Emissions from Ships

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The International Maritime Organization (IMO) has recently made the first attempts to address air pollution from ships (*1*). Multinational policies will likely be implemented soon; these will have broad implications for international law and trade. Here we show that ships are a significant source of air pollution on a global scale and discuss the policy implications.

Global Inventory of Emissions

The world's ships are primarily powered by diesel engines. Diesel engines consume less fuel than other propulsion systems (*2–3*) and have replaced most of the steam turbine systems that were dominant in the 1940s (*4*). Most marine fuels, or bunkers, are residual fuels. Since the 1973 fuel crisis, crude oils have been processed using secondary refining technologies to extract the maximum quantity of refined products (distillates). As a consequence, the concentration of contaminants such as sulfur, ash, asphaltenes, and metals in the residuals has increased (*5–6*). Other ship fuels are distillate oils of higher grade; however, these often are blended with residual oils. Most commercial shippers (70 to 80%) prefer to use the cheaper residual fuels (*7*).

We used data from three primary sources to assess global ship emissions: (i) marine exhaust emission test data (*8–9*) that report fuel-based emission rates for sulfur and nitrogen; (ii) international marine-fuel usage information (*10*); and (iii) the engine characteristics of the world's registered commercial ships weighing 100 gross registered metric tons or more (*11*) and those of naval ships (*12*). The total world fleet includes approximately 55% slow-speed diesel, 40% medium-speed diesel, and 5% other engine types (see Table 1).

On average, 57 kg of NO_x are released per ton of fuel by medium-speed engines and 87 kg NO_x per ton by slow-speed engines (*8*). NO_x emissions depend on the type of combustion system (because of peak temperatures) and to a lesser extent on the nitrogen content in the fuel. In contrast, sulfur emissions depend solely on the fuel's sulfur content. Sulfur dioxide (SO_2) emissions (in kg) follow an empirical relationship: SO_2 per ton of fuel = 20 × (S%), where S% is the percent of sulfur contained in the fuel (*8*). Bunker fuel sulfur content varies from 2.1 to 5% by weight (*13*). We used the following equation to obtain total emissions from shipping:

$$P_P = \sum_{i=1}^{n} E_{P,i} \cdot (F \cdot A_i)$$

P_P is the total propulsion emissions for pollutant P (either nitrogen or sulphur); $E_{P,i}$ is the fuel-based pollutant emission factor based on engine type (for nitrogen) or fuel type (for sulfur); F is the annual marine fuel (bunkers) used; A_i is the percent of all vessels with each engine type (for NO_x) or with each fuel type (for SO_x); i is for NO_x calculation (engine type: 1, slow-speed; 2, medium-speed; 3, steam/other) and for the SO_x calculation (fuel type: 1, residual bunkers; 2, other bunkers); n, number of categories: three engine types for NO_x; two fuel types for SO_x.

In addition to the emission factors given above for diesel engines (*8*), we used a rate of 8.8 kg of NO_x per ton of fuel for steam turbine emissions. This rate is conservative, as it was derived from a study (*14*) reporting only low-load emissions at the dock. To estimate global NO_x emissions, we weighted marine fuel use by the percent of marine engines of each type. Our best estimate for annual emissions are 10.12 teragrams (Tg) of NO_x per year (3.08 Tg N/year) and 8.48 Tg of SO_x per year (4.24 Tg S/year), using the European average sulfur level of 3.3% for residual fuels (*13*) and the maximum sulfur level of 2% for marine diesel oil.

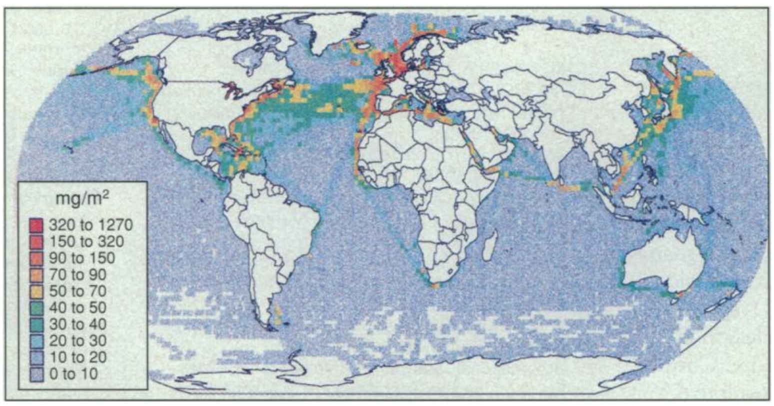
World Ship Engine Profile		
Engine type	**Military**	**Commercial**
Slow-speed diesel	1,289	56,628
Medium-speed diesel	14,940	27,758
Steam and others	3,417	1,820
Total	19,646	82,206

Table 1.

To examine the geographic distribution of emissions, we averaged global vessel traffic densities (*15*) for various engine types over a 2° by 2° grid (see the figure). Cargo ships are the largest polluters (Table 2).

Worldwide ship nitrogen emissions are equal to 42% of nitrogen emissions from North America, nearly half of the total emissions from the United States, 74% of emissions from Organization for Economic Cooperation and Development (OECD) Europe, and 190% of those from East and West Germany (*16*). They are equal to 87% of nitrogen emissions from U.S. stationary sources and equal to 100% of those from U.S. mobile sources. Ship sulfur emissions equal 35% of sulfur emissions from North America, 43% of total sulfur emissions from the United States, 53% of emissions from OECD Europe, and 178% of those from Germany. Most of the continental sulfur emissions are from stationary sources.

Ship emissions account for 14% of nitrogen emissions from fossil fuels (*17*) and 16% of all sulfur from petroleum uses. Ship sulfur accounts for 5% of sulfur emitted by all fuel combustion sources. This is equivalent to 10% of sulfur from hard coal combustion and 45% from lignite combustion. Carbon dioxide emissions from ships are only 2% of the 6000 Tg of carbon emitted from fossil fuel use (*18*). Ship engines are thus among the world's highest polluting combustion sources per ton of fuel consumed.



Annual ship sulfur emissions (*34*).

These estimates indicate that ship emissions affect global background pollution levels of nitrogen and sulfur. Ship emissions, occurring mostly in the Northern Hemisphere, are equal to approximately 20% of global estimates for natural marine sulfur sources (*19*). Aged marine air is more polluted over the northern Pacific than over the Southern Pacific (*20*). Although this pattern is generally attributed to persistent continental pollution, anthropogenic emissions from ships provide an alternate explanation. Moreover, models used to predict atmospheric SO_2

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levels often under-predict the concentrations measured over remote ocean areas (*21*). In some regions of the Northern Hemisphere, sulfur emissions from ships can be of the same order of magnitude as modeled estimates of the flux of dimethyl sulfide (DMS) (*19*); in the Southern Hemisphere, ship emissions are much lower than the DMS flux.

Ship emissions may contribute to pollution hundreds of kilometers inland. Emitted SO_2 and NO and their atmospheric oxidation products are thought to have residence times of ~1 to ~3 days, which are consistent with mean transport distances of ~400 to ~1200 km (*22*).

World Fleet (1996) and Emissions by Vessel Type				
	Contribution to fleet (%)		Percent of ship emissions	
Vessel type	Ships	Tonnage	N	S
Transport	42	86	69	73
Bulk cargo	15	67	33	35
General cargo	23	18	31	32
Passenger	4	<1	5	6
Nontransport	58	14	31	27
Fishing	23	1	7	7
Service craft	15	1	10	10
Military	19	11	13	9
Other	1	1	1	1

Table 2 (*31–33*).

Policy Implications

Global emission limits were approved by the IMO diplomatic session in September 1997. NO_x regulations will apply only to new ships or major ship conversions on or after 1 January 2000. With a 1.5% yearly fleet replacement rate (*23*), a measurable reduction in nitrogen emissions will not occur for many years. For NO_x controls that reduce individual ship emissions by 30 to 50%, IMO regulations would reduce total emissions by less than 1% per year based on current fleet size. Current IMO language limits fuel sulfur levels to 4.5% (*1*). This provides little reduction, if any, in sulfur and practically codifies the status quo, because ISO limited fuel to 5% sulfur in 1987 (*6*). In spite of these limitations, both of these global regulations are valuable, because adoption of the IMO regulations means that a multinational consensus has been achieved on the principles of ship emission control.

The IMO named the Baltic Sea the first SO_x Emission Control Area. However, the Baltic Sea accounts for only 19% of the 465 thousand tons of annual ship sulfur emissions within 400 km of land in the region, where ship sulfur is 2.1 times the combined total domestic sulfur emissions of Norway, Denmark, Sweden, and Finland [217,000 tons (*16*)]. If even 50% of these sulfur emissions fall out before reaching land, the surviving sulfur pollution nearly doubles the atmospheric sulfur produced in these four nations.

Another problem is that many different nations register ships. The top 20 of 206 nations with registered vessels account for 56% of the world's ships (*11*) and 55 to 65% of global ship nitrogen and sulfur emissions. However, 10 of these nations are considered foreign registers, because vessel ownership is in another nation. Foreign flag registry has increased recently (*23*). In other words, emissions from ships attributed to nations of registry would be substantially different than emissions from ships attributed to nations of ownership. Enforcement aimed at registering nations may inadvertently shift foreign nation registry selection by vessel owners instead of achieving reduction goals.

Open-market interests and treaty commitments may also limit effective emission control. Moreover, water transportation of cargo produces lower emissions (per ton moved) than other modes of transport (*24*). Without attention to these policy issues, the potential exists to affect the flow of trade in unplanned ways.

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31. We used brake horsepower data as an indicator of relative fuel consumption. For commercial ships, all vessels operate along similar engine duty cycles (*25, 26*). On average, military ships operate below 50% power for 90% of the time that they are under way (*27*); moreover, they spend as much as 60 to 70% of their time in port (*28*). Typical deployment rates for the U.S. Navy range between 40 and 55% (*29*); we used an average military vessel deployment of 50%. We estimated NO_x emissions from military ships by multiplying the brake horsepower by 22.5%, which represents the product of the percent load and the percent time deployed. Up to 65% of the world's navies use lower-grade (higher-sulfur) fuels (*30*); more developed navies, particularly those of the North Atlantic Treaty Organization (NATO), use higher distillates with lower sulfur content. Therefore, we multiplied the military fuel-use factor derived for NO_x emissions by 65% to estimate military vessel SO_x emissions. Nontransport ships emit much less because most have less brake horsepower and fewer military ships use diesels or high-sulfur fuels (*32*).
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33. Total values: Oceangoing ships, 105,854; fleet size, 771 million deadweight tons (DWT); nitrogen emissions, 3.08 Tg of N; sulfur emissions, 4.24 Tg of S.
34. The quantile scale provides greater contrast and resolution of flux in the regions nearer land.

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