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The Enviornmental Impacts Of International Maritime Shipping Past Trends And Future Perspectives

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Abstract:
The paper discusses the environmental impacts of changes in international maritime activity and stresses the need for strengthening the accuracy and validity of the modeling 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.

1. Introduction

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 and this paper focuses on anthropogenic emissions of compounds leading to such environmental impacts mainly Carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions. 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). 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. 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) . Different operational and technical alternatives for reducing cargo VOC emissions (*e.g.* recovery systems) are available. Past, present, future emissions and their impacts on the atmosphereare studied in this paper.

2. Quantifying Fuel Consumption, Emissions And Impacts From Shipping

2.1. Fuelconsumption

There are mainly two different approaches to calculate the fuel consumption. One is by summing up world-wide bunker sales per country indicating shipping consumptions and other by summing up the fleet activity (summing up per ship/segment). As the emissions are directly proportional to fuel consumption geographical resolved emission inventories are used to asses regional and global impacts of ship emissions. **Figure 1** illustrates the integrated approach applied, where ship emissions and impacts are calculated based on activity based fleet modeling or by marine sales.

2.1.1. Activity-Based Estimates

The actual days at sea and the service speed in the future are estimated based on AIS (Automatic identification systems) for individual ocean-going ships. Such data 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). The International Maritime Organization requires AIS to be fitted aboard all international ships. **Figure 2** shows analysis of 500 small and medium sized ships (greater than 300 GT).

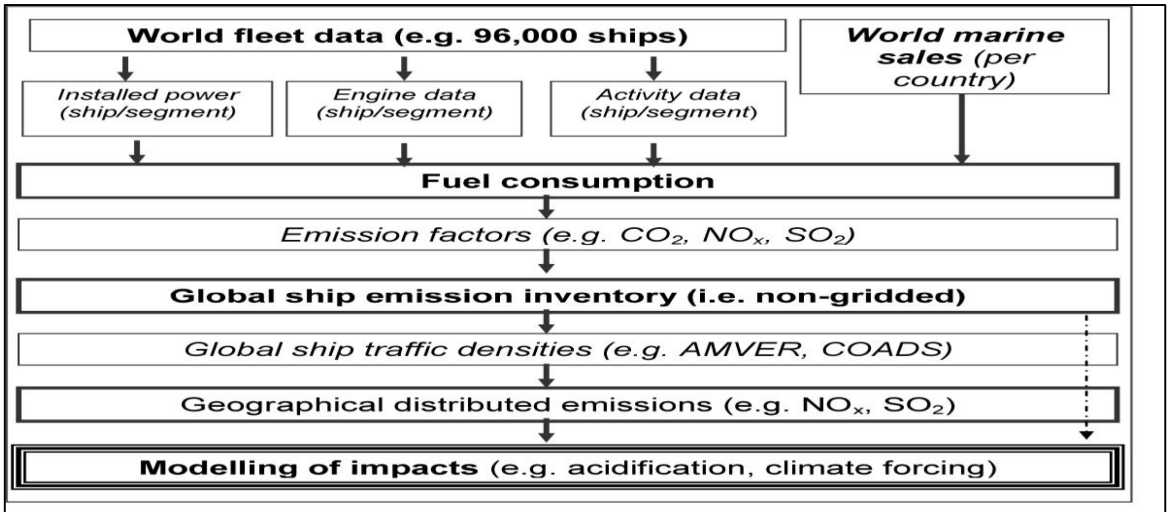


Figure 1: Illustrates the integrated modelling consepts for quantifying fuel consumption, emissions and impacts from shipping.

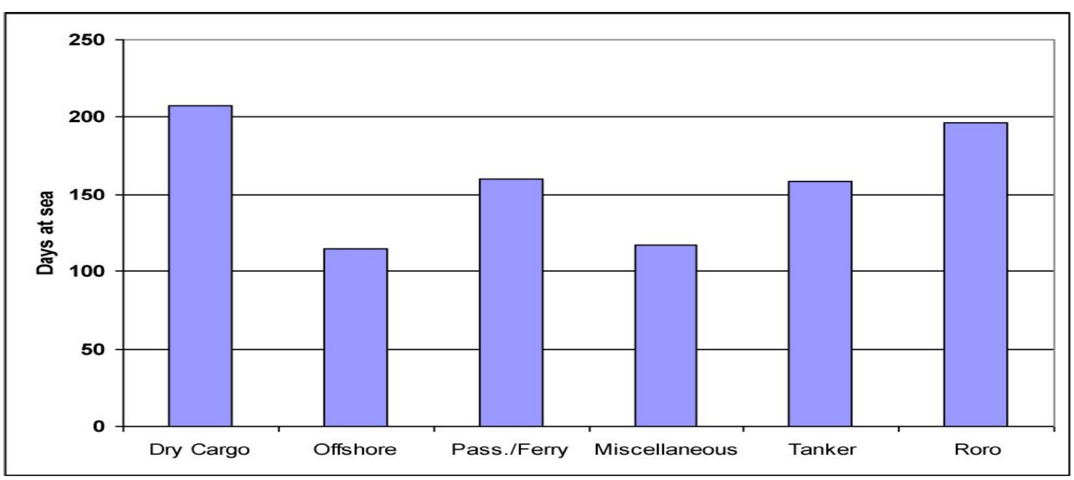


Figure 2:Calculated days at sea, based on AIS data for 500 small and medium sized ships (above 300 GT) tracked in Norwegian waters, first six months of 2007 (data from: The Norwegian Coastal Administration).

Note that offshore ships have low activity, as dynamic position operations are not included.

2.1.2. Estimates based on fuel sales

Figure 3 shows estimated worldwide bunker fuel consumption by vessel type. Fuel consumption in year 2001 was equal to 278 million tonnes. By 2020, bunker fuel demand approaches 500 million tonnes per year.

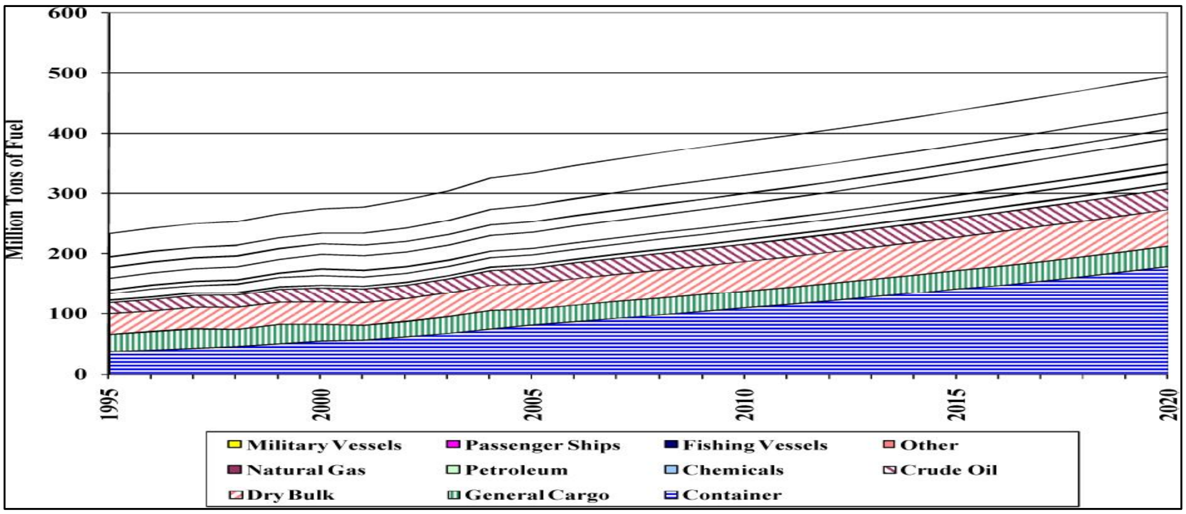


Figure 3: Worldwide Bunker Fuel Use, Source: Global Insights, Inc. 2005. World Trade Service.Customized Data Export.

2.2.Fuel Consumption And Emissions

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. 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(Table 2).The present world fleet is mostly diesel powered and consists of about 96,000 ships above 100 GT , 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). The ocean going civil world fleet gradually shifted from sail around 1870 to a full engine powered fleet around 1940 (Table 2). 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 made a huge difference in emissions. 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. 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. 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.

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 1: Percentage of world's total merchant fleet (From 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*

Table 2: Estimated global coal sales based on coal leaving United kingdom ports 1850 to 1913(From Fletcher 1997)

2.2.1.1870-1910

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% , illustrating the shift from sail to steam ship. At the turn of the century, more than 50% of the British coal exports (Table 2) were ultimately used for ship transportation. The United States Shipping board has estimated annual bunker consumptions before the First World War.The British Empiresupplied 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).Table 2 shows the estimated coal sales and CO_2 emissions, assuming 2.58 CO_2 per tonnefuel .Thus fuel sales to shipping increased by a factor about 7 from 1870 to 1913 (Table 2). Table 2 also illustrates that the estimated CO_2 emissions in 1913 are only slightly lower than in 1925 (Figure 4).This is due to increased focus on fuel economy and a shift from coal to oil.

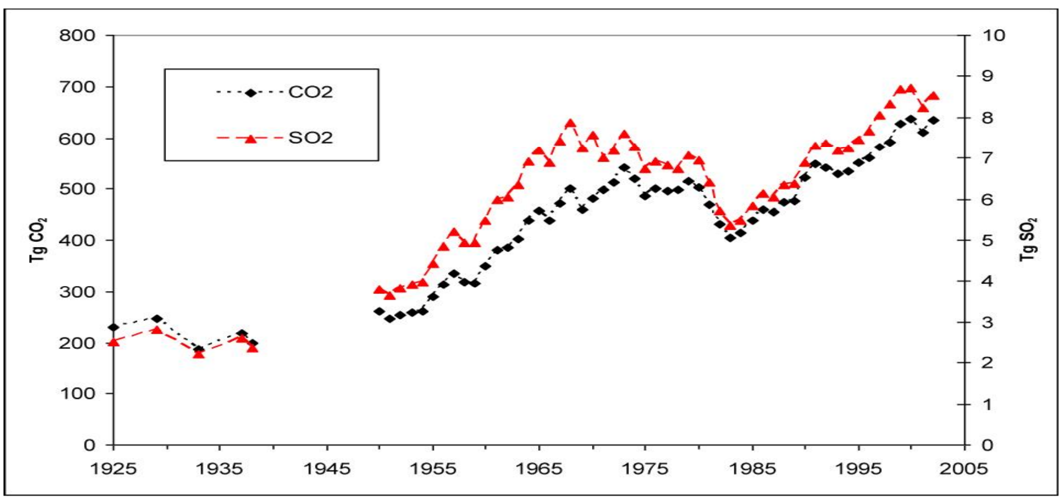


Figure 4:Development of CO2 and SO2 ship emissions, based on estimated sales of marine fuel, 1925-2002 (including the fishing and military fleet). Note that no data is available for the World War II period (From: Endresen et al., 2007).

2.2.2.1910-2002

Large deviations are observed in this period (Figure 5). Variation in the demand for sea transport and operational and technical changes over the years is taken into account for better representation ofreal fuel consumption and corresponding emissions.Fleet growth is not necessarily followed by increased fuel consumption, as technical and operational characteristics have changed. For instance, the peak level of 1979 was not reached again before 1991 (Figure 6 right). The detailed fuel based estimates (based on sales) from

1925 up to 2000 indicates 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%. Figure 4 showshistorical CO_2 and SO_2 emissions based on fuel sales. 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.

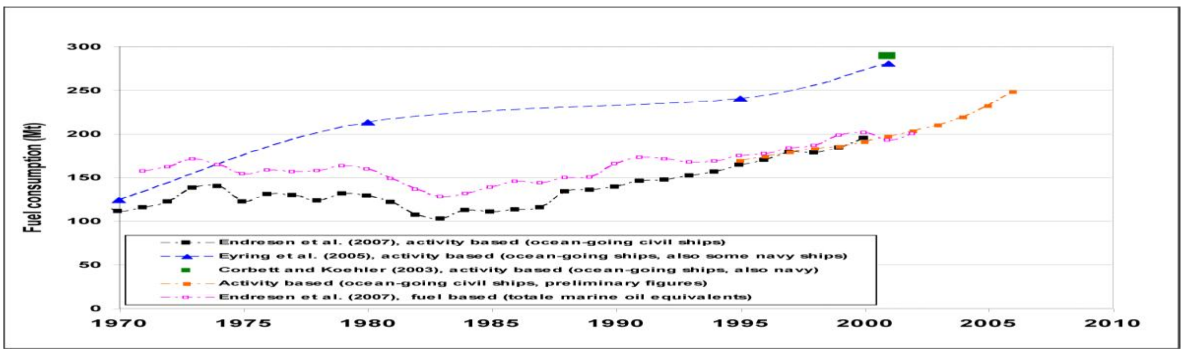


Figure 5: Comparison of reported estimates of fuel consumption, and activity-based estimates (simplified) up to 2006.

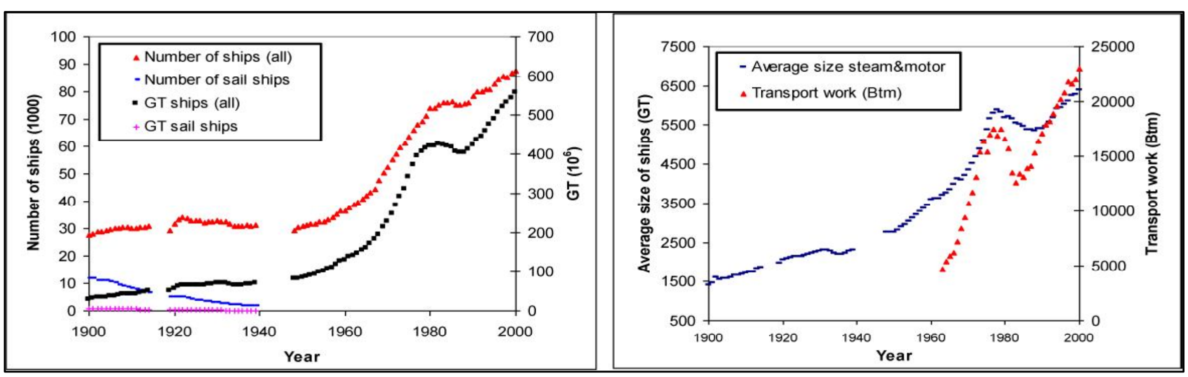
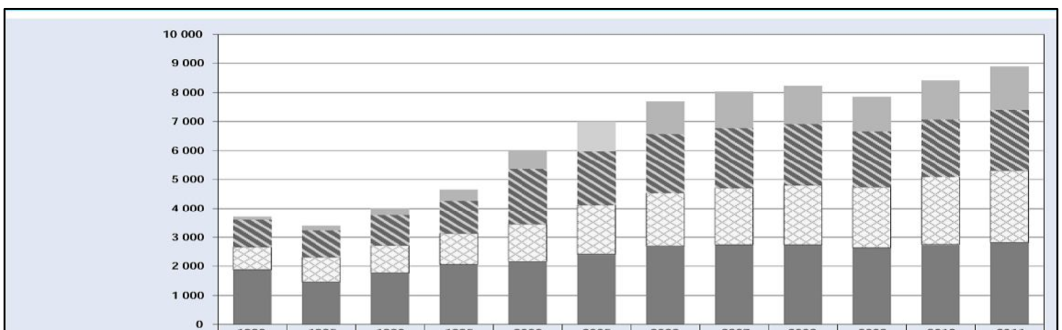


Figure 6:Development of the world fleet of ocean-going civil vessels above or equal 100 GT and transport work, 1900-2000 (not including the military fleet). Left: Development of size and tonnage(data from Lloyd's register of Shipping). Right: The development of average size (including also non-cargo 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).

2.2.3.2002-2011

In January 2010, there were 102,194 commercial ships in service, with a combined tonnage of 1,276,137 thousand dwt . Oil tankers accounted for 450 million dwt (35.3 per cent) and dry bulk carriers for 457 million dwt (35.8 %), representing annual increases of 7.6 and 9.1 per cent respectively. Container ships reached 169 million dwt – an increase of 4.5 per cent over 2009 – while the fleet of general cargo ships declined during 2009, reaching 108 million dwt in January 2010, corresponding to just 8.5 per cent of the fleet. Among other vessel types, the tonnage of liquefied gas carriers continued to grow, reaching 41million dwt. Figure 7shows International seaborne trade (millions of tons loaded) from 1980 to 2011. Annual growth rates in total seaborne trade in ton miles have been 23% from 2002 to 2006, while only 10% from 1999 to 2002 . Accordingly, the fuel consumption from 2001 to 2006 has increased significantly as the total installed power increased by about 25% .In addition, the world-wide sales of marine bunkers have increased by some 20% from 2001 to 2005 .The significant growth in container trade, as well as ship activity in Asian waters over recent years changed the geographical distribution of emissions. 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. In addition, from 2000 to 2004 the sales of marine bunker in Asia (and Oceania) increased by 45%.



	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011
Container	102	160	246	389	628	1 020	1 134	1 264	1 319	1 201	1 347	1 477
Other dry	935	918	1 039	1 131	1 905	1 852	2 032	2 066	2 109	1 921	1 976	2 105
Five major bulks	796	857	968	1 082	1 288	1 701	1 836	1 957	2 059	2 094	2 333	2 477
Crude oil and products	1 871	1 459	1 755	2 049	2 163	2 422	2 698	2 747	2 742	2 642	2 752	2 820

Source: *Review of Maritime Transport*, various issues. For 2006–2010, the breakdown by dry cargo type is based on Clarkson Research Services, *Shipping Review and Outlook*, various issues. Data for 2011 are based on a forecast by Clarkson Research in *Shipping Review and Outlook*, Spring 2011.

Figure 7:International seaborne trade (millions of tons loaded)

2.3. Future Ship Emissions

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). Extrapolating the growth trend in total fleet installed power in the period 1996-2011 gives a growth of 34%from 2006 to 2020. However, the growth from 1979 to 2011, or from 1986 to 2011, 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.This growth in the installed power corresponds to growth in emissions.

Second is by extrapolating the growth in transport work (tonne-miles). If the extrapolation is based on the growth trend in transport work from 1995 to 2011, the growth in installed fleet power to 2020 would be 33%.If the extrapolation is based on the trend from 2002 to 2011, 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. Thus by both methods growth of approximately 30% in emissions towards 2020 (Figure 8) is observed. Fuel consumption and emissions are calculated for the years 2025 and 2050 based on the estimates in the IPCC A1(Globalisation,rapid economic growth) and A2(Regionilisation,regional growth) scenarios. Estimates for 2050 indicate fuel 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

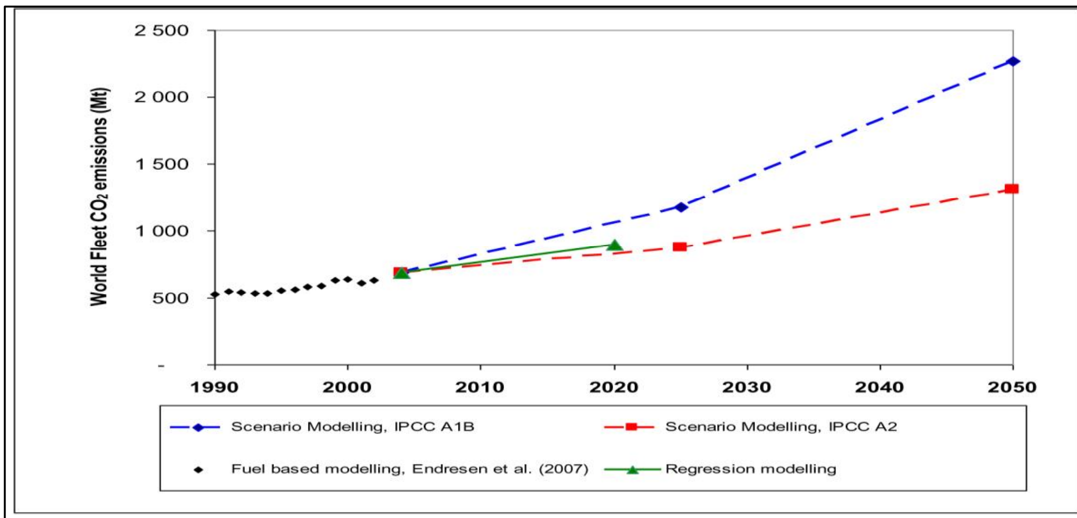


Figure 8: World fleet CO_2 emissions, based on IPCC scenarios (*Eide et al.*, 2008) and extrapolation of trends giving 30% growth by 2020 (this study).

2.4. Impact on pollution levels and climate

Primary components, like particles NO_2, CO, NMVOCs and SO_2, potentially cause problems in coastal areas and harbors with heavy traffic because of their impact on human health at high concentrations. Secondary species formed from the effluents in the ship emissions have longer chemical lifetimes and are transported in the atmosphere over several hundreds of kilometers. 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). 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. Ozone is also a major greenhouse gas. Ozone is estimated to be the third most important of the greenhouse gases contributing to warming. Exposure to high ozone levels are linked to aggravation of existing respiratory problems like asthma, increased susceptibility (infections, allergens and pollutants), inflammation, chest pain and coughing. 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 result in reductions in agricultural crops and commercial forest yields, reduced growth, increased susceptibility for disease and visible leaf damage on vegetation.Ozone also damage polymeric materials such as paints, plastics and rubber. 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). Figure 9 shows the relative contribution from international shipping to surface ozone.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 are 7% to 14% in the northern hemisphere and 2-7% in the southern hemisphere.

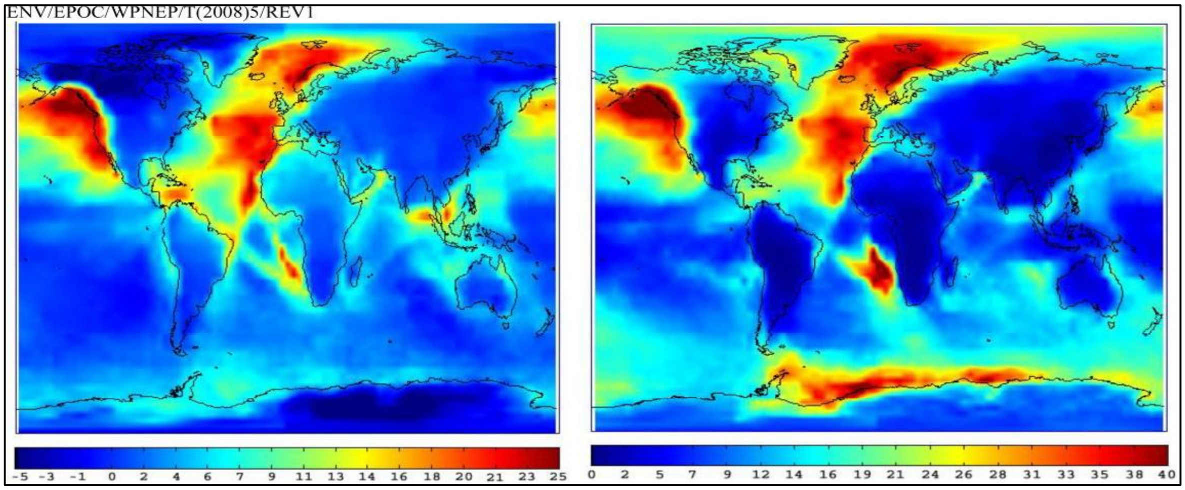


Figure 9: Relative ozone contribution (%)from ship traffic at the surface in July due to year 2004 ship emissions. Figure from Dalsøren et al. (2008).

Hydroxyl (OH) is the main oxidant in the troposphere. 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 , 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 . 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.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 acidification in vulnerable ecosystems .Sulphur emissions 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. Increases in the OH radical due to NO_x emissions will enhance the gaseous oxidation pathway. Currently shipping increases the global sulphate loading with about 3%. These are major components of acid rain. 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. Aerosols also have a direct effect on climate and visibility by scattering and/or absorbing solar radiation, thereby influencing the radiative balance.Aerosols increases the number of cloud drops, and thereby increase reflected solar radiation to space which lead to a cooling. The effects of aerosols emissions from ships on clouds are visible as so called ship-tracks in satellite images. The smaller water droplets are less likely to grow into larger drops of precipitation size, extending the lifetime of the cloud and increasing reflectivity. Radiative forcing (RF) calculations quantify the radiation balance at the top of the atmosphere due to components affecting the radiation budget. RF has a linear relationship global mean surface temperature. 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 radiative forcing (RF). Table 3summarises estimates of the present-day contribution of ship emissions to RF .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.

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**

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).

2.5.Future Impacts

For next 10-20 yearsthe present development in shipping shows 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, shipping activities in 2015 lead to more than 20% increase in NO_2 .Ozone increases are in general small. Wet deposition of acidic species increases up to 10% in areas where current critical loads are exceeded. 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. 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. 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. Maximum contributions from shipping to annual mean near-surface O_3 are found over the North Atlantic. Tropospheric O_3forcings due to shipping are 9.8±2.0 mW/m2 in 2000 and 13.6±2.3 mW/m2 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. Globally, shipping contributes 3% to increase in O_3 burden between 2000 and 2030, and 4.5% to increase in sulphate.

3. Conclusion

Shipping activity has increased significantly over the last century, and represents currently a notable contribution to the global emissions of pollutants and greenhouse gases. 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.

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

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. NO_2concentrations aredoubled 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). Formation of sulphate and nitrate resulting from nitrogen and sulphur emissions causes acidification that are harmful to ecosystems in regions with low buffering capacity, and have harmful health effects.

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. 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. 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.

Projections up to year 2020 indicate a growth in fuel consumption and emission in the range of 30%. Results for year 2050 indicate fuel consumptions between 453 and 810 Mt (2-3 times present level), with 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.

- **Nomenclature**

  Tg= Teragrams

  IPCC= Intergovernmental Panel on Climate Change

  LRF = Long range Forcasting

  GDP= Gross Domestic Product

  ACIA= Artic Climate Impact Assessment

  NMVOC= Non Methane Volatile Organic Compounds

  AMVER= Automated Merchant Vessel Reporting system

  COADS = Comprehensive Ocean Atmospheric Data Set

  Btm = Billion ton miles

  GT = Gross Tonnage

  Mt = Million Tons

  RF= Radoactive Forcing

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