Emissions from international shipping: 1. The last 50 years

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[1] Seagoing ships emit exhaust gases and particles into the marine boundary layer and significantly contribute to the total budget of anthropogenic emissions. We present an emission inventory for international shipping for the past five decades to be used in global modeling studies with detailed tropospheric chemistry. The inventory is a bottom-up analysis using fuel consumption and fleet numbers for the total civilian and military fleet including auxiliary engines at the end of 2001. Trend estimates for fuel mass, CO_2, NO_x, and other emissions for the time between 1950 and 2001 have been calculated using ship number statistics and average engine statistics. Our estimate for total fuel consumption and global emissions for the year 2001 is similar to previous activity-based studies. However, compared to earlier studies, a detailed speciation of nonmethane hydrocarbons (NMHCs) and particulate matter is given, and carbon monoxide emissions are calculated explicitly. Our results suggest a fuel consumption of approximately 280 million metric tons (Mt) for the year 2001 and 64.5 Mt in 1950. This corresponds to 187 (5.4) Tg CO_2 (NO_x) in 1950, and 813 (21.4) Tg CO_2 (NO_x) in 2001. From 1970 to 2001 the world-merchant fleet increased rapidly in terms of ship numbers, with a corresponding increase in total fuel consumption. The fuel consumption estimates are compared against historical marine bunker fuel statistics, and our emission estimates are related to emission budgets of other transport modes. Global ship emissions are distributed geographically according to global vessel traffic densities of the AMVER (Automated Mutual-assistance Vessel Rescue system) data set for the year 2000. This work also sets the basis to develop future emission scenarios based on average-fleet emission indices in part 2 of this study.

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1. Introduction

[2] The principal exhaust gas emissions from ships include CO_2, NO_x, SO_x, CO, hydrocarbons, and particulate matter. Furthermore, during tanker loading, evaporation leads to additional emissions of hydrocarbons. The exhaust gases are emitted into the atmosphere from the ship stacks and diluted with the ambient air. During the dilution process inside the ship plumes they are partly chemically transformed or removed. The emissions can regionally and globally change the composition of the atmosphere, are radiatively active and have a climate impact. An accurate assessment of the impact of the shipping emissions on the atmosphere requires detailed knowledge of the emission patterns and fluxes. Several emission inventories for shipping based on energy statistics have been established in the past [*Olivier et al.*, 1996; *Corbett and Fischbeck*, 1997; *Corbett et al.*, 1999; *Endresen et al.*, 2003]. *Corbett and Köhler* [2003] published an updated inventory for global fuel burned by internationally registered ships above 100 gross tons (GT), based on international shipping statistics [*Lloyd's Maritime Information System* (*LMIS*), 2002] for September 2001. This represents an activity-based estimate including main propulsion and auxiliary engine equipment onboard both cargo and noncargo ships, and the military fleet. The total worldwide fleet fuel consumption (civilian and all military ships) in 2001 according to this work is 289 million metric tons (Mt). This estimate is higher than all published inventories that are based on energy statistics. For example, *Endresen et al.* [2003] calculated a fuel consumption of 144 Mt for the cargo and passenger ship fleet, which more closely agrees with published fuel statistics. Recently, *Endresen et al.* [2004] questioned the higher values of *Corbett and Köhler* [2003]. *Corbett and Köhler* [2004] replied to this publication and confirmed their earlier work. They consider alternative input parameters in their activity-based fuel consumption and emission model and conclude that alternative assumptions in the input parameters even-

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tually could reduce their estimates, but not more than 14% to 16%.

[3] Even though the first model studies on the impact of ship emissions on ozone used the lower total fuel consumption corresponding to lower NO_x emissions of 3.08 Tg (N) per year [*Corbett et al.*, 1999], an overestimate of the impact of shipping on the NO_x and ozone distribution results [*Lawrence and Crutzen*, 1999; *Kasibhatla et al.*, 2000; *Davis et al.*, 2001; *Endresen et al.*, 2003]. This discrepancy can partly be attributed to an inadequate or oversimplified parameterization of chemical dilution within ship plumes [*Kasibhatla et al.*, 2000; *Davis et al.*, 2001; *Endresen et al.*, 2003; *Song et al.*, 2003; *von Glasow et al.*, 2003]. Recent satellite measurements of NO_2 from the Global Ozone Monitoring Experiment (GOME) [*Burrows et al.*, 1999] over the Indian Ocean [*Beirle et al.*, 2004] and from the SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) instrument on board the ENVISAT satellite [*Bovensmann et al.*, 1999] over the Red Sea and the Indian Ocean [*Richter et al.*, 2004] clearly show enhanced NO_2 occurrence along the major international shipping routes for the regions studied. Within the uncertainties of the methods applied by *Richter et al.* [2004] and *Beirle et al.* [2004], it appears that the observed NO_2 column amounts are somewhat lower than those implied by inventories. However, to conclude from these measurements that the lower NO_x estimates published by *Endresen et al.* [2003] are more realistic, would be misleading. Further ship plume model studies and measurements are necessary to clarify these discrepancies.

[4] Emission inventories provide important input for global atmospheric modeling studies. During the last decade, a number of global atmospheric models with detailed chemistry have been developed [*IPCC*, 2001; *WMO*, 2003]. They have generally improved in their representation of physical and chemical processes, as have their computational resources. Thus, transient model simulations under changing conditions have become now a standard, creating a need to develop emission inventories for transient changes of all anthropogenic and natural emissions. In order to reach statistical significance, ensemble simulations (i.e. various transient model simulations with equal forcings) are now envisaged.

[5] This study aims to define a ship emission inventory with detailed nonmethane hydrocarbon (NMHC) speciation as well as spatial and temporal disaggregation for the time period between 1950 and 2001. Compared to the *Corbett and Köhler* [2003] publication carbon monoxide emissions and speciated NMHCs have been calculated explicitly. The derived data set is suitable for use as input for chemical transport models (CTMs) and coupled chemistry-climate models (CCMs) with detailed tropospheric chemistry. In part 2 of this study the ship emission inventory is extended until the year 2050 [*Eyring et al.*, 2005].

[6] In this article we first describe the activity-based method to calculate total fuel consumption and emissions and review existing vessel traffic densities for international shipping (section 2). In section 3 we verify and extend present-day fuel consumption and global emissions in a format useable for atmospheric modeling and discuss our estimates with previous studies and emissions from other transport modes. The ship emission inventory includes NO_x, CO_2, CO, SO_2, particulate matter (PM, usually given by the size fraction below 10 μm, PM_{10}), methane (CH_4) and a detailed NMHC speciation. Historical emission trends based on number of ships and fuel consumption for all important ship emissions are estimated in section 4.

2. Methodology

[7] As this study aims to provide a detailed ship emission inventory for global modeling studies, total fuel consumption and emissions of the world fleet as well as vessel traffic densities have to be defined. This section describes the activity-based approach to calculate fuel consumption and emissions and gives a summary of existing data sets to distribute total emissions over the globe.

2.1. Vessel Traffic Densities

[8] Emissions for individual exhaust gases in a grid cell j ($M_{g,j}$) can be distributed geographically according to the total emissions for individual exhaust masses (M_g) and the ship relative reporting frequency in cell j (I_j) [*Endresen et al.*, 2003]:

$$M_{g,j} = M_g I_j \tag{1}$$

Total emissions for the individual exhausts (M_g) for present-day conditions are calculated in section 3, those for past emissions in section 4. The relative reporting frequency in each grid cell (I_j) is currently available from three different data sets, with a spatial resolution of 1° × 1°:

[9] The Comprehensive Ocean-Atmosphere Data Set (COADS) from the National Centre for Atmospheric Research (NCAR) and the National Oceanic and Atmosphere Administration (NOAA) is based on 6931 ships reporting of routine meteorological observations ideally at 6-hours intervals according to procedures by the World Meteorological Organization (see http://www.wmo.ch/web/www/ois/ois-home.htm). The data are based on monthly means for the year 1996.

[10] The Purple Finder (PF) data set is a web-based interface (available at http://www.purplefinder.com) that communicates with each vessel's Inmarsat-C terminal and automatically reports position. The PF data set for the year 2000 used in the *Endresen et al.* [2003] study contains 685,492 vessel observations for 1863 ocean-going cargo vessels.

[11] AMVER (Automated Mutual-assistance Vessel Rescue system) holds detailed voyage information based on daily reports for different ship types. Participation is generally limited to merchant ships over 1000 GT on a voyage for 24 or more hours. The participation is 12,550 ships that represent very well the international merchant fleet.

[12] *Endresen et al.* [2003] show that the regional distributions of the emission indicators for AMVER and PF largely agree, but differ significantly from COADS. They explain the difference partly by the fact that COADS includes a large fraction of (smaller) noncargo vessels, whereas the other two data sets mainly represent the international cargo fleet. Furthermore they found that the COADS data set emits around 50% in the North Atlantic region, which is inconsistent with PF and AMVER, but also with port data and bunker statistics. The AMVER data set is

Table 1. Fleet-Average Summary for the End of 2001 and for Ships of 100 GT and More[a]

		Cargo Vessels					Noncargo Vessels		
	All Vessels	All Cargo Ships	Tanker[c]	Container Ships	Bulk and Combined Carriers	General Cargo Vessels	Passenger and Fishing Ships, Tugboats, Others	Auxiliary Engines (Gensets)	Military Vessels[b]
Number of ships	90,363	43,967	11,156	2759	6457	23,595	45,096	-	1300
P_{MCR}, MW	343,384	218,733	54,514	46,461	46,297	71,461	67,051	40,000	17,600
F_{MCR}, %			75	72	80	70	65–75	60	80
Time τ,[d] hours/yr			6500	6600	5400	6500	4000–5500	3000	2500
SFOC,[e] g/kWh	212	210	191–229	194–222	192–202	200–230	207–240	230–240	250–280
FC, [f] Mt	279.7	207.8	56.8	42.7	39.4	68.9	46.2	16.3	9.4
EI_{NOx}, g/kWh	16.2	-	9.3–16.8	11.9–18.8	10.9–16.8	10.9–15.8	7.9–10.9	8.9	8–15
kg/t fuel	76.4	85.9	50–90	64–101	58–90	58–85	42–58	48	42–80
TE_{NOx}, Tg NO_2	21.38	17.85	4.44	4.67	3.78	4.96	2.39	0.8	0.34
EI_{CO2}, g/kWh	616	605	600	600	610	610	620	625	800
Kg/t fuel	2905	2860	2830	2830	2880	2880	2930	2950	3776
TE_{CO2}, Tg CO_2	812.63	593.76	160.89	120.93	113.47	198.47	135.23	48.03	35.61
EI_{SOx}, g/kWh	9.12	9.47[g]	9.47[g]	9.47[g]	9.47[g]	9.47[g]	8.52[h]	8.52[h]	3.80[i]
Kg/t fuel	43.0	44.7[g]	44.7[g]	44.7[g]	44.7[g]	44.7[g]	40.2[h]	40.2[h]	18.0[i]
TE_{SOx}, Tg SO_2	12.03	9.34[g]	2.54[g]	1.91[g]	1.81[g]	3.08[g]	1.86[h]	0.66[h]	0.17[i]
EI_{HC},[j] g/kWh	1.5	1.4	1.4	1.4	1.4	1.4	1.7	1.8	1.6
Kg/t fuel	7.0	6.6	6.6	6.6	6.6	6.6	8.0	8.5	7.6
TE_{HC}, Tg HC	1.96	1.38	0.38	0.28	0.26	0.46	0.37	0.14	0.07
EI_{PM},[j] g/kWh	1.27	1.25	1.25	1.25	1.3	1.3	1.4	1.2	1.0
Kg/t fuel	6.0	5.9	5.9	5.9	6.1	6.1	6.6	5.7	4.72
TE_{PM}, Tg PM	1.67	1.23	0.32	0.25	0.24	0.42	0.31	0.09	0.04
EI_{CO},[j] g/kWh	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.7
Kg/t fuel	4.67	4.72	4.72	4.72	4.72	4.72	4.72	4.72	3.3
TE_{CO}, Tg CO	1.306	0.98	0.268	0.201	0.186	0.325	0.218	0.077	0.031

[a]The table summarizes the installed engine power (P_{MCR}), the engine load cycle based on duty cycle profiles (F_{MCR}), the average annual engine running hours (τ), the specific fuel oil consumption (*SFOC*) and specific emission for each pollutant X (EI_x) for each of the main ship classes. The calculated total fuel consumption *FC* (in Mt/yr) and total emission (TE_X) for each pollutant (in Mt X/yr) are also listed. Average emission factors for all vessels have been calculated from the resulting total emission of each pollutant divided by the total fuel consumption of 280 Mt.

[b]About 300 GT and above (equals approximately 100 t standard displacement and more) including some 520 submarines, 190 of which are nuclear powered. The total navy fleet consists of almost 20,000 military ships (including 750 submarines) with 34,633 main engines and a total installed engine power (MCR) of 172,478 MW.

[c]Including 1301 crude oil carriers and 1153 gas carriers.

[d]From engine start to total engine stop, including port operation.

[e]Minimum/maximum values taking into account engine type (two-stroke, four-stroke, turbines), engine cylinder rating, fuel type, with SFOC tolerance (3 and 5%), engine driven pumps, SFOC increase due to the average ship age of some 20 years.

[f]The 2% reduction of the *Corbett and Köhler* [2003] figures due to the lower installed MCR in mid 2001 compared to the end of 2001.

[g]Average fuel-sulfur content 2.4–2.6%.

[h]Average fuel-sulfur content 2.25%.

[i]Average fuel-sulfur content 1.0%.

[j]Tolerance ±20% for HC, PM, and CO; HC and CO emission measurements according to ISO 8178, PM according to VDI 2066 or U.S. EPA method 17.

more detailed and larger than COADS and PF and is found to reflect the distributions of merchant ships in international trade very well [*Corbett and Köhler*, 2003]. For these reasons, we use the AMVER data set in our study to geographically distribute total emissions over the globe.

2.2. Modeling Total Fuel Consumption and Emissions

[13] Our bottom-up approach follows the method described by *Corbett and Köhler* [2003] and *Köhler* [2002, 2003]. All civilian ships of the 2001 fleet are divided into 11 main ship classes. The corresponding 117,500 engines for the 11 classes are further divided into 132 engine sub-groups. For each engine sub-group the fuel consumption FC_i (in tons per year) is calculated by multiplying the accumulated installed engine power P_i (in MW) with the engines' average load based on duty cycle profiles $F_{MCR,i}$ (in %), the average annual engine running hours τ_i (in hours per year) and the power-based specific fuel-oil consumption rate $SFOC_i$ (in kg/kWh). Summing up over all 132 sub-groups gives the total fuel consumption (*FC*) in 2001:

$$FC = \sum_{i=1}^{132} FC_i = \sum_{i=1}^{132} P_i * F_{MCR,i} * \tau_i * SFOC_i \quad (2)$$

The number of ships in each of the 11 main classes and also the number of engines as well as their total installed propulsion power in the 132 engine sub-groups and the resulting accumulated engine power *P* in MW for the end of the year 2001 is based on ship registered data [*LMIS*, 2002]. Specific fuel-oil consumption rates are based on measurements of the manufacturers at their test beds: confidential data from the leading diesel engine manufacturers have been used for the calculations [*Köhler*, 2002, 2003].

[14] For our advanced ship emission inventory, these results were re-calculated to fit into a system consisting of a total of six main ships types plus auxiliary engines: four cargo ship types, a single noncargo class "all other civilian ships", auxiliary engines and military vessels (see Table 1). This was necessary because the AMVER data set was available only for a limited number of ship types (see end of section 3.1).

[15] Total NO_x emissions from oceangoing ships above 100 GT have also been obtained from detailed calculations using the same 132 engine sub-groups. Measured NO_x emission factors $EI_{Nox,i}$ (in kg per ton fuel) were supplied for a series of engines from the industry. Multiplied by the total fuel consumption FC_i of each engine sub-group and

summing up over all sub-groups gives the total estimate for NO_x emissions (TE_{NOx}) in 2001:

$$TE_{NOx} = \sum\nolimits_{i=1}^{132} FC_i * EI_{NOx,i} \quad (3)$$

In addition, the total emissions of the pollutants CO_2, SO_x, HC, particulate matter and CO have been estimated explicitly for each of the six main ship classes and auxiliary engines listed in Table 1. Also the numerous on-board auxiliary engines (gensets) have been taken into account. Total emissions (TE_X) except NO_x are obtained by applying equation (4). Unlike to NO_x, the emission factors of the other pollutants X in kg per ton of fuel ($EI_{X,i}$) are not readily available from the industry, that seems to prefer such data in specific power-based units g/kWh. The link between the power-based emission factor ($EP_{X,i}$) in g/kWh and $EI_{X,i}$ in kg/t fuel is the specific fuel-oil consumption rate *SFOC* (in kg/kWh). If *SFOC* is known and $EP_{X,i}$ is given in g/kWh, the emission factor (in kg/t fuel) can be calculated by dividing the power-based emission factor (in g/kWh) by the specific fuel-oil consumption, see equation (5).

$$TE_X = \sum_{i=1}^{7} FC_i * EI_{X,i} \quad (4)$$

$$EI_{X,i} = EP_{X,i}/SFOC \quad (5)$$

Therefore, when *EI* in kg/t fuel is divided by *EP* in g/kWh, the resulting value is the reciprocal of SFOC, a conversion factor which, for a given engine, is the same for all exhaust gas pollutants. This is convenient for our work, because we could calculate all the pollutants in Table 1 from the main ships' known fuel consumption rates by applying equation (4). Since the fleet's NO_x emission for 2001 was exactly calculated by using averages of the measured emission factors (in kg/t fuel) across engine load from almost 50 sample engines of different types and makes [*Köhler*, 2002, 2003], an average worldwide fleet conversion factor of 4.72 kWh/kg could be obtained by assuming a fleet-average specific fuel-oil consumption rate *SFOC* of 0.212 kg/kWh.

3. Update of Present-Day Fuel Consumption and Global Emissions

[16] Based on published data [*Corbett and Köhler*, 2003] we have verified and extended global ship emissions for the year 2001 using the principal method described in section 2.

3.1. Fleet-Average Summary for End of 2001 and Results

[17] According to basic statistical information of *Lloyd's Maritime Information System* (*LMIS*) [2002] the world merchant fleet at the end of the year 2001 consisted of 89,063 ocean-going ships (43,967 cargo ships and 45,096 noncargo ships) of 100 GT and above. The total cargo fleet included 11,156 tanker (8702 tanker without crude oil carriers and gas carriers, 1301 crude oil carriers, 1153 gas carriers), 2759 container ships, 6261 bulk carriers, 196 combined carriers, and 23,595 general cargo vessels (e.g., lolo ships, roro ships, product carriers, etc.). The noncargo fleet included 971 fish factories, 22,141 fishing vessels, 12,209 tugs, and 9775 other ships (e.g., ferries, passenger ships, cruise ships, research vessels, dredgers, cable layers, etc). Table 1 summarizes the fleet-average values for different ship types and the total fleet which have been used in this study. Resulting fuel consumption, NO_x emissions and total emissions of other pollutants for the different ship types and the total fleet have been calculated using equations (2), (3), and (4), respectively.

[18] We estimate the world fleet fuel consumption for the year 2001 to be approximately 280 million metric tons. Global annual emission budgets for the year 2001 are estimated to be 21.38 Tg (NO_2) for NO_x, 12.03 Tg (SO_2) for SO_x, 812.6 Tg (CO_2) for CO_2, 1.31 Tg (CO) for carbon monoxide, 1.67 Tg for particulate matter and 1.96 Tg (HC) for hydrocarbons. In addition, 1.959 Tg (HC) hydrocarbons from crude oil transport evaporate yearly during loading, transport, and unloading [*Endresen et al.*, 2003].

[19] The total estimate of CO and HC emissions is based on an average emission index of 4.67 and 7.0 kg/t fuel, respectively. The measurements at the manufacturers' engine test beds are according to ISO 8178 with a tolerance of ±20%. Limited field observations of ship plumes have shown first indications that CO emissions vary significantly between different ship types and that large marine vessels emit very little to no CO (T. B. Ryerson and E. J. Williams, NOAA, personal communication). Also the maintenance of the engine might play an important role. In general, CO emission is the result of incomplete combustion. Since large-bore diesel engines operate at high air excess ratios and high combustion temperatures, carbon monoxide emissions from diesel engines are much lower than from other internal combustion engines. In our study this is reflected by the fact that the average emission index of CO is low compared to all other emissions (see Table 1). To include emissions from BC, OC, CH_4 and speciated NMHC the data from this study was modified as follows: The emissions of PM_{10} are 1.67 Tg in total. Using the emission factor for black carbon (BC) measured by *Sinha et al.* [2003] (0.18 g per kg fuel), the BC fraction estimated from the total fuel consumption of 280 Tg is 0.05 Tg. This result is consistent with the work of *Petzold et al.* [2004], who measured the exhaust gas of a single-cylinder test bed diesel engine. The engine was operated at various load conditions, running on fuel with a sulfur content of 3.45 wt.–%. For an engine load of 100%, *Petzold et al.* [2004] measured a BC fraction of 2% of the total particle mass. The BC fraction increases with decreasing engine load. Thus, the resulting total BC emissions of 0.033 Tg estimated from this measurement have to be regarded as a lower boundary. In an analogous manner, the amounts of organic carbon (OC), sulfate (SO_4) and fly ash can be estimated. *Petzold et al.* [2004] found a mass fraction of 8% (OC), 47% (SO_4) and 6% (ash) of total particle mass at 100% load. This results in global annual emissions of 0.134 Tg (OC), 0.785 Tg (SO_4) and 0.100 Tg (ash).

[20] Hydrocarbon emissions have been compiled into a format suitable for atmospheric modeling using the speciation into 25 categories of nonmethane volatile organic compounds from the Emission Database for Global Atmospheric Modeling v2 (EDGAR [*Olivier et al.*, 1996]). Since our study estimates total hydrocarbons, the fraction between

Table 2. NMHC Speciation of Ship Emissions[a]

	Fuel Combustion				Tanker Loading	
	Gas Oil, Mg	Fuel Oil, Mg	Fraction	Tg NMHC	Fraction	Tg NMHC
v01: Alkanols	-	-	-	-	-	-
v02: Ethane	-	-	-	-	0.093	0.155
v03: Propane	-	-	-	-	0.258	0.429
v04: Butanes	-	-	-	-	0.272	0.453
v05: Pentanes	-	-	-	-	0.146	0.243
v06: Hexanes and higher alkanes	159	3	0.302	0.525	0.056	0.093
v07: Ethene	22	90	0.209	0.364	-	-
v08: Propene	11	112	0.229	0.398	-	-
v09: Ethyne	0	3	0.006	0.010	-	-
v10: Isoprenes	-	-	-	-	-	-
v11: Monoterpenes	-	-	-	-	-	-
v12: Other alkenes	0	12	0.022	0.038	-	-
v13: Benzene	11	39	0.093	0.163	0.001	0.002
v14: Toluene	11	17	0.052	0.090	0.002	0.003
v15: Xylenes	17	6	0.043	0.075	0.006	0.010
v16: Trimethylbenzenes	20	0	0.037	0.064	-	-
v17: Other aromatics	-	-	-	-	0.076	0.126
v18: Esters	-	-	-	-	-	-
v19: Ethers	-	-	-	-	-	-
v20: Chlorinated hydrocarbons	-	-	-	-	-	-
v21: Methanal	-	-	-	-	-	-
v22: Other alkanals	-	-	-	-	-	-
v23: Alkanones	-	-	-	-	-	-
v24: Acids	-	-	-	-	-	-
v25: Other NMHC	3	0	0.006	0.010	0.091	0.151
Total NMHC	254	282	1.000	1.737	1.000	1.665

[a]Total emissions of 1.737 Tg NMHC as calculated in this work have been assigned to each of the 25 NMHC categories as identified in EDGAR [*Olivier et al.*, 1996] using the measurement data from *Cooper et al.* [1996]. *Cooper et al.* [1996] distinguish gas oil and fuel oil emissions, of which the average has been used to assign the NMHC emissions. NMHC emissions from tanker loading (1.665 Tg) have been taken from *Endresen et al.* [2003] and are assigned to the 25 NMHC categories using data on evaporation from oil tanks [*EPA*, 2004].

CH_4 and NMHC is based on the split of 11.36% of CH_4 and 88.64% of NHHC as presented by *Endresen et al.* [2003]. Using this fraction and a total of 1.96 Tg HC emissions, the resulting CH_4 (NMHC) emissions are 0.223 Tg (1.737 Tg), respectively. The speciation of NMHC from fuel combustion into 25 categories is based on the work by *Cooper et al.* [1996], which is to our knowledge the only published work on NMHC speciation from shipping combustion. *Cooper et al.* [1996] distinguish between gas oil and fuel oil as fuel types and have measured in total 21 different NMHC compounds. These compounds belong to 10 of the 25 NMHC categories as defined in EDGAR. The measurement value for both, gas fuel and heavy fuel, have been combined in an aggregated fraction of each specific NMHC category which is then used to attribute the total NMHC emission of 1.737 Tg to each NMHC category. In addition to the fuel combustion emissions, evaporation during tanker loading and transport of crude oil is a significant source of hydrocarbons. According to *Endresen et al.* [2003], evaporation during tanker loading and transport leads to an additional burden of 0.294 Tg CH_4 and 1.665 Tg NMHC. Speciation of evaporative NMHC emissions from tanker loading and transport is based, in analogy with *Endresen et al.* [2003], on data on evaporation from oil tanks [*EPA*, 2004]. In contrast to *Endresen et al.* [2003], who distinguish 5 NMHC categories, the fraction of NMHC emissions into 25 categories has been used (Table 2).

[21] Table 3 summarizes global emissions from international shipping presented in this study and compares the results to estimates of the work by *Corbett and Köhler* [2003] likewise for 2001 and by *Endresen et al.* [2003] for 2000.

[22] Total emissions calculated in this study have been gridded using the global distribution of vessel traffic densities for the year 2000 based on the reported distributions from AMVER data with a $1^\circ \times 1^\circ$ spatial resolution [*Endresen et al.*, 2003] for different ship types (tanker, container ships, bulk carriers, and rest). *Endresen et al.* [2003] used the same global distribution from AMVER, but a sum of 3.63 Tg (N) for the annual total NO_x emissions from ship engines instead of 6.51 Tg (N) for the year 2001 as used in this work. As an example the resulting global NO_x emission inventory for oil tanker, container vessels, bulk carriers and the total fleet for the year 2001 is shown in Figure 1.

3.2. Discussion

[23] In section 3.1, total fuel consumption and emissions from the ocean-going fleet in 2001 above 100 GT have been estimated. Here we compare these results with previous studies and with emissions from other transport modes.

3.2.1. Comparison to Other Ship Emission Inventories

[24] Our study follows the bottom-up approach described in *Corbett and Köhler* [2003]. Compared to the *Corbett and Köhler* [2003] study, which is based on statistical information of Lloyd's Maritime Information Services for September 2001, we have used updated information for the end of the year 2001 [*LMIS*, 2002]. In our study, military vessels about 300 GT and above are included, whereas *Corbett and Köhler* [2003] include all military vessels (i.e., even those smaller than 100 GT). Especially for emissions from hydrocarbons, particulate matter and CO new and more accurate measurements of emission indices from engine test beds were available for our study. This enabled us to update the

Table 3. Annual Emissions From International Shipping Estimated by E2003 [*Endresen et al.*, 2003] for the Year 2000, by CK2003 [*Corbett and Köhler*, 2003] for September 2001, and in This Study for End of 2001[a]

		E2003	CK2003	This Study	
Total fuel consumption	**Mt**	**166**	**289**	**280**	
NO_x	Tg NO_2	11.92	22.57	**21.38**	
CO_2	Tg CO_2	557.32	912.37	**812.63**	
CO	Tg CO	1.12	-	**1.31**	
SO_x	Tg SO_2	6.82	12.98	**12.03**	
Particulate matter			-		
BC	Tg BC	-	-	0.05	
OC	Tg OC	-	-	0.134	
SO_4	Tg SO_4	-	-	0.785	
Ash	Tg ash	-	-	0.100	
Other particulate matter	Tg	-	-	0.601	
Total particulate matter	Tg PM_{10}	**0.912**	**1.64**	**1.67**	
Hydrocarbons				**fuel**	**loading**
CH_4	Tg	**0.046**	**-**	**0.223**	**0.294**
v02: Ethane	Tg	b	-	-	0.155
v03: Propane	Tg	b	-	-	0.429
v04: Butanes	Tg	b	-	-	0.453
v05: Pentanes	Tg	b	-	-	0.243
v06: Hexanes higher alkanes	Tg	b	-	0.525	0.093
v07: Ethene	Tg	b	-	0.364	-
v08: Propene	Tg	b	-	0.398	-
v09: Ethyne	Tg	b	-	0.010	-
v12: Other alkenes	Tg	b	-	0.038	-
v13: Benzene	Tg	b	-	0.163	0.002
v14: Toluene	Tg	b	-	0.090	0.003
v15: Xylenes	Tg	b	-	0.075	0.010
v16: Trimethylbenzenes	Tg	b	-	0.064	-
v17: Other aromatics	Tg	b	-	-	0.126
v25: Other NMHC	Tg	b	-	0.010	0.151
Total NMHC	**Tg**	**0.359**	**-**	**1.737**	**1.665**
Total hydrocarbons	**Tg**	**0.405**	**0.769**	**1.96**	**1.96**

[a]The split of particulate matter into BC, OC, SO_4 and ash is taken from *Sinha et al.* [2003] and *Petzold et al.* [2004]. The HC estimates have been split into NMHC and CH_4 using the ratios from E2003. For HC evaporation from tanker loading, transport and uploading the values from E2003 have been used. NMHC emissions have been fitted to the EDGAR NMHC classification [*Olivier et al.*, 1996]. For fuel combustion the fit is based on measurements by *Cooper et al.* [1996] and for tanker loading on *EPA* [2004].

[b]Since the NMHC speciation by *Endresen et al.* [2003] does not match with the 25 categories of EDGAR, this speciation has been excluded here.

calculations and to extend the inventory by calculating CO emissions explicitly. In contrast to *Corbett and Köhler* [2003], we are using slightly shorter average annual engine running hours for some ship types. However, our resulting estimate of 280 Mt total annual fuel consumption in 2001 is very similar to the 289 Mt calculated by *Corbett and Köhler* [2003] (see Table 3).

[25] The total annual fuel consumption derived by the *Corbett and Köhler* [2003] approach and this study is higher than the fuel consumption released by the international marine bunker industry and also by organizations such as the International Energy Agency (IEA) and the Energy Information Administration (EIA). Interestingly, these parties publish differing marine fuel sales figures and it seems the term international marine bunkers is not well defined [*MARINTEK*, 2000]. EIA defines international bunkers as fuels supplied to ships and aircraft in international transportation, whereas IEA defines international marine bunkers as those quantities delivered to seagoing vessels, including warships. Not included in the marine bunker statistics are ships engaged in coastal waters (cruise ships, ferries, offshore vessel, dredgers, fishing vessels, research vessels, cable layers, etc.) and cargo ships for inland waters. Another distinction is that fuel data from EIA is given in thousand barrels per day, whereas the IEA reports are in Mt per year. Some uncertainties are involved when barrels are converted into tons for comparison purposes, since the density of fuels differs between 862 kg/m^3 for distillate fuels to a maximum of 991 kg/m^3 for residual fuels.

[26] If bunker fuel is loaded by a tanker as cargo in one of the major ports and sold to other ships outside of the port, this quantity might not be listed as international marine bunkers. Part of the fuel burned in propulsion engines is supplied from agricultural or domestic sources. Therefore it is not surprising that, years ago, the total worldwide fleet consumption was estimated to be only 100 Mt [*Corbett and Fischbeck*, 1997]. It seems marine fuel consumption and ship emissions have been systematically underestimated in the past. Figure 2 shows the change in international marine bunker fuel statistics in Mt of oil equivalents (source: energy statistics [*IEA*, 2003]) for the time period 1971 to 2001 compared to the change in the total number of ships (>100 GT) [*LMIS*, 2002] as well as the estimated total fleet fuel consumption of this work over the same time period. From 1970 to 2001 the world-merchant fleet increased rapidly in terms of ship numbers (by 70%), with a corresponding increase in total fuel consumption. During the time period of rapid increase of the fleet, with the most significant increase in the eighties, marine bunker statistics surprisingly give approximately constant and even lower figures. World seaborne trade since 1985 as on average gained 3.3% in terms of volumes and 3.6% p.a. in terms of ton-miles [*Fearnresearch*, 2004].

[27] Recently, *Endresen et al.* [2004] have questioned the *Corbett and Köhler* [2003] results by claiming that their high estimate of bunker consumption is mainly caused by an assumed high utilization of engine power and too many days in service operations for small and medium-sized vessels. *Endresen et al.* [2003] modeled the year 2000 fuel consumption by the main engines to be only about 144 Mt. It should be noted that this fuel consumption refers to cargo and passenger ships only (approximately 45,000 vessels), excluding all other ships.

[28] The study by *Endresen et al.* [2003] differs from the *Corbett and Köhler* [2003] calculations and from our study in two further important aspects:

[29] 1. The *Endresen et al.* [2003] model depends upon an indirect statistical relationship between known vessel size and inferred main engine power, based on information from 4500 Det Norske Veritas (DNV)-classed vessels (SPRINT database), whereas *Corbett and Köhler* [2003] and this study directly use installed engine power characteristics by vessel type for almost 90,000 ships based on Lloyd's Ship Particular File Data [*LMIS*, 2002].

[30] 2. *Endresen et al.* [2003] estimate the number of vessel hours at sea, where ships cruise at high speeds with their propulsion engines operating at high loads, whereas *Corbett and Köhler* [2003] and this study directly input all engine operating hours including low-load and idling in and close to ports. A ship approaching the coast or the harbor with reduced engine load is no longer at sea, but still burns

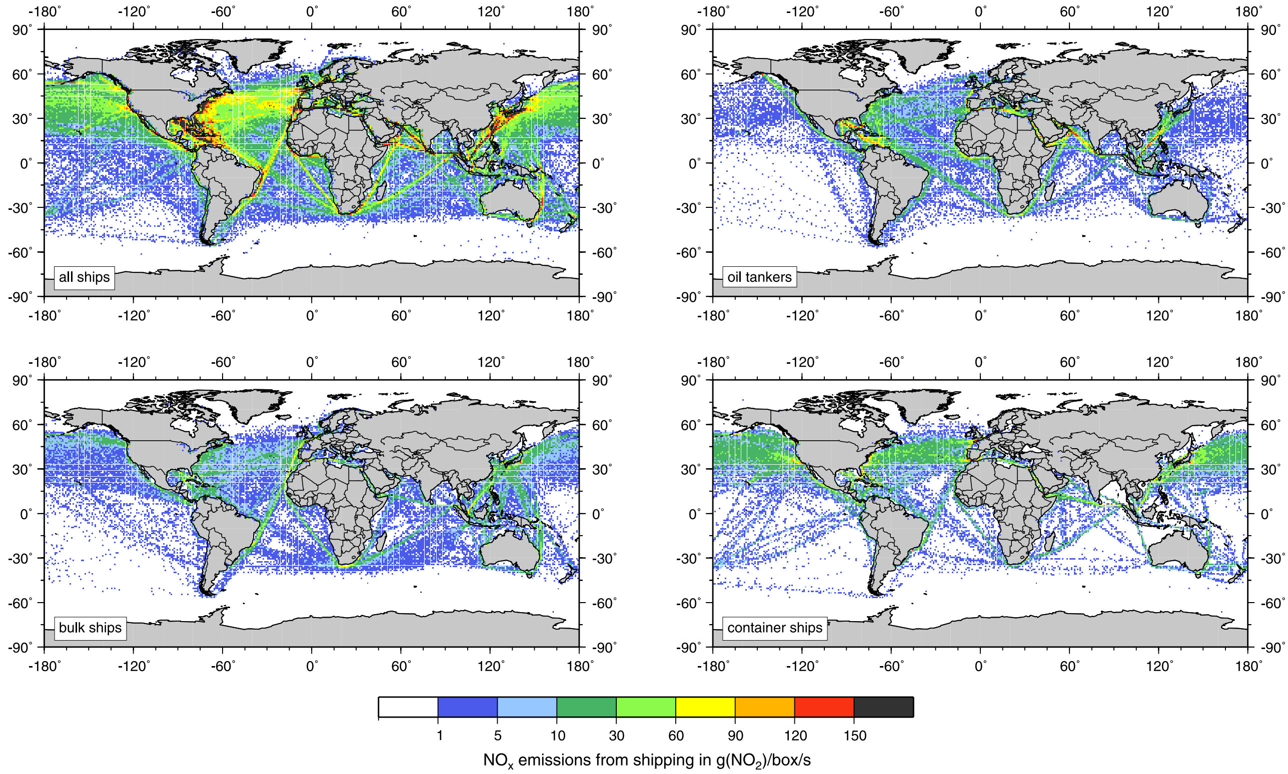

Figure 1. Global distribution of NO_x emissions for different ship types. Global NO_x emissions of the world fleet have been estimated to be 21.38 Tg (NO_x), whereof tankers contribute with 4.44 Tg (NO_x), container ships with 4.67 Tg (NO_x), and bulk carriers with 3.78 Tg (NO_x) (see Table 1). Global distribution of vessel traffic densities for the different ship types and the year 2000 are based on the reported distributions from AMVER data [*Endresen et al.*, 2003].

huge amounts of fuel and emits exhaust gases, which cannot be neglected.

[31] It goes without saying that engine power used in actual service is lower for smaller and medium-sized vessels, but the major contribution in global marine fuel consumption and emissions is determined by the larger vessels in the fleet. This can be demonstrated by the current tanker fleet [*Fearnresearch*, 2003]: from the 2954 registered large tanker above 10,000 dead weight tons (Dwt) (total sum: 228,103 million Dwt), status end of 2003, the 431

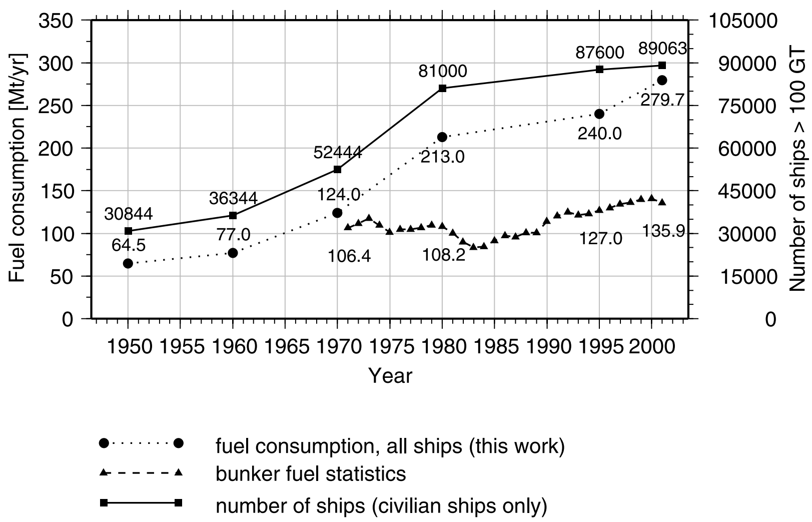

Figure 2. Number of civilian ships (>100 GT) for the time period 1950 to 2001 [*ISL*, 1994; *LMIS*, 2002] as well as the estimated total fleet fuel consumption (civilian, military, and auxiliary) from this work and international marine bunker fuel statistics in million ton of oil equivalents (Mt) (source: *IEA* [2003]).

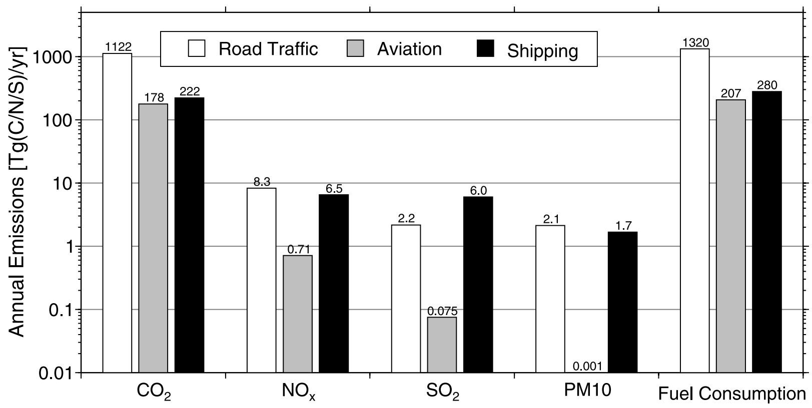

Figure 3. Transport-related annual emissions of CO_2 in Tg (C), NO_x in Tg (N), SO_2 in Tg (S), and PM_{10} in Tg (PM) and the fuel consumption in Mt estimated for the year 2000. PM_{10} from road traffic includes black (BC) and organic carbon (OC) only. For details and references, see text.

largest (=14.5%) with 200,000 Dwt and above constitute 124,990 million Dwt (=55%). The conclusion is that these 431 ships consume more fuel than the remaining 2523 smaller tanker. Should operating times and average engine load of the smaller ships have been assumed somewhat too high, the effect on total fuel amount is limited and lies within the tolerance of the assumptions.

[32] Furthermore, a fuel consumption of 144 Mt for all cargo and passenger ships seems to be very low: for example, the international organization INTERTANKO in their study for UN's GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) has estimated an annual fuel consumption of 62 Mt for the international tanker fleet consisting of 8156 vessels of all tanker categories. Therefore, it is not very likely that all cargo ships and passenger ships together consume only 144 Mt (personal correspondence, INTERTANKO/Oslo, 2002). With an additional 10% add-on for auxiliary engines and 5% add-on for port operations, *Endresen et al.* [2003] estimate the international fuel consumption from cargo and passenger vessels above or equal to 100 GT to be 166 Mt. An average annual engine running hour of 3260 hours per year results when applying equation (2) with the fleet-average values of 2001 (Table 1) and a fuel consumption of 166 Mt, instead of the 280 Mt that has been calculated in this study. This value corresponds to an annual average of 136 vessel days in service and is much lower than all average annual engine running hours published so far [*Endresen et al.*, 2003, 2004; *Corbett and Köhler*, 2003, 2004].

[33] The following calculation demonstrates that the annual worldwide bunker fuel consumption of the world's total fleet cannot be below a 220 Mt level. The civilian fleet's total installed main engine power in 2001 was 286,000 MW [*LMIS*, 2002] and, as a lowest reasonable number for the average engine load, 65% of the maximum installed engine output (MCR) can be assumed. If we further assume an average annual engine running time of approximately 6000 hours and an estimated mean specific fuel-oil consumption rate of all main propulsion engines across the whole fleet of (only) 200 g/kWh, the resulting fuel amount is 223 Mt. It has to be pointed out that this amount does not contain the fuel mass burned by auxiliary engines onboard and by the military fleet.

[34] *Corbett and Köhler* [2004] considered alternative input parameters in their activity-based fuel consumption and emission model. They conclude that alternative assumptions in the input parameters could reduce their estimates, but not more than 14% to 16%. Compared to the *Corbett and Köhler* [2003] estimates our results are slightly lower, but lie within the uncertainties of the activity-based approach [*Corbett and Köhler*, 2004].

[35] It is due to the existing inconsistencies that *Köhler*'s [2002, 2003] and *Corbett and Köhler*'s [2003] work as well as this work are not based on published marine fuel sales figures. Instead, a bottom-up estimate for fuel consumption and vessel activity for the internationally registered fleet was employed, including military vessels. The calculation includes fuel consumptions and emissions not only at sea but also in ports during low-load and idling-modes of the engines and considers consumption rates and emissions of the auxiliary engine equipment.

3.2.2. Comparison to Emissions From Other Transport Modes

[36] The exhaust composition of different transport modes strongly depends on the fuel burned, the size of the engine and additional technological optimizations, e.g., with respect to NO_x emissions. Although shipping contributes only about 16% to the total fuel consumption of all traffic related sources (aviation: 207 Mt, international shipping: 280 Mt, road traffic: 1320 Mt), ship emissions significantly contribute to emissions of pollutants from all transport modes, particularly because there have been no strict international emission regulations in the past as for road traffic and aviation. A summary of current regulations is given in *Eyring et al.* [2005]. For example, sulfur content up of 4.5% (currently still 5.0%) in the fuel-oil for ships will become mandatory, which is well above the levels for kerosene or petrol. A summary of the total fuel consumption, CO_2, NO_x, SO_x and PM_{10} emissions for the year 2000 and a comparison of the three transport modes shipping, aviation and road traffic is given in Figure 3.

[37] We have used the road traffic related emissions of CO_2, SO_2 and NO_x from the EDGAR 3.2 data for the year 1995 and 1990 [*Olivier and Berdowski*, 2001]. To calculate the emissions for the year 2000, we assumed the same average growth rate from 1995 to 2000 as obtained from the EDGAR data for the period 1990 to 1995. A fuel consump-

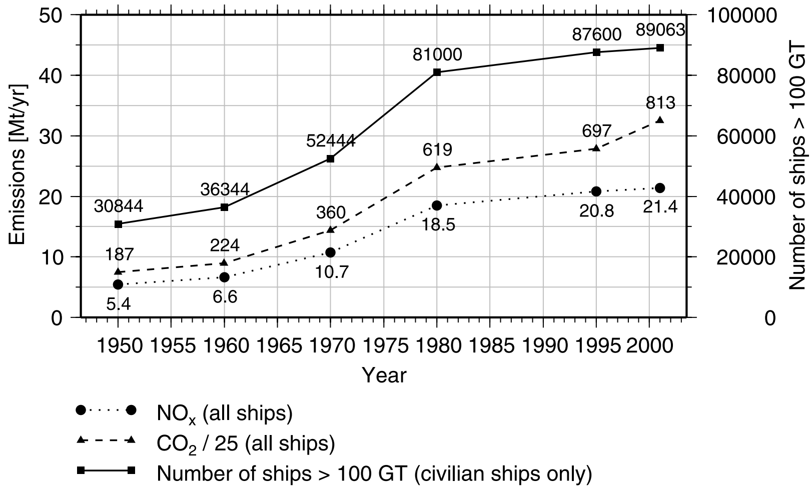

Figure 4. Number of civilian ships (>100 GT) for the time period 1950 to 2001 [*ISL*, 1994; *LMIS*, 2002] as well as the estimated CO_2 emissions in Tg (CO_2) and NO_x emissions in Tg (NO_2). Trend estimates for CO_2 and NO_x for the time between 1950 and 2001 have been calculated by using ship number statistics and average engine statistics as well as the emission estimates for 2001.

tion for road traffic of 1320 Mt has been estimated from the CO_2 emissions using an emission index of 850 g(C)/kg(fuel) following *Olivier et al.* [1996], who assumed an average fuel mix for the whole fleet of 55% gasoline and 45% diesel. The emissions of particulate matter from road traffic are estimated by the sum of black (BC) and organic carbon (OC) given by *Bond et al.* [2004]. Carbonaceous particles are assumed to account for the major amount of PM_{10} emitted by fuel combustion of road traffic. The emissions of NO_x, SO_2, PM_{10} from aviation and the fuel consumption (207 Mt) for the year 2000 are taken from *Tarrason et al.* [2004]. The corresponding CO_2 emissions are calculated from the fuel consumption using the emission index 3.16 kg(CO_2)/kg(fuel) given by *IPCC* [1999]. However, other studies estimate different fuel consumptions for aviation. For example, *Schumann et al.* [2001] suggest total fuel consumption between 200 and 220 Mt per year. This demonstrates uncertainties in current emission inventories.

4. Emissions From International Shipping Over the Past Decades

[38] To estimate past fuel consumption rates of the fleet and, from that, exhaust gas emissions, the method as described in section 2.2 could be used. However, this would require reliable input data such as detailed ship and engine as well as engine performance statistics, none of which are available for earlier decades. The detailed fleet structure before 1970 is not known either, and some of the modern ship types did not even exist in the early 1950s or 1960s. The ship fleet at this time consisted of vessels commissioned in 1940 or even in 1930, equipped with low-efficiency power plants without any existing technical documentation (duty profiles, fuel consumption rates, exhaust gas emissions) which could have been helpful for this study. Needless to say, 40 or 50 years ago, emissions and pollutants from ships were not a topic at all, not even mentioning that the measurement equipments for gaseous or solid trace substances like CO, HC, PM with the necessary accuracy were not available.

[39] What is reliably known as the basis for emission estimates for the past decades is the development of the world civilian shipping in terms of ship numbers and the accumulated associated gross tonnage. In 1950 the civilian fleet consisted of 30,844 vessels of 100 GT and above with a total of 84.6 million GT [*ISL*, 1994]. An indication of the installed engine power onboard early engine-driven ships can be taken from statistics released by UK's trade magazine "The Motor Ship" since 1953. Unfortunately this table lists only the larger vessels above a deadweight tonnage (Dwt) of 2000. Deadweight tonnage is a unit of measurement expressed in tons of the maximum permitted load of a ship, i.e. the weight of cargo, passengers, fuel, stores and crew when loaded down to its maximum summer load line [*ISL*, 1994]. 2000 Dwt roughly equals 1300 GT, whereas this work considers all ships of 100 GT and above. But the mean ship engine output for these larger ships is clearly increasing with time on a long-term basis, even though not with the same percentage on a year-to-year basis. Whereas in 1953 the average ship engine output for a ship of 2000 Dwt and above was 4725 kW, it was 4820 kW in 1960, 6545 kW in 1965, 5900 kW in 1970, 8290 kW in 1975, and 8704 kW in 1978.

[40] For the present work we have estimated historical emissions back to 1950. The results can be seen in Figures 2 and 4. The upper line shows the ship number for all civilian vessels with 100 GT and above. Starting around 1960, the world merchant fleet increased rapidly: the ship number more than doubled in the period between 1960 and 1980. Part of this ship boom was the tanker business, which reached its peak around 1973 – 1975, and the introduction of a new type of cargo ship, the container vessel.

[41] For the estimation of fuel consumption, CO_2 and NO_x emissions the following assumptions were made:

[42] 1. The structure of the ocean-going fleet of the earlier decades, i.e. the classification according to main types of ships, is similar to that of 2001.

Table 4. Changes of the World Fleet Over the Past Decades[a]

		1950	1960	1970	1980	1995	**2001**
Number of ships (>100 GT)		30,844	36,344	52,444	81,000	87,600	**89,063**
Total fuel consumption	Mt	64.5	77	124	213	240	**280**
NO_x	Tg NO_2	5.4	6.6	10.7	18.5	20.8	**21.4**
CO_2	Tg CO_2	187	224	360	619	697	**813**
CO	Tg CO	0.30	0.36	0.58	0.99	1.12	**1.31**
SO_2	Tg SO_2	2.77	3.31	5.33	9.16	10.32	**12.03**
Particulate matter	Tg PM_{10}	0.39	0.46	0.74	1.27	1.43	**1.67**
CH_4	Tg	0.12	0.14	0.23	0.40	0.45	**0.52**
NMHC	Tg	0.78	0.84	1.51	2.58	2.91	**3.40**
Total hydrocarbons	Tg	0.90	1.08	1.74	2.98	3.36	**3.92**

[a]The table summarizes the number of civilian ships (>100 GT), annual fuel consumption of the total fleet (including all civilan and military ships and auxiliary engines), and total emission estimates as calculated in this study.

[43] 2. Merchant and military fleet show similar developments between 1950 and 2001.

[44] 3. The average ship-based engine output for the fleet with ships greater than 100 GT could be exactly calculated for the years 2001 (3.2 MW/ship), 1995 (2.81 MW/ship) and 1980 (2.72 MW/ship) and was extrapolated back to 1950 by taking into account the average propulsive power per vessel for the ships of 2000 Dwt and more as mentioned above.

[45] 4. Slightly lower annual engine running hours as those used for the 2001 calculation (reducing the fleets' total fuel consumption) and lower engine efficiencies of the earlier engine generations (leading to somewhat higher specific fuel-oil consumption rates (SFOC)) are considered. The effects of these two factors nearly compensate each other.

[46] 5. All propulsion engines started-up in 1995 and earlier were strictly fuel-optimized and not NO_x-optimized, resulting in a correspondingly higher NO_x emission factor than for the state-of-the-art emission-regulated ship engines which are part of the fleet in 2001.

[47] 6. For the fleet in 1970 and earlier, the share of steamships was much higher, leading to lower NO_x emissions.

[48] Our estimate started from the exact values for 2001 summarized in Table 1. For earlier years, first the total fleet's accumulated installed engine output (in MW) was calculated by multiplying the corresponding ship numbers with the average engine output per ship (MW/ship). To achieve the engines' fuel amount, the resulting total fleet's accumulated installed engine output was multiplied with the fuel amount (in tons per MW output), burned by the fleet in the preceding year. This fuel amount was corrected by the assumed change in annual running hours and SFOC. Finally, the trend estimates CO_2 and NO_x emissions were determined.

[49] It is worth noting that, while the number of ships between 1995 and 2001 increased on average only by 0.3% per year, the fuel consumption and CO_2 increased by 2.6% (see Figures 2 and 4 and Table 4). The reason is that, on average, the installed engine power per ship in 2001 is higher than in 1995 (3.2 instead of 2.81 MW/ship), leading to higher fuel consumption and CO_2 emission per ship. 14% of the total installed engine power in 2001 is already produced by NO_x-optimized engines which comply with the IMO regulation (with a slight penalty in fuel consumption and, therefore, CO_2), whereas in 1995 the rate of NO_x optimized engines in the fleet was zero. This leads only to a slight increase in NO_x emissions between 1995 and 2001.

[50] The fleet fuel consumption as well as CO_2 and NO_x emissions in Figures 2 and 4 is to be understood as totals for all military and all nonmilitary ships including their auxiliary machineries.

[51] All other emissions (CO, SO_2, particulate matter, methane, and NMHCs) have been scaled with the historical fuel consumption, starting with the 2001 value as calculated in this study. Historical emissions from tanker loading have been determined by applying the ratio between total CH_4 and NMHC from tanker loading as calculated by *Endresen et al.* [2003] to the emissions from fuel combustion as calculated in this work. All results for the years 1950, 1960, 1970, 1980, 1995 and 2001 are summarized in Table 4.

5. Summary and Conclusions

[52] Total fuel consumption and emissions of the world fleet have been derived with an activity-based approach for the year 2001, following the method of *Köhler* [2002, 2003] and *Corbett and Köhler* [2003]. The estimate is based on statistical information of the total fleet greater than 100 GT including the larger military vessels and auxiliary engines [*LMIS*, 2002]. Our results suggest fuel consumption of approximately 280 million metric tons (Mt) for the year 2001, which is very similar to a previous bottom-up approach of 289 Mt [*Corbett and Köhler*, 2003] and which lies within the uncertainties of an activity-based approach [*Corbett and Köhler*, 2004]. This corresponds to 813 Tg CO_2 and 21.4 Tg NO_x emissions in 2001. Compared to previous activity-based studies, a detailed speciation of nonmethane hydrocarbons (NMHCs) and particulate matter is given and carbon monoxide emissions are calculated explicitly. As new measurements of HC and PM_{10} emission factors at the engine test beds became available meanwhile, the calculated total emissions are slightly higher than the *Corbett and Köhler* [2003] estimate. All other emissions and the total fuel consumption are slightly lower due to a smaller average engine load for cargo vessels, which has been identified to be one of the major uncertainties in the *Corbett and Köhler* [2003] estimate [*Corbett and Köhler*, 2004]. Our detailed calculations allow us to estimate the fleet-average emission factors for the total ocean-going fleet in 2001 for each pollutant. We are using these fleet-average emission factors in part 2 of our study [*Eyring et al.*, 2005] to develop plausible technology scenarios for the future.

[53] Recently, *Endresen et al.* [2004] questioned the *Corbett and Köhler* [2003] results, and argue that the estimated fuel consumption of 289 Mt is too high. However,

following some very strict assumptions on fleet average values we conclude that realistic fuel consumption for the year 2001 must be at least 220 Mt per year. Furthermore, a fuel consumption of less than 200 Mt would result in unrealistically low average engine hours. A comparison of the development of bunker fuels and the number of ships above 100 GT shows a discrepancy: during the time period of a rapid increase of the fleet in terms of number of ships, marine bunker statistics surprisingly do not increase significantly. Due to the existing inconsistencies this work is not based on published marine fuel sales figures, but on a bottom-up estimate for fuel consumption and vessel activity for the internationally registered fleet.

[54] The main uncertainties in our estimate appear for the emissions of HCs, particulate matter and CO. Very few measurements of emission factors are available for those emissions, as they have not been of relevance for ship operators so far. Further measurements under different engine loads at the engines test beds would help to clarify uncertainties. Both measurements and modeling studies of ship plume chemistry under different meteorological conditions are necessary to achieve more accurate input data for the speciation of emissions. For example, very little about the speciation of NMHCs into sub-groups and about the composition of particulate matter is currently known. In our study the speciation of NMHCs into 10 sub-groups is based on a single study [*Cooper et al.*, 1996].

[55] Although shipping contributes only about 16% to the total fuel consumption of all traffic related sources, ship emissions significantly contribute to emissions of pollutants from all transport modes. The ocean-going fleet produces about 9.2 (0.8) times more NO_x emissions than aviation (road traffic), but due to a high sulfur content in the fuel about 80 (2.7) times more SO_x emissions. Shipping emits approximately 1200 times more particulate matter than aviation. The comparison of total emission from different transport modes demonstrates that clear information is needed on the climate impact of ship emissions, to allow the industry to incorporate, with greater confidence, environmental considerations into their design and development work. *Schlager and Pacyna* [2004] summarize the major impacts of shipping on the atmosphere to be the overall radiative forcing and unregulated CO_2 emissions. The total amount of emitted particulate matter and SO_x from shipping could possibly modify existing clouds in the marine boundary layer and could contribute to the indirect aerosol effect.

[56] Trend estimates for fuel consumption, CO_2, NO_x and other emissions for the time between 1950 and 2001 have been calculated by using ship number statistics and average engine statistics. Our results suggest fuel consumption of approximately 64.5 Mt in 1950, which corresponds to 187 Tg CO_2 and 5.4 Tg NO_x. A rapid increase in the number of ships and a corresponding rapid increase in fuel consumption are present from 1970 to 2001. Uncertainties in our estimate arise from the fact that reliable input data such as detailed shipping and engine as well as engine performance statistics, and the fleet structures before 1970 are not known.

[57] To distribute global emissions over the globe we have used the AMVER data set [*Endresen et al.*, 2003], which is based on the relative reported frequency of different ship types. *Corbett and Köhler* [2003, 2004] point out that the AMVER data set may represent the distribution of cargo ships very well. Nevertheless we see the need of further research as there are substantial regional differences between the AMVER and COADS vessel traffic densities. *Richter et al.* [2004] show that the pattern of satellite SCIAMACHY NO_2 data is in good agreement with the inventory, although the inventory does not for example capture the slope of the lane between Sri Lanka and Sumatra and is clearly too far east of the coast of Singapore. This reflects possible uncertainties of the geographical location of major ship routes.

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