Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050

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[1] In this study the today's fleet-average emission factors of the most important ship exhausts are used to calculate emission scenarios for the future. To develop plausible future technology scenarios, first upcoming regulations and compliance with future regulations through technological improvements are discussed. We present geographically resolved emission inventory scenarios until 2050, based on a mid-term prognosis for 2020 and a long-term prognosis for 2050. The scenarios are based on some very strict assumptions on future ship traffic demands and technological improvements. The four future ship traffic demand scenarios are mainly determined by the economic growth, which follows the IPCC SRES storylines. The resulting fuel consumption is projected through extrapolations of historical trends in economic growth, total seaborne trade and number of ships, as well as the average installed power per ship. For the future technology scenarios we assume a diesel-only fleet in 2020 resulting in fuel consumption between 382 and 409 million metric tons (Mt). For 2050 one technology scenario assumes that 25% of the fuel consumed by a diesel-only fleet can be saved by applying future alternative propulsion plants, resulting in a fuel consumption that varies between 402 and 543 Mt. The other scenario is a business-as-usual scenario for a diesel-only fleet even in 2050 and gives an estimate between 536 and 725 Mt. Dependent on how rapid technology improvements for diesel engines are introduced, possible technology reduction factors are applied to the today's fleet-average emission factors of all important species to estimate future ship emissions. Combining the four traffic demand scenarios with the four technology scenarios, our results suggest emissions between 8.8 and 25.0 Tg (NO_2) in 2020, and between 3.1 to 38.8 Tg (NO_2) in 2050. The development of forecast scenarios for CO_2, NO_x, SO_x, CO, hydrocarbons, and particulate matter is driven by the requirements for global model studies of the effects of these emissions on the chemical composition of the atmosphere and on climate. The developed scenarios are suitable for use as input for chemical transport models (CTMs) and coupled chemistry-climate models (CCMs).

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1. Introduction

[2] Combustion from ships produces gaseous and particulate emissions and leads to a change of the chemical composition of the atmosphere [*Lawrence and Crutzen*, 1999; *Kasibhatla et al.*, 2000; *Davis et al.*, 2001; *Endresen et al.*, 2003] and of climate [*Capaldo et al.*, 1999; *Endresen et al.*, 2003]. Emissions of ozone precursors, like nitrogen oxides (NO_x) from ships [*Richter et al.*, 2004; *Beirle et al.*, 2004], carbon monoxide (CO) and unburned hydrocarbons (HC) contribute to the formation of ground-level ozone, which may damage human health and vegetation, and which changes the radiative budget as ozone is radiatively active. Additionally, these emissions also change the oxidation capacity of the marine boundary layer and the free atmosphere, which significantly affects lifetime and abundance of the greenhouse gas methane.

[3] Over the past decades, fuel consumption and emissions from international shipping have been substantially increased [*Eyring et al.*, 2005]. Ship emissions have been recognized as a growing problem for both scientists and environmental policy makers [*Corbett*, 2003]. Currently they are one of the least regulated sources of anthropogenic emissions with a high reduction potential through technological improvements, alternative fuels and ship modifications. In order to protect the atmosphere, the Maritime Environmental Protection Committee (MEPC) of the Inter-

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national Maritime Organization (IMO), who is responsible for international regulations of pollution from ships, has given international limits for NO_x emissions by ship engines in 1996 in Annex VI of the Marine Pollution (MARPOL) Convention [*International Maritime Organization*, 1998]. Annex VI entered into force in May 2005. National or regional regulations call for even more stringent NO_x and SO_x limits than those given by IMO. As a result, compliance with emission regulations through technological improvements will impact ship operators and the technology currently in use.

[4] The vast majority of marine propulsion and auxiliary plants onboard ocean-going ships are diesel engines. In terms of the maximum installed engine output of all civilian ships above 100 gross tons (GT), 96% of this energy is produced by diesel power. These engines typically have lifetimes of 30 years and more. Because of missing alternative propulsion systems with similar power density, prime costs and fuel efficiency, it is expected that diesel engines are not replaced in a foreseeable period of time. Therefore, at least for a mid-term period, emission reduction of existing engines will be based on effective emission reduction technologies. Since about 15 years, the engine industry concentrates their efforts on reduction of the pollutants from the engine exhaust gas as well as on reduction of CO_2 [e.g., *Fleischer*, 1996; *Heider and Eilts*, 2001; *Schlemmer-Kelling*, 2002; *Köhler*, 2000c; *Lustgarten*, 2005]. Most pollutants are formed during the combustion process. It is possible to reduce NO_x emissions by aiming at lower combustion temperatures, but this will cause slightly higher fuel consumption (= higher CO_2 emissions) as well as higher soot emissions. This trade-off effect is termed "diesel-dilemma" in the industry. Therefore, it is necessary to compensate the consumption and soot-impairing effects of the NO_x improvement by additional design measures, such as higher firing pressures. Consequently, whenever emission reduction strategies are discussed, it is mandatory to address the effects on all pollutant species.

[5] The development of future emission inventories is a challenge, driven by requirements for global model studies of the effects of these emissions on climate. Detailed atmospheric studies on the impact of ship emissions will help policy makers to develop appropriate reduction strategies. Clear information is needed on the climate impact of different ship emissions, to allow the industry to incorporate, with greater confidence, environmental considerations into their design and development work. Future emissions and their underlying driving forces are highly uncertain. The way to assess how future evolution might unfold is to design different scenarios [*IPCC*, 1999, 2000]. Scenarios encompass different future developments. They are neither predictions nor forecasts. Rather each scenario is an alternative image of the future, aiming at understanding our knowledge on how the system might unfold. Future ship emissions are influenced by very complex dynamic systems, driven by economic growth and seaborne trade development, as well as by technological change. Emissions can be reduced through different technical, operational, and market-based approaches [e.g., *Kjemtrup*, 2002].

[6] The only currently available forecasts for the development of the future merchant fleet undertaken so far are for the next six or eight years. A long-term forecast of the total ship traffic demand up to 45 years ahead is not available, neither on a global nor on a regional basis. In the IPCC SRES scenarios [*IPCC*, 2000], for example, future changes in the transport sector are projected based on changes in transport energy intensity. However, ship emissions are not separately included in these projections, even though the factors determining future marine fuel consumption and emissions, e.g., the total seaborne trade or new techniques for the marine industry, are quite different from those determining other transport sectors.

[7] In this work we develop ship traffic demand and technology scenarios until 2050, based on assumptions on the future economic growth and technology improvements. In section 2 we summarize current international and national maritime regulations. Those regulations will affect the industry and impact on the development of future technologies. This has to be borne in mind when setting up plausible technology scenarios. In sections 3 and 4, possible reduction strategies for existing and future diesel engines and alternative fuels are discussed. This section sets the base on what is possible from a technological point of view. Section 5 describes the method to calculate future fuel consumption and emissions based on historical statistical correlations of the world's economic growth, the total seaborne trade and the number of ships. The ship traffic demand scenarios follow the economic development of the four IPCC SRES storylines and are described together with the technology scenarios in section 6. Results for fuel consumption and total emissions of the world ocean-going fleet are presented and interpreted for 16 different scenarios in section 7.

2. International Conventions

[8] Since ship borne exhaust gases contribute to the worldwide pollution of air and sea, ships are meeting an increasing number of rules and regulations as well as voluntary appeals from international, national and local legislators [e.g., *Kjemtrup*, 2002].

2.1. International Regulations by the International Maritime Organization (IMO)

[9] The most well-known and established rules are the MARPOL (International Convention for the Prevention of Marine Pollution from Ships) Annex VI rules issued by the International Maritime Organization [*International Maritime Organization*, 1998]. IMO has declared the goal of a 30% NO_x reduction from internationally operating vessels and introduced a NO_x limiting curve which depends on engine speed (Figure 1). Different techniques to reduce NO_x emissions will be explained in section 3. From 1 January 2000 on all new marine diesel engines delivered for new vessels comply with this regulation (NO_x-optimized engines). Fifteen states controlling almost 55% of world merchant shipping tonnage have ratified Annex VI in May 2004 to become international law. Therefore, MARPOL Annex VI entered into force one year later, in May 2005, even though several important shipping nations such as the United States, Japan, and most of the European countries have still not ratified (status: end of 2004). On the same day a global cap of maximum 4.5% (currently still 5.0%) on the sulfur content of fuel oil will become mandatory for all

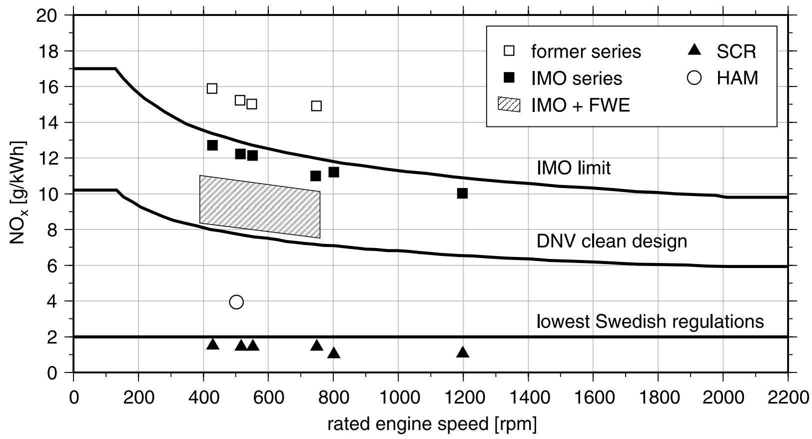

Figure 1. Specific NO_x emissions depending on the rated engine speed for different diesel engine techniques available from MAN B&W (SCR, Selective Catalytic Reduction; HAM, Humid Air Motor; FEW, Fuel Water Emulsification). Former series refer to four-stroke diesel engines without any NO_x optimization, IMO series refer to the same diesel engines, which fulfill the IMO NO_x regulations, and IMO + FWE are IMO series plus use of fuel water emulsion. Also shown are NO_x emission IMO limits, the DNV clean design proposal, and the lowest Swedish regulations.

ships. In addition, the first sulfur emission control area (SECA, with only 1.5% sulfur content) in the Baltic Sea will enter into force in May 2006. The next SECA is planned for parts of the English Channel and the North Sea and will enter into force, at the earliest, in 2007 [*World Bunkering*, 2004].

[10] Smoke and particulate matter is not yet subject to international emission legislation. However, there seems to be an increasing tendency to ban ships with dark plumes out of protected areas, such as the Glacier Waters of Alaska, the Galapagos Archipelago, and some major ports [*Köhler*, 2000b].

2.2. Kyoto Protocol (CO_2 Emissions)

[11] The industrial countries have made commitments under the Kyoto Protocol to reduce their greenhouse gas emissions, in particular carbon dioxide. The Kyoto Protocol entered into force in February 2005 (see United Nations Framework Convention on Climate Change, http://unfccc.int/2860.php). However, no decision has yet been taken on how to allocate the international greenhouse gas emissions from ships to the individual countries. Since no legislative action in this respect was agreed by the IMO in 2003, the EU is required to identify and take action to reduce the greenhouse gas emission from shipping. The IMO has identified some policies and measures to reduce greenhouse gases from ships, including improving the efficiency of the vessel, reducing the specific emissions, and reducing the turn-around times to allow for speed reductions.

2.3. National Regulations

[12] The Swedish authorities aimed at a 75% emission reduction by the beginning of 2000 [*Swedish Maritime Administration*, 1998]. In order to reach this goal, Swedish authorities applied financial incentives in the form of environmentally differentiated fairway and port dues. This means that the ship-based portion of the fairway dues is differentiated according to the ship-generated emissions of NO_x and the sulfur content of the fuel. These new incentives entered into force already on 1 January 1998 and have particularly stimulated emission reductions from the ferry traffic and from other frequent traffic to and from Sweden, regardless of the ship's Flag State.

[13] In Europe, seagoing ships in the past were widely exempted from existing EU quality legislation. Furthermore, marine heavy fuel-oils up to now have not been subject to EU environmental legislation. The result was that ships' contribution to EU emissions was rising, which was a reason for the European Commission to work towards a strategy to reduce air pollution from seagoing ships. Initially, the EU encouraged its member countries to adopt the IMO MARPOL convention and suggested expanding the low-sulfur restricted area to include also the French coast of the English Channel, and the North Sea. In June 2004, the EU environment ministers agreed upon a common position on the EU sulfur directive [*World Bunkering*, 2004], with a 1.5% sulfur limit for fuels used by all ships in the Baltic Sea, North Sea and Channel and a 0.2% sulfur limit on fuel used by inland vessels and by seagoing ships "at berth" in EU ports. Once agreed, this regulation will be about in line with IMO. The exceptions are the requirements for passenger vessels to use 1.5% sulfur fuels and the use of 0.2% sulfur fuels "at berth" reducing further in 2010. Future low sulfur requirements mean that ships may have to carry several grades of fuel.

[14] The United States' Environmental Protection Agency (EPA) has adopted ship emissions standards for NO_x, CO and HC for all U.S. ships with engines manufactured on or after 1 January 2004 [*U.S. EPA*, 2004]. In 2004, the so-called Tier 1 standards, which are in line with IMO's internationally negotiated NO_x limiting curve, became effective. This means NO_x emissions must be within 9.8 and 17.0 g/kWh depending on the engines' maximum operating speed (see Figure 1). The EPA has committed itself to drawing up legislation that will lead to stricter Tier 2 limits, coming into force between 2005 and 2007, depending on engine size/swept volume, and, eventually, Tier 3 limits,

coming into force during the next decade. The Tier 2 NO_x limits will be approximately 30% lower than the current IMO NO_x limiting curve and the Tier 1 limits. Simultaneously, the Tier 2 standards will limit particulates, CO and hydrocarbons.

[15] Det Norske Veritas (DNV), one of the classification societies, has suggested a strict environmental class notation CLEAN DESIGN, which, for the time being, is to be considered as a voluntary contribution for the shipping industry [*Olsen and Haugen*, 2001]. According to DNV, CLEAN DESIGN is considered as the notation most suited for ships in coastal and passenger trades. Since NO_x limits are set at 40% reduction of IMO's curve (see Figure 1), this notation covers environmental requirements in addition to those already covered by the mandatory MARPOL regulation. In order to reach this stringent NO_x level, more effective and more costly NO_x reduction technologies than the well known engine internal measures for NO_x-optimized engines have to be applied. Such measures are, among others, fuel water emulsification (FWE, section 3.1), Humid Air Motor (HAM, section 3.1) or Selective Catalytic Reduction (SCR, section 3.2). DNV furthermore suggest maximum 3% sulfur in the fuel. In addition there are special requirements applicable when a ship is in port or within special areas. In such cases CLEAN DESIGN suggests only 0.5% sulfur in the marine fuel.

3. Possible Reduction Strategies for Existing Diesel Engines

[16] Within the past 15 years, the engine industry has studied and thoroughly tested almost two dozens of different measures to cut emissions [e.g., *Fleischer*, 1996; *Köhler*, 2000c; *Eilts and Borchsenius*, 2001; *Schlemmer-Kelling*, 2002; *Kjemtrup*, 2002; *Grone and Kjeld*, 2004; *Köhler*, 2004a]. In these efforts the primary concern in shipping up to now is NO_x, because other pollutants are not yet regulated internationally. However, there are regional and local emission legislations, not only on the emission of NO_x, but also on SO_x and particulate matter (see section 2). Since about 1998/1999, all new marine propulsion engines are NO_x-optimized by their manufacturers in order to meet the IMO requirements (section 2.1), which result, compared to previous decades, in substantial reductions of NO_x emission. By using low-sulfur bunkers, it is possible to reduce SO_x: using fuel with only 2% sulfur instead of 4% will halve SO_x emissions, however at the penalty of an increased fuel price.

[17] Emission reduction methods can be classified as primary (section 3.1) and secondary strategies (section 3.2). Primary strategies are methods that control harmful species formation during the combustion process, and are often used in order to comply with the IMO NO_x regulation. Secondary methods refer to after-treatment of the exhaust gas after leaving the cylinder. In addition to primary and secondary methods optimization of various ship systems other than the engines (propeller, rudder, hull) are promising options to reduce fuel consumption rates and, with them, emissions [*Maeda et al.*, 1998; *Isensee*, 2003]. The energy-reduction potential, and therefore the emission reduction potential, of an optimized hull shape and a better propeller for a new ship is estimated to be up to 30% [*MARINTEK*, 2000].

[18] Also, alternative propulsion techniques like diesel-electric drives or the marine gas turbine could be used. However, in terms of efficiency, current diesel-electric drives cannot compete with diesel-mechanic propulsion. They lead to higher fuel consumption and emissions [*Köhler and Öhlers*, 1998; *Sekula*, 2004]. Part of this increase can be offset by having the engines optimized for operation at constant speed. In this case they can be adjusted in such a manner that the exhaust gas contains less harmful pollutants [*Nurmi*, 1998]. Marine gas turbines so far burn only high-quality, high-priced clean fuels such as Marine Gas Oil (MGO). Their real advantage is their eco-friendliness as far as SO_x and NO_x and also vibration and noise are concerned. The serious drawback of gas turbines is their low efficiency when compared to diesel engines of the same output, which increases fuel consumption rates (= operating costs) and CO_2 [*Köhler*, 2000a].

3.1. Primary Emission Reduction Strategies

[19] To achieve greater NO_x reductions than those possible by engine-internal measures, addition of water to the diesel combustion process is a promising approach. Any method of introducing water into the combustion space reduces the formation of NO_x by cutting temperature peaks in the engine cylinder [*Köhler*, 2004a]. The fuel water emulsification (FWE) technique itself cuts NO_x emissions by up to 30%. Generally, 10% of water addition to the fuel reduces NO_x formation by 10%. When simultaneously injection timing is retarded, the combined reduction effect is much higher (see Figure 1). The associated fuel consumption penalty with FWE ranges from zero to maximum 1% increase for each 10% water addition. As an additional benefit of FWE, soot production is slightly decreased too, especially at very low load and idling, contrary to all other methods of water introduction into the combustion space. The achievable NO_x level in marine applications for medium-speed diesel engines with FWE and variable injection timing is approximately 8–9 g/kWh, well below the current IMO NO_x limit [*Köhler*, 2004a]. Direct introduction of water into the combustion chamber (direct water injection, DWI) is also possible, but the method causes higher prime costs for the additional engine equipment and higher operating costs to produce the high amount of fresh water (with DWI about 50% water can be added). The Humid Air Motor (HAM) concept is a different way of introducing water into the combustion zone of a diesel engine. The system works by humidifying the scavenging air after the compressor of the exhaust-gas turbocharger [*Jansson*, 2000; *Riom et al.*, 2001; *Keiler*, 2004]. The involved distillation process makes it possible to use readily available seawater rather than the other methods of water injection into the cylinder for which clean fresh water is mandatory. The energy for heating the sea water is taken from the engine (exhaust gas, cooling water). It is possible to transport as much as three times more water than fuel into the cylinder, consequently a NO_x reduction of up to 80% can be achieved depending on engine load conditions. This means specific NO_x reductions to about 4.0 g/kWh can be reached (see Figure 1). The only drawback so far is the large surface and the volume of the humidifier and the required heat exchanger, associated with

very high prime costs. An alternative to HAM and an improved humidification method is the Combustion Air Saturation System (CASS), but no commercial marine application exists so far [*Hupli and Paro*, 2004].

[20] One of the latest primary reduction methods is the electronically controlled fuel injection and combustion process in the cylinder. In a conventional diesel engine the injection characteristics over the whole engine operating range are fixed. It is not possible to change them in order to improve engine performance and/or to reduce emissions. This drawback changes with common rail injection (CR), known from small high-speed diesel engines used in cars. CR systems are now being introduced in large-bore diesel engines burning low-quality heavy fuel-oils [e.g., *Aeberli*, 2004; *Eilts and Tinschmann*, 2004; *Köhler*, 2004b; *Vogel et al.*, 2004]. By being able to freely select injection pressure and injection start, and also have the possibility of pilot and post injection, a CR marine diesel engine can meet differing requirements at the same time, for instance invisible exhaust at idling and very low load, as well as NO_x reduction at medium load. Primarily, CR injection is a possibility to improve part-load operation. At higher and at full engine load the improvements by CR are small, because diesel engines with conventional injection systems have been optimized for high loads throughout the years.

3.2. Secondary Emission Reduction Strategies

[21] The only practical way to cut NO_x and other emissions of diesel engines considerably is selective catalytic reduction (SCR). SCR systems are secondary strategies to reduce emissions and have been successfully used onboard ships since several years. Contrary to spark-ignition engines, e.g., used in the automobile industry, exhaust gases from diesel engines have substantial oxygen content and a low gas temperature. Therefore a conventional three-way catalyst is not possible for removal of NO_x, HC and CO. The technique involves the conversion of the nitrogen oxides generated during the diesel combustion into the noncritical products nitrogen and water vapor with the aid of an aqueous urea solution as a selective, nontoxic reducing agent injected into the exhaust piping upstream of a catalytic reactor [*Roemich et al.*, 2002]. SCR is able to reduce different pollutants simultaneously, e.g., for full load of a diesel engine it reduces NO_x emissions by 90 to 99%, HC by 80 to 90%, CO by 80 to 90%, and soot by 30 to 40%. SCR investment costs, operating costs (per unit weight, urea is higher in price than heavy fuel-oil) and important items (such as urea storage tank), costs for maintenance as well as costs for occasional replacements of the catalyst are very high compared to other techniques [*Köhler*, 2000c]. However, costs are assumed to be reduced in the next few years.

3.3. Reduction Potential of Diesel Engines

[22] Considering onboard handling, reliability, performance and costs, additional engine internal measures may result, within the next 5 to 10 years, in a 20 to 30% reduction of NO_x compared to today's IMO standards, topped by a further 20 to 30% reduction when using, e.g., fuel water emulsification (FWE). Significantly higher NO_x reduction rates are achievable when HAM or SCR are applied. However, prime and operating costs especially for HAM and SCR as well as space requirements in the machine room are very high. SCR would be more attractive if the system could be upgraded for safely burning poor-quality fuels with more than 1.5% sulfur.

[23] Reduction of sulfur oxide emissions (SO_x) largely depends on the sulfur content of the fuel. Already today, soot emissions can be reduced to invisibility of the exhaust plume over the complete engine load range [*Köhler*, 2000b]. Other particle emissions also mostly depend on the fuel quality [*Fleischer*, 2002].

[24] Table 1 summarizes how different technologies discussed in this chapter affect the average specific fuel consumption (SFOC in g/kWh) and emission factors for each pollutant X (EI_X in kg/t fuel), as well as prime costs and operating costs. Highest NO_x reduction can be achieved with the SCR technique. Sulfur reduction only relies on the fuel burned and not on technology. When the SCR technology is adopted or marine gas turbines are applied, low-sulfur fuels have to be used which results in a reduction of SO_x. Compared to today's values, CO_2 emission factors remain constant or they increase. The reason is that currently conventional engines run at the highest engine efficiencies, resulting in a low specific fuel-oil consumption and low CO_2 emission. HC, CO, and particulate matter emissions are efficiently reduced by marine gas turbines, but SCR reduces particulate matter even better. Table 1 serves to derive plausible technology scenarios that consider what is possible from a technological point of view in section 6.2.

4. Alternative Fuels and Alternative Energy Sources

[25] The total world's reserves-to-production ratio of oil currently stands at 41 years [*British Petrol*, 2004] giving a need to develop techniques that allow the use of alternative fuels and energy sources.

4.1. Alternative Fuels

[26] Bio-oils, such as palm oil, coconut oil, rapeseed oil, soya oil, and others have been suggested as fuel for small low-power combustion engines since many years. When directly produced for marine propulsion, the operating costs would be unreasonably high, but this situation could change when wastes from the food industry would be used. Within the last few years, first tests with bio-fuels have been made with land-based medium-speed diesel engines in the power range of several MW, and the first few commercial bio-fuel engines have been sold already by manufacturers [*Gros*, 2002].

[27] Bio-diesel, defined as the mono alkyl esters of long-chain fatty acids derived from renewable lipid sources, could reduce CO_2 emissions and also particulate matter, but it is only in recent years that bio-diesel has gained a commercial application, primarily in land-based installations.

[28] The use of hydrogen diesel in large-bore diesel engines has been developed for high power densities and low exhaust-gas emissions [*Vogel*, 1999; *Vogel et al.*, 1999, 2000]. NO_x is the only pollutant of such an engine, but slightly more is produced than with marine distillate oil (MDO) or heavy fuel oil (HFO). This means NO_x reduction

Table 1. Average Specific Fuel-Oil Consumption (SFOC in g/kWh) and Emission Factors for Each Pollutant X (EI_X in kg/t Fuel) for the Total Merchant and Military Fleet Including Auxiliary Engines at the End of the Year 2001 and for Ships of 100 GT and More Taken From *Eyring et al.* [2005][a]

Technology	SFOC	EI_{CO2}	EI_{NOx}	EI_{SOx}	EI_{HC}	EI_{CO}	EI_{PM}	Prime Costs	Operating Costs
All Vessels 2001	212	2905	76.4	43.0	7.0	4.67	6.0		
Ship modifications	–	–	–	–	–	–	–	0	0
Diesel-electric propulsion	0	0	–	–	–	–	–	+	0
Marine gas turbine	+++	+++	– –	– – –	– –	– –	– –	+	+++
Fuel water emulsion (FEW)	+	+	– –	0	0	0	–	++	+
Humid Air Motor (HAM)	+	+	– –	0	0	0	+	+++	0
Selective Catalytic Reduction (SCR)	0	0	– – –	– – –	–	–	– – –	+++	+++
Common rail (CR) injection	0	0	–	0	–	0	– –	+	+

[a]The table shows how different technologies decrease (–) or increase (+) the emission factors as well as prime and operating costs. The scale reaches from +++ (high increase) to – – – (high decrease), where 0 means no change compared to present-day conditions.

methods have to be applied, which, due to the relatively clean exhaust gas, work more efficiently. Only traces of HC and CO are formed during hydrogen combustion. CO_2 is less than 2% of the CO_2 emission of a conventional diesel engine. Although the test results at MAN B&W were highly promising, the program was not carried on due to the very high current procurement costs of the fuel as compared to fossil fuels.

4.2. Alternative Energy Sources

[29] A few commercial installations of fuel cells (FC) onboard very small ships such as the 15 kW FC propulsion for a 12 m yacht on the Lake Constance in Germany [*MTU*, 2003] or the FC unit of *Hydra*, a 12 m, 4.3 ton wooden passenger launch [*Marsh*, 2001] are currently in use. For larger vessels, however, the power demand is in a 60 MW plus range, and it seems that a capable and reliable FC-based ship propulsion system is still a very long way into the future. Apart from this, the infrastructure for the ideal FC fuel, hydrogen, is missing. With this in place, FC-driven ships would need a much larger tankage volume to cover the same distance as with diesel fuels. Many technical problems in FC technology still have to be resolved within the next few years, quite aside from the efforts required to drastically reduce kW-based capital costs to more competitive levels.

[30] Nuclear marine propulsion has been so far only used onboard many military vessels and icebreakers. The reasons for the low distribution of nuclear propulsion in shipping are primarily safety reasons. Not all ports allow entrance to nuclear-powered ships. For these reasons it seems unlikely that existing propulsion machinery will be replaced by nuclear installations.

[31] Wind can be used as propellant for ships in two ways, as a power producer by wind turbines or as a thruster producer by sails or similar devices. A German company promotes a wind sailing concept with sail areas of up to 5000 square meters, stating that fuel consumption of a ship with this concept will be almost halved.

[32] Solar cells, as fuel cells, are the type of prime movers that produce energy without torque. They deliver voltage and the electrical current drives the motor which in turn drives the propeller of a ship. The advantages are no fuel consumption and no emission [*Ahlqvist*, 1999]. Although already in use today for demonstration purposes on a few small boats, the disadvantage of solar panels today is their enormous price level and their size in order to provide an appropriate power density.

4.3. Reduction Potential of Alternative Fuels and Energy Sources

[33] A significant shift from a primarily diesel-only fleet to a fleet that uses alternative fuels and energy sources until 2020 cannot be expected, as most of the promising alternative techniques are not yet tested to an extent that they can compete with diesel engines. Furthermore, the availability of alternative fuels is currently limited and time is needed to establish the infrastructure for alternative fuels. For these reasons, it is not likely that existing propulsion machinery will be replaced with alternative energy sources or fuels in the near future. This judgment refers primarily to our mid-term prognosis year of 2020.

[34] For the long-term scenario (2050), however, the situation might be different. It seems that future use of alternative fuels will mainly depend on availability and costs. For example, a combination of solar panels and sails is not out of question and also a small percentage of ships (more military than merchant vessels) might use nuclear-powered machinery. The introduction of hydrogen-propelled ships and the use of fuel cell power at least for the auxiliary engines seem to be a possibility. For larger vessels the power demands for FC for a capable and reliable FC-based ship propulsion system is still a very long way into the future, but might be possible in 2050.

[35] It is hard to assess which of the alternative techniques or fuels are likely to be in use in 2050. However, keeping in mind that the world's oil reserves are limited [*British Petrol*, 2004] and that first tests with alternative fuels and energies are already underway, a shift from a diesel-only fleet to a fleet that partly uses alternative fuels and energies in 2050 is likely. For one future technology scenario a 25% reduction of the fuel consumption of a diesel-only fleet in 2050 could be assumed. In order to show the possible range, another scenario for 2050 could be, if diesel propulsion will still deliver most of the fleets' electrical and propulsion energy and no further emission reductions are applied.

5. Methodology for Estimating Future Emissions From Ships

[36] To estimate the future total fuel consumption of the world's fleet, assumptions on the development of the

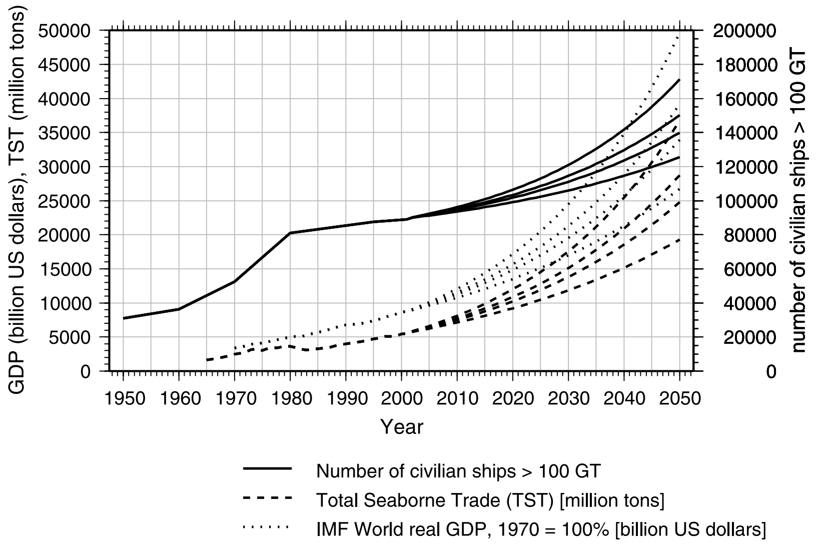

Figure 2. Global real GDP (total gross domestic product) at constant prices and market exchange rates [*IMF*, 2004] and world seaborne trade in tons [*Fearnresearch*, 2004] from 1960 to 2001. Respective values for the future GDP scenarios (DS1-4) until 2050 are prescribed assuming an annual growth of 2.3%, 2.8%, 3.1%, and 3.6%. The seaborne trade in our ship traffic demand scenario grows with 2.6%, 3.1%, 3.4%, and 4.0% annually. The estimated number of ships (civilian ships only) >100 GT over the time period 1950 to 2050 is also shown for the four different ship traffic demand scenarios. From 1950 to 2001 the number of ships is based on *Eyring et al.* [2005].

world's real Gross Domestic Product (GDP) and its correlation to the total seaborne trade, the number of ships, and the total installed engine power of the fleet have to be made. To estimate global future emissions, in addition plausible technology reduction factors have to be introduced. In order to meet the requirements of global modeling studies the total emissions have to be distributed over the globe. In this section we summarize the main assumptions and the methods applied in this study in order to derive future emission scenarios.

5.1. Correlation Between Economic Growth and Seaborne Trade

[37] For the development of future emission scenarios one of the key assumptions is the annual growth of the world's real GDP. In the case of shipping, the most important underlying demand is international trade.

[38] A constant annual growth of the world's real GDP did not necessarily mean the same increase in seaborne trade over the past decades (see Figure 2). During the past two decades, real GDP according to the statistics of the *International Monetary Fund* (*IMF*) [2004] grew by 2.8% p.a. on average. During the same period international trade experienced an average annual growth rate of 6.2% [*IMF*, 2004]. Since 1985 the world seaborne trade gained 3.3% in terms of volumes and 3.6% p.a. in terms of ton-miles in average [*Fearnresearch*, 2004; *Clarkson*, 2004]. The lower growth rate of seaborne trade compared to international trade results from the fact that international trade is measured in monetary values while seaborne trade is measured in weight.

[39] A good correlation between the total seaborne trade (*TST*) in terms of volume in million tons and real GDP in billion U.S. dollars at constant 1970 prizes exists over the time period 1985 to 2001 (see Figure 2) [see also *Fearnresearch*, 2004; *Clarkson*, 2004; *IMF*, 2004]. The future world seaborne trade in terms of volume in million tons ($TST_{f,DS}$) for a specific ship traffic scenario *DS* in a future year *f* can be estimated from the scenario's future GDP ($GDP_{f,DS}$) using a linear fit to historical data:

$$TST_{f,DS} = -1081 + 0.76 * GDP_{f,DS} \qquad (1)$$

5.2. Correlation Between Seaborne Trade and Number of Ships

[40] An increase in seaborne trade does in turn not necessarily increase the number of ships by the same extent, because a higher transportation capacity is possible with the same amount of ships having higher cargo capacities and/or higher speed. To estimate the future number of civilian ships in different ship traffic demand scenarios *DS* ($N_{ships,f,DS}$), the historical correlation between the number of ships and the total seaborne trade (*TST*) in terms of volume in million tons has been used. For the time period 1985 to 2001 a good correlation between the total seaborne trade [*Fearnresearch*, 2004] and the number of civilian ships [*ISL*, 2004; *Lloyd's Maritime Information System* (*LMIS*), 2002] exists, allowing a linear extrapolation into the future. The number of civilian ships in any year *f* between 2002 and 2050 can be estimated using equation (2), where $TST_{f,DS}$ is the future total seaborne trade in million tons depending on the chosen scenario *DS* and calculated by equation (1):

$$N_{ships,f,DS} = 74,983 + 2.62 * TST_{f,DS} \qquad (2)$$

5.3. Future Total Installed Engine Power

[41] In 1990, the average main engine output in the commercial fleet was 2.65 MW, for the fleet in 2000 this figure has increased to 3.1 MW, and further to 3.3 MW in

2003 [*LMIS*, 2002]. In order to estimate future average installed engine power per civilian ship ($P_{MW/ship,f}$), these values are linearly extrapolated to 2020 and 2050, giving an average installed power per civilian ship of 4.1 MW in 2020. In 2050, the fleet-average ship propulsion power would be 6.1 MW when extrapolated from 2020 and earlier decades. Because there are limiting factors such as port sizes, costs, and ship sizes, the power of ships cannot increase at the same rate forever. Following *Köhler* [2005], we used a lower average power quotient of 4.65 MW per civilian ship or 5.2 MW per ship, if all merchant and military vessels as well as auxiliary engines are considered.

[42] The future installed engine power per military ship ($P_{MW/mil,f}$) as well as the number of military ships ($N_{ships,mil,f}$) is assumed to remain constant, i.e., the values for 2001 (13.5 MW per military ships) from the first part of this study are used [*Eyring et al.*, 2005].

[43] To estimate the total future installed power for auxiliary engines ($P_{tot,aux,f,DS}$), we assume that the installed power grows linearly with the number of ships (equation (3a)) and use the values for the year 2001 [*Eyring et al.*, 2005] as baseline. The total installed power for auxiliary engines ($P_{tot,aux,2001}$) according to this work is 40,000 MW.

$$P_{tot,aux,f,DS} = P_{tot,aux,2001} * N_{ships,f,DS} / N_{ships,2001} \tag{3a}$$

The total installed power of the world's future fleet for a certain ship demand scenario DS ($P_{tot,f,DS}$) can be calculated as the sum of the total installed power for civilian ships, auxiliary engines and military ships in the respective year *f*:

$$\begin{aligned} P_{tot,f,DS} = {} & P_{MW/ship,f} * N_{ships,f,DS} + P_{tot,aux,f,DS} \\ & + P_{MW/mil,2001} * N_{ships,mil,2001} \end{aligned} \tag{3b}$$

5.4. Future Total Fuel Consumption

[44] For each technology scenario *TS* defined in section 6.2 a factor ρ_{TS} is introduced, which represents a shift from a fleet where the fuel consumption produced by a diesel-only fleet is partly, with a factor of ρ_{TS}, saved by alternative energies or fuels in 2050. Assuming basically constant specific fuel consumptions of the prime movers, the future fuel consumption ($FC_{f,DS,TS}$) can be estimated by applying equation (4a) for 2020 and equation (4b) for 2050:

$$FC_{2020,DS} = FC_{2001} * P_{tot,2020,DS} / P_{tot,2001} \tag{4a}$$

$$FC_{2050,DS,TS} = (1 - \rho_{TS}) * \left(FC_{2001} * P_{tot,2050,DS} / P_{tot,2001} \right) \tag{4b}$$

FC_{2001} is the fuel consumption consumed by the world's shipping fleet in 2001 and $P_{tot,2001}$ is the total installed power.

5.5. Future Total Emissions

[45] The basis to calculate total future emissions of all pollutants *X* until 2050 are the fleet-average emission factors for the total civilian and military fleet (>00 GT) and auxiliary engines in 2001 from the first part of our study [*Eyring et al.*, 2005] and the estimated future fuel consumption. For different technology scenarios, technology reduction factors ($R_{X,f,TS}$) can be introduced. For a certain ship traffic demand scenario (*DS*) and a technology scenario (*TS*), future total emissions of the pollutant *X* ($TE_{X,f,DS,TS}$) are obtained by multiplying the total future fuel consumption ($FC_{f,DS,TS}$) with the today's emission factor in kg per ton of fuel ($EI_{X,2001}$) multiplied by the technology reduction factor of pollutant X in the future technology scenario:

$$TE_{X,f,DS,TS} = FC_{f,DS,TS} * EI_{X,2001} * R_{X,f,TS} \tag{5}$$

5.6. Possible Change in Vessel Traffic Densities

[46] To distribute the emissions over the globe in order to meet the requirements of global modeling studies, the future change in current vessel traffic densities have to be addressed. Looking at the three most important market segments in world shipping it must be noted that the dynamics of container, tanker and dry bulk cargo are very different [*Fearnresearch*, 2004]. While dry and liquid bulk cargo on average grew by annual rates of 3.2% or 3.3%, respectively, container trade jumped by about 10% p.a. (see Figure 3). Also, the different structure of the fleet has to be addressed. As for the total seaborne trade in 2001, container ships contributed to 11%, tanker to 37%, bulker to 37% and the rest to 15% [*Clarkson*, 2004].

[47] Besides these general distinctions of major segments, there are several aspects within the market influencing the past and also the future vessel traffic and its distribution over the world. A major factor leading to under-proportionate growth of vessel traffic compared to cargo traffic (i.e., seaborne trade) is the development in ship size. During the past 20 years the average capacity of container vessels increased from about 1000 TEU (twenty feet equivalent unit, standard container) to more than 2200 TEU [*ISL*, 2003, 2004]. That results in the fact that the number of vessels and hence vessel traffic in the container market grew to a lesser extent than the volume of containers transported. Similar trends can be observed in other shipping markets.

[48] Considering the global distribution of ship emissions, it must be pointed out that current vessel traffic very much concentrates on the major routes between Europe, Asia and North America, connecting also the Middle East with these industrial centers [*Endresen et al.*, 2003]. In addition, some important bulk trades exist from South America, Australia, and Africa to locations in the northern hemisphere. The main determinant of our ship traffic demand scenario is the economic growth. Here it can be assumed that average growth in the current developing countries is higher than in today's industrialized ones [*IPCC*, 2000]. This assumption also influences the development of trade. Therefore, as consequence of the relations between economic development and trade (section 5.1), it can be expected that traffic volumes in north-south trades will grow faster compared to the existing main trades [*Lemper and Hader*, 2001]. While international trade, especially in north-south direction and within the southern hemisphere, is likely to speed up, the east-west trade on the long-term might reach a level of saturation and hence reduced growth.

[49] Regarding vessel sizes a similar split might be realistic. Larger vessels have already proven their feasibility

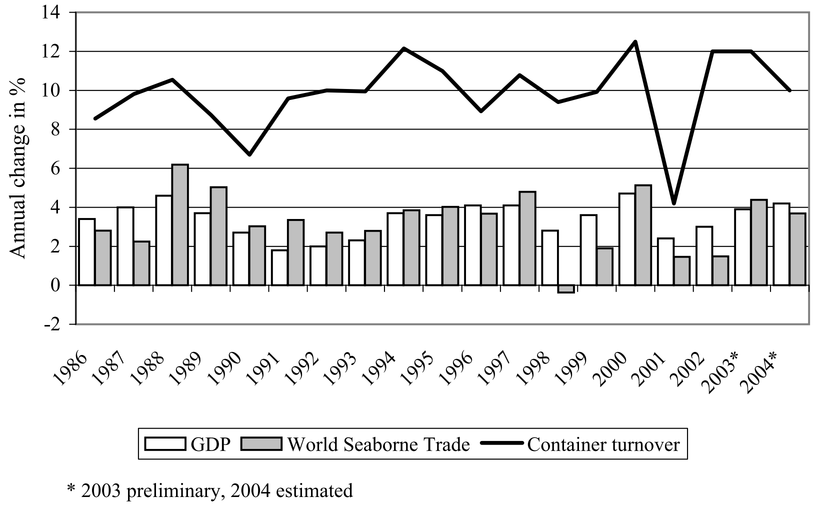

Figure 3. Annual change of global gross domestic product (GDP) [*IMF*, 2004], world seaborne trade (tons), and container turnover (TEU) [*Fearnresearch*, 2004; *ISL*, 2004] for the time period from 1986 to 2004.

in the high-volume, east-west trade. While vessel size in the east-west trades may already have reached a level from which further strong growth is unlikely, in the less developed trades further vessel growth must be expected [*Lemper*, 2001]. Under current conditions the application of large vessels are not economically feasible in these trades, but because of the expected higher volumes of transported goods, it is only a question of time and further trade growth, until larger vessels will also be used.

[50] Consolidating the possible trends in ship size and today's vessel traffic densities, the steeper economic and trade growth of the north-south trade is compensated by expected larger vessel sizes, while reduced growth of economy and trade in the current industrial countries is only slightly affected by a further ship size expansion.

6. Future Ship Traffic Demand and Technology Scenarios

[51] In this section plausible scenarios for future ship traffic demands as well as specific technology scenarios used in this study are described. The ship traffic scenarios are determined by the assumed future growth of GDP, whereas the technology scenario are determined by the technological reduction factors for each of the pollutants and the fraction to what extent alternative energies and fuels will replace diesel engines in a future fleet.

6.1. Ship Traffic Demand Scenarios

[52] In this study we use the annual growth of GDP of the four IPCC SRES storylines [*IPCC*, 2000] as one of the main underlying assumptions to set up future ship emission scenarios. IPCC SRES scenarios are divided into four different storylines that correspond to different assumptions on economic, technical, environmental, and social development. All scenarios are treated as equally possible in the IPCC assessment. The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. The A2 storyline and scenario family describes a very heterogeneous world with high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures. The B2 storyline and scenario family describes a world with moderate population growth and intermediate levels of economic development, in which the emphasis is on local solutions to economic, social, and environmental sustainability.

[53] For this study only the annual growth of GDP of the SRES scenarios is used. Over the time period between 1990 and 2050 the world's average annual economic growth rates are very high in the SRES A1 storyline (3.6%), high in the SRES B1 storyline (3.1%), and medium in SRES B2 (2.8%) and SRES A2 (2.3%).

[54] Four different ship traffic demand scenarios DS1 to DS4 are developed in this study in order to span a wide range of possible future economic development, leading to a wide range in possible ship traffic demand. Our ship traffic demand scenario DS1 follows the SRES A2 storyline, i.e., an annual increase in GDP of 2.3% up to 2050 is applied, DS2 follows SRES B2 (2.8%), DS3 follows SRES B1 (3.1%), and DS4 follows SRES A1 (3.6%).

6.2. Technology Scenarios

[55] The diesel engine has to be adjusted to comply with future emission regulations as a number of international and national regulations have recently entered into force or will enter into force in the near future (section 2).

[56] An estimate of how future emissions change with time can be based on assumptions how rapid different technologies (section 3) will be introduced. Depending on the technology, the average emission factor of the fleet will change. In this section we set up four different future technology scenarios to represent the range of possible

Table 2. Main Features for the Different Technology Scenarios (TS1-4)[a]

	Today's Fleet Average (2001)	Technology Scenario TS1: Clean Scenario	Technology Scenario TS2: Medium Scenario	Technology Scenario TS3: IMO Compliant Scenario	Technology Scenario TS4: Business-as-Usual, but Meeting IMO Emission Limits
		Low sulfur content Aggressive NO_x reduction	Relatively low sulfur content Moderate NO_x reduction	Still high sulfur content NO_x reduction according to IMO regulations, but no further reductions	Still high sulfur content NO_x reduction according to IMO regulations, but no further reductions
			Fleet Average Fuel Sulfur Content in 2020/2050		
Fuel sulfur content	2.4%	1%/0.5%	1.8%/1.2%	2%/2%	2%/2%
			Technology Reduction Factors in 2020/2050		
EI_{SOx}	43 kg/t fuel	0.42/0.21	0.75/0.5	0.83/0.83	0.83/0.83
EI_{NOx}	76.4 kg/t fuel	0.3/0.1	0.5/0.3	0.8/0.7	0.8/0.7
EI_{CO2}	2905 kg/t fuel	1/0.95	1/0.95	1/0.95	1/0.95
EI_{CO}	4.67 kg/t fuel	0.9/0.8	0.95/0.9	1/1	1/1
EI_{HC}	7.0 kg/t fuel	0.8/0.6	0.9/0.8	0.95/0.9	0.95/0.9
EI_{PM}	6.0 kg/t fuel	0.8/0.6	0.9/0.8	0.95/0.9	0.95/0.9

[a]The scenarios chosen in this study are combined with the traffic demand scenarios DS1 to DS4 to develop future ship emission inventories. Whereas in the scenarios TS1-3 it is assumed that 25% of the fuel consumption in 2050 for a diesel-only fleet is saved by use of alternative propulsion plant, for TS4 we assume a diesel-only fleet even in 2050.

technological change. The scenarios consider possible future technology improvements for diesel engines. Alternative propulsion plants and fuels (section 4) are taken into account in the fuel consumption of three of our scenarios (TS1-3). Here we assume that 25% of the calculated fuel consumption in 2050 will be saved by alternative propulsion plants. The fourth scenario (TS4) is based on a diesel-only fleet in 2050. In equation (4b) the factor ρ_{TS} in the four different technology scenarios is therefore assumed to be 0.25 in TS1-3 and 0 in TS4.

[57] Table 2 summarizes the main features as well as the technology reduction factors of the four technology scenarios. We have designed a clean, medium, IMO compliant and business-as-usual scenario.

[58] The different scenarios result in a decrease of the today's average emission factors. As baseline, the year 2001 is used. The average emission factors in kg per ton fuel for the year 2001 have been calculated in the first part of this study [*Eyring et al.*, 2005, Table 1], based on international shipping statistics [*LMIS*, 2002] and measurements of the emission factors (in kg per ton fuel) at the engine's test beds. The technology reduction factors in the different scenarios vary within what is possible from a technological point of view. The technologies to reduce emissions summarized in section 3 are already tested and in use for a small part of the fleet. To what extent they will be introduced into the entire fleet determines the technology factor in the different scenarios. How different technologies impact on emissions is summarized in Table 1.

[59] The clean scenario (TS1) assumes very low sulfur content of the fuels and an aggressive NO_x reduction in the future. It is a very optimistic scenario assuming that most of the new buildings that will replace old ships in the future will be equipped with a technique that substantially reduces all emissions, except CO_2. This can be achieved if techniques that efficiently reduce NO_x and other emissions (like FWE, HAM, or SCR, see Table 1) are widely introduced. A wide use of SCR would also automatically reduce total SO_x emissions. However, as total SO_x emissions only rely on the sulfur content in the fuel burned, aggressive sulfur reductions can also be achieved by strict international and national legislations (e.g., SECA [*World Bunkering*, 2004], see section 2.1). A shift to technologies like FWE, HAM, or SCR would also reduce the other emissions HC, CO, and PM (Table 1), but not to the same extent. Until 2050 we, e.g., assume that a reduction of the average 2001 NO_x emission factor of 90% is possible, i.e., a technology reduction factor of 0.1 for $R_{NOx,2050,TS1}$ is used. All other technology reduction factors are summarized in Table 2.

[60] The medium design (TS2) assumes only a relatively low sulfur content and moderate NO_x reduction, which is likely to be reached through the introduction of the above mentioned techniques, but to a lesser degree of the total fleet.

[61] The IMO compliant scenario (TS3) is based on the assumption that the future sulfur content is still high and NO_x reductions according to current IMO regulations will become standard in all new buildings, but no further reductions will be made. The term IMO compliant is defined as a scenario, where future new buildings entering the fleet are equipped with techniques that fulfill the today's IMO regulations, depending on the rated engine speed (see Figure 1).

[62] The business-as-usual scenario (TS4) is, like the IMO compliant design TS3, based on the assumption that the future sulfur of the fuel is still high and NO_x reductions are standard in all new buildings according to current IMO regulations, but in contrast to TS3 no shift to alternative fuels and energies is assumed, which leads to a higher fuel consumption and therefore higher total emissions.

Table 3. Profile of the World Fleet for Internationally Registered Ships Greater Than 100 GT Based on Ship Registered Data for the Year 2001 [*LMIS*, 2002] and on Projected Changes for the Years 2020 and 2050 for the Four Different Ship Traffic Scenarios (DS1-DS4)[a]

	Number of Vessels > 100 GT (Including Military Ships)			Average Installed Power per Ship, MW			Total Installed Engine Power, MW			Fuel Consumption, Mt		
	2001	2020	2050	2001	2020	2050	2001	2020	2050	2001	2020	2050
DS1	90,363	100,400	126,800	3.8	4.7	5.2	343,384	468,900	657,400	280	382	402/536
DS2	90,363	103,000	141,200	3.8	4.7	5.2	343,384	480,800	730,800	280	392	446/595
DS3	90,363	104,700	151,600	3.8	4.7	5.2	343,384	488,500	783,800	280	398	479/638
DS4	90,363	107,700	172,400	3.8	4.7	5.2	343,384	502,200	890,300	280	409	543/725

[a]The average installed power per ship and the fuel consumption for the year 2001 is from *Eyring et al.* [2005]. In 2050 the first figure for the fuel consumption refers to technology scenario 1–3 (TS1-3) where 25% of the fuel consumption for a diesel-only fleet is saved by the use of alternative propulsion plants. The second column refers to a business-as-usual scenario with a diesel-only fleet even in 2050, technology scenario 4 (TS4).

[63] Each of the four technology scenarios (TS1-4) is combined with the four ship traffic demand scenarios (DS1-4), leading to 16 future ship emission scenarios. The 16 scenarios present a wide but possible range of how future ship emissions could develop in the future. The combination of ship traffic scenario 1 (DS1, GDP growth 2.3%) with technology scenario 1 (TS1, high technology reduction factors, 25% of fuel-consumption saved by alternative plants in 2050) leads to the lowest emissions, whereas a combination of ship traffic scenario 4 (DS4, GDP growth 3.6%) with technology scenario 4 (TS4, high technology reduction factors, diesel-only fleet even in 2050) leads to the highest emissions within all the 16 scenarios until 2050.

7. Results

7.1. Future Fuel Consumption

[64] The first part of our study included a detailed analysis of the world's fleet in the year 2001, why we use 2001 as baseline [*Eyring et al.*, 2005]. The total fuel consumption of the world's fleet derived in part 1 of this study is an estimate based on statistical information of the total fleet greater than 100 GT including larger military vessels and auxiliary engines [*LMIS*, 2002]. The results suggest fuel consumption of approximately 280 million metric tons (Mt) for the year 2001, which is very similar to a previous bottom-up approach of 289 Mt [*Corbett and Köhler*, 2003]. From *Eyring et al.* [2005] we also use the total installed engine power in 2001 (343,384 MW), the installed engine power for auxiliary engines (40,000 MW) and the average installed power per military ships of about 300 GT and above (13.5 MW). In addition, we use the total seaborne trade in terms of volume in 2001 (5513 million tons) from *Fearnresearch* [2004] and the number of ships of 100 GT and above including military vessels (90,363) from *LMIS* [2002].

[65] The growth of the world's real GDP is related to the total seaborne trade as described in section 5. A higher economic growth results in a higher total seaborne trade. This in turn affects the number of ships, the total installed power and therefore the total fuel consumption and emissions.

[66] Each of the future scenarios is based on a certain growth of the world's real GDP according to the four IPCC SRES storylines (section 6.1). Applying equation (1) and assuming an economic growth of 2.3% (2.8%/3.1%/3.6%) in the ship traffic demand scenarios DS1 (DS2/DS3/DS4), results in an annual increase of 2.6% (3.1%/3.4%/4.0%) in total seaborne trade for the time period 2001 to 2050, respectively.

[67] Using equation (2), the total number of all civilian and military ships in 2020 in the four different ship traffic demand scenarios can be calculated and results into 100,400 ships (103,000/104,700/107,700) in 2020 and 126,800 ships (141,200/151,600/172,400) in 2050, according to the scenarios DS1 (DS2/DS3/DS4), respectively. The past development of the world's GDP, seaborne trade and number of ships over the time period 1950 to 2001 as well as the growth within the four ship traffic demand scenarios is displayed in Figure 2.

[68] The total installed engine power in the future can now be estimated with the help of equation (3b). Multiplying the average installed power per civilian ship with the total estimated ship number in 2020, and adding the installed power for military vessels and auxiliaries, results for the total installed fleet engine output range between 468,900 and 502,200 MW in 2020 and between 657,400 and 890,300 MW in 2050, depending on the ship traffic demand scenario.

[69] Applying equation (4a), the 2020 fuel consumption lies within 382 and 409 Mt for the four different ship traffic demand scenarios. In technology scenario 4 (TS4) a diesel-only fleet even in 2050 is assumed. The results suggest an increase up to 536 and 725 Mt, depending on the ship traffic demand scenarios. In three of our four technology scenarios it is assumed that 25% of this fuel can be saved by applying future alternative propulsion plants. This will bring the fleet's 2050 fuel consumption down to about 402 to 543 Mt for TS1 to TS3. Energy needed to produce modern propulsion equipments and their fuels is neglected. For all 16 scenarios the resulting fuel consumption in 2050 therefore varies between 402 and 725 Mt in 2050.

[70] The profile of the world fleet for internationally registered ships greater than 100 GT based on ship registered data for the year 2001 [*LMIS*, 2002] and on projected changes for the years 2020 and 2050 of this study for the four ship traffic demand scenarios (DS1–DS4) and the four technology scenarios (TS1-4) is summarized in Table 3.

7.2. Future Emissions

[71] Table 2 summarizes the underlying technology reduction factors ($R_{X,f,TS}$) that are assumed in this study for pollutant X, a future year f in one of the four technology scenarios TS1-4, Table 3 the future fuel consumption. Applying equation (5), all emissions can be estimated.

Table 4. Estimates of Global Annual CO_2, NO_x, SO_x, HC, PM, and CO Emissions for the Four Different Ship Traffic Demand Scenarios (DS1-4) and the Four Technology Scenarios (TS1-4) in 2020 and 2050[a]

	Scenario DS1 (GDP Growth 2.3%)						Scenario DS2 (GDP Growth 2.8%)					
2020	CO_2	NO_x	SO_x	HC	PM	CO	CO_2	NO_x	SO_x	HC	PM	CO
TS1	1110	8.8	6.9	4.1	1.8	1.6	1138	9.0	7.1	4.2	1.9	1.7
TS2	1110	14.6	12.3	4.4	2.1	1.7	1138	15.0	12.6	4.4	2.1	1.7
TS3	1110	23.4	13.6	4.5	2.2	1.8	1138	23.9	14.0	4.6	2.2	1.8
TS4	1110	23.4	13.6	4.5	2.2	1.8	1138	23.9	15.9	4.8	2.4	2.1
2050												
TS1	1109	3.1	3.6	3.7	1.5	1.5	1232	3.4	4.0	3.8	1.6	1.7
TS2	1109	9.2	8.6	4.2	1.9	1.7	1232	10.2	9.6	4.5	2.1	1.9
TS3	1109	23.4	14.3	4.5	2.2	1.9	1232	23.9	15.9	4.8	2.4	2.1
TS4	1478	23.4	19.1	5.3	2.2	2.5	1643	31.8	21.4	5.7	3.2	2.8
	Scenario DS3 (GDP Growth 3.1%)						Scenario DS4 (GDP Growth 3.6%)					
2020	CO_2	NO_x	SO_x	HC	PM	CO	CO_2	NO_x	SO_x	HC	PM	CO
TS1	1156	9.1	7.2	4.2	1.9	1.7	1188	9.4	7.4	4.3	2.0	1.7
TS2	1156	15.2	12.8	4.5	2.2	1.8	1188	15.6	13.2	4.5	2.2	1.8
TS3	1156	24.3	14.2	4.6	2.3	1.9	1188	25.0	14.6	4.7	2.3	1.9
TS4	1156	24.3	14.2	4.6	2.3	1.9	1188	25.0	14.6	4.7	2.3	1.9
2050												
TS1	1321	3.7	4.3	4.0	1.7	1.8	1501	4.2	4.9	4.2	2.0	2.0
TS2	1321	11.0	10.3	4.6	2.3	2.0	1501	12.5	11.7	5.0	2.6	2.3
TS3	1321	25.6	17.1	5.0	2.6	2.2	1501	29.1	19.4	5.4	2.9	2.5
TS4	1762	34.1	22.8	6.0	3.5	3.0	2001	38.8	25.9	6.5	3.9	3.4

[a]CO_2 is given in [Tg(CO_2)/yr], NO_x in [Tg(NO_2)/yr], SO_x in [Tg(SO_2)/yr], HC in [Tg(HC)/yr] (HC includes emissions from tanker loading, which are assumed to remain constant on the level of the year 2001), PM in [Tg(PM)/yr], and CO in [Tg(CO)/yr].

The resulting total emission for all pollutants in all 16 different scenarios are given in Table 4.

[72] NO_x emissions range from 8.8 to 25.0 Tg (NO_2) in 2020, and 3.1 to 38.8 Tg (NO_2) in 2050, depending on the scenario. SO_x emissions range from 6.9 to 14.6 Tg (SO_2) in 2020, and 3.6 to 25.9 Tg (SO_2) in 2050, HC from 4.1 to 4.7 Tg (HC) in 2020, and 3.7 to 6.5 Tg (HC) in 2050, PM from 1.8 to 2.3 Tg (PM) in 2020, and 1.5 to 3.9 Tg (PM) in 2050, and CO from 1.6 to 1.9 Tg (CO) in 2020, and 1.5 to 3.4 Tg (CO) in 2050. HC includes emissions from tanker loading, which are assumed to remain constant on the level of the year 2001. CO_2 emissions mainly depend on the fuel consumption. Our estimates suggest CO_2 emissions between 1110 and 1188 Tg (CO_2) in 2020 and between 1109 to 2001 Tg (CO_2) in 2050.

[73] Figure 4 shows the development of all calculated emissions for the time period 1950 to 2050. The values from 1950 to 2001 are taken from the first part of the study [*Eyring et al.*, 2005].

[74] For NO_x emissions the range of projected changes until 2050 in the 16 different scenarios is the largest. The total amount of NO_x emissions in 2001 (21.4 Tg(NO_2)) is based on a detailed calculation of the total fleet including all merchant ships (>100 GT) as well as military vessels and auxiliary engines [*Eyring et al.*, 2005]. Whereas in the highest emission scenario (DS4-TS4), NO_x emissions increase with an average annual growth rate of 1.2% between 2001 and 2050, they decrease in the lowest emission scenario (DS1-TS1) on average by 3.87% yearly. Even in the DS4-TS1 scenario which assumes 3.6% annual growth of GDP, NO_x decreases on average by 3.87% each year. It is important to note, that the different scenarios can be grouped with respect to the technology scenarios. For a certain scenario the NO_x emissions depend to a lesser extent on the chosen economic growth rates (i.e., 2.3%, 2.8%, 3.1%, and 3.6%) than they depend on the chosen technology reduction factors (see Table 2). Especially for technology scenario 1 (TS1) the assumed technology reduction factor of 0.1 dominates the NO_x emissions. For TS1 NO_x emissions are therefore quite similar in all four ship traffic demand scenarios (see Figure 4). In other words, this means that if diesel engines will not be equipped with NO_x reduction techniques, NO_x emissions from the international fleet might further increase up to 38.8 Tg(NO_2) in 2050, which would even exceed today's NO_x emissions from road traffic (i.e., 27.3 Tg(NO_2) [*Eyring et al.*, 2005]). We conclude that future NO_x emissions are mainly determined by the technology reduction factors and to a lesser extent by the economic growth and the factor ρ_{TS}, which represents a shift from a fleet where the fuel consumption produced by a diesel-only fleet is partly, with a factor of ρ_{TS}, saved by alternative energies or fuels in 2050 (see equation (4b)).

[75] This is similar for SO_x emissions, but in contrast to NO_x, SO_x emissions could simply be reduced by using a higher quality fuel with less sulfur content without almost any change in the current engine design. For SO_x the scatter in the projected changes is quite similar to those of NO_x emissions. If no international and national laws to restrict the sulfur content of the fuel will enter into force in the future, SO_x might increase up to 25.9 Tg (SO_2) in 2050. SO_x emissions from shipping already dominate the transport sector today [*Eyring et al.*, 2005], but increase even further with an average annual growth rate of 1.58% until 2050 in our highest emission scenario (DS4-TS4).

[76] The CO_2 emissions mainly depend on the underlying growth of GDP and the factor ρ_{TS}. Today's marine diesel engines run at highest efficiency (equal to low fuel costs), which also means lowest possible CO_2. Some future techniques might reduce CO_2, but only slightly compared to today's values. In our scenarios therefore the technology reduction factor in 2050 is only 0.95.

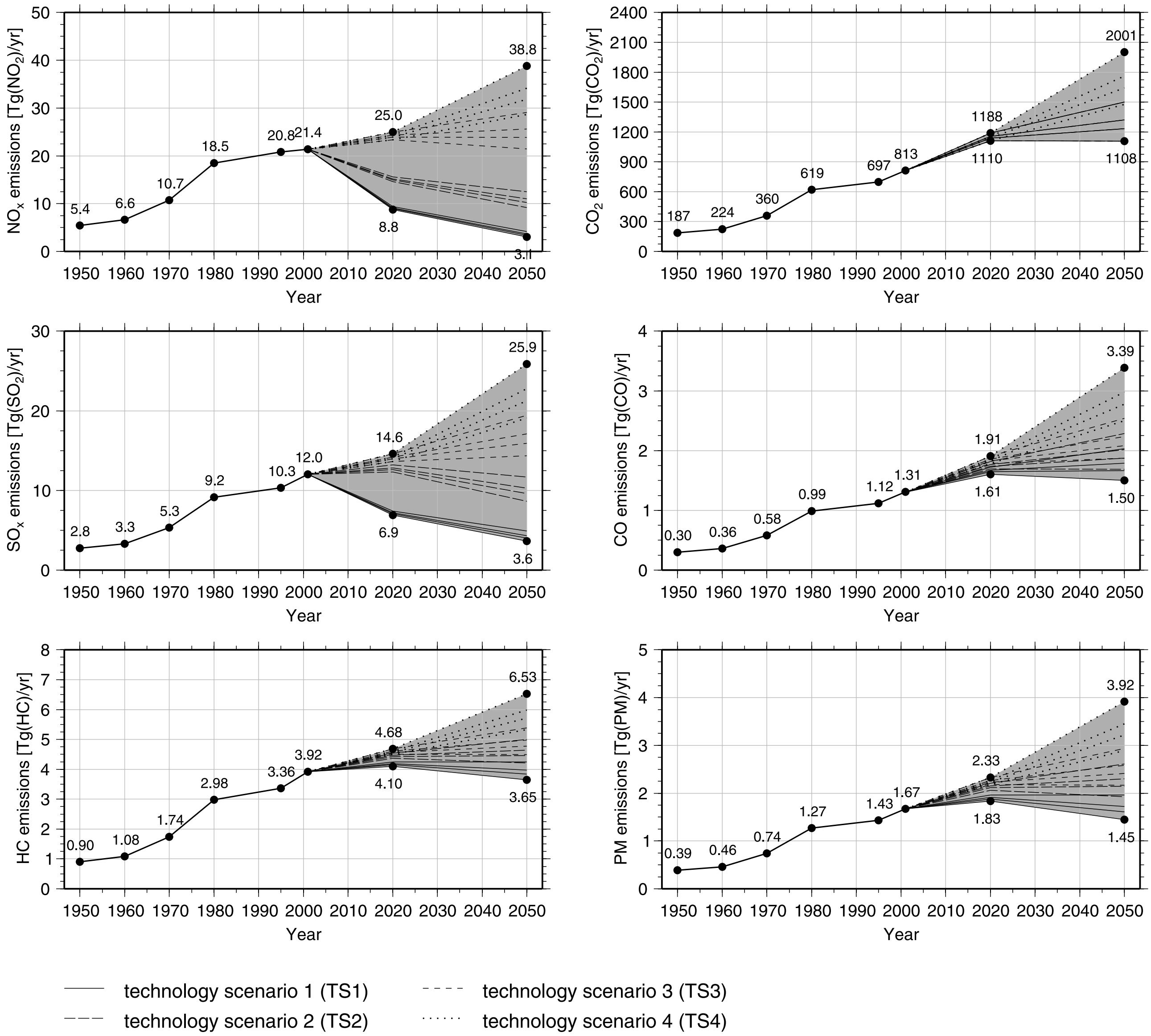

Figure 4. Possible range of future NO_x emissions in $Tg(NO_2)$, CO_2 in $Tg(CO_2)$, SO_x in $Tg(SO_2)$, CO in Tg(CO), HC in Tg(HC), and PM in Tg(PM) according to the four different technology scenarios (TS1-4) and the four different ship traffic demand scenarios (DS1-4). Results for the technology scenario 1 (TS1) are shown for different ship traffic demand scenarios (DS1-4) with solid lines in black, those for TS2 with long dashed lines, for TS3 with short dashed lines, and for TS4 with dotted lines.

[77] For all other emissions (CO, HC, and PM) the further increase of the total fleet can be partly compensated through technological improvements, and might even decline, if stringent improvements are introduced in major parts of the fleet.

7.3. Future Vessel Traffic Densities

[78] To estimate the change in future vessel traffic densities, we keep the current structure of the fleet, i.e. 11% of the seaborne trade is transported by container ships, 37% by tanker, 37% by bulker and 15% by the rest [*Clarkson*, 2004]. Furthermore, the change in ship size is considered. While international trade, especially in north-south direction and within the southern hemisphere, is likely to speed up, the east-west trade on the long-term might reach a level of saturation and hence reduced growth (section 5.6).

[79] Table 5 summarizes assumed plausible annual growth rates of the world seaborne trade and vessel traffic density by main trade routes (in particular east-west trades) and other trade routes (in particular north-south trades) and different ship types (container, tanker, bulker, and others). The annual growth rates are based on the growth of seaborne trade for the four different ship traffic demand scenarios, i.e., 3.6% (3.1%/3.4%/4.0%) in DS1 (DS2/DS3/DS4), respectively. As described in section 5.6, the vessel traffic densities grow under-proportionally compared to the seaborne trade. The present-day main trade routes increase with an average annual growth between 1.7% and 2.9%, whereas other trades increase with an annual growth rate

Table 5. Plausible Annual Growth Rates From 2001 to 2050 of Sea Trade Volumes (Tons) and Expected Vessel Traffic Densities for Today's Main and Ancillary Trades and Different Ship Types (Container, Tanker, Bulker, and Others) for the Four Different Ship Traffic Demand Scenarios (DS1-4)

	Scenario DS1 (GDP Growth 2.3%)			Scenario DS2 (GDP Growth 2.8%)		
	Main Trade Routes	Other Trade Routes	Total	Main Trade Routes	Other Trade Routes	Total
			Sea Trade Volume			
Container	5.0%	6.5%	5.4%	6.0%	7.9%	6.6%
Tanker	1.8%	2.1%	2.0%	2.2%	2.6%	2.4%
Bulker	2.1%	2.6%	2.4%	2.6%	3.2%	2.9%
Others	2.4%	2.6%	2.5%	2.9%	3.2%	3.0%
Total	2.3%	2.8%	**2.6%**	2.8%	3.5%	**3.1%**
			Average Vessel Movements			
Container	3.9%	4.6%	4.1%	4.9%	6.0%	5.2%
Tanker	1.2%	1.4%	1.3%	1.6%	1.8%	1.7%
Bulker	1.6%	1.9%	1.8%	2.0%	2.5%	2.3%
Others	1.8%	2.0%	1.9%	2.3%	2.6%	2.4%
Total	1.7%	2.0%	**1.9%**	2.2%	2.6%	**2.4%**
	Scenario DS3 (GDP Growth 3.1%)			Scenario DS4 (GDP Growth 3.6%)		
	Main Trade Routes	Other Trade Routes	Total	Main Trade Routes	Other Trade Routes	Total
			Sea Trade Volume			
Container	6.6%	8.6%	7.2%	7.6%	9.9%	8.3%
Tanker	2.3%	2.8%	2.6%	2.7%	3.2%	3.0%
Bulker	2.8%	3.4%	3.2%	3.2%	4.0%	3.7%
Others	3.1%	3.4%	3.3%	3.6%	4.0%	3.7%
Total	3.1%	3.8%	**3.4%**	3.6%	4.3%	**4.0%**
			Average Vessel Movements			
Container	5.5%	6.7%	5.8%	6.4%	7.9%	6.9%
Tanker	1.8%	2.1%	2.0%	2.1%	2.5%	2.3%
Bulker	2.3%	2.8%	2.6%	2.7%	3.3%	3.0%
Others	2.6%	2.9%	2.7%	3.0%	3.4%	3.2%
Total	2.5%	3.0%	**2.7%**	2.9%	3.5%	**3.2%**

between 2.0% and 3.5% over the time period 2002 to 2050.

[80] The annual growth rates have been applied to the AMVER vessel traffic densities for the different sub-types (tanker, container, bulker, and rest) for the year 2000 from *Endresen et al.* [2003]. Figure 5 shows the vessel traffic densities of the total fleet in 2000 and, as an example, the calculated 2050 vessel traffic densities for ship traffic demand scenario DS2. For the year 2000 the vessel traffic densities are based on the reported distributions from AMVER data [*Endresen et al.*, 2003], whereas for 2050 the figure shows projected changes in vessel traffic densities from this study.

8. Summary and Conclusion

[81] We have developed future emission scenarios for the international ocean-going fleet until 2050. To represent possible economical and technological changes, four ship traffic demand scenarios and four technology scenarios are considered. The ship traffic demand scenarios are based on the change in the world's global domestic product, following the four IPCC SRES storylines A1, B1, B2, and A2 [*IPCC*, 2000]. The technology scenarios are based on assumptions on how rapid technology improvements are introduced and on how technological improvements or alternative fuels and energy sources impact on the fuel consumption and specific emission factors of different pollutants. Each of the four technology scenarios (TS1-4) is combined with the four ship traffic demand scenarios (DS1-4), leading to 16 scenarios. The 16 scenarios present a wide but possible range of how future ship emissions might develop in the future. It will depend on the scientific question, which of the scenarios should be used in modeling studies.

[82] All our estimates use the year 2001 as baseline, because the structure of the world's total fleet (including all civilian and military vessels of 100 GT and above as well as auxiliary engines) and the fleet-average emission factors have been calculated in detail in the first part of this study [*Eyring et al.*, 2005]. We have used the fuel consumption in 2001 (i.e., 280 Mt) as a basis to design possible future scenarios. The fleet-average installed engine power per ship [*LMIS*, 2002] and the estimated fleet-average emission factors in kg per ton fuel in the year 2001 [*Eyring et al.*, 2005] are also key initial values for future estimates. For the four different technology scenarios plausible technology reduction rates have been applied, bearing in mind what is possible from a technological point of view and from compliances with upcoming regulations. The total emissions for all pollutants (i.e., CO_2, NO_x, SO_x, HC, PM, and CO) until 2050 have been calculated. The technology scenarios range from a clean to a medium, an IMO compliant, to a business-as-usual scenario. The clean scenario is based on the assumption of aggressive NO_x reduction and low fleet average fuel sulfur content of the fuel. This can, e.g., be achieved if future diesel engines will be equipped with techniques that efficiently reduce NO_x-emis-

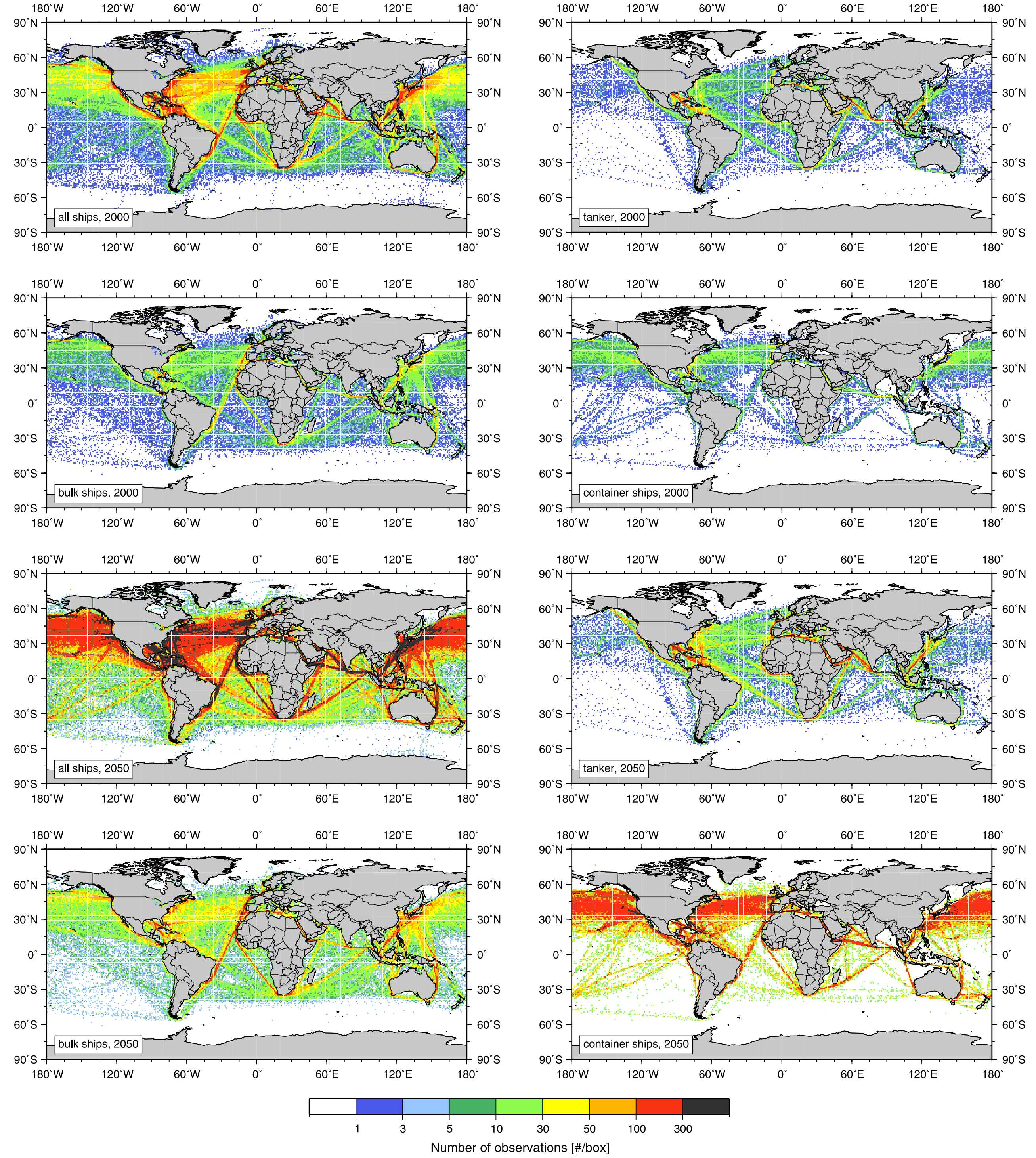

Figure 5. Vessel traffic densities for different ship types of the total fleet in 2000 (upper plot) and 2050 (lower plot). For the year 2000 the vessel traffic densities are based on the reported distributions from AMVER data [*Endresen et al.*, 2003]. As an example, the vessel traffic densities in 2050 are shown for the ship traffic demand scenario 2 (DS2) (for details, see text and Table 5).

sions (like, e.g., FWE, direct water injection, HAM, or SCR, see section 3). The IMO compliant scenario considers no further reduction for diesel engines, but new buildings that will meet the IMO regulations [*International Maritime Organization*, 1998]. In all four scenarios the fuel consumption in 2020 is based on a diesel-only fleet resulting in 382 to 409 Mt, depending on the ship traffic demand scenario. A shift to alternative energy sources and fuels is not very likely before 2020. For three of our technology scenarios (TS1-3) in 2050 we assumed that 25% of the fuel consumed by a diesel-only fleet can be saved by applying future alternative propulsion plants. As the total world's reserves-to-production ratio of oil currently stands at 41 years [*British Petrol*, 2004] and first tests with alternative fuels and energies are already underway, this seems to be a realistic estimate. However, the percentage of 25% is only an assumption and therefore one of the major uncertainties in our future scenarios. In order to give an upper limit of the fuel consumption and total emissions in 2050 we have also set up a forth technology scenario (TS4), where we assume that even in 2050 the complete fleet consists of diesel engines, and no further reduction (except that the scenario is compliant with today's IMO regulations) will be undertaken. With these assumptions the fuel consumption in 2050 within all 16 scenarios varies between 402 and 725 Mt.

[83] In order to distribute the emissions over the globe to meet the needs of data sets suitable for global modeling studies, we estimated the change in future vessel traffic densities in the four ship traffic demand scenarios. The average movement grows under-proportionally compared to seaborne trade. Future vessel traffic densities have been estimated on the basis of number of vessel observations per grid cell from the AMVER data set for the year 2000 and different ship classes (tanker, container, bulker, and rest) [*Endresen et al.*, 2003]. Here we assumed that today's frequently sailed trade routes (in particular east-west trades) will grow less than the today's less frequently sailed trade routes (in particular south-north trades) due to upcoming saturation effects. However, although our assumptions are reasonable from our today's point of view, the estimate of future changes in vessel traffic densities would benefit if, instead of the number of observations per grid cell, the actual ship movement data would be used. This is an outstanding issue which has to be addressed in future studies.

[84] The growth rates of the real gross domestic product impact on our estimates of the growth rate in seaborne trade and in vessel movements. However, it also influences our technology scenarios in terms of number of ships and further in the estimate of fuel consumption and total emissions. A higher (lower) annual growth rate in real GDP would obviously lead to higher (lower) future total emissions and fuel consumption and is therefore another uncertainty in our estimates. The future world economic growth rates assumed in our traffic demand scenario follow the IPCC SRES storylines [*IPCC*, 2000]. They span a wide range of possible future economic growth, which should address these uncertainties. The world-fleet fuel consumption in 2001 calculated in part 1 of our study [*Eyring et al.*, 2005] and the assumption for technology reduction factors are further main determinants of our future scenarios. Recently, *Endresen et al.* [2004] have questioned the fuel consumption of 289 Mt of the activity-based approach calculated by *Corbett and Köhler* [2003], which is, compared to the fuel consumption of approx. 170 Mt calculated in *Endresen et al.* [2003] and previous studies, much higher. Obviously, lower fuel consumption in 2001 would also lower our future estimates for fuel consumption, but also total emissions. However, due to inconsistencies of previous estimates which have been discussed in detail by *Corbett and Köhler* [2004] and in the first part of this study, an activity-based approach that leads to a fuel consumption of approximately 280 Mt seems to be reliable.

[85] As mentioned above, there are various uncertainties in the input parameters, such as the technology reduction factors, annual growth in GDP, the fraction ρ_{TS} to which extent the future fuel consumption of a diesel-only fleet is saved by alternative energies and fuels or the present-day fuel consumption. The method to estimate future fuel consumption and emissions presented in this study is based on historical correlations in economic growth, total seaborne trade and number of ships, as well as the average installed power per ship. It is a flexible method that allows calculations with other baseline values. Also, as time goes by, the baseline values will change, whereas the method to estimate future emissions can still be used.

[86] This study showed that future total ship emissions, especially NO_x and SO_x emissions, will be mainly determined by the technology, and to a lesser extent by the future global economic development. In future scenarios this means that the calculated total emissions are dominated by the chosen technology reduction rates, and to a lesser extent by the assumed annual growth in GDP and the factor ρ_{TS} by which the fuel consumption of a diesel-only fleet in 2050 is saved through application of alternative energies and fuels. With aggressive NO_x reduction, a significant decrease compared to today's NO_x emissions can be reached until 2050, even though the fleet grows. On the other hand, if no further reduction techniques are applied and future diesel engines will be equipped with techniques that fulfill the current IMO regulations, a further significant increase has to be expected until 2050. In our highest emission scenario, NO_x emissions from the international fleet further increase up to 38.8 Tg(NO_2) in 2050, which would even exceed today's NO_x emissions from road traffic. Future SO_x emissions will mainly be determined by the sulfur content of the fuel. If the fleet average sulfur content of the fuel remains at today's level, the projected increase in seaborne trade and fuel consumption suggest a further increase of SO_x emissions up to 25.9 Tg(SO_2) in 2050, which corresponds to an average annual increase of 1.6% between 2001 to 2050. Future CO_2 emissions will on the other hand mainly be determined by the total fuel consumption, which in turn is mainly determined by the economic growth and the amount of the fuel consumption that is saved by alternative energies and fuels.

[87] The linkage between the emissions presented in parts 1 and 2 of this study and their atmospheric impacts remain an open question. Once this question has been answered, atmospheric science can contribute to the question on the best options to reduce the future atmospheric impact by emissions from the world ocean-going fleet.

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