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The Environmental Impacts of Increased International Maritime Shipping

Past trends and future perspectives

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FOREWORD

This paper was prepared by Øyvind Endresen and Magnus Eide, Det Norske Veritas, Høvik, Stig Dalsøren and Ivar S. Isaksen, University of Oslo and Eirik Sørgård, Pronord AS, Bodø, Norway, as a contribution to the OECD/ITF *Global Forum on Transport and Environment in a Globalising World* that was held 10-12 November 2008 in Guadalajara, Mexico.

The paper discusses the environmental impacts of changes in international maritime activity. Minor modifications have been made to the paper in the aftermath of the Global Forum.

The views expressed are those of the author, and do not necessarily reflect the views of the OECD or its member countries.

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THE ENVIRONMENTAL IMPACTS OF INCREASED INTERNATIONAL MARITIME SHIPPING – PAST TRENDS AND FUTURE PERSPECTIVES

1. Introduction

1. Increasing pressure is put on industry and businesses, including the various transportation modes, to accomplish sustainable development. Global warming, acidification and degradation of air quality are environmental impact categories high on the international agenda. Consequently, studies have focused on anthropogenic emissions of compounds leading to such environmental impacts: Carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions. Recent studies indicate that the emission of CO_2, NO_x and SO_2 by ship corresponds to about 2-3%, 10-15% and 4-9% of the global anthropogenic emissions, respectively (*Corbett and Köhler*, 2003; *Endresen et al.*, 2003; 2007; *Eyring et al.*, 2005a). Emission inventories are a fundamental input to evaluating the impact of emission on the environment and human health and to guide the policy makers on mitigation options.

2. Regulations and incentives to control pollution sources are often directly aimed at reducing total emissions, typical on a source-by-source basis. Focus is either on sources causing the greatest impact or on the most cost efficient source to control (*Corbett and Koehler*, 2003). Ship emissions have not previously been regulated, but the International Maritime Organisation (IMO) and EU have recently implemented requirements for ships. A new set of regulations is in process by IMO, EU and US EPA (*Dalsøren et al.*, 2007; *Eyring et al.*, 2005b). Focus is mainly on NO_x and SO_2 emissions, but strategies for CO_2 reductions are also considered (*International Maritime Organisation (IMO)*, 2005).

3. Exhaust emissions from a marine diesel engine, the predominant form of power unit in the world fleet, largely comprise of excess carbon dioxide and water vapour with smaller quantities of carbon monoxide, oxides of sulphur and nitrogen, partially reacted and non-combusted hydrocarbons and particulate material (*Lloyd's Register of Shipping (LR)*, 1995). The exhaust gases are emitted into the atmosphere from the ship stacks and diluted through interaction with ambient air. During the dilution process in the ship plume the active chemical compounds are partly transformed and deposited on ground and on water surfaces. Furthermore, during oil transport and cargo handling, evaporation leads to VOC (Volatile Organic Compounds) emissions (*Endresen et al.*, 2003). Shipping also contributes with emission of other compounds (*e.g.* refrigerants and fire fighting agents), but they are not covered by this study.

4. In order to reduce exhaust emissions, measures can be taken either before the combustion process (fuel oil treatment and fuel oil modifications), during the combustion process (reduce formation of air pollutants in the combustion process) or through after treatment of exhaust gases. The fuel consumption and emissions may also be reduced by improved technical conditions (*e.g.* antifouling systems, engine efficiency), operational means (*e.g.* reduced speed, weather routing), alternative fuels (*e.g.* LNG) and alternative propulsion systems (*e.g.* fuel cells, sails) (*Eyring et al.*, 2005b; *Tronstad & Endresen*, 2006). Different operational and technical alternatives for reducing cargo VOC emissions (*e.g.* recovery systems) are available.

5. The main fraction of sulphur dioxide emitted from ships will oxidize in the atmosphere to form sulphate, and nitrogen compounds will form nitric acid and nitrate, and thus contribute to acidification. Sulphate and nitrate aerosols together with directly emitted particles like organic and black carbon might

have impacts on both health and climate. Emissions of nitrogen oxides, carbon monoxide and VOCs will affect pollution levels, especially through enhanced surface ozone formation. Ozone is also an important greenhouse gas and emissions of ozone precursors impact the oxidation of methane (CH_4) another important greenhouse gas. Direct emissions of greenhouse gases (CO_2 and small amounts of N_2O and CH_4) change the radiative balance of the atmosphere. There is a significant delay in building up the concentrations of some of the greenhouse gases (*e.g.* CO_2) and thereby in the climate impact. Knowledge on how ship emissions have developed over time is required to quantify climate effects and trends. Since the response time of the climate compounds is very different, ranging from days to centuries, and the chemical interaction between pollutants are highly non-linear, integrated studies estimating more than the impact of one single pollutant will give a better basis to assess the effect of different emission control options.

6. A reliable and up-to-date ship emission inventory is essential when evaluating impacts, but also when assessing the effect of different emission control options. Shipping activity has increased considerably over the last century (*Eyring et al*. 2005a; *Endresen et al.*, 2007), and currently represents a significant contribution to the global emissions of greenhouse gases and pollutants, in particularly NO_x and SO_2 (*Corbett et al.,* 1999; *Corbett and Koehler*, 2003; *Endresen et al.*, 2003; 2007; *Eyring et al.*, 2005a). Despite this, information about the historical development of fuel consumption and emissions is in general limited, with little data published prior to 1950. There are in addition large deviations reported for estimates covering the last three decades (*Endresen et al.,* 2007). Significant differences are also apparent among the reported present fuel consumption and emission inventories. It is for this reason challenging to evaluate and quantify the impacts of ship emissions, as well as to propose implementation of effective regulations and incentives for emission reductions. This has led to an ongoing scientific debate regarding past and current levels of emissions and impacts from ships. The debate revolves around whether bunker sale statistics are representative when estimating fuel based emissions, whether input data on engine operational profiles for different ship types and size categories are representative (*Corbett and Koehler*, 2003; 2004; *Endresen et al.*, 2003; 2004a; *Eyring et al.*, 2005a), whether the geographical distribution of emissions capture the world fleet traffic (*Corbett and Koehler*, 2003*; Endresen et al.*, 2003; *Dalsøren et al.,* 2007), and whether large scale models might overestimate nitrogen oxides concentrations (*Beirle et al.,* 2004; *Chen et al.*, 2005; *Dalsøren et al.,* 2007). A new report from an IMO working group claims that the ship emissions are significantly under-reported (*IMO,* 2007).

7. There is a need for better estimates of ship emissions and understanding the impacts from shipping operations. Experts on international shipping and emissions (Det Norske Veritas) and experts on atmospheric transport and chemistry (University of Oslo) have over several years investigated these issues in collaboration. Both past, present and future emissions and impacts have been studied. This report presents the main results from this research, including two Ph.D. studies within the area (*Endresen et al.*, 2008; *Dalsøren et al.*, 2007). The main results from other recent studies are also briefly given. Due to the ongoing scientific discussion about the actual level of ship emissions, this report also stresses the need for strengthening the accuracy and validity of the modelling of world fleet fuel consumption and emissions, as well as the need to establish geographical resolved ship emissions inventories for assessments of climate and environmental impacts.

8. The following sections will present the methodological approaches and the main results from this research. Section 2.1 outlines alternative approaches to the modelling of environmental impacts from ships. Section 2.2 gives past, present and future fuel consumption and emission data. The geographical distribution of these emissions is addressed in Section 2.3, with environmental impacts in section 2.4. Section 2.5 summarizes the main results and findings.

2. Quantifying fuel consumption, emissions and impacts from shipping

2.1 Modelling approach

9. In general, ship emissions are calculated by quantifying the fuel consumption from power production first and then multiplying the consumption by emission factors. VOC (Volatile Organic Compounds) emission from oil cargo handling is an exempt from this general approach. There are mainly two different bottom-up approaches to calculate the fuel consumption. The world-wide bunker sales per country and transport mode may be summed to indicate shipping consumptions. The other approach models the fleet activity and estimates the consumption resulting from this activity (summing up per ship/segment). Detailed methodologies for constructing ship emission inventories have been published by the Atmospheric Emission Inventory Guidebook (*EMEP/CORINAIR*, 2002).

10. The calculated emissions can be distributed according to global traffic data (*e.g. Corbett et al.*, 1999; *Endresen et al.*, 2003). Alternatively, geographically resolved emission inventories can be developed directly by calculating emissions for individual ship movements on defined trades (*e.g. Whall et al.*, 2002; *Endresen et al.*, 2003; *Dalsøren et al.*, 2007). The geographical resolved emission inventories can then be used to asses regional and global impacts of ship emissions (*e.g. Capaldo et al.*, 1999; *Lawrence and Crutzen*, 1999; *Endresen et al.*, 2003; *Dalsøren et al.*, 2007). Figure 1 illustrates the integrated approach applied, where ship emissions and impacts are calculated based on activity based fleet modelling or by marine sales.

2.2 Fuel consumption and emissions

11. The annual fuel consumption by the fleet is strongly affected by demand for sea transport, technical and operational improvements as well as changes in the fleet composition (*Endresen et al.*, 2007). During the last century the total fuel consumption and emissions from the ocean-going civil world fleet increased significantly, as the fleet expanded by 72,000 motor ships to a total of 88,000 in year 2000. The corresponding increase in gross tonnage (GT) was from 22 million GT to 558 million GT (*Endresen et al.*, 2007)(Figure 2). This growth has been driven by increased demand for passenger and cargo transport, with 300 million tonnes (Mt) cargo transported in 1920 (*Stopford*, 1997) and 5,400 Mt in 2000 (*Fearnleys*, 2002). Up to around 1960, the world fleet still transported large numbers of passengers, and the passenger ships were the largest ship type in the fleet (*Kunnskapsforlaget*, 1999). It was not until 1958 that airplanes transported more transatlantic passengers than large passenger ships (*Hansen*, 2004). More efficient and specialized ships have also pushed their way into the marked (*e.g.* the first deep sea cellular container ship in 1965 (*Stopford*, 1997)). The specialized ships have different operational and technological characteristics, which results in a particular logistic efficiency, with related energy and emission profiles. The present world fleet (2007) is mostly diesel powered and consists of about 96,000 ships above 100 GT (*LRF*, 2007), of which cargo-carrying ships (incl. passenger ships) account for roughly 50%. The other half is employed in non-trading activities like offshore supply, fishing, and general services (*e.g.* towage, surveying).

12. The ocean going civil world fleet gradually shifted from sail around 1870 to a full engine powered fleet around 1940 (Figure 2)(*Stopford*, 1997; *LR*, 1961;1984). Steamships, burning coal, dominated up to around 1920 (*Fletcher*, 1997). Coal was thereafter gradually replaced by marine oils due to shift to diesel engines and oil fired steam boilers (Table 1). The shift to modern marine diesel engines has been a slow process taking more than 100 years. In 1961 there were still over 10,000 steam engine powered ships and 3,536 steam turbine powered ships in operation (36% by number) (*LR*, 1961). As modern diesel engines have about half the daily fuel consumption compared to the old inefficient steam engines with the same power outtake, the shift to diesel is important to consider when developing historical estimates of fuel consumption (*Endresen et al.*, 2007).

13. The scrapping of inefficient steamers was economically motivated (also political). When the oil price was low, little attention was paid to fuel costs and many large vessels were fitted with turbines, since the benefits of higher power output and lower maintenance cost appeared to far overweigh their high fuel consumption. During the period 1970 to 1985, the fuel price increased by 950% (*Stopford*, 1997). This was followed by increased focus on the design of more fuel efficient ships and adjustments of the operational practice (*Stopford*, 1997). The main focus areas for improvements have been on the main engine, the hull and the propeller. For instance, between 1979 and 1983 the efficiency of energy conversion in slow-speed diesel marine engines improved by nearly 30% (*Stopford*, 1997). As a result, the tankers fitted with inefficient steam turbines were among the first to go to the scrap yards in the 1970s, when the fuel price was rising (*Stopford*, 1997; *Wijnolst & Wergeland*, 1997). By 1984 only 1,743 turbine powered ships remained in service (*LR*, 1984). These vessels were normally the largest ships in the fleet, as turbine propulsion commonly was used in the upper power range (*SNAME*, 1988).

14. The annually fuel consumption is also strongly affected by operational conditions, such as market situation and bunker price. The depressions in the world economy in the 1930s and 1970s resulted in laid-up tonnage and lower productivity, as world economy generates most of the demand for sea transport, through either the import of raw materials for manufacturing industry, or trade in manufactured products (*Stopford*, 1997). For instance, 21% of the fleet tonnage was out of service in 1932 and 13% in 1983 (*Stopford*, 1997). In addition, crude oil tankers reached a peak in productivity in 1972 (measured in tonne miles per deadweight (total carrying capacity)). By 1985 this had nearly halved, and a few years later it increased by 40% (*Stopford*, 1997). These operational changes have a significant impact on the fuel consumption, and are included in the activity-based fleet modelling for the period 1970 to 2000 (Section 2.2.2).

15. Operational speed significantly influences the power requirements and fuel consumption, and it has also varied widely over time. Depending on the market situation and oil bunker price, vessels operating in the spot market have the possibility to reduce the operating speed. At low freight rates it pays to steam at low speed, because the fuel cost saving may be greater than the loss of revenue. A substantial increase in bunker price will for the same reason change the optimum operating speed. Thus, for any level of freight rates and bunker price there is an optimum speed, that ship-owners will seek for. For example Very Large Crude oil Carriers typically operated at 10 knots when freight rates were low in 1986, but this increased to 12 knots when the rates were higher in 1989 (*Stopford*, 1997). Changes in operational speed will have a large impact on fuel use. For instance a reduction in the average operating speed by 2–3 knots below design speed may halve the daily fuel consumption of the cargo fleet (*Stopford*, 1997; *Wijnolst and Wergeland*, 1997). Moreover, the technical development on antifouling systems (*Evans*, 2000) which have influenced fuel consumption and emissions over the past 100 years should also be taken into account.

2.2.1 1870-1913

16. From 1870 to 1910 the world fleet doubled from 16.7 million GT to 34.6 million GT. In this period the steamers grew from 15% of the tonnage to 75% (*Stopford*, 1997), illustrating the shift from sail to steam ships. The development of fuel consumption over the period is based on statistics reported by *Fletcher* (1997). At the turn of the century, more than 50% of the British coal exports (Table 2) were ultimately used for ship transportation (*Fletcher*, 1997). The statistics does not include coal shipped to foreign stations within Great Britain. The amount of coal burned by ships exporting British coal was 21 Mt in 1913. About 270,000 tons of coal was consumed by the transporting ships for every million tons of coal delivered abroad (*Fletcher*, 1997). These figures only include the total amount of British coal consumed by vessels refilling at UK ports, and not the total amount of British coal consumed by the world fleet. The United States Shipping board has estimated annual bunker consumptions before the First World War (assumed here to be year 1913). Out of 80 Mt of bunker consumed annually to shipping purposes, 60 Mt were supplied by Britain and 5 Mt by British colonies (*Annin*, 1920). In other words, the British Empire

supplied 81% and Britain 75% of the coal consumed as bunkers by all ships in the world fleet. This indicates that 64% of the British coal export (94.4 Mt for 1913) was used as bunker for ships (60 Mt). We then assume that these factors are representative for the period 1870 to 1913, *i.e.* that 64% of the annual British coal export was used by shipping, and that Britain supplied 75% of the coal consumed as bunkers by all ships in the world fleet. Table 2 shows the estimated coal sales and CO_2 emissions, assuming 2.58 CO_2 per tonne fuel (*SNAME*, 1983; *Endresen et al.*, 2007). We find that the sales to shipping increase by a factor about 7 from 1870 to 1913 (Table 2). As the tonnage with steamers increased by a factor 6 from 1870 to 1910 (see above), our estimates may be reasonable. Table 2 also illustrates that the estimated CO_2 emissions in 1913 are only slightly lower than in 1925 (Figure 3). As the fleet grew by number and motor powered tonnage, this could be explained with increased focus on fuel economy (*Kofoed*, 1926) and a shift from coal to oil (17 Mt oil in 1925, *Endresen et al.*, 2007). It is not possible to conclude on the actual uncertainty or bias in the estimates, but the uncertainty could be significant.

2.2.2 1925-2002

17. Large deviations are reported for estimates covering the last three decades (Figure 4). *Eyring et al.* (2005a) produced one of the first estimates for fuel usage over a historical period from 1950 to 2001. They have reported simplified activity-based inventories from 1950 up to 1995 using ship-number statistics and average engine statistics, while the estimate for 2001 is based on detailed fleet-modelling. *Endresen et al.* (2007) reported more detailed activity estimates for each year from 1970 to 2000. They suggested that activity-based estimates for past fuel consumption and emissions must take into account variation in the demand for sea transport and operational and technical changes over the years, to better represent the real fuel consumption and corresponding emissions. For instance, the model separates on diesel and steam ships, as steam ships have a significantly higher fuel consumption. Their results suggest that the fleet growth is not necessarily followed by increased fuel consumption, as technical and operational characteristics have changed. An important input to the modelling is the change in fleet productivity (measured in ton-miles). For instance, the peak level of 1979 was not reached again before 1991 (Figure 2 right). They also reported detailed fuel based estimates (based on sales) from 1925 up to 2000. The results indicated that ocean-going ships had a yearly fuel consumption of about 80 Mt of coal (corresponding to 56.5 Mt of heavy fuel oil) before the First World War. This increased to a sale of about 200 Mt of marine fuel oils in 2000 (including the fishing fleet), *i.e.* about a 3.5-fold increase in fuel consumption. Of this sale, international shipping accounts for some 70-80%. Based on estimated fuel sale *Endresen et al.* (2007) modelled the historical CO_2 and SO_2 emissions (Figure 3). Ships emitted around 229 Tg (CO_2) in 1925 and these emissions grew to 638 Tg (CO_2) in 2000. The corresponding SO_2 emissions are about 2.5 Tg (SO_2) in 1925 and 8.7 Tg (SO_2) in 2000. The CO_2 emissions per tonne transported by sea have been significantly reduced as a result of larger and more energy efficient ships.

18. *Endresen et al.* (2003) developed a detailed activity based modelling approach, separating on 7 ship type and 3 size categories in the world cargo and passenger fleet. The model calculates consumption and emissions for year 1996 and 2000. Global ship emission inventories (not geographically distributed) were developed by combining the modelled fuel consumption with specific emission factors. The fuel consumption was based on; the number of hours at sea (depending on ship size), statistical relations between size (in Dwt or GT) and engine power for the ship types (container, bulk, general cargo, etc.), distribution of engine types on ship types (slow, medium and high speed engines), bunker fuel consumed per power unit (kW) (depends on engine type), and an assumed average engine load. The total fuel consumptions were calculated to 145 Mt and 158 Mt for 1996 and 2000, respectively. Emissions were calculated for 7 exhaust compounds and the CO_2, NO_x and SO_2 emissions were calculated to 501 Tg, 11.9 Tg and 6.8 Tg, respectively (for year 2000). If consumption by 45,000 non-cargo ships is taken into account, this work estimated total fuel consumption for the entire world fleet above or equal 100 GT (ocean-going) to be of the order 200 Mt in 2000. However, higher activity based estimates are presented by *Corbett and Koehler* (2003) and *Eyring et al.* (2005a) (Figure 4). The sensitivity analysis carried out

revealed that applied number of days at sea and engine load were the dominating factors determining the uncertainty in the estimates.

2.2.3 2002-2007

19. The maritime industry is currently in a period with rapid growth in global demand for transport, with corresponding increase in ship fuel consumption and emissions. Recent annual growth rates in total seaborne trade in ton miles have been 23% from 2002 to 2006, while only 10% from 1999 to 2002 (*Fearnleys*, 2006). Accordingly, the fuel consumption from 2001 to 2006 has increased significantly as the total installed power increased by about 25% (*LRF*, 2007). The increased engine power for the fleet over the last few years indicate that the year 2000 inventory should be increased with some 30% to about 260 Mt in 2006. This is supported by a detailed activity modelling made for 91,000 ships (above or equal 100 GT), with a breakdown on 13 ship type and 7 size categories. The results indicate a fuel consumption of 220 Mt in 2004 (*Eide et al.*, 2008). A simplified activity based modelling based on input from *Endresen et al.* (2007) also supports these findings (Figure 4). In addition, the world-wide sales of marine bunkers have increased by some 20% from 2001 to 2005 (*IEA*, 2007). However, an IMO working group has recently reported a significantly higher fuel consumption estimate of 369 Mt for 2007 (*IMO*, 2007). In addition, *Buhaug et al.* (2008) have reported estimate of 333 Mt for 2007. The deviation is likely due to different reference year, input data and assumptions (*e.g.* days at sea).

20. It is important to recognize that the significant growth in container trade, as well as ship activity in Asian waters over recent years will change the geographical distribution of emissions (section 2.3). Over the last two decades, global container trade (in tonnes) is estimated to have increased at an average annual rate of 9.8%, while the share of containerized cargo in the world's total dry cargo is estimated to have increased from 7.4% in 1985 to 24 % in 2006 (*UNCTAD*, 2007). In this context, it is important to note that more than 70% of the cargo value of world international seaborne trade is being moved in containers. In addition, the Chinese ports (including Taiwan Province of China and Hong Kong, China) accounted for 102.1 million TEUs in 2005, representing some 26.6 % of world container port throughput. In 2006 preliminary figures show that throughput has increased to 118.6 million TEUs, a rise of 16% over 2005 (*UNCTAD*, 2007). In addition, from 2000 to 2004 the sales of marine bunker in Asia (and Oceania) increased by 45% (*EIA*, 2007). Clearly, the last years increase in shipping in general, and particular in Asian waters need to be taken into account in upcoming studies.

2.2.4 Uncertainties

21. One major uncertainty in calculating the ship emissions are the use of average emissions factors. The recommended ship emission factors (*EMEP/CORINAIR*, 2002) are mainly based on exhaust measurement from old ships (and engines) typically built before 1990 (*LR*, 1995). Some changes in these factors are expected due to recently implemented regulator regimes (*e.g.* NO_x requirements for new engines, and SO_x Emission Control Areas (SECA)) and improved engine technology, and it is recommended to update these factors regularly. It is also important to establish more accurate historical ship emissions factors (*Endresen et al.* 2007). The following section also suggests ways to improve the activity- and fuel- (sales) based modelling.

2.2.4.1 Activity-based estimates

22. Uncertainties in activity-based estimates arise from the fact that reliable input data, such as detailed shipping and engine as well as engine performance statistics, activity data and the detailed fleet structures before 1960, are not available. Also, the detail level of the fleet modelling approach is important. *Endresen et al*. (2007) estimates that fuel consumption in the period 1980-2000 was significantly lower than reported by other activity-based studies (*Corbett and Koehler*, 2003; *Eyring et al.*, 2005a,b) (Figure

4). By considering alternative input data to their simplified activity-based model (*i.e.* t=270 days at sea etc.), they concluded that the main reason for the large deviations between activity-based fuel consumption estimates are the number of days assumed at sea (Figure 5). *Endresen et al.* (2004a; 2007) reported an average number of days at sea of 212 days. This was based on yearly tracking of more than 3,400 ships in the AMVER database, mainly medium and large cargo vessels. For smaller ships, the number of days at sea is lower (typically below 200 days), as indicated by AIS data shown in Figure 6.

23. *Endresen et al.* (2007) outline that the actual days at sea and the service speed in the future could be estimated based on AIS (Automatic identification systems) for individual ocean-going ships. Such data will also make it possible to indirectly estimate the engine power utilization per ship (and for fleet segments) by combining recorded service speed with installed main engine power for each individual ship (available from Lloyds' fleet data bases). *Dalsøren et al.* (2006) also reports that in the future, local and regional ship emission inventories (geographical distribution of emissions) will be based on AIS statistics. AIS is primarily an anti-collision system, and is designed to be capable of automatically providing position and identification information about the ship to other ships and to coastal authorities (*United States Coast Guard*, 2002). The International Maritime Organisation requires AIS to be fitted aboard all international ships above a certain size. A premilary analysis based on AIS data and individual profil for 500 small and medium sized ships (greather than 300 GT) sailing in Norwegian waters, do not support the an activity level of 225-270 days at sea assumed by recent activity based studies (Figure 6). *Buhaug et al.* (2008) have made a first attempt to establish global operational profiles using AIS data, but the reported profiles represent small vessels only crudely. This issue need to be addressed in new studies, also considering larger ships. When the global identification and tracking of ships is implemented, using Long Range Identification and Tracking (LRIT) technology, the potential for effective monitoring and reliable emission modelling on an individual ship basis would increase further. LRIT is a satellite-based system with planned global coverage of maritime traffic from 2008 (*IMO*, 2006).

24. Ships operate differently according to type and size, but cargo ships mostly operate in a similar way, transporting cargo between ports (the length of the voyages will vary). *Endresen et al.* (2004a) reported the average number of days at sea for 5 size categories and 6 ship types, based on yearly tracking of cargo ships in the AMVER database. Number of days at sea was found to vary with about 50 days between the cargo ships types, for a given ship size category. Also, the difference between a small and a large ship can be 100 days for a defined ship type. Thus, dependency on ship type and size should be included when performing detailed activity modelling. The engine-load assumed for different types and sizes, is also important input. Our premilary analysis, based on AIS data for Norwegian waters, also indicates that the applied engine-loads in the activity-based modelling may be too high.

25. It is important to recognize that the cargo fleet, accounting for 80% of the installed power (*Endresen et al.*, 2007), normally will have a higher engine utilization (load) and a higher number of sailing-days compared to non-cargo ships (*Endresen et al.*, 2004a). The relative energy production (kWh) will then exceed 80%, and could be as high as 90%. Consequently, to reduce the uncertainty in the activity modelling, it is important to apply pre-defined size and type categories (with mostly the same characteristic of the input variables) which resolves main characteristics. Alternatively, the non-linear effects have to be taken into account when simplified models are used. It is recommended to use yearly movement and tracking data (*e.g.* AIS data) available for individual ships to increase the reliability of model results.

2.2.4.2 Estimates based on fuel sales

26. Several studies have questioned the reduction in fuel sales for given time-periods without considering important operational and technical changes. This has led to the assumption that significant under-reporting of sales have occurred. However, the activity-based studies have reported fuel consumption excluding ocean-going ships less than 100 GT. The fuel consumption by these ships is not

addressed in the literature, and could be significant. For instance, in 1998, the global number of engine-powered fishing vessels (decked) was about 1.3 millions vessels (*Food and Agriculture Organization of the United Nations*, 2006), while only some 23,000 of these vessels were larger than 100 GT in year 2000 (*LR*, 2000). The fishing fleet of less than 100 GT represents nearly half of the installed power for the entire fishing fleet (*Endresen et al.*, 2007). Norway, for example, has approximately 3,000 cargo and service ships between 25 and 100 GT in coastal trade (*Statistics Norway*, 2000). Data for the rest of the world fleet of less than 100 GT operating mainly in national waters have not be identified, but this fleet (*e.g.* national fleet for US and Japan) could account for a large part of the global fuel consumption. When comparing activity-based and marine fuel sales this needs to be considered. Results from our work illustrate that improved activity modelling, with the use of high-resolution time series as input data, gives corresponding trends in fuel consumption as fuel sales numbers (Figure 4, activity based versus fuel based estimates). In addition, *Endresen et al*. (2007) illustrated strong correlation between the sales to the world fleet and the total seaborne trade in tonne miles (r=0.97) (Figure 7). This result indicates that if under-reporting occur over the period, the ratio is probably approximately constant. *Endresen et al.* (2005) indicated, based on sales data per country, that the under-reporting could be in the range of 25 Mt (*e.g.* for Russia). This study concludes that the reported sales number may be representative and not significantly under-reported, as previous activity-based studies have suggested.

2.2.5 Future ship emissions

27. Emissions generated from the shipping industry are an important contributor to the global emissions and scenarios for future activities indicate a significant increase in energy consumption and emissions (*Eyring et al., 2005b*; *Dalsøren et al.*, 2006; *Skjølsvik et al.*, 2000; *Eide et al.*, 2008). The future development of ship emissions to the atmosphere, versus other transport and industry segments, is essential to quantify climate effects and trends, and to implement adequate regulations and incentives. It is reasonable to expect that developments in energy prices, regulatory regimes, sea transport demand, technical and operational improvements, and the introduction of alternative fuels and propulsion systems will explain most of the development in fuel consumption and emissions by the fleet during the next 100 years. There is an increased pressure on industry and businesses, including the various transportation modes, to accomplish sustainable development. In combination with the expected higher energy prices and possible oil shortages, this will increase the focus on development of more energy-efficient and environmentally friendly systems for ships. The FellowSHIP project's (www.fuelcellship.com/) goal is to develop ultra-clean and highly efficient power packs for the maritime power industry, building on leading Norwegian maritime industrial competence, in synergy with state-of-art fuel cell technology. The prototype power pack will be tested 2008-2010 on board a supply ship, with no expected emissions of NO_x, SO_2 or particles and up to 50% reduction in CO_2 emissions compared to diesel engines run on oil.

28. Two approaches are applied to estimate future ship emissions. The first is extrapolation of historical growth trends (either emissions directly, or via number of ships in fleet or installed fleet power). The second is scenario-based estimates. In its simplest form, extrapolating the growth trend in total fleet installed power (*LRF*, 2007) in the period 1996-2006 gives a growth of 34% from 2006 to 2020. However, the growth from 1979 to 2006, or from 1986 to 2006, indicates a 4% and 16% increase from 2006 to 2020 respectively. In other words, using shorter regression periods leads to higher estimates, due to higher growth in recent years. Assuming that all fuel and emission factors are kept constant, this growth in the installed power corresponds to growth in emissions.

29. Another approach is to extrapolate the growth in transport work (tonne-miles) (*Fearnleys*, 2006). Transport work is linearly correlated with installed fleet power for historic data (*LRF*, 2007) (correlation coefficient higher than 0.95). When this linear correlation is assumed valid also for the future, the extrapolated values for transport work yields estimates for future fleet power by the same linear function. If the extrapolation is based on the growth trend in transport work from 1995 to 2005, the growth in installed

fleet power to 2020 would be 33%. However, if the extrapolation is based on the trend from 2002 to 2005, the growth to 2020 will be 64%. Again, using shorter regression periods leads to higher estimates due to higher growth in transport activity in recent years. In all, these methods suggest a best guess growth of approximately 30% in emissions towards 2020 (Figure 8).

30. Of course, the above growth trends (in installed power) do not directly translate into emission growth rates, but may indicate future growth of fuel consumption and emissions. Most studies on future scenarios, however, take historic trends for some recent period and extrapolate, with adjustments for expected changes in trends. Often, these adjustments are the responses to economic and population drivers affecting global trade or consumption. The TREMOVE maritime model (*Ceuster et al. 2006; Zeebroeck et al.*, 2006), is an example of such a model. It estimates fuel consumption and emissions trends derived from forecasted changes in ship voyage distances (maritime movements in km) and the number of port calls.

31. The IMO study on Greenhouse Gas Emissions from Ships (*Skjølsvik et al.*, 2000) forecasted a growth rate in seaborne trade (combined cargoes in terms of tonnage) of 1.5-3% annually. The IMO study applied these growth rates in trade to represent growth in energy requirements.

32. *Eyring et al.* (2005b) estimated future world seaborne trade in terms of volume in tonnes for a specific ship traffic scenario in a future year based on the historical correlation between the total seaborne trade and the world gross domestic product (GDP) over the time period 1985 to 2001. Following the annual growth rate in GDP for four Intergovernmental Panel on Climate Change (IPCC) storylines (varying between 2.3% and 3.6%) (*IPCC*, 2000), seaborne trade increased by 2.6% to 4.0% per year. According to this study, fuel consumption by the world fleet may increase from 280 Mt in 2001 to 409 Mt by 2020 and 725 Mt by 2050. It should be noted that the calculations done by *Eyring et al.* (2005b) starts in 2002 and does not include the recent unexpectedly high growth between 2002 and 2007. *Buhaug et al.* (2008) have also reported scenarios for 2020 and 2050, with even higher projections. It should also be mentioned that an IMO working group gives an estimated fuel consumption of 486 Mt in 2020 (*IMO*, 2007).

33. The studies by *Granier et al.* (2006) and *Dalsøren et al.* (2007) give estimates for future ship traffic in Arctic areas. Climate changes will very likely lead to more ice-free conditions, opening new sea routes for trading and passenger traffic. Oil and gas activity is already increasing in the region, especially in Northern Norway and Northwest Russia (*Dalsøren et al.*, 2007). *Granier et al.* (2006) use a high emission estimate for 2050 from *Eyring et al.* (2005b) and introduce some of the traffic into Arctic waters. The outcome of this study is discussed in section 2.4.2.

34. In the Quantify project[1] future fuel consumption, emissions and geographical distribution of emissions for shipping in the years 2025, 2050 and 2100 has been modeled based on four IPCC scenarios. The IPCC storylines are translated into maritime scenarios exploring the major factors expected to determine the development in shipping, most notably GDP development, environmental policy development and pace of technology development. Separate models for fuel consumption, total emissions and geographical distribution of ship emissions were made for each scenario, taking into consideration future changes in world-wide trading patterns. Cargo and non-cargo ships are modeled separately in this study. This allows alternative input data per scenario (*e.g.* based on availability of fossil fuel and ship power supply). Two of these scenarios are presented below.

35. Primary input from the IPCC scenario descriptions are projections of growth in the world economy expressed as gross domestic product (GDP). Using historical data, aggregated global GDP is linked to the size of the world fleet, through world seaborne trade volumes. Hence, future expectation of

1. www.pa.op.dlr.de/quantify/.

economic development stipulate future world shipping fleet which, along with historical data for average installed engine power, gives an estimate of the future fleet's total installed engine power (Figure 9). The future fuel consumption for the fleet is estimated based on an activity based approach, taking into account (among other factors) future distribution of power- and fuel-types for the estimated installed power. The future emissions are then estimated based on the calculated fuel consumption and the assumed time dependent technological factors.

36. In order to establish future development for the fleet (*e.g.* related to powering, fuel types, plausible emission reduction factors), qualitative indications of technological and legislative development outlined in the IPCC scenario have been considered. As the IPCC scenarios give very little information on shipping specifics, knowledge must be extracted from the general scenario information. However, future development is not only based on the relevant developments in the IPCC scenarios, but also on the current options and trends that have been identified, experience of the past and relevant industry insights (see Figure 10). The future extent of the use of biofuels is highly dependent on environmental focus and technological developments. The use of gas in shipping is likely to increase significantly in the years to come, but with considerable variation, depending on the given scenario. For instance, supply ships (*e.g.* Viking Energy built in 2003) and ferries (*e.g.* Glutra built in 2000) operating in Norwegian waters have been fuelled by gas for several years. The opportunities for fuel-cells running on gas is expected first in the small ship segment (and auxiliary engines)(*e.g.* Supply ship, see above), but depending on the technology focus in the scenarios, more general use can be expected later. Wind and solar energy will not power ships alone, but may contribute alongside diesel engines with a few percentages for individual ships. Various sail arrangements, both fixed wing and soft cloth, have been tested out on merchant vessels over the years. Experiments conducted from 1979 to 1985 did show that sails represent an interesting supplementary propulsion system when the wind direction is favourable (*e.g.* tested on M/V Ususki Pioner)(*Det Norske Veritas*, 1984). Ongoing testing of kites on merchant ships have also been reported (*e.g.* MV Beluga SkySails[2]). Their usage will increase beyond 2025 depending on technology focus (and environmental focus). Nuclear propulsion has been used in military vessels for decades (also icebreakers). However, nuclear propulsion has been used only within a limited number of merchant ships (4 vessels: Savannah (USA), Otto Hahn (Germany), Mutsu (Japan), Enrico Fermi (Italy)). Due to need for a special infrastructure and societal fears, it is considered to play a minor role in all scenarios.

37. It is difficult to assess the impact these technologies will have in the future, but within a foreseeable timeframe, marine diesel engines will continue to dominate. It is expected that the environment will continue to be a general focus and the scenarios assume phasing in of emissions reduction options, as well as measures that improve energy efficiency. For instance, *Skjølsvik et al.* (2000) reports a potential of 20% reduction of CO_2 in 2010 via implementation of a range of different technical measures (*e.g.* optimal hull and propeller) in the world fleet. It should be noted that they report higher reduction potential for individual new ships. In addition, technologies exist that could reduce NOx (*e.g.* Selective Catalytic Reduction (SCR)) and SO_2 (*e.g.* Scrubber, low sulphur fuel) by 80% or more for ships (also for existing ships) (*e.g. Skjølsvik et al.* 2000; *Eyring et al.*, 2005b, *Cofala et al.*, 2007). Recent studies have also reported the cost-effectiveness of different measures, as well as promising incentive-mechanisms for emission reduction (*e.g. OECD*, 1997; *Skjølsvik et al.*, 2000; *NERA Economic Consulting*, 2005; *Kågeson*, 2007; *Cofala et al.*, 2007; *Longva et al.*, 2008). Higher emissions reduction could also be achieved in the long term via shift to non-fossil-fuel-based and low-polluting propulsion systems like fuel cells and propulsion by wind and solar power. In the defined future maritime scenarios, both existing and emergent technologies and solutions are assumed to be phased gradually in to the future fleet.

38. Fuel consumption and emissions were calculated for the years 2025 and 2050 based on our estimates of the storylines in the IPCC A1 and A2 scenarios. Our model estimates for 2050 indicate fuel

2. http://skysails.info/index.php?id=6&L=1.

consumption between 453 and 810 Mt, with appurtenant emissions from the maritime fleet ranging from 1308 to 2271 Tg (CO_2), 17 to 28 Tg (NO_x) and 2 to 12 Tg (SO_2). The results for CO_2 emission are shown in Figure 8. Scenario A1B gives the highest CO_2 estimates, while Scenario A2 gives the lowest estimates. This is in line with the results for fuel consumption, for which A1 gives the highest estimate, while A2 gives the lowest. These results suggest that by adopting the range encompassed by the A1 and A2 scenarios, ships in 2050 will account for significantly higher share of world anthropogenic CO_2 emissions, compared to the 2-3% today. It is important to recognize that while CO_2 emission (and fuel consumption) reduction in the scenarios are mainly dependent on improved technical and operational conditions, alternative fuels and propulsion systems, additional reduction of NO_x and SO_2 emissions (and other exhaust compounds) can be achieved via specific emission reduction measures (*e.g.* after-treatment of exhaust gases).

39. The emission volumes must be distributed on a geographical grid in order to be useful for impact models. Distributing future ship emissions geographically entails prediction of possible future ship traffic patterns. Comprehensive data exist for the traffic pattern of the recent past. However, this traffic pattern is unlikely to remain unchanged in the coming decades. The traffic patterns for year 2000 do not reflect any divergence in future economic development, and in particular, discrepancies between developed economies and developing economies. To estimate the geographical distribution of ship activity in the years 2025 and 2050, the traffic distribution for 2000 has been amended with projections for trade routes which are expected to have extraordinary growth in the coming decades, above the growth expected for shipping in general. In total 12 sea routes, assumed to reflect the major changes in trading pattern and volume, have been defined. The underlying assumption, when selecting routes, has been expectations of future GDP levels in developing regions. In addition energy supply routes and other specific cases, such as the Northern Sea Route (NSR), has been considered and included. The NSR represents a 40-50% saving in sailing distance from Europe to northeastern Asia (*FNI*, 2000; *ACIA*, 2004). As the navigation season on this route is projected to double by the year 2050 (*ACIA*, 2004), a significant increase in traffic is assumed in the Quantify modelling up to 2050. Based on the World Trade Organizations international trade statistics (*WTO*, 2006) we have considered existing, albeit emerging regional trading routes, for the purpose of identifying specific routes with disproportional growth, *i.e.* growth considerable higher than the world average. In order to concretize specific trade routes, regional trade levels are funneled to specific countries and thereby specific harbors that are selected due to their importance within the specific trading routes. The resulting worldwide distributions of ship emissions, taking into account both new trade routes and growth on the existing trade pattern, were then developed (*Eide et al.*, 2008). An alternative approach is outlined in *Eyring et al.* (2005b).

40. While the current study is not a forecast study, but rather an evaluation of possible future outcomes considering several scenarios, the similarities between the two types of studies are many, and experience with forecast studies may be of value also to a scenario study. Long-term forecasting in general is a highly challenging and uncertain science. A few aspects impacting on uncertainty are briefly discussed in the following. Firstly, there is a vast potential to improve the level of recycling of industry input factors. Increased recycling leads to less need for imports of raw materials used in production of steel, plastics etc, thus reduced volumes of seaborne trade. Achievable recycling levels are illustrated by the case of Norway, where 76% of all metal waste is recycled. For lead batteries, electrical and electronic waste, used car tiers and glass the level of recycling is at 90% (*The Ministry of Finance, Norway*, 2007). On the other hand, as a significant part of current recycling involves transport of the wastes from *e.g.* Europe to China or India, increased recycling could also involve increased seaborne trade. Also, significant trade volumes between big actors, such as China and India on the one side and Russia and Central Asia countries such as Azerbaijan and Turkmenistan on the other, may be transported in pipelines, as an alternative to seaborne transportation. Another issue is the scarcity of water which in some regions may translate into a need for water transportation. Seaborne transportation can be an attractive solution to expensive pipelines and/or desalination plants when coping with local water scarcity. Other commodities in which trade is strongly

expanding are rock, gravel and sand. Such materials are in growing demand as foundation for construction sites and for civil works such as dams and dikes. With increasing sea-levels due to global warming, and increasingly fierce weather leading to serious damages, demand for these materials will increase. Of course, increased recycling of construction waste could reduce the transport demand for these materials. Furthermore, it is realized that growth in GDP may affect the value of merchandise trade, but not necessarily merchandise trade volume. In other words, higher GDP may result in less increase in demand for seaborne trade based on our historical relation.

2.3 Geographically resolved emission inventory

41. *Corbett et al.* (1999) developed the first global spatial representations of ship emissions using a shipping traffic intensity proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS). *Endresen et al.* (2003) collected and presented alternative global data and methods for the geographical distribution of emissions. The modelled exhaust gas emissions were distributed according to a calculated emission indicator per grid cell referring to the relative ship reporting frequency or relative ship reporting frequency weighted by the ship size. The indicator was based on global ship reporting frequencies collected by COADS, PurpleFinder and AMVER (Automated Mutual-assistance Vessel Rescue system). The reporting frequency weighted by the ship size was only available from the AMVER data. Recently, *Wang et al.* (2007) demonstrate a method to improve global-proxy representativity. *Endresen et al.* (2003) also developed a separate global oil cargo VOC vapour inventory.

42. The best estimate is that 80% of the maritime traffic is in the Northern Hemisphere, and distributed with 32% in the Atlantic, 29% in the Pacific, 14% in the Indian and 5% in the Mediterranean ocean. The remaining 20% of the traffic in the Southern Hemisphere is approximately equally distributed between the Atlantic, the Pacific the Indian Ocean (*Endresen et al.*, 2003). Considering the number and type/size of vessels reporting and reference year, the AMVER data set was found most suitable for the distribution of emissions from the international cargo traffic. The relative reporting frequency weighted by the ship size may be applied to take into account large variation in emission between small and large vessels (was only available for the AMVER data). The COADS data set is recommended when considering the entire world fleet (also non-cargo ships). However, national inventories covering coastal shipping have to be added, as outlined by *Dalsøren et al.* (2006). The inventories developed by *Endresen et al.* (2003) have been applied in several studies (*e.g. Dalsøren et al., 2007*; *Eyring et al.*, 2005b; *Beirle et al.*, 2004). *Endresen et al.* (2007) also pointed out that this is important, as ships of less than 100 GT typically in coastal operations are not included (*e.g.* today some 1.3 million fishing vessels). Results of this work suggest that the coastal fleet could account for an important part of the total fuel consumption. Also, it should be noted that recent changes to the worlds trading patterns, in particular in Asian waters over the last seven years, need be covered by future updates in the global inventory.

43. *Endresen et al.* (2004b) presented a ship-type dependent geographical distribution of the traffic based on AMVER data (bulk ships, oil tankers and container vessels) (Figure 11). These data were recently applied by *Eyring et al.* (2005b), and illustrates large variation in traffic patterns (and emissions) for different ship types.

2.4 Atmospheric impacts

44. Emission of pollutants to the air from ship is often chemically transformed to secondary species. Mixing with ambient air takes place and dry deposition or rainout occurs. The meteorological state of the atmosphere and insolation are also decisive for the chemical reactions taking place. These factors make the interaction between chemical active gases highly nonlinear and atmospheric perturbations may deviate substantially from perturbations in emissions. Ship emissions might affect the levels of ozone (climate, health effects), sulphate (acidification, climate, health effects), nitrate (acidification, eutrophication), NO_2

(pollution, precursor ozone and nitrate), NMVOCs (pollution, precursors ozone), SO_2 (pollution, precursor sulphate), OH and its effect on methane (climate), and aerosols (pollution, climate). A much-used tool to quantify the impacts is computer models. Global and regional Chemical Transport Models (CTMs) contain comprehensive chemical packages, including the calculation of some or all the above-mentioned compounds. Meteorological data (winds, temperature, precipitation, clouds, etc) used as input for the CTM calculations are provided by weather prediction models or climate models. Satellite observations indicate high NO_x concentrations along major shipping lanes (*Beirle et al.,* 2004; *Richter et al.*, 2004). Regional emission estimates based on these observed concentrations are in good agreement with global emission inventories. Ship plume processes are generally not resolved by global models with a resolution (grid box sizes) from hundred to several hundreds of kilometres. These models therefore distribute emissions over larger areas. Detailed chemical box-model studies and measurements increase our understanding of subgrid-scale processes taking place within fresh undiluted plumes and during the first stages of dillution. Studies and measurements indicate that plume chemistry have to be better taken into account in the impact modeling (*Kasibhatla et al.,* 2000; *Chen et al.,* 2005; *Song et al.,* 2003; *von Glasow et al.,* 2003). These studies suggest enhanced NO_x destruction within the ship plumes. It is possible that some models might overestimate the effect of ship emissions on the NO_x, OH and ozone budget and one way to overcome this is to multiply with a reduction factor (effective emission) or introduce plume chemistry in the global models. However, the amount of observational data from ship plumes is limited and more data and studies are needed. This was also concluded from comparison between global models and observations over oceanic and coastal areas (*Dalsøren et al.,* 2007; *Eyring et al.,* 2007).

2.4.1 Impact on pollution levels and climate

45. Primary components, like particles NO_2, CO, NMVOCs and SO_2, may potentially cause problems in coastal areas and harbours with heavy traffic because of their impact on human health at high concentrations (*Saxe et al.*, 2004; *EPA*, 2003). Secondary species formed from the effluents in the ship emissions have longer chemical lifetimes and are transported in the atmosphere over several hundreds of kilometres. Thereby they can contribute to air quality problems on land. This is relevant for ozone and the deposition of sulphur and nitrogen compounds, which cause acidification of natural ecosystems and freshwater bodies and threaten biodiversity through excessive nitrogen input (eutrophication) (*Vitousek et al*., 1997; *Galloway et al.,* 2004; *Bouwman et al.*, 2002).

46. The highest surface increases in a short-lived pollutant like NO_2 are found close to the regions with heavy traffic around the North Sea and the English Channel. Model studies in general find NO_2 to be more than doubled along the major world shipping lanes (*Endresen et al.*, 2003; *Lawrence and Crutzen*, 1999; *Dalsøren et al.*, 2007; *Eyring et al.*, 2007).

47. The ozone levels in the lower atmosphere are dependent on competitive reactions between formation and sink cycles. The abundance of NO_x (NO+ NO_2) is crucial for ozone formation but the number of ozone molecules formed is also dependent on CO and NMVOCs. In general, an emission perturbation is most effective in increasing ozone in regions with low background pollution. Ozone is also a major greenhouse gas. Ozone is estimated to be the third most important of the greenhouse gases contributing to warming since the pre-industrial era (*Ramaswamy et al.*, 2001). Exposure to high ozone levels are linked to (*Mauzerall and Wang*, 2001; *EPA*, 2003; *WHO*, 2003; *HEI*, 2004) aggravation of existing respiratory problems like asthma, increased susceptibility (infections, allergens and pollutants), inflammation, chest pain and coughing. Some of these studies have strengthened indications of short-term effects on mortality, but evidences of long -term health effects are limited. Repeated long-term exposure could possibly lead to premature lung aging and chronic respiratory illnesses like emphysema and chronic bronchitis. Elevated ozone levels during the growing season may result in reductions in agricultural crops and commercial forest yields, reduced growth, increased susceptibility for disease and visible leaf damage

on vegetation (*Emberson et al.*, 2001; *Mauzerall and Wang*, 2001). Ozone might also damage polymeric materials such as paints, plastics and rubber.

48. The effect on surface ozone shows a profound seasonality at northern latitudes. Absolute increases in ozone due to ship emissions are largest in July (Figure 12) when sufficient sunlight results in an active photochemistry and a significant ozone production in the northern hemisphere over large regions including coastal areas. Large increases are found in regions with large traffic (the North Sea, fishing docks west of Greenland, the English Channel, the western Mediterranean, the Suez Channel, the Persian Bay) (*Dalsøren et al.*, 2007). Some of these regions already suffer from high summer ozone levels due to pollution from nearby land sources. Figure 13 shows that the relative contribution from international shipping to surface ozone is even larger over mid-oceans where, as earlier mentioned, ozone production is relatively more efficient due to low background pollution levels. The relative contribution is also significant over coastal areas on the west coast of North America and Western Europe. Similar contributions to ozone are found by *Cofala et al.* (2007), *Derwent et al.* (2005), *Collins et al.* (2007), and *Eyring et al.* (2007). *Cofala et al.* (2007) discuss the European health impacts related to ground level ozone and the contribution from shipping both for current (year 2000) and future scenarios (year 2020).

49. With regard to climate effects, the ozone perturbations at high altitudes are important. Ozone produced near the emission sources or produced during the transport process is lifted by convection and frontal systems to higher altitudes where the lifetime is longer and transport faster. Typical relative tropospheric column increases due to ship traffic (not shown) are 7% to 14% in the northern hemisphere and 2-7% in the southern hemisphere (*Dalsøren et al.*, 2007).

50. Hydroxyl (OH) is the main oxidant in the troposphere (*Levy*, 1971). This radical reacts with and removes several pollutants and greenhouse gases; one of them is methane (CH_4). The OH abundance itself is in turn highly dependent on some of these pollutants, in particular CH_4, NO_x, O_3 and CO (*Dalsøren and Isaksen*, 2006; *Wang and Jacob* 1998; *Lelieveld et al.*, 2002). Whereas CO and CH_4 emissions tend to reduce current global averaged OH levels, the overall effect of NO_x emissions are to increase OH (*Dalsøren and Isaksen*, 2006). Due to the large NO_x emissions from shipping, this emission source leads to quite large increase in OH concentrations. Since reaction with OH is the major loss of methane from the atmosphere, ship emissions (for current atmospheric conditions) decrease the concentration of the greenhouse gas methane. Reductions in methane lifetime due to shipping NO_x vary between 1.5% and 5% in different calculations (*Lawrence and Crutzen*, 1999; *Endresen et al.*, 2003; *Dalsøren et al.*, 2007; *Eyring et al.*, 2007).

51. NO_x oxidation by OH leads to formation of nitric acid and nitrate. When nitric acid and nitrate undergo dry deposition or rainout it may contribute to eutrophication or acidification in vulnerable ecosystems (*Vitousek et al*., 1997; *Galloway et al.*, 2004). Sulphur emissions might reduce air quality over land *e.g.* by contributing to sulphate particles and sulphate deposition. SO_2 emissions from shipping are oxidized to sulphate primarily in the aqueous phase (in cloud droplets and sea salt particles) and also in the gas phase by the OH radical. The largest impact of shipping on sulphate chemistry is through the direct emissions of SO_2. However, increases in the OH radical due to NO_x emissions will enhance the gaseous oxidation pathway. This pathway is important since it leads to new particle generation whereas aqueous oxidation adds mass to existing particles. Currently shipping increases the global sulphate loading with about 3% (*Endresen et al.*, 2003; *Eyring et al.*, 2007). But the relative load in some coastal areas is much higher. Figure 14, taken from *Dalsøren et al.* (2008), shows the impact of ship emissions on wet deposition of nitrate and sulphur. These are major components of acid rain. The largest contributions can be seen in seasons with much rainfall on the west coast of the continents where westerly winds often prevail. Parts of Scandinavia are vulnerable to acid precipitation due to slowly weathering bedrock. The impact on this region is large with a contribution above 30% in nitrate wet deposition and 10-25% in sulphate wet deposition. Coastal countries in Western Europe, north-western America and partly eastern America are

substantially impacted with relative contribution between 5% and 20%. Similar numbers are found by *Endresen et al.* (2003), *Collins et al.* (2007), *Dalsøren et al.* (2007), and *Lauer et al.* (2007). *Marmer and Langmann* (2005) find large increases in sulphate in the Mediterranean Sea due to shipping. For other particles than sulphate (Black carbon (soot), organic carbon, etc), the contribution from shipping is moderate, a few percent in the most impacted areas (*Lauer et al.*, 2007; *Dalsøren et al.*, 2007; *Dalsøren et al.*, 2008). But it should be noted that the uncertainty of the amounts emitted of these components is large. There is much concern about a number of health impacts of the fine and ultra-fine aerosols in polluted areas (*Martuzzi et al.*, 2003; *Nel*, 2005). Severe short- and long-term influences on illness and mortality due to effects on the cardiovascular system and lungs (for example lung cancer) occur with current pollution episodes and average levels in large world cities (*HEI*, 2004; *WHO*, 2003). A non-threshold linear relationship with mortality and hospital admissions has been observed in several settings. Particles like soot may also lead to soiling of materials. *Corbett et al.* (2007) estimates 20,000 to 104,000 premature deaths globally related to particles caused by shipping.

52. Aerosols also have a direct effect on climate and visibility by scattering and/or absorbing solar radiation, thereby influencing the radiative balance (*Penner et al.*, 2001; *Ramanathan et al*., 2001). Whether this leads to an overall cooling or heating of the surface depends on several factors, like the ratio of scattering and absorption (aerosols composition/properties), cloud fraction and surface albedo (*Ramanathan et al*., 2001). Aerosols can act as condensation nuclei, modify cloud properties and precipitation rates, and through that have indirect climate effects. Aerosols may increase the number of cloud drops, and thereby increase reflected solar radiation to space which lead to a cooling (called 1^{st} indirect effect (*Twomey*, 1974)). When the number of cloud droplets increases, this may decrease precipitation efficiency. This could also result in an increase in cloud lifetime and amount (*Kaufman and Koren*, 2006), which increases the reflection of solar radiation (2^{nd} indirect effect (*Rosenfeld et al.*, 2000)). Reactions on aerosol surfaces may also modify the chemical composition of both the aerosol and gas phases (*Tie et al.*, 2005). The effects of aerosols emissions from ships on clouds are visible as so called ship-tracks in satellite images. Narrow stripes shows up downwind of the ships as bright features in the images (*Schreier et al.*, 2007). Airborne measurements in a cloud-free environment above a cargo ship showed that approximately 12% of exhaust particles act as nuclei where clouds could form (*Hobbs et al., 2000*). Several studies show that the droplet concentration in the ship-tracks was enhanced significantly compared to ambient clouds and that the effective radius was reduced (*Durkee et al.,* 2000*; Ferek et al.,* 2000*; Schreier et al.,* 2006). The smaller water droplets are then less likely to grow into larger drops of precipitation size, extending the lifetime of the cloud and increasing reflectivity. A satellite study of clouds forming in the region of the English Channel showed a trend of increasing cloud reflectivity and decreasing cloud top temperature (*Devasthale et al*., 2006), which may be related to increased ship emissions. Nearby polluted land regions showed opposite trends, probably due to reductions in particle emissions from land sources.

53. Radiative forcing (RF) calculations quantify the radiation balance at the top of the atmosphere due to components affecting the radiation budget. RF is a metric to quantify climate impacts from different sources in units of W per m^2, since there is an approximately linear relationship between global mean radiative forcing and change in global mean surface temperature (*Forster et al.,* 2007). Ship emissions impact the concentrations of greenhouse gases (mainly CO_2, CH_4 and O_3) and aerosols, causing both positive and negative contributions to direct radiative forcing (RF). In addition, ship-derived aerosols cause a significant indirect RF, through changes in cloud microphysics (previous paragraph). Table 3 summarises estimates of the present-day contribution of ship emissions to RF from several studies (*Capaldo et al.,* 1999; *Endresen et al*., 2003; *Eyring et al.*, 2007; *Lee et al.*, 2007; *Lauer et al.,* 2007; *Dalsøren et al.,* 2007; *Fuglestvedt et al.,* 2008). The range of values are wide, some of the uncertainties are related to use of different emission distributions and totals. Much of the rest is connected to uncertain historical evolution of long-lived components like CO_2 and CH_4, uncertainties in chemical calculations for reactive components (nonlinear chemistry), and the complexity and limited understanding of indirect effects. In summary, the

studies indicate that ship emissions lead to a net global cooling. This is different from other transport sectors (*Fuglestvedt et al.,* 2008). However, it should be stressed that the uncertainties are large in particular for indirect effects, and RF is only a first measure of climate changes. It is also important to have in mind that the forcing from different components act on different temporal and spatial scales. A long-lived well-mixed component like CO_2 has global effects that last for centuries. Shorter lived species like ozone and aerosols might have effects that are strongly regionally confined, lasting over a few weeks. The regional aspects are important as weather systems tend to be driven by regional gradients in temperature.

2.4.2 Future impacts

54. Model studies of future impacts from ship emissions are dependent on the projections used as baseline for the emission calculations. Most scenarios for the near future, the next 10-20 years, indicate that regulations and measures will be outweighed by an increase in traffic resulting in a global increase in emissions. Assuming no changes in non-shipping emissions, *Dalsøren et al.* (2007) finds that the scenarios for shipping activities in 2015 lead to more than 20% increase in NO_2 from 2000 to 2015 in some coastal areas. Ozone increases are in general small. Wet deposition of acidic species increases up to 10% in areas where current critical loads are exceeded. Regulations limiting the sulphur content in the fuel in the North Sea and English Channel (IMO regulations, discussed 2nd paragraph introduction) will be an efficient measure to reduce sulphate deposition in nearby coastal regions. Expected increased oil and gas transport by ships from Norway and Northwest Russia, sea transport along the Northern Sea Route will have a significant regional effect by increases of acid deposition in the North Scandinavia and the Kola Peninsula. Augmented levels of particles in the Arctic are calculated, and thus the contribution from ship traffic to phenomena like Arctic haze could be increasing. With sea ice expected to recede in the Arctic during the 21st century as a result of projected climate warming, global shipping patterns could change considerably in the decades ahead. *Granier et al.* (2006) uses one of the upper emission estimates for 2050 from *Eyring et al.* (2005b) and introduce some of the traffic into Arctic waters. During the summer months, surface ozone concentrations in the Arctic could be enhanced by a factor of 2–3 as a consequence of ship operations through the northern passages. Projected ozone concentrations from July to September are comparable to summertime values currently observed in many industrialized regions in the Northern Hemisphere. *Cofala et al.* (2007) finds that at present ships are responsible for 10-20 % of sulphur deposition in European coastal areas. The contribution is expected to increase by 2020 to more than 30 % in large areas, and up to 50 % in coastal areas. Technologies exist to reduce emissions from ships beyond what is currently legally required. *Cofala et al.* (2007) perform cost-effectiveness analysis for several possible set of measures. *Eyring et al.* (2007) used results from ten state-of-the-art atmospheric chemistry models to analyse present-day conditions (year 2000) and two future ship emission scenarios. In one scenario ship emissions stabilize at 2000 levels; in the other ship emissions increase with a constant annual growth rate of 2.2% up to 2030. Most other anthropogenic emissions follow the IPCC SRES (Special Report on Emission Scenarios) A2 scenario, while biomass burning and natural emissions remain at year 2000 levels. Maximum contributions from shipping to annual mean near-surface O_3 are found over the North Atlantic. Tropospheric O_3 forcings due to shipping are 9.8 ± 2.0 mW/m^2 in 2000 and 13.6 ± 2.3 mW/m^2 in 2030 for the increasing ship scenario. Increasing NO_x simultaneously enhances hydroxyl radicals over the remote ocean, reducing the global methane lifetime by 0.13 year in 2000, and by up to 0.17 year in 2030, introducing a negative radiative forcing. Increasing emissions from shipping would significantly counteract the benefits derived from reducing SO_2 emissions from all other anthropogenic sources under the A2 scenario over the continents, for example in Europe. Globally, shipping contributes 3% to increases in O_3 burden between 2000 and 2030, and 4.5% to increases in sulphate. However, if future non-ship emissions follow a more stringent scenario, the relative importance of ship emissions will increase. A new model assessment is currently being performed within the EU project Quantify, using new ship emission scenarios for 2025 and 2050 (*Eide et al.*, 2008).

2.5 Conclusion

55. Shipping activity has increased significantly over the last century, and represents currently a notable contribution to the global emissions of pollutants and greenhouse gases. Despite this, information about the historical development of energy consumption and emissions is limited, with little data published pre-1950 and large deviations in estimates covering the last three decades. This study indicate global ship CO_2 emissions in 1870 to be 30 Tg (CO_2), growing to be about 206 Tg (CO_2) in 1913. The main development during this period was the transition from sail to steam powered ships.

56. Global ship CO_2 emissions are estimated based on sales of bunker to be 229 Tg (CO_2) in 1925, growing to about 634 Tg (CO_2) in 2002. The corresponding SO_2 emissions are estimated to be approximately 2.5 Tg (as SO_2) in 1925 and 8.5 Tg (as SO_2) in 2002. The main developments during this period were that oil replaced coal, and the transition to a diesel-powered fleet. The majority of today's ship emissions occur in the Northern Hemisphere within a well defined system of international sea routes. The most accurate geographical representations of the emissions are obtained using a method based on the relative reporting frequency weighted by the ship size. When the global identification and tracking of ships is implemented, using LRIT technology, the potential for effective monitoring and reliable emission modelling would increase significantly.

57. Activity-based modelling for the period 1970-2000 indicates that the size and the degree of utilization of the fleet, combined with the shift to diesel engines, have been the major factors determining yearly energy consumption. Interestingly, the modelling from around 1973 suggests that growth in the fleet is not necessarily followed by increased energy consumption. It is concluded that the main reason for the large deviation between the activity-based estimates are the number of days assumed at sea. Vessel type and size dependency need to be better analysed and described to improve the accuracy of detailed activity-based estimates. Available operational data indicate a strong dependency on ship type and size. It is recommended to use yearly movement and tracking data available (*e.g.* AIS) for individual ships to increase the reliability in model results. Results from this study indicate that reported sales seems not to be significantly under-reported as previous activity-based studies have suggested. Activity-based studies have not considered ships less than 100 GT (*e.g.* today some 1.3 million fishing vessels), and we suggest that this fleet could account for an important additional fuel consumption.

58. Recent studies indicate that the emission of CO_2, NO_x and SO_2 by ship corresponds to about 2-3%, 10-15% and 4-9% of the global anthropogenic emissions, respectively. Ship emissions of NO_2, CO, NMVOCs and SO_2 and primary particles cause problems in coastal areas and harbours with heavy traffic and high pollution levels because of their impact on human health and materials. Particularly high surface increases of short-lived pollutants like NO_2 are found close to the regions with heavy traffic around the North Sea and the English Channel. Model studies in general find NO_2 concentrations to be more than doubled along the major world shipping routes. Absolute increases in surface ozone (O_3) due to ship emissions are pronounced during summer months with large increases found in regions with heavy traffic (North Sea, fishing docks west of Greenland, the English Channel, the western Mediterranean, the Suez Channel, the Persian Bay). Some of these regions already suffer from high summer months ozone levels due to pollution from nearby land sources. Increased ozone levels in the atmosphere are also of concern with regard to climate change, since ozone is an important greenhouse gas. Formation of sulphate and nitrate resulting from nitrogen and sulphur emissions causes acidification that might be harmful to ecosystems in regions with low buffering capacity, and have harmful health effects. Coastal countries in Western Europe, North-Western America (and partly eastern America) and the Mediterranean are substantially affected by ship emissions. Relative ship-induced increases are estimated to be in the range 5%-35% in wet deposition of sulphate and nitrate. Nitrate and sulphate aerosols and directly emitted organic and black carbon (soot) affect the climate due to scattering/absorption of radiation (direct effect) and impact on clouds (indirect effect). The large NO_x emissions from ship traffic lead to significant

increases in OH which is the major oxidant in the lower atmosphere removing several pollutants and greenhouse gases. Since reaction with OH is the major loss of methane from the atmosphere, ship emissions decrease methane concentrations. Reductions in methane lifetime due to shipping NO_x vary between 1.5% and 5% in different calculations. The effect on concentrations of greenhouse gases (CO_2, CH_4 and O_3), and aerosols, have different impacts on the radiation balance of the earth-atmosphere system. Ship-derived aerosols also cause a significant indirect impact, through changes in cloud microphysics. In summary, most studies so far indicate that ship emissions lead to a net global cooling. This is different from other transport sectors. However, it should be stressed that the uncertainties are large, in particular for indirect effects, and global temperature is only a first measure of climate changes. It is also important to have in mind that the forcing from different components act on different temporal and spatial scales. A long-lived well-mixed component like CO_2 has global effects that last for centuries. Shorter-lived species like ozone and aerosols might have effects that are strongly regionally and lasting for only a few days to weeks. The regional aspects are important as weather systems tend to be driven by regional gradients in temperature.

59. Projections up to year 2020 indicate a growth in fuel consumption and emission in the range of 30%. However, if more weight in the estimates of future trends is connected to the large increase in emissions during the last few years, we obtain larger increases in ship emissions in the coming decades. In any case, scenarios for future activities indicate a significant increase in energy consumption and emissions. Our results for year 2050 indicate fuel consumptions between 453 and 810 Mt (2-3 times present level), with appurtenant emissions ranging from 1308 to 2271 Tg (CO_2), 17 to 28 Tg (NO_x) and 2 to 12 Tg (SO_2). The high and low estimates reflect the different assumptions with regard to future use of low-polluting propulsion systems, low/non-fossil-fuel-based fuel types, reduction means etc.

60. Model studies of future impacts from ship emissions are dependent on the projections used as baseline for the emission calculations. Most scenarios for the near future, the next 10-20 years, indicate that regulations and measures will be outweighed by an increase in traffic leading to a significant global increase in emissions from shipping. Global studies for the future including emission scenarios for non-ship land based sources indicate that the relative contribution to pollutants (ozone, NO_2, particles) from shipping could increase, especially in regions like the Arctic and South-East Asia, where a substantial increase in ship traffic is expected. However, impact studies show that regulations could have positive effects, if regional differences are considered. One example is that limiting the sulphur content in the fuel in the North Sea and English Channel (IMO regulations) seems to be an efficient measure to reduce sulphate deposition in nearby coastal regions. Technologies also exist to reduce emissions from ships beyond what is currently legally required.

TABLES

Table 1: Percentages of World's total merchant fleet (exclusive of Sailing Ships) using the specified form of motive power (from *Fletcher*, 1997).

Year	**Coal**	**Oil fuel under boilers**	**Internal combustion (diesel) engines**
1914	96.6	2.9	0.5
1922	74.1	23.4	2.5
1924	68.9	27.9	3.2
1927	63.9	29.3	6.8
1929	60.8	29.2	10.0
1935	51.0	31.2	17.8

Table 2: Estimated global coal bunker sale, based on quantity of coal (Mt) leaving United Kingdom Ports during selected years, 1850-1934 (*Fletcher*, 1997).

Year	**Exported as cargo**	**Shipped as bunker fuel**[1]	**Total Export**	**Estimated**		**Emissions**
				UK parts of bunker sale[2]	**Total bunker sale**[3]	**CO_2 (Mt)**
1870	10.2	3.2	13.4	8.6	11.4	30
1880	17.9	4.9	22.8	14.6	19.5	50
1890	28.7	8.1	36.8	23.6	31.4	81
1900	44.1	11.8	55.9	35.8	47.7	123
1913	*73.4*	*21.0*	*94.4*	*60*	*80*[4]	*206*

[1] Engaged in foreign trade.
[2] 64% of the annual British coal export was used by shipping.
[3] Assuming that Britain supplied 75% of the coal consumed as bunkers by all ships in the world fleet.
[4] Reported by *Annin* (*1920*), based on estimates presented by The United States Shipping board.

Table 3: Radiative forcing (mW/m^2) for year 2000 from several studies (*Capaldo et al.*, 1999; *Endresen et al.*, 2003; *Eyring et al.*, 2007; *Lee et al.*, 2007; *Lauer et al.*, 2007; *Dalsøren et al.*, 2007; *Fuglestvedt et al.*, 2008). The text in blue italics denotes positive forcing (warming) and the red bold denotes negative forcing (cooling).

Components	**CO_2**	**SO_4**	**CH_4**	**O_3**	**BC**	**OC**	**Indirect**
Range	*+ 26-43*	**÷12-47**	**÷11-56**	*+8-41*	*+1.1-2.9*	**÷0.1-0.5**	**÷38-600**

FIGURES

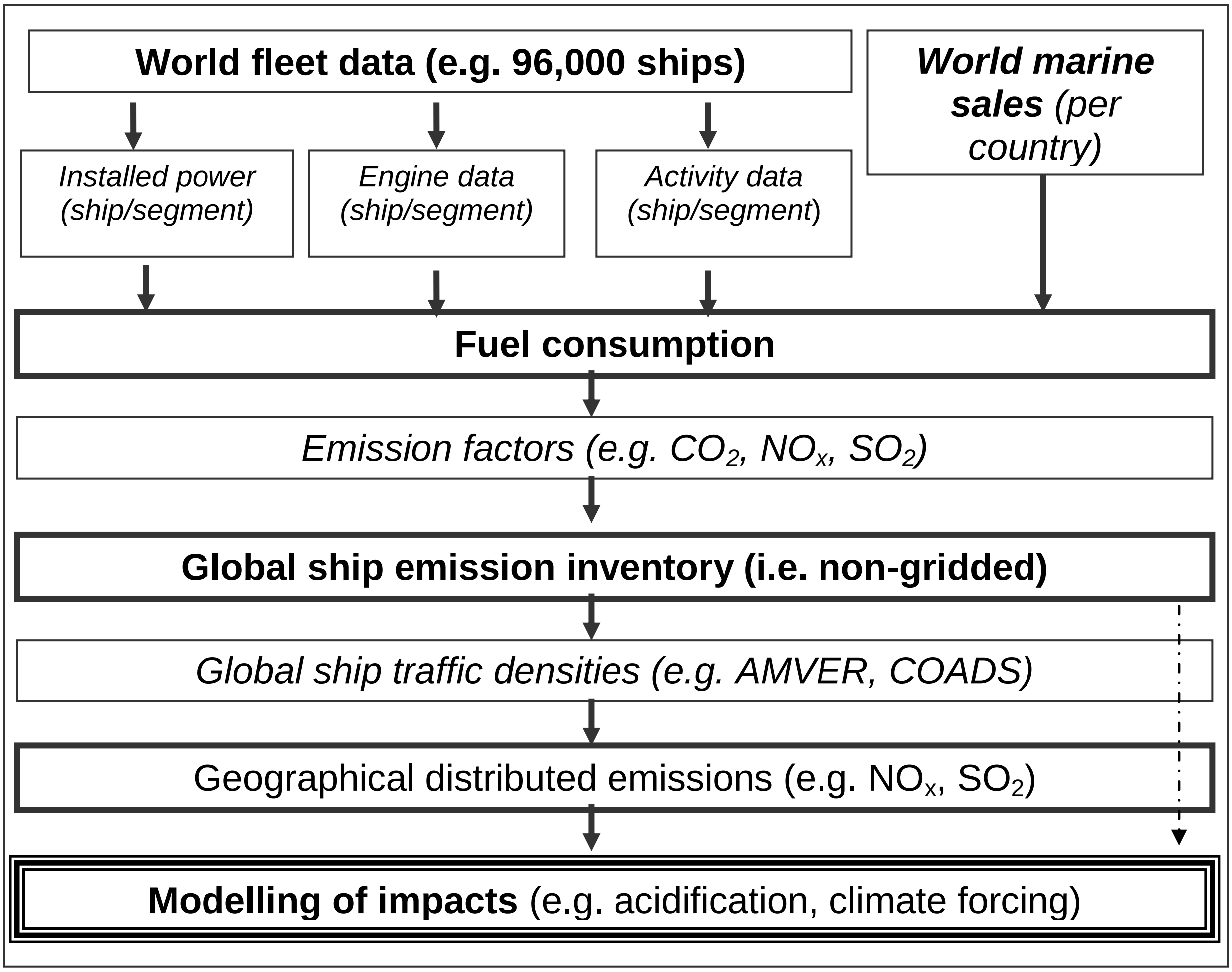
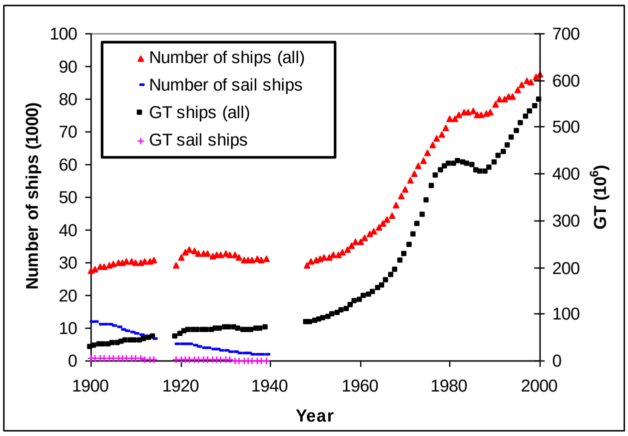


Figure 1: Illustrates the integrated modelling consepts for quantifying fuel consumption, emissions and impacts from shipping.



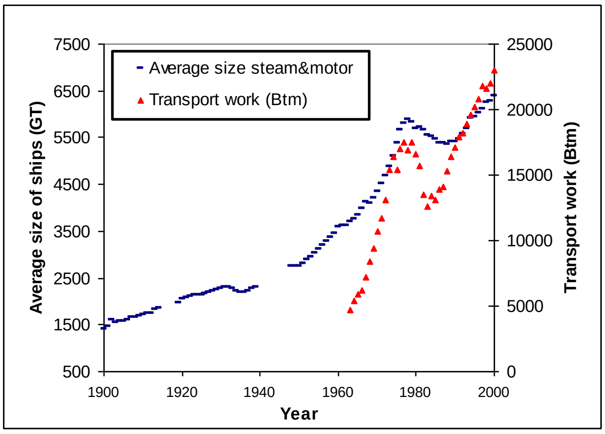


Figure 2: Development of the world fleet of ocean-going civil vessels above or equal 100 GT and transport work, 1900-2000 (not including the military fleet). *Left:* Development of size and tonnage (*data from Lloyd's register of Shipping*). *Right:* The development of average size (including also non-cargo ships) and transport work (Btm- billion tonne-miles) (*Stopford*, 1997; *Fearnleys*, 2002). Note that no data is available for the World War II (From: *Endresen et al.*, 2007).

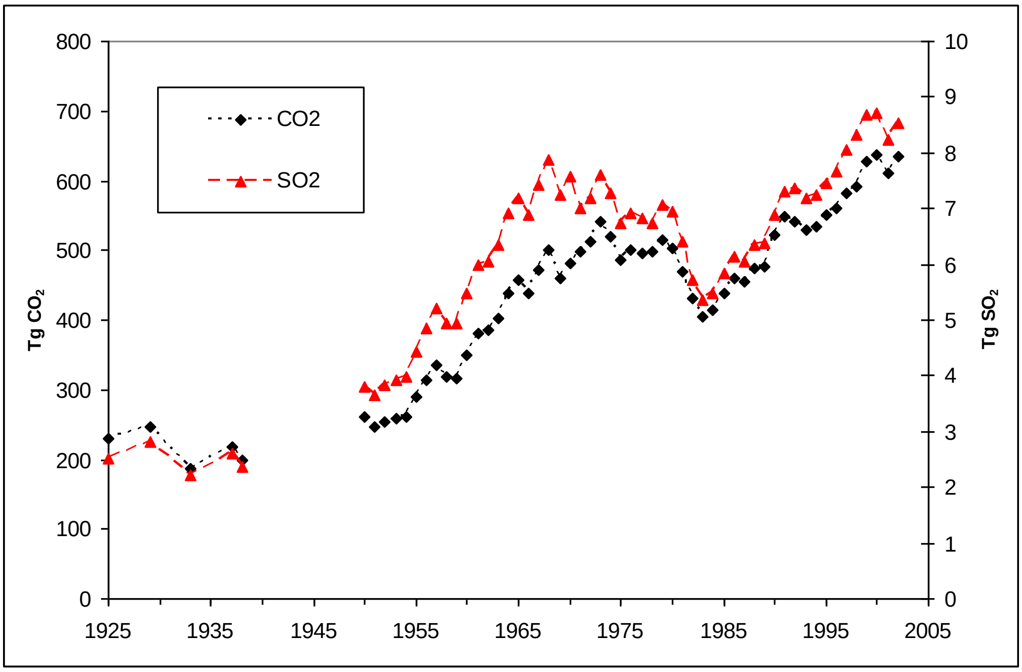


Figure 3: Development of CO_2 and SO_2 ship emissions, based on estimated sales of marine fuel, 1925-2002 (including the fishing and military fleet). Note that no data is available for the World War II period (From: *Endresen et al.*, 2007).

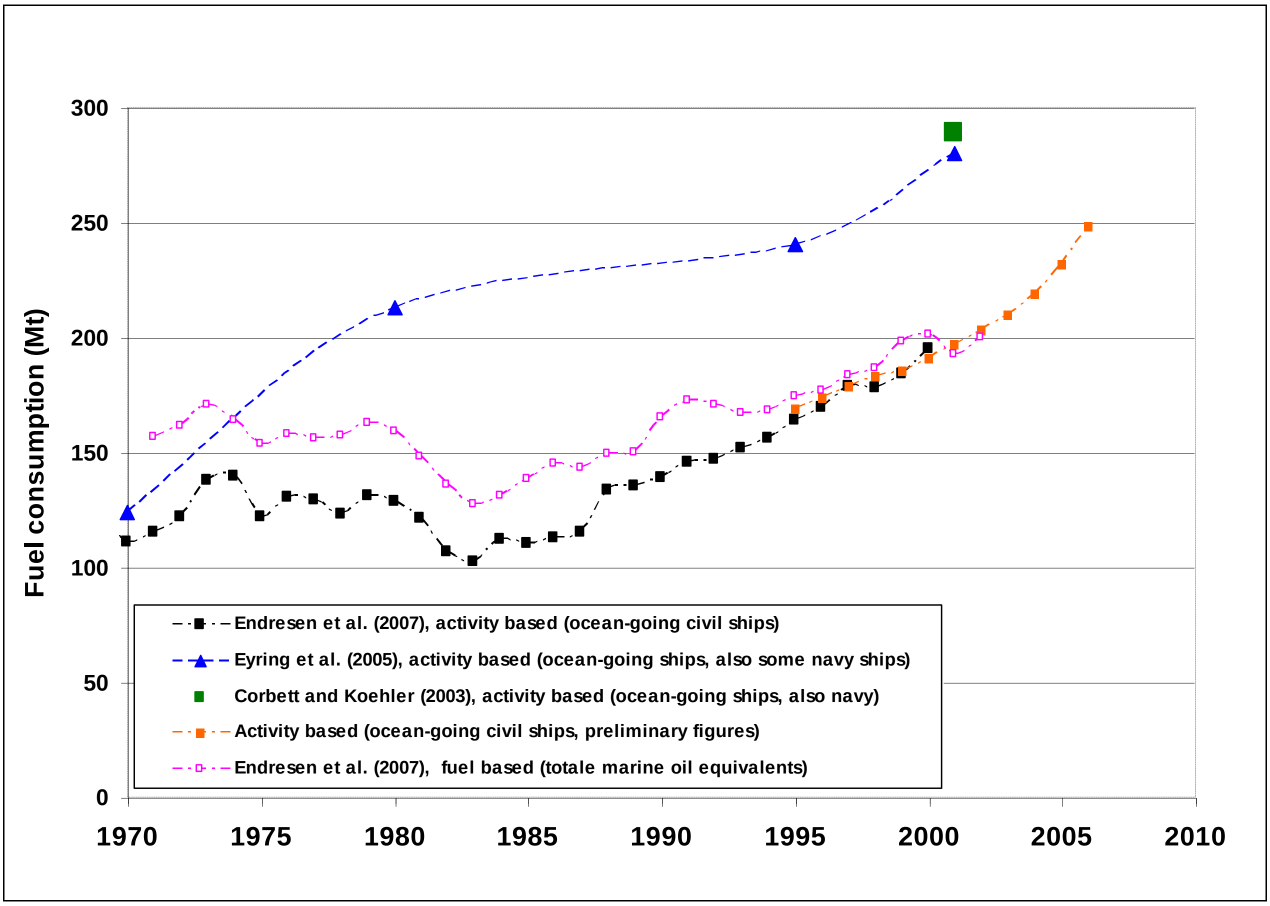


Figure 4: Comparison of reported estimates of fuel consumption, and activity-based estimates (simplified) up to 2006.

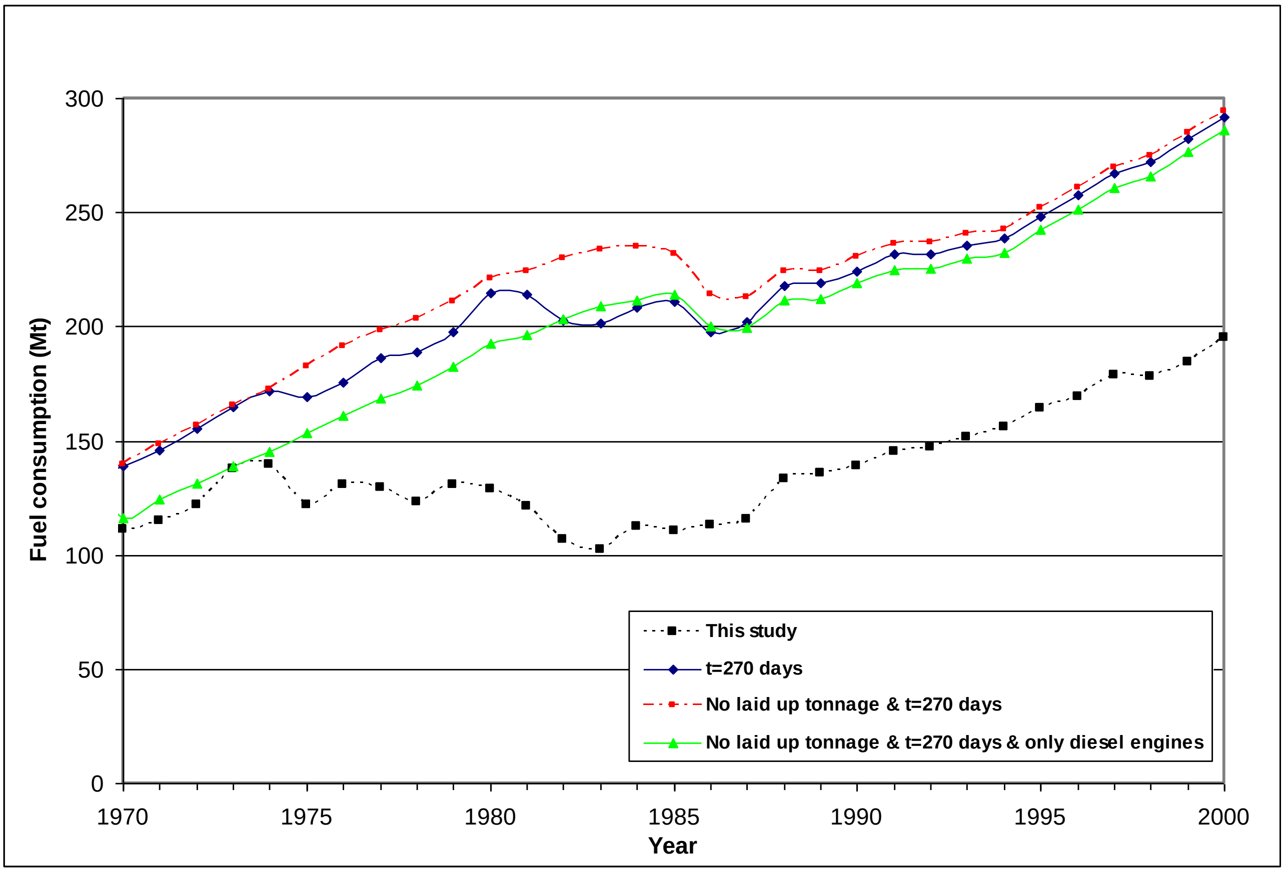


Figure 5: Sensitivity analyses, considering alternative input data. Modelling is made for all ocean-going civil ships above or equal to 100 GT, 1970-2000 (From: *Endresen et al.*, 2007).

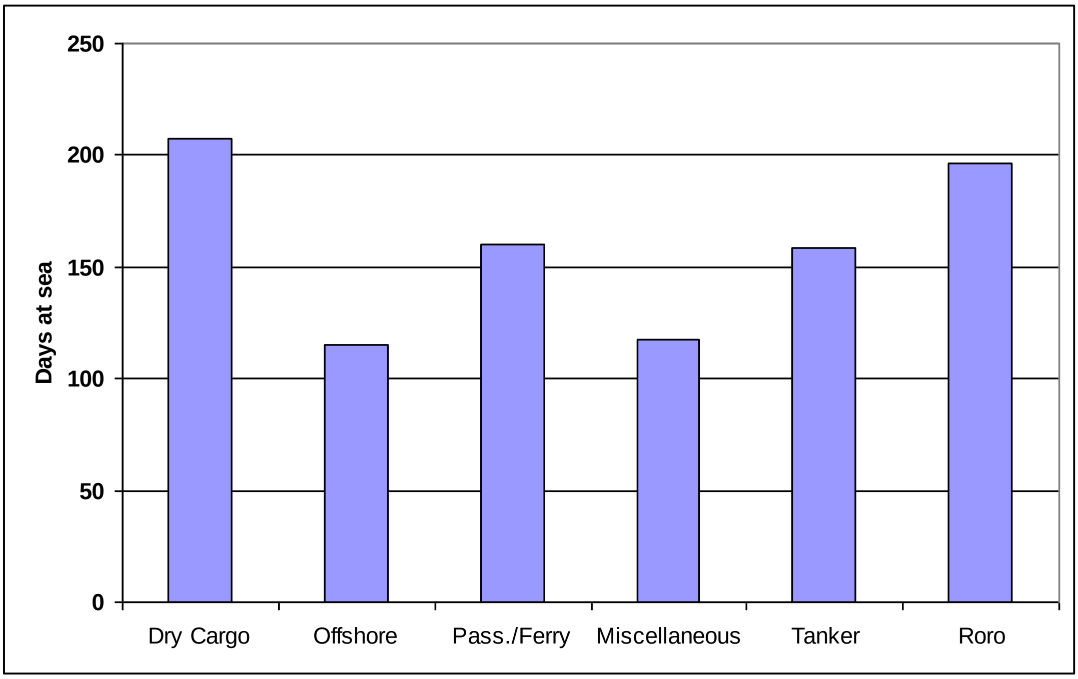


Figure 6: Calculated days at sea, based on AIS data for 500 small and medium sized ships (above 300 GT) tracked in Norwegian waters, first six moths of 2007 (data from: *The Norwegian Coastal Administration*). Note that Offshore ships have low activity, as dynamic position operations are not included.

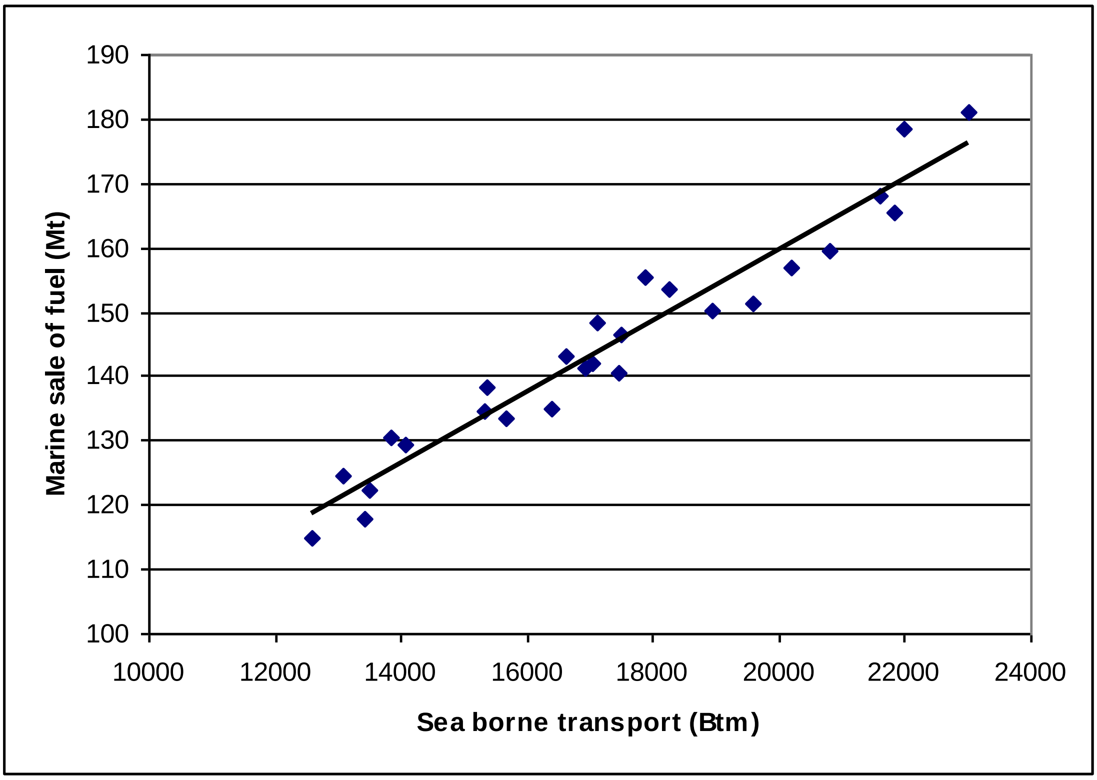


Figure 7: Correlation between reported IEA sales of marine oil products world-wide (Mt) and transport work (Billion tonne miles (Bmt)) (*Stopford*, 1997; *Fearnleys*, 2002). For the period 1975-2000, the correlation is 0.97 (From: *Endresen et al.*, 2007).

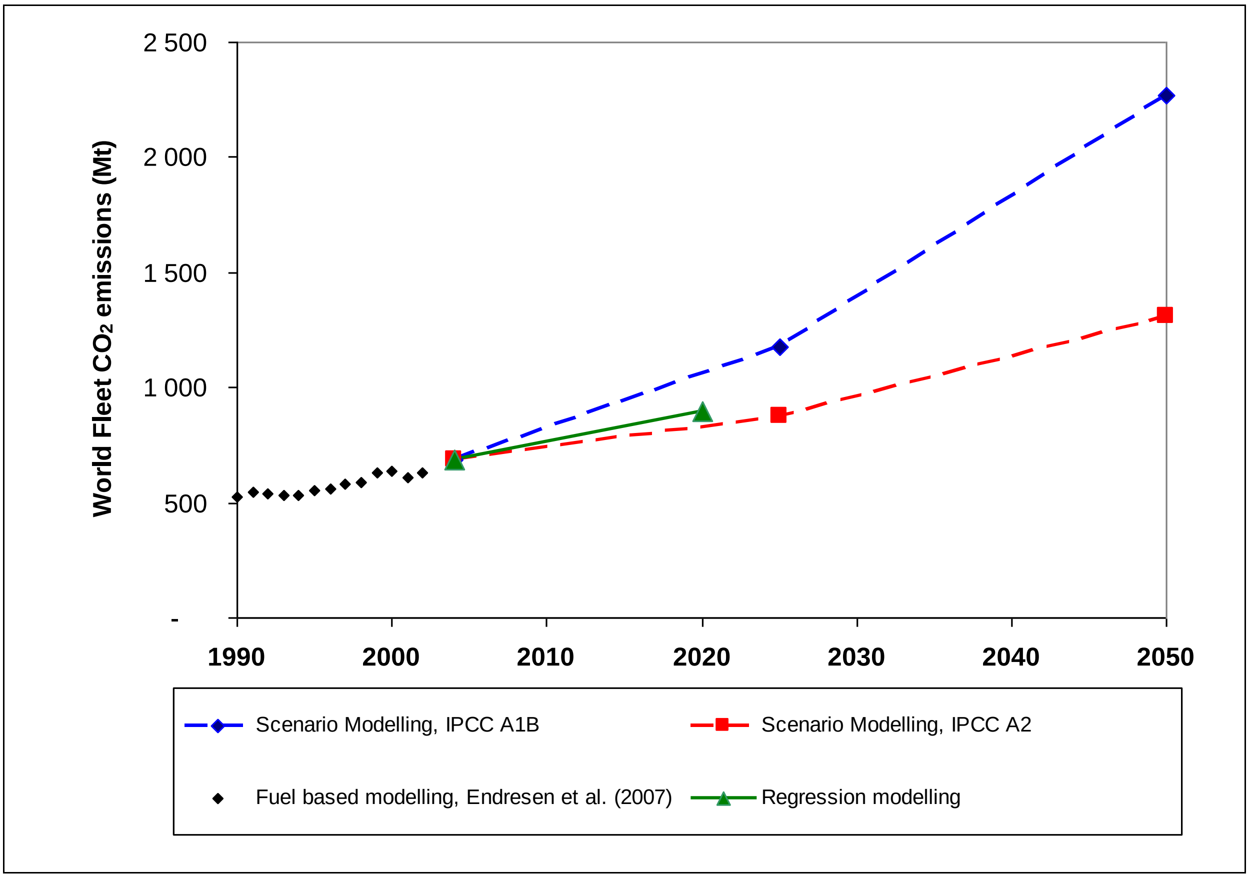


Figure 8: World fleet CO_2 emissions, based on IPCC scenarios (*Eide et al.*, 2008) and extrapolation of trends giving 30% growth by 2020 (this study).

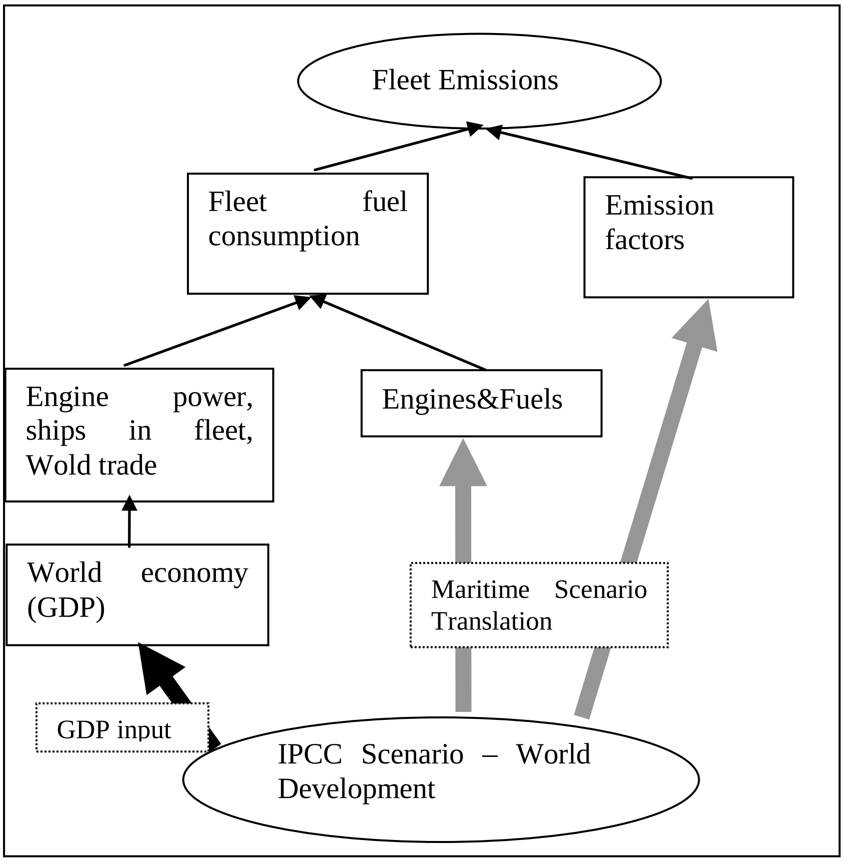


Figure 9: Model overview, future ship fleet emissions (*Eide et al.*, 2008). World GDP estimates from the IPCC Scenarios are transformed into fleet installed engine power using regression. Interpretations of scenario storylines provide future engine and fuel distributions as well as future emission factors. Emission factors and fuel consumption combined results in fleet emissions.

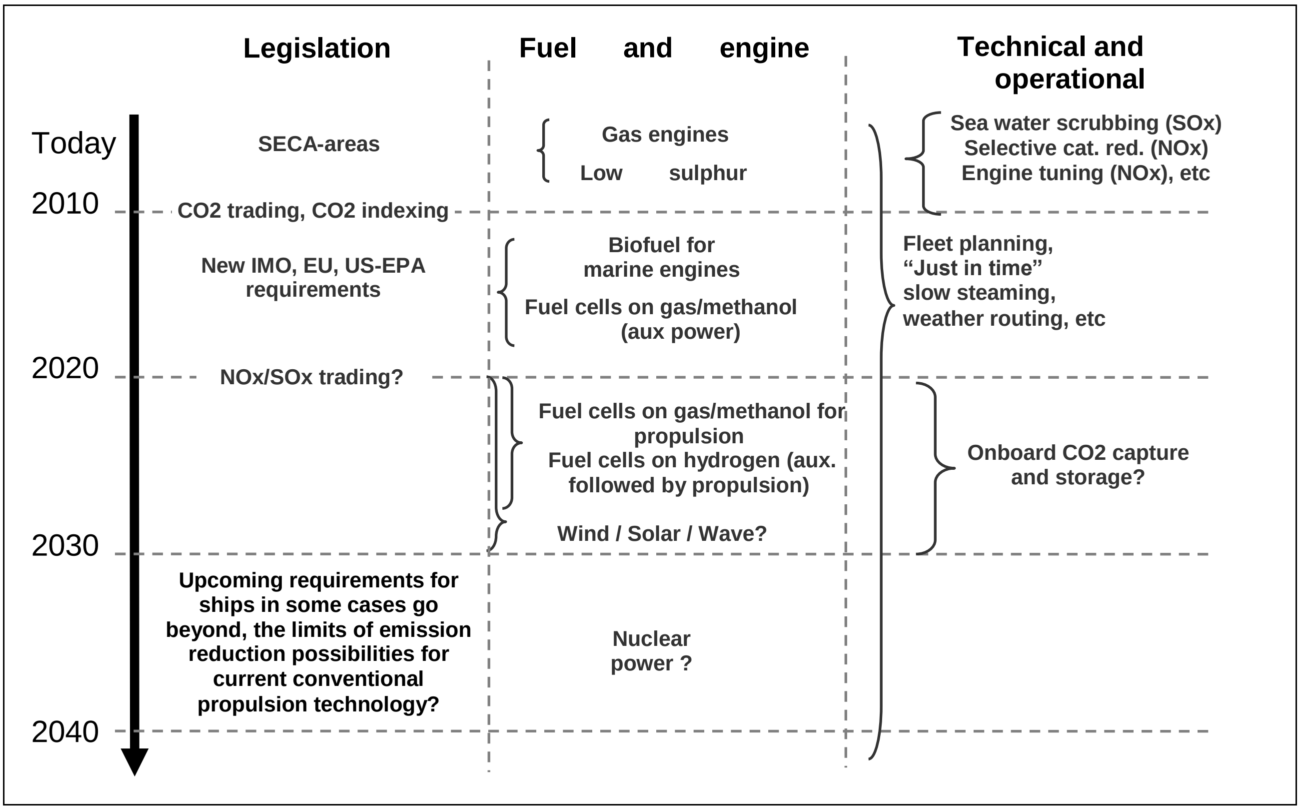


Figure 10: Indicative overview of possible future legislation initiatives, fuel and engine types available for shipping, and technical and operational measures available for emission reduction (*Eide et al.*, 2008).

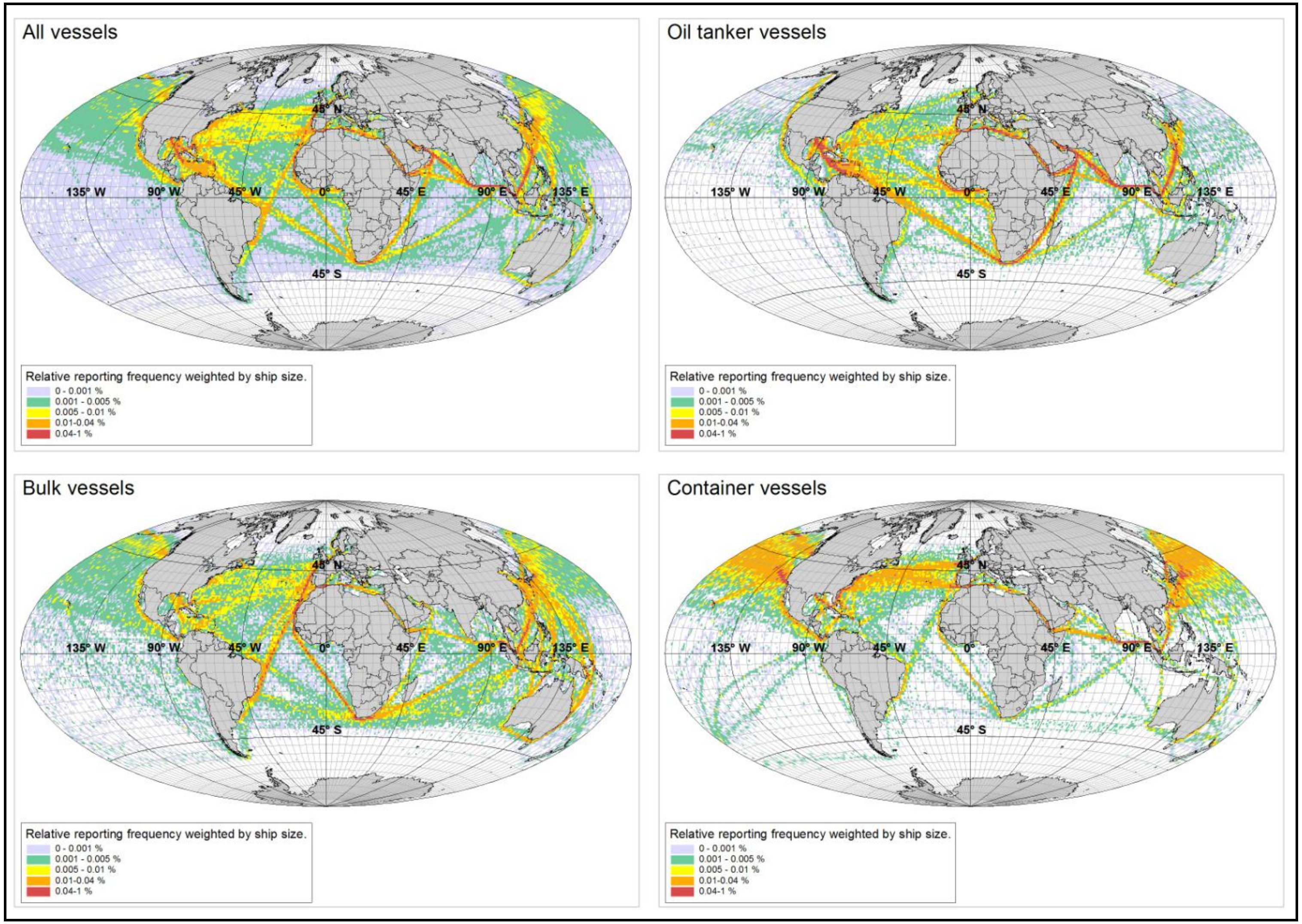


Figure 11: Vessel traffic densities for year 2000 based on the AMVER data (*AMVER,* 2001). *Upper left*: All cargo and passenger ships in the AMVER merchant fleet, *upper right*: Oil tankers, *lower left*: Bulk carriers, *lower right*: Container vessels (from *Endresen et al.*, 2004b).

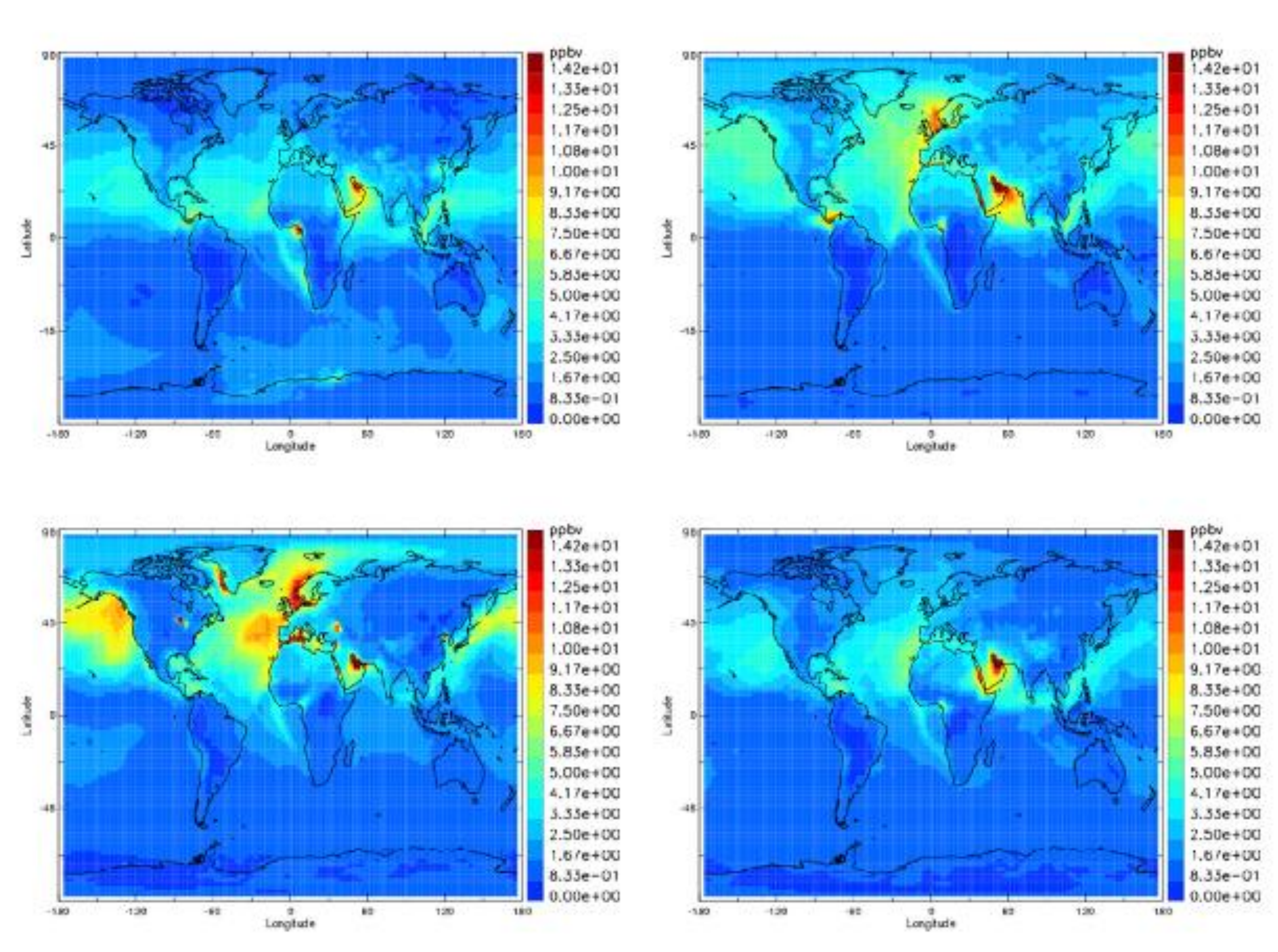


Figure 12: Ozone change (ppbv) at the surface due to year 2000 ship emissions for the months January (upper left), April (upper right), July (lower left) and October (lower right). Figure from *Dalsøren et al*. (2007).

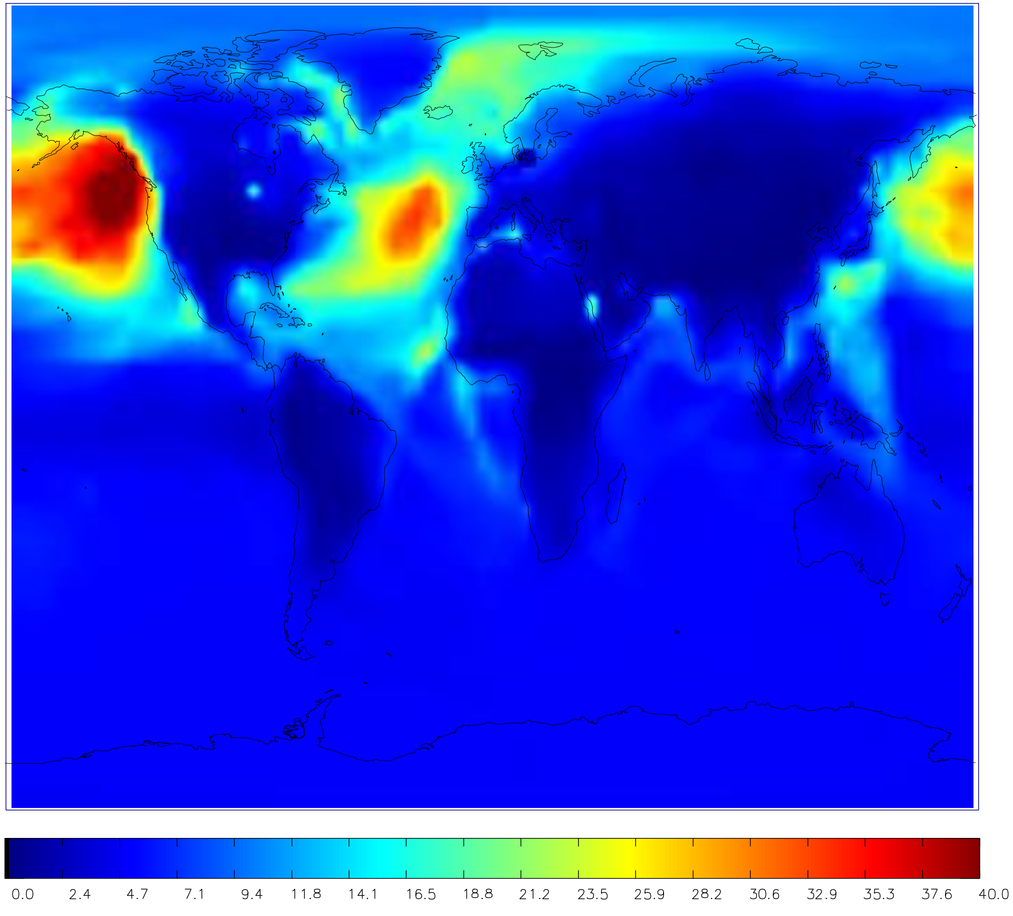


Figure 13: Relative ozone contribution (%)from ship traffic at the surface in July due to year 2004 ship emissions. Figure from *Dalsøren et al.* (2008).

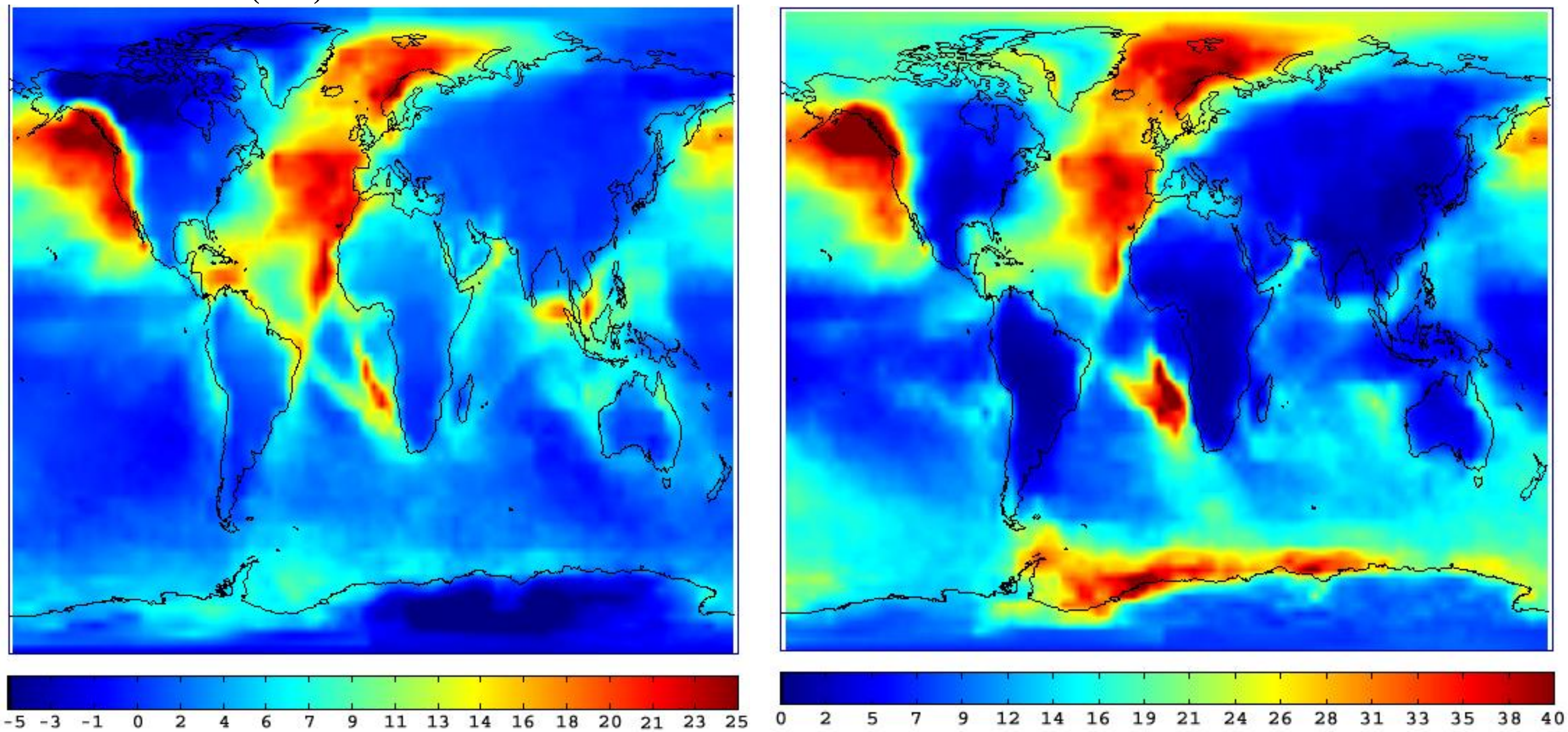


Figure 14: Yearly average contribution (%) from ship traffic to wet deposition. Left: sulphur. Right: nitrate. Figure from *Dalsøren et al.* (2008).

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