with the estimated 1,158.824 TEUs per port call from WSC-2005 yields an estimate of 10,174.5 cargo tons per port call.

13. HC, CO, NO_x and PM emission factors were developed using two methods. First, aggregate emission rates were obtained from Eyring-2005 (Table 1, page 3 of 12). Second, in order to validate the Eyring-2005 estimates, emission factor relationships (emission rates by fractional engine load) for global marine operations were obtained from EEA-1999 (Table 3-5, page 3-44). Based on an assumed fractional engine load of 0.8 (from item 10 above), the two methods produce emission factors estimates as follows:

TABLE A-1. HC, CO, NO_x and PM Emission Factors (g/kW-hr)

SOURCE	HC	CO	NO_x	PM
EEA-1999	0.479	1.202	15.785	0.263
Eyring-2005	1.5	1.0	16.2	1.27
Percent Difference	213%	-17%	3%	383%

The emission rates for CO and NO_x are generally in good agreement, but the Eyring-2005 emission rates for HC and PM are substantially greater than those of EEA-1999. Although the emissions dataset used in Eyring-2005 is not well documented, the data are attributed to "new and more accurate measurements of emission indices from engine test beds" (Section 3.2.1, page 5 of 12). Eyring-2005 indicates these new data to be especially significant for hydrocarbons, PM, and CO. Since this agrees well with the differences observed in Table A2-1, and since the EEA-1999 data were collected in 1990-1991 timeframe, the Eyring-2005 values were used without change for HC, CO, NO_x, and PM emission rates.

14. HC, CO, NO_x and PM emissions from global marine operations were estimated for 1970-2050 by multiplying the Eyring-2005 emission rates presented in Table A2-1 (from item 13 above) by the total global marine work performed in 1970-2050 (from item 11 above).

15. The average sulfur content of global marine fuel was assumed to be 2.5 percent by weight based on a rough average of fuel sample data collected in LR-1990 and LR-1991. Average sulfur contents for heavy, intermediate, and light fuel oil were calculated to be 2.7, 3.6, and 2.2 weight percent respectively, and 2.5 weight percent was taken as a rough median value. This agrees well with the average fuel sulfur content from Eyring-2005, which can be calculated on a fuel consumption weighted basis to be 2.4 weight percent (using data presented in Table 1, page 3 of 12).

16. The SO_2 emission rate for marine operations should be approximately equal to the specific fuel consumption rate of 212 g/kW-hr (from item 10 above) multiplied by the assumed average marine fuel sulfur content of 2.5 weight percent (from item 15 above) multiplied by a factor of 2 to account for the mole weight of SO_2 (64) relative to the mole weight of sulfur (32). This would imply an SO_2 emission rate of 10.6 g/kW-hr. Eyring-2005 indicates an SO_2 emission rate that is about 14 percent lower at 9.12 g/kW-hr. If this value is corrected by the ratio of the 2.5 weight percent sulfur content assumed in this work to the 2.4 weight percent content assumed in Eyring-2005, the Eyring-2005 value would increase to 9.5 g/kW-hr, about 10 percent lower than expectations based on sulfur mass balance. However, Eyring-2005 also attributes 47 percent of particulate mass emissions to SO_4, which implies an elemental sulfur PM emission rate of 0.2 g/kW-hr (1.27 g/kW-hr PM from Table A2-1 above times 0.47 times 32 grams sulfur per 96 grams SO_4), or an SO_2 emissions "sink" of 0.4 g/kW-hr (0.2 g/kW-hr time 64 grams SO_2 per 32 grams sulfur). Finally, if this is corrected once more for the 2.5 weight percent sulfur content assumed in this work relative to the 2.4 weight percent content assumed in Eyring-2005, the net SO_2 emissions "sink" due to SO_4 PM emissions is 0.42 g/kW-hr. Thus, the net SO_2 emission rate should be about 10.2 g/kW-hr on a mass balance basis. It is unclear why Eyring-2005 would assume a value that is effectively about 7 percent lower than mass balance expectations, but given the primacy associated with the conservation of mass, an SO_2 emission rate of 10.2 g/kW-hr is assumed. SO_2 emissions from global marine operations were then estimated for 1970-2050 by multiplying total global marine work performed for 1970-2050 (from item 11 above) by the assumed SO_2 emission rate.

17. The average carbon content of global marine fuel was assumed to be 87 percent by weight based on carbon coefficients for distillate and residual fuel from EIA-1999 (Table B-1, page 37), in conjunction with the respective energy content and fuel density estimates for both fuels from item 8 above. This value is quite consistent with the carbon weight fractions of 86 percent for light, medium, and heavy fuel oil in EEA-1999 (Table 3-4, page 3-10), which are based on testing data from LR-1990 and LR-1991. Based on a specific fuel consumption rate of 212 g/kW-hr (from item 10 above), this would imply a total carbon emission rate (including carbon emitted as HC, CO, and PM) of about 184 h/kW-hr. Corrected for carbon emitted as HC, CO, and PM using the Eyring-2005 emission rates presented in Table A2-1 above, the net carbon (carbon emitted as CO_2) emission rate is about 182.05 g/kW-hr, implying a CO_2 mass emission rate of about 667.53 g/kW-hr. Eyring-2005 indicates a CO_2 emission rate that is about 8 percent lower at 616 g/kW-hr. Based on the Eyring-2005 specific fuel consumption rate and emission rates of HC, CO, and PM, marine fuel carbon content would have to be about 0.80 weight percent to result in a CO_2 emission rate equal to 616 g/kW-hr. This is substantially lower than testing data of marine fuel would imply, and therefore the Eyring-2005 emission rate has been rejected on the basis of mass balance considerations. Instead, an emission rate of 182.05 g/kW-hr carbon has been assumed on the basis of mass balance calculations.

18. Carbon emissions from global marine operations were estimated for 1970-2050 by multiplying total global marine work performed for 1970-2050 (from item 11 above) by the assumed average marine carbon emission rate of 182.05 g/kW-hr (from item 17 above).

19. CO_2 emissions from global marine operations were estimated for 1970-2050 by multiplying total global carbon emissions for 1970-2050 (from item 18 above) by 3.67 to account for the mole weight of CO_2 (44) relative to the mole weight of carbon (12).

20. Emission factors and fuel consumption estimates for marine port operations were developed from BAH-1991. BAH-1991 reports total port emissions and fuel consumption for ocean-going underway, ocean-going hotelling, harbor, and fishing vessels, as well as cargo tonnage handled for six major U.S. ports (Baltimore, Baton Rouge, Houston-Galveston, New York-New Jersey, Philadelphia, and Seattle-Tacoma). From these data, emission factors (CO, HC, NO_x, SO_2, and PM) and fuel consumption rates per unit cargo ton handled were developed. The estimated emission rate for SO_2 was adjusted to correct for differences between the fuel sulfur contents assumed in BAH-1991 and the 2.5 weight percent sulfur value assumed in this analysis (see item 17 above).

21. Port fuel consumption and port emissions of CO, HC, NO_x, SO_2, and PM were estimated for 1970-2050 by multiplying the fuel consumption and emission factors for marine port operations (from item 20 above) by the total global marine cargo tonnage for 1970-2050 (from items 1 and 2 above).

22. Carbon emissions from marine port operations were estimated for 1970-2050 by multiplying total marine port fuel mass for 1970-2050 (from item 21 above) by the assumed average marine fuel carbon content (from item 17 above), and subtracting from the result the carbon emitted as HC or CO.

23. CO_2 emissions from marine port operations were estimated for 1970-2050 by multiplying total port carbon emissions for 1970-2050 (from item 22 above) by 3.67 to account for the mole weight of CO_2 (44) relative to the mole weight of carbon (12).

24. Total marine emissions were estimated as the sum of global cruise and port operation emissions (from items 14-19 and 21-23 above respectively).

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APPENDIX B: RESULTS OF THE SWEDISH ENVIRONMENTALLY DIFFERENTIATED NO_X FAIRWAY DUES PROGRAM (SMA 2006)

Ship Name	Ship Type	GRT*	Latest Certification Date	Installed Engine Power (kW)	NO_X EMISSION LEVEL (G/KWH)				ANNUAL USE (HOURS/ YEAR)	CONTROL MEASURE	CAPITAL COST INCENTIVE
					PRIOR	1ST CERT.	2ND CERT.	3RD CERT.			
Atle	Icebreaker	7457		21810	15	2				SCR	
Aurora af Helsingborg	Ro-Pax	10918	Jan-03	9840	14.5	3.71			4380	SCR + Low NO_x	
Balder Viking	Icebreaker	3382		14440	14.5	3.5				SCR	
Balticborg	Ro-Ro	1246	Sep-04	10950	14.5	2.5	2.5		6100	SCR	
Baltic Press	Ro-Ro	6413	Dec-05	2899	14.5	8.6			6100	EIM	
Baltic Print	Ro-Ro	6415	Dec-05	2849	14.5	8.5			6100	EIM	
Birka Exporter	Ro-Ro	6620	Dec-03	6570	14.5	1.3	1.3		6100	SCR	Yes
Birka Princess	Cruise	22412	May-02	22780	14.5	0.54			4380	SCR	Yes
Birka Shipper	Ro-Ro	6620	Nov-04	6618	14.5	1.3	1.3		6100	SCR	
Birka Transporter	Ro-Ro	6620	Nov-02	6618	14.5	1.2			6100	SCR	Yes
Birka Paradise	Cruise	34728	Nov-04	34440	14.5	0.4			4380	SCR	
Bothniaborg	Ro-Ro	12460	Feb-05	10950	14.5	1.9			6100	SCR	
Cellus	General Cargo	4231	Jan-05	4619	14.5	1.3	1.8		6100	SCR	Yes
Constellation	Cruise	90280	Jun-05	50000	5.6	5.6				Gas turbine	
Forrester	Dry Cargo	4110	Aug-03	3016	14.5	1.9			6100	SCR	Yes
Gotland	Ro-Pax	29746	Apr-04	54990	14.5	1.6			4380	SCR	
Gotlandia	High Speed Ferry	5632	Dec-02	29685	14.5	0.8			4380	SCR	Yes
Gotlandia II	Cruise	6554	May-06	37530	14.5	1.57			4380	SCR	
Jewel of the Seas	Cruise	90090	Jun-05	50000	5.2	2.5				Gas turbine	
Mariella	Ro-Pax	37860	Jun-04	23055	15	4.4	4.4		4380	HAM	
Navigo	Tanker	10543	Jul-02	6860						Magnetizer	
Dania Spririt	Tanker	7821	Jan-05	6745	15	4.1	5.4		6100	SCR	Yes
Obbola	Ro-Ro	20186	Nov-04	9930	14.5	1			6100	SCR	
Ortviken	Ro-Ro	18265	Feb-04	9930	14.5	0.8	1		6100	SCR	
Scandica	Work Vessel	980	Mar-96	2100	12	0.8				SCR	
Schieborg	Ro-Ro	21005	Mar-06	12800	15	2	0.2		6100	SCR	Yes
Sigyn	Nuclear Waste	4166	Dec-08	3690	14.5	1.1	0.93			SCR	Yes
Silja Europa	Ro-Pax	59912	May-05	40800	15	2.6			4380	SCR	Yes
Silja Festival	Ro-Pax	34417	Jul-04	34400	14.5	4.2	4.2		4380	SCR	
Silja Serenade	Ro-Pax	58376	Sep-05	44060	14.5	5.94	5.94	5.94	4380	Waterinj +SCR	

Table continues on next page

APPENDIX B: RESULTS OF THE SWEDISH ENVIRONMENTALLY DIFFERENTIATED NO_X FAIRWAY DUES PROGRAM (SMA 2006), continued

Ship Name	Ship Type	GRT*	Latest Certification Date	Installed Engine Power (kW)	NO_x EMISSION LEVEL (G/KWH)				ANNUAL USE (HOURS/ YEAR)	CONTROL MEASURE	CAPITAL COST INCENTIVE
					PRIOR	1ST CERT.	2ND CERT.	3RD CERT.			
Silja Symphony	Ro-Pax	58377	Sep-05	44060	14.5	5.51	5.77	5.77	4380	Waterinj +SCR	
Slingeborg	Ro-Ro	21005	Mar-04	12890	14.5	1.8	2.9		6100	SCR	
Spaarneborg	Ro-Ro	21005	Mar-04	12890	14.5	2.5	3.5		6100	SCR	
Stena Carisma	High Speed Ferry	8613	Oct-05	36600	14.5	6.4	6.3		4380	Gas turbine	
Stena Jutlandica	Ro-Pax	26800	Oct-03	32880	14.5	1.3	1.2		4380	SCR	Yes
Thjelvar/Color Traveller	Ro-Pax	17046	Dec-01	17320	14.5	0.6			4380	SCR	Yes
Timbus	Genral Cargo	4230	Mar-03	4627	15	1.6			6100	SCR	Yes
Tor Viking	Icebreaker	543		14440	15	3.5				SCR	
Vidar Viking	Icebreaker	3382		14440	14.5	3.5				SCR	
Viking Cinderella	Ro-Pax	46398	Oct-03	38640	14.5	0.4			4380	SCR	
Vicktoria I	Ro-Pax	40233	Jun-04	33344	14.5	3.9			4380	SCR	
Villum Clausen	High Speed Ferry	6402	Oct-03	37304	14.5	3.7	3.8		4380	Gas turbine	
Visby	Ro-Pax	29748	Apr-04	54990	14.5	1.6			4380	SCR	
Östrand	Ro-Ro	20171	Nov-04	9930	14.5	1.2			6100	SCR	

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